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VIBRATIONS OF REPAIRED WOODEN FLOORS CAUSED BY HUMAN ACTION

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ABSTRACT

This paper deals with vibrations induced by human movements on floor structures constructed with timber beams and lightweight concrete. These vibrations are analyzed both theoretically and practically in order to evaluate and prevent induced vibrations from causing decreased functionality or creating unacceptable discomfort to building occupants. Pouring concrete slabs over existing timber floors is common construction practice when renovating, constructing add-ons or seismic retrofitting of buildings. Concrete slab in the upper section of the floor structure increases its rigidity and decreases vibrations in comparison to classic timber floor. Use of high-strength lightweight concrete instead of normal concrete reduces added load on existing foundations of the building. The dynamic behavior of the floor structure was numerically analyzed, based on the finite element method (FEM). Serviceability requirements for vibrations of repaired floors are also discussed.

KEYWORDS: Timber floors, renovation, vibration, serviceability, FEM.

INTRODUCTION

When renovating, reconstructing or seismic retrofitting of buildings, it is common to construct concrete slab over existing timber floor structure while ensuring composite action of the two. Concrete slab as the upper slab of this composite floor structure increases its rigidity and decreases vibrations when compared to conventional timber floor structures. However, there is a need to reduce overall weight as it causes additional stresses on existing foundations. Weight reduction can be achieved by application of high-strength lightweight concrete such as described by Kekanovic et al. (2014). This keeps the favorable effects of the composite action and emphasizes the advantage of the reduced weight.

Vibrations of the timber-concrete composite floor structure caused by human movement have been experimentally researched by Chien & Richie (1984), Bachmann & Ammann (1987), Allen and Murray (1993), Williams & Waldron (1994) and Nor Hayati et al. (2009). Finite element method for numerical simulations of floor structures subjected to human live load was first introduced by Silva et al. (2003), Hicks (2004) and Ebrahimpour and Sack (2005).

Multiple directives have been suggested for design of timber-concrete composite floor structure: Smith and Chui (1988), Allen and Pernica (1998), Murray et al. (2003) and Eurocode 5 (2004). Proposed empirical methods yielded directives which define fundamental frequencies, whereas the knowledge of natural higher order frequencies is limited.

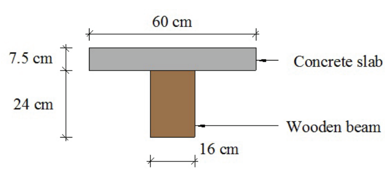
Following the tests made on over 100 problematic floors, Murray (1991) concluded that their fundamental frequency is mostly between 5 and 8 Hz. It was recommended to avoid frequencies below 8 Hz because these cause discomfort to people, while human walk induces great displacements of floor structures with natural frequencies below 3 Hz. Also, Eurocode 5 (2004) recommends that special research has to be carried out for floor structures with natural frequency below 8 Hz.

However, it seems