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Concrete upgrade to improve the vibration response of timber floors

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Timber floors suffering from poor serviceability performance can be upgraded with a concrete topping to form a timber–concrete composite. The upgrade stiffens the floor, reducing the perception of a vibration response to dynamic excitation. Despite timber–concrete composites becoming an established research area in recent years, relatively little is known about the vibration response of these floor types. This paper explores how the vibration response of a timber floor changes when upgraded with a concrete topping, with particular attention given to the fundamental frequency of vibration. An analytical model, utilising the gamma method of Eurocode 5 (EN 1995-1-1), is used to predict how the fundamental frequency of vibration changes with the addition of a topping. The model is compared with experimental testing of timber–concrete panels before it is used to conduct a parametric study to establish the effect of common factors. It is found that high interaction between the topping and timber floor, identifying a suitable topping thickness and considering the change in transverse stiffness are key to a successful upgrade. It is suggested that topping upgrades which are thin (20 mm or less) are suitable for this application.

Notation

A_i	cross-sectional area of timber or topping
b	breadth of floor
b_i	breadth of timber or topping
c_p	a dimensionless parameter representing the ratio of timber and topping breadths and modular ratio
d	log diameter
E_i	modulus of elasticity of timber or topping
$(EI)_b$	transverse plate bending stiffness
$(EI)_l$	longitudinal plate bending stiffness
EI_{max}	fully composite effective bending stiffness
e	depth of interlayer
$f_{1,1}$	fundamental frequency (first modal frequency)
f_{TCC}	first modal frequency of a timber–concrete composite panel
f_t	first modal frequency of a timber panel

g_k	characteristic superimposed dead load
h_i	depth of timber or topping
I_i	second moment of area of timber or topping
j	mode number
K_{ser}	connector serviceability slip modulus
l	span of panel or floor
m	mass per unit area
NA	distance of neutral axis from underside of timber joist
s	connector spacing
γ	shear bond coefficient
ρ_i	mean density of timber or topping

Subscripts

c	topping
t	timber

1. Introduction

Timber floors are present in a large proportion of existing residential and office buildings. Occupants with these floor types are known to complain that some floors have insufficient stiffness and suffer from vibration serviceability problems. An existing, cost-effective solution (Steinberg *et al.*, 2003) is to upgrade the floor by first fixing shear connectors into the floor joists before placing a concrete topping. The resulting composite is lighter than a reinforced concrete slab and stiffer than a timber-only floor, with the concrete acting in combined compression and bending, and the timber in combined tension and bending. Other advantages of this system include improved airborne sound transmission compared to timber floors, owing to the increased mass and improved load-carrying capacity (Ceccotti, 2002; Fragiacomo, 2012). Although many researchers have commented that the addition of a concrete topping also improves the vibration performance of timber floors (Ceccotti, 1995; Deam *et al.*, 2007; Fragiacomo and Lukaszewska, 2011; Steinberg *et al.*, 2003), relatively little is known about how the vibration response of a timber floor changes with the addition of a topping. This is despite the vibration performance governing some timber–concrete composite floor designs (Toratti and Kevarinmäki, 2001).

Current research at the University of Bath is investigating the upgrade and refurbishment of existing floors with thin concrete toppings (less than 20 mm). Thin topping upgrades add less permanent load to the existing structure than conventional toppings and minimise the change in finished floor level to ceiling height while providing a significant increase in the bending stiffness of the floor. A key aim of the research project is to understand how the vibration response of a timber floor can be improved with the addition of the topping.

The vibration performance of office and residential timber floors relates to the human perception of occupant-induced excitation. Excitation is caused by footfall, characterised as a series of impacts with each resulting in a transient vibration response. Researchers agree that the magnitude of the response, its frequency components and damping characteristics are the most critical factors to affect the human perception of vibration (Rijal *et al.*, 2011). Generally, vibrations of a low magnitude, high frequency and short duration are least perceptible to occupants and this is reflected in design guidelines (CEN, 2004a; ISO, 1989).

Timber and timber–concrete composite (TCC) floors are classified as high-frequency floors (Toratti and Kevarinmäki, 2001) as they are light and stiff enough to ensure that the fundamental natural frequency at which they vibrate is above 8 Hz. Below 8 Hz there is the possibility of resonance as the forcing frequency of footfall and the frequency of the response coincide. The fundamental frequency at which a timber floor vibrates is proportional to the square root of the bending stiffness of the floor divided by its mass per unit area (Equation 1). Adding a topping to a timber floor increases the bending stiffness and mass of the floor, and researchers have found that the increased mass can outweigh the beneficial increase in stiffness, resulting in a lowering of the fundamental frequency (Ghafar *et al.*, 2008; Hu *et al.*, 2001). Timber floors behave in an orthotropic manner but with a concrete topping the stiffness perpendicular to the direction of the joists is increased and the behaviour is more akin to a ribbed plate. As a result the higher modes of vibration have greater separation than a timber floor, which reduces the perceptibility of the vibration response (Mertens *et al.*, 2007)

$$f_{1,1} \propto \left[\frac{(EI)_1}{m}\right]^{1/2} \tag{1}$$

Damping, an important consideration in the vibration response of floors, is not well understood for timber floors and less so for timber–concrete floors. EN 1995-1-1, CEN, 2004a suggests designers allow 1% damping in residential timber floors, whereas the UK National Annex advises 2%. Measured damping ratios for TCC floors and beams have ranged from 1·0% to 7·5% in testing, depending on type and spacing of connectors and whether prefabricated or cast-in-situ concrete slabs were assessed (Fragiacomo and Lukaszewska, 2011; Ghafar *et al.*, 2008; Rijal *et al.*, 2011).

Predicting the change in a transient vibration response owing to an upgrade is dependent on understanding how the magnitude of the response, frequency components and damping are affected. The equations proposed by Ohlsson (1988) and which appear in EN 1995-1-1, CEN, 2004a require both the change in stiffness, damping and mass to be known to calculate the overall change in response. When upgrading a timber floor with a concrete topping, the change in mass of the floor is significant whether a thick or thin topping is used. This means that even the addition of a very thin topping will have a meaningful effect on the magnitude of the transient vibration response. However, there is a risk that if insufficient interaction is achieved between the topping upgrade and the existing floor, the fundamental frequency will decrease such that the floor will respond in a resonant manner to dynamic excitation. A resonant response would result in a response with amplified amplitude and consequently be more perceptible to occupants. In addition, high-frequency vibrations are generally less perceptible to occupants (ISO, 1989). For these reasons the fundamental frequency is considered the most important parameter to investigate.

This paper considers how the fundamental frequency of vibration changes when a timber floor is upgraded to a TCC floor. A simple analytical method, utilising the so-called γ-method from EN 1995-1-1, CEN, 2004a, Annex B, is developed to predict the change in fundamental frequency of a T-beam. The method is then compared with experimental test results of TCC panels before the theoretical analysis is expanded to a parametric analysis identifying appropriate topping thicknesses for upgrade and the sensitivity of the analysis to common factors. Finally, comment is made on the change in transverse stiffness of an upgraded floor.

2. Analytical method

2.1 Predicting the change in fundamental frequency of a composite beam

Clause 7.3.3.4 of EN 1995-1-1, CEN, 2004a provides an equation for predicting the natural frequency for a timber floor simply supported on all sides. This equation, reproduced below as Equation 2, has been formed following several simplifications of an equation derived by Hearmon (1946) for the frequency of vibration of an orthotropic rectangular plate simply supported on all sides. Hearmon's equation was simplified to Equation 3 by Ohlsson (1988) by assuming the torsional rigidity of a timber floor is approximately equal to the transverse stiffness. Equation 2 was then formed by presuming that the ratio of transverse and longitudinal stiffness of a timber floor is always small, leading to the second square root term of Equation 3 equalling 1. As these assumptions are also true for a simply supported beam, Equation 2 is appropriate for calculating the fundamental frequency of simply supported TCC beams

2. $$f_{1,1} = \frac{\pi}{2l^2}\left[\frac{(EI)_1}{m}\right]^{1/2}$$

3. $$f_{1,j} = \frac{\pi}{2l^2}\left[\frac{(EI)_1}{m}\right]^{1/2} \times \left\{1 + \left[2j^2\left(\frac{l}{b}\right)^2 + j^4\left(\frac{l}{b}\right)^2\right]\frac{(EI)_b}{(EI)_1}\right\}^{1/2}$$

For upgrade of an existing floor it is useful to be able to predict the change in fundamental frequency based on knowing the performance of the existing timber beam and the topping that will be added. This is described by Equation 4

4. $$\Delta f_{1,1} = \left(\frac{f_{\mathrm{TCC}}}{f_{\mathrm{T}}} - 1\right) \times 100\% = \left\{\left[\frac{(EI)_{\mathrm{TCC}} m_{\mathrm{t}}}{(EI)_{\mathrm{t}} m_{\mathrm{TCC}}}\right]^{1/2} - 1\right\} \times 100\%$$

where $(EI)_{\mathrm{t}}$ is the bending stiffness of the timber floor, $(EI)_{\mathrm{TCC}}$ is the effective bending stiffness of the TCC beam and m_{t} and m_{TCC} are the mass of the timber and TCC beam respectively.

2.2 Change in bending stiffness and change in mass

The effective bending stiffness of a TCC beam is determined by the dimensions and material properties of the timber and topping components and the interaction achieved between them. Shear connectors, joining the components together, resist slip at the adjoining interface as the beam undergoes bending, creating interaction between the parts. Various types of shear connector have previously been experimentally characterised including: screws (Steinberg *et al.*, 2003), angel brackets (Deam *et al.*, 2007), notches (Yeoh *et al.*, 2011) and proprietary connectors (Fragiacomo *et al.*, 2006; Fragiacomo and Lukaszewska, 2011). The resistance to slip provided by the connectors is a product of the connector slip stiffness and their spacing. The effective bending stiffness of the composite section is calculated using the γ-method in Annex B of EN 1995-1-1, CEN, 2004a in conjunction with the section, material and connector properties.

Based on an approximate solution of the differential equation for beams with partial interaction, the γ-method procedure calculates the effective bending stiffness by Equation 5

5. $$(EI)_{\mathrm{ef}} = E_{\mathrm{c}}I_{\mathrm{c}} + \gamma E_{\mathrm{c}}A_{\mathrm{c}}a_1^2 + E_{\mathrm{t}}I_{\mathrm{t}} + E_{\mathrm{t}}A_{\mathrm{t}}a_2^2$$

where E_i, I_i and A_i are the modulus of elasticity, second moment of area and cross-sectional area respectively (topping is denoted by $i = \mathrm{c}$ and timber, $i = \mathrm{t}$). The distances between the centroids and neutral axis of the timber section, a_1 and a_2, are given by Equation 6 and 7

6. $$a_1 = \frac{h_{\mathrm{c}} + h_{\mathrm{t}}}{2} + e - a_2$$

7. $$a_2 = \frac{\gamma E_{\mathrm{c}}A_{\mathrm{c}}(h_{\mathrm{c}} + h_{\mathrm{t}} + e)}{2(\gamma E_{\mathrm{c}}A_{\mathrm{c}} + E_{\mathrm{t}}A_{\mathrm{t}})}$$

where h_c, h_t and e denote the thickness of the topping, height of the joist and depth of the floorboards respectively. The shear bond coefficient, γ, is expressed by Equation 8

$$8. \quad \gamma = \frac{1}{1 + (\pi^2 E_c A_c s / K_{ser} l^2)}$$

where s, l and K_{ser} represent the spacing of the connectors, span of the beam and slip modulus of the connectors at 40% of their maximum load respectively. For beams with connectors spaced in proportion to the shear force along the beam an effective spacing (Equation 9) can be used

$$9. \quad s = s_{ef} = 0{\cdot}75 s_{min} + 0{\cdot}25 s_{max}$$

Van der Linden's dimensionless parameter, C_p (Equation 10), (Van der Linden, 1999) describes the aspect ratio of a TCC beam. Typical traditional UK timber floors upgraded with a topping have a C_p between 16 and 32, whereas a cross-laminated timber–concrete composite floor has a C_p of approximately 3

$$10. \quad C_p = \frac{E_c}{E_t} \frac{b_c}{b_t}$$

Critical to the increase in bending stiffness is the thickness of the topping, which is often chosen so that the neutral axis of the composite section lies at the interface of the timber and concrete. This approach utilises the strengths of each material by ensuring that the topping solely acts in compression and the timber in combined tension and bending. However, it ignores the magnitude to which the bending stiffness of the section increases as the concrete is added. Figure 1 demonstrates how as the topping thickness is initially increased, the neutral axis moves rapidly up through the section before slowing and becoming almost linear thereafter. This in turn affects the rate at which the bending stiffness of the section increases as the topping depth is increased (Figure 2). For floors with a C_p between 16 and 32, typical of traditional UK floors, a 20 mm topping increases the bending stiffness by between 150% and 200%, which is sufficient for most practical upgrade scenarios; for example, change of use from residential to office occupancy.

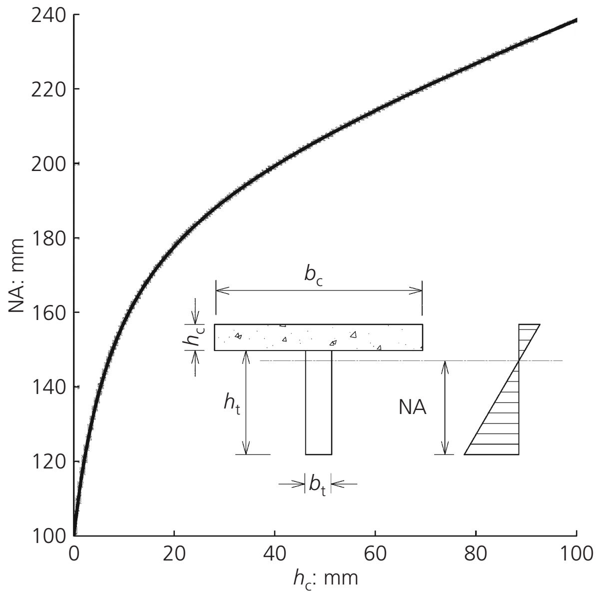

Figure 1. Change in neutral axis (NA) position for a typical UK joist as concrete topping depth is increased, full composite action assumed $C_p = 24$, $h_t = 200$ mm

In contrast to the change in bending stiffness, the change in mass is linear with topping thickness. The difference in mass between a traditional UK timber floor and a concrete topping is very large. In Table 1 the mass of the components in a typical floor are listed; the sum is equal in mass to a topping which is 12·3 mm thick and has a density of 2200 kg/m^3. Therefore the mass of the upgraded floor is much greater than the original timber floor, for practical topping thicknesses, and consequently the change in the magnitude of the transient vibration response will always be meaningful.

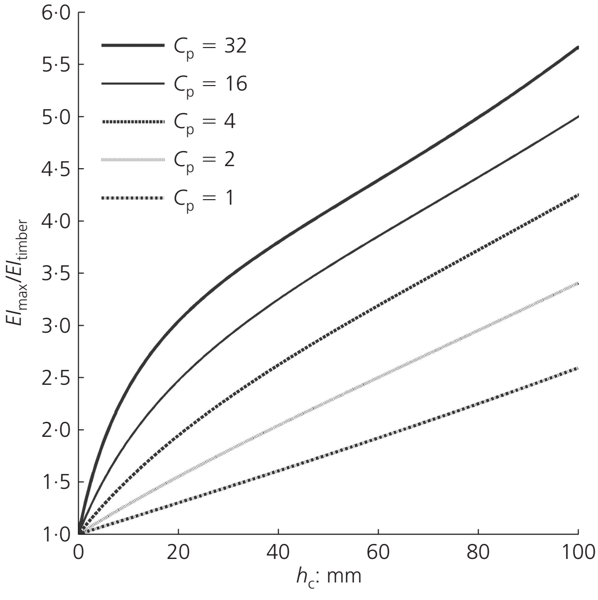

Figure 2. Change in stiffness, $h_t = 200$ mm

Description	Mass: kg/m^2
18 mm thick floorboards	7·0
200 × 50 mm joist @ 400 c/c	9·8
Plasterboard and skim	10·2
Total	27·0

Table 1. Mass of a typical UK timber floor

3. Experimental comparison

To compare the analytical model with experimental test results two types of panels were constructed. Type 1 panels were constructed and tested at the University of Bath as part of the ongoing thin topping TCC research project. Type 2 specimens were constructed and tested at the University of Coimbra as part of a project investigating the utilisation of Portuguese Maritime Pine round wood logs in TCC floors.

3.1 Panel specification and construction

Type 1 panels were constructed from two 4·8 m long 170 × 44 C24 joists, spaced at 400 mm c/c, spanning 4·5 m and boarded with 18 mm thick particleboard. The panels were covered with a plastic membrane before 6 mm diameter inclined screws, acting in tension, were installed as shear connectors. The slip stiffness of the connectors was evaluated in a separate study (Skinner *et al.*, 2013) and the relevant results are reproduced in Table 2, alongside the mean modulus of elasticity of the joists in each panel. The upgrade was completed by placing a 20 mm thick topping over the panels. The mean flexural and compressive strength of the topping was established from 40 × 40 × 160 mm prisms which were tested using BS EN 1015-11 (CEN, 1999). At testing, the topping had a mean modulus of elasticity of 41·2 kN/mm^2 (calculated according to EN 1992-1-1 (CEN, 2004b)) and mean compressive and flexural strengths of 70·5 N/mm^2 and 7·6 N/mm^2 respectively.

Beam No.	E_t: kN/mm^2	Screw inclination	s: mm	K_{ser}: N/mm
1–1	14·0	45°	100	4340
1–2	13·4	35°	100	4150
1–3	12·5	45°	75–225	4340

Table 2. Type 1 TCC beam specification

Type 2 panels were constructed from single maritime pine round-wood logs which varied in diameter and length. Shear connectors were fixed at an even spacing along each log and a 500 mm wide 50 mm concrete topping was placed on top. The dimensions of each log were established according to EN 14251 (CEN, 2003). Two types of shear connectors were used: crossed screws inserted at 45° (with a head diameter of 12 mm and a length of 100 mm divided in two parts: a shank part with a length of 33 mm and 4 mm diameter and the threaded part with 61 mm and 6 mm) and 8 mm steel dowels (obtained from concrete reinforcement steel bars of steel grade S500) inserted by hammering the fastener perpendicular to the timber logs. The slip modulus of each connector type was established in a separate study (Dias and Martins, 2012) and the relevant results, alongside the modulus of elasticity, diameter and length of the logs, are recorded in Table 3. A lightweight concrete mix was used for the topping; details of the mix and mechanical properties can be found in Table 4. Cross-sections of each specimen type are illustrated in Figure 3.

Beam No.	l: mm	d: mm	E_t: kN/mm^2	Connector type	s: mm	K_{ser}: N/mm
2–1	2655	152	13·5	Crossed screws	200	11 500
2–2	2640	160	12·1			
2–3	2645	148	14·0			
2–4	2690	156	16·3	8 mm dowel	100	7400
2–5	2555	122	7·8			
2–6	2720	122	11·1			

Table 3. Type 2 TCC beam specification

Component	Mass: kg/m^3	Mechanical property	Value
Sand	465·5	Density	1830 kg/m^3
Coarse aggregate	831·2	Compressive strength	12·7 N/mm^2
Cork 0/3 mm	16·2	Modulus of elasticity	18 100 N/mm^2
Cork 3/10 mm	12·4		
Cement 42·5 Type 1	300·0		
Water	192·2		

Table 4. Type 2 concrete topping

3.2 Testing methodology

Each panel underwent vibration testing before and after the topping was added. The panels were simply supported at their ends while clamps were used to provide some torsional restraint. They were subjected to excitation by way of a quick release

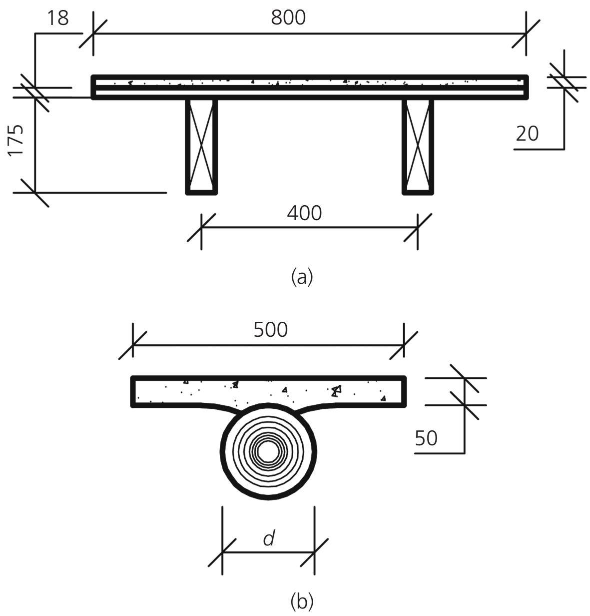

Figure 3. Specimen dimensions: (a) type 1 specimen; (b) type 2 specimen (all dimensions in mm)

method which provided the specimens with an initial displacement from a mass hung from the underside. When the cable suspending the mass was cut, the panel rebounded causing them to vibrate freely. The acceleration time response of the panels was measured by accelerometers mounted on the top and underside of the specimens. The fundamental frequency of each panel was found by transforming the data from the time domain to the frequency domain, using the Fast Fourier transform method.

3.3 Results

Results for each panel are presented in Table 5 alongside predicted fundamental frequencies. Predicted values, marked *, were estimated from the measured effective bending stiffness (established from a typical non-destructive ramp loading test) rather than the γ-method, as it was found that in these beams the γ-method provided an imprecise prediction of the beams' stiffness. The correlation between experimentally measured fundamental frequencies and values predicted using the measured effective bending stiffness was acceptable; values differed between 0·2% and 10·3%, whereas the correlation between experimental measured fundamental frequencies and values predicted using the effective bending stiffness from the γ-method was less satisfactory; values differed between 14·3% and 26·6%. As the γ-method usually provides a very good estimate of the effective bending stiffness of TCC beams (Ceccotti *et al.*, 2006; Fragiacomo, 2012; Fragiacomo and Lukaszewska, 2011; Persaud and Symons, 2005; Yeoh, 2010), the theoretical approach discussed so far, although not accurate for these panels, has worthwhile application in many TCC systems.

For both types of panel the fundamental frequency of vibration decreased with the addition of the concrete topping, which was as predicted (using the measured effective bending stiffness). This was because the interaction achieved between the topping and timber was relatively low and the mass of the topping compared to the timber was high, even for specimens with the lightweight topping. However, interaction is easier to achieve in panels with longer spans (Van der Linden, 1999) and as floors with these spans are most likely to have vibration problems, the poor interaction observed in these tests should not be of concern.

4. Parametric analysis

Although the experimental results did not validate the theoretical approach, this was because the effective bending stiffness of the panels could not be accurately predicted using the γ-method. However, since the γ-method is usually a good estimate of the effective bending stiffness of TCC beams (Ceccotti *et al.*, 2006; Fragiacomo, 2012; Fragiacomo and Lukaszewska, 2011; Persaud and Symons, 2005; Yeoh, 2010) the approach has merit and is now expanded to explore the effect of various parameters. The aim of the parametric analysis is twofold. First, to understand the topping thicknesses at which a significant increase in fundamental

Beam No.	Experimental timber f_1: Hz	Experimental TCC f_1: Hz	Experimental Δf_1: %	Predicted Δf_1 (exp. EI_{ef}): %	Predicted Δf_1 (analyt. EI_{ef}): %
1–1	14·4	13·2	−8·5	−15·7*	6·1
1–2	15·3	13·2	−13·4	−9·4*	6·3
1–3	15·6	12·5	−20·0	−16·1*	0·4
2–1	33·3	27·0	−18·9	−8·6*	−36·7
2–2	33·8	30·0	−11·2	−5·2*	−37·4
2–3	28·8	26·7	−7·3	−13·3*	−28·8
2–4	31·7	29·3	−7·6	−12·2*	−29·4
2–5	33·9	25·8	−23·9	−23·5*	−38·2
2–6	28·1	27·3	−2·8	−3·0*	−29·4

Table 5. Comparison between predicted and experimental fundamental frequency

frequency is achieved so as to avoid resonance and reduce the perceptibility of the transient vibration response. Second, to investigate how the shear bond coefficient, semi-permanent load and joist depth affect the change in fundamental frequency. As the analysis cannot be non-dimensional, a specific case was considered, from which parameters were varied. The parameters of the analysis of the specific case are listed in Table 6; the mass of the existing floor is assumed to be 27 kg/m^2.

In case 1 (Figure 4) the shear bond coefficients (γ) 0·25, 0·5 and 1 were studied. The shear bond coefficient, a term from Annex B of EN1995-1-1, is used to describe the extent of interaction between timber and topping, with 0 signifying no interaction and 1 complete interaction. Of the three factors considered it was the most important. Not only does it have the largest effect on the change in fundamental frequency but it also has the largest effect on the topping thickness at which this peak in performance occurs. With full interaction, the greatest increase in fundamental frequency occurred at a topping thickness of 12·5 mm, much thinner than conventional topping thicknesses of 40 mm or greater. The topping thickness at which the greatest increase in frequency was attained, reduced by 58% between complete interaction to a shear bond coefficient of 0·25, whereas the increase in frequency diminished by 47%. With a shear bond coefficient of 0·25, topping thicknesses greater than 16 mm caused the fundamental frequency to decrease.

b_t	50 mm	b_c	400 mm
h_t	200 mm	e	20 mm
ρ_t	400 kg/m^3	ρ_c	2300 kg/m^3
E_t	10 000 N/mm^2	E_c	30 000 N/mm^2
h_t	1·0	g_k	0·20 kN/m^2

Table 6. Parametric analysis case variables

In case 2 (Figure 5) the semi-permanent load applied to the floor (e.g. from furniture) was considered. In the analysis the semi-permanent load was assumed to be the same before and after the topping was added. As with the previous case, three scenarios were considered: semi-permanent loads of 0·35, 0·20 and 0·05 kN/m^2. As the semi-permanent load on the floor increased, the effect of the mass of the topping was diminished as it became a smaller proportion of the total mass of the floor. Therefore floors with large existing semi-permanent loads will show greater increase in fundamental frequency. Low semi-permanent loads also tended to narrow the peak in performance in comparison with floors with higher semi-permanent loads. Although it has been shown that timber floors are lightweight and thus semi-permanent loads have a large effect on the fundamental natural frequency, the analysis presumed a uniformly distributed load, which differs from actual floors where the semi-permanent load consists mainly of furniture placed at the edges of the floor (Ohlsson, 1982). Application of load nearer the supports reduces the observed effect.

Case 3 (Figure 6) studied the sensitivity to joist depth. Of the three variables presented, it had the least effect on the change in frequency and the topping thickness at which the maximum increase occurred. Greatest improvement in performance was found to be for joists which were least deep. The topping thickness at which the greatest increase in frequency was attained, increased by 11·5% from 200 mm to 300 mm deep joists, whereas the increase in frequency diminished by 14%.

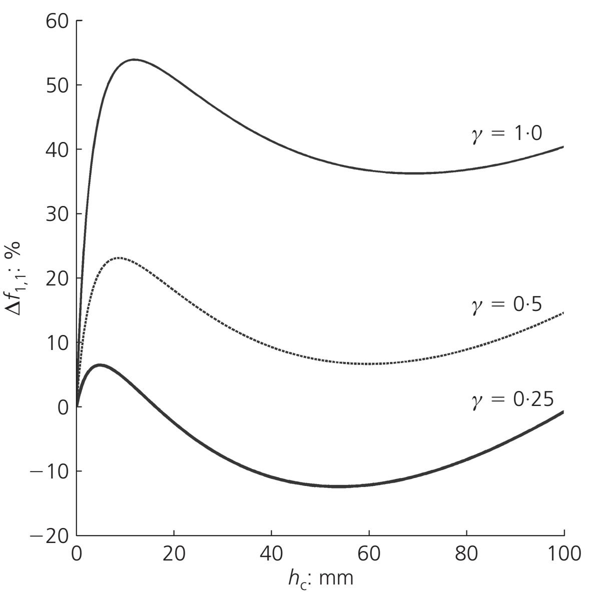

Figure 4. Sensitivity to shear bond coefficient

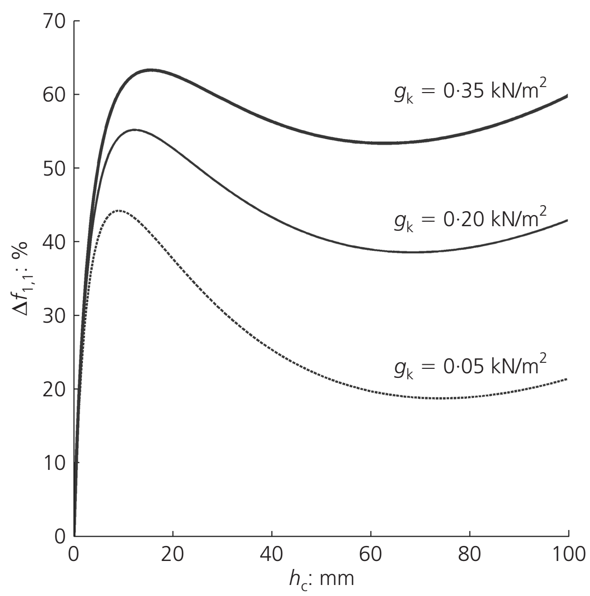

Figure 5. Sensitivity to semi-permanent load

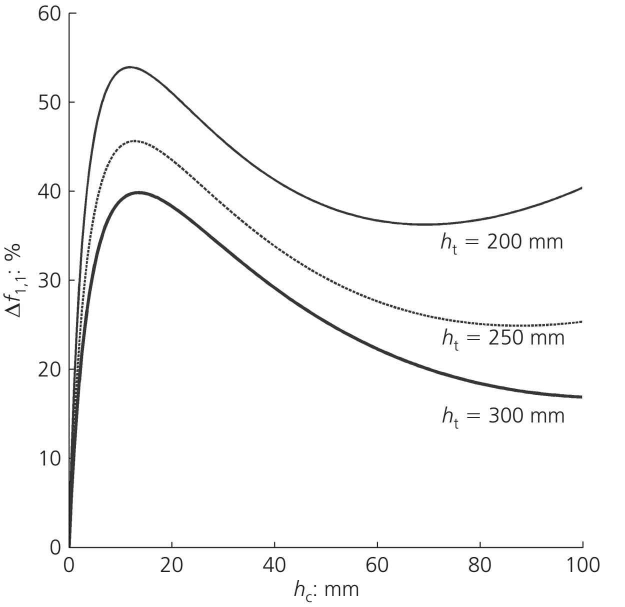

Figure 6. Sensitivity to joist depth

In all three cases the topping thickness at which the greatest increase in fundamental frequency was found, lies between 5 mm and 16·5 mm. Toppings of these thicknesses are certainly not practical on site and provide technical challenges such as preventing excessive topping shrinkage. At currently achievable topping thicknesses of 20–100 mm, an appreciable increase in fundamental frequency is achievable. For example, for the cases presented, the difference in change in fundamental frequency between the greatest increase and the increase with a 40 mm thick topping was less than 20% and generally between 10% and 15%. However, there are literature examples of the fundamental frequency of timber T-beams decreasing with the addition of a topping where there has been a combination of unfavourable factors, despite high levels of interaction being achieved (Ghafar *et al.*, 2008). This example illustrates that care should be taken when designing a concrete upgrade for a timber floor and achieving good interaction between the existing floor and topping upgrade may not be sufficient to increase the fundamental frequency.

5. Increase in transverse stiffness

So far this paper has only discussed the change in fundamental frequency of a T-beam rather than a complete floor. This ignores how the orthotropic behaviour of timber floors can often result in closely spaced higher modes of vibration, which cause a phenomenon known as beats where adjacent modes coincide. This coincidence effect leads to a greater perception of the vibration response than would occur by solely allowing for the individual modes, consequently only considering the fundamental mode of vibration is insufficient (Ohlsson, 1982). For TCCs the behaviour will tend towards that of a plate as the concrete topping becomes thicker. This will cause adjacent modes to separate and reduce their interaction. An approach to measure the effect is to consider how the ratio of the transverse stiffness (EI_b) to longitudinal stiffness (EI_l), found in Equation 3, changes as the thickness of the topping increases (Figure 7). For the purposes of the analysis the timber floor is assumed to have negligible transverse stiffness.

Although the effect of including the transverse stiffness would appear from Figure 7 to be small for thin toppings (less than 20 mm), this is not the case because Equation 3 contains second- and fourth-order terms relating to the mode number being considered which for higher modes of vibration causes significant separation. The effect of mode separation is magnified for composites with less composite action, although it is likely that the perception of the complete vibration response will be lower for composites with complete interaction.

6. Conclusion

This paper has investigated how the transient vibration response of a timber floor changes when upgraded to a timber–concrete composite with particular attention paid to the fundamental frequency of the response. An analytical method of assessing how the frequency will change which used the γ-method in Annex B of EN1995-1-1 to estimate the effective stiffness was described. A total of nine panels were subjected to dynamic excitation and their acceleration response recorded. Unlike other studies, the γ-method was found to be imprecise at predicting the effective bending stiffness of both panel types and only fundamental frequencies predicted using the measured effective bending stiffness were found to correlate well with the fundamental frequency of each panel. A parametric study indicated

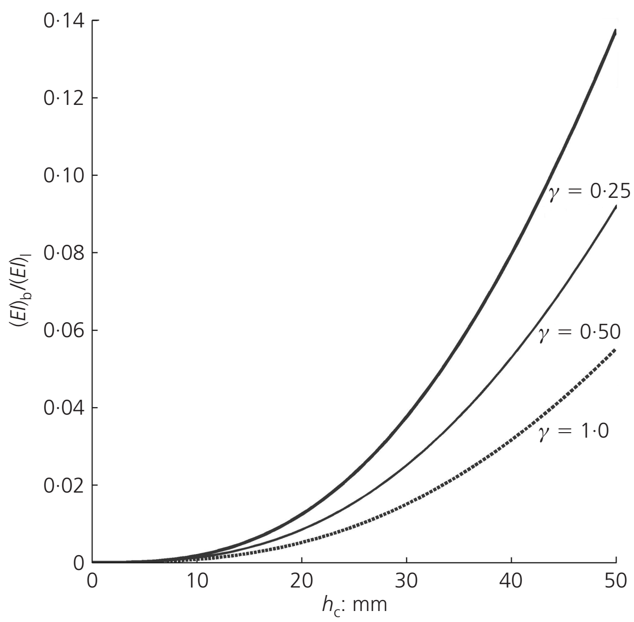

Figure 7. Ratio of transverse to longitudinal floor stiffness against topping thickness for shear bond coefficients: 0·25, 0·5 and 1

that strong interaction between the components is key to maximising the effectiveness of the material added to the floor, thereby increasing the effective bending stiffness and in turn increasing the fundamental frequency.

Thin concrete toppings provide a solution for existing timber floors with insufficient stiffness and vibration performance problems. They significantly increase the stiffness of existing timber floors while minimising the load added to the existing structure and the change to the finished floor-to-ceiling height. Furthermore thin toppings have been shown to have the best performance within the boundaries of standard topping thicknesses (0–100 mm).

Future work should consider the behaviour of complete floors rather than panels. The increase in stiffness perpendicular to the joists was shown to separate the higher modes of vibration, which is known to reduce the perceptibility of a transient vibration response.

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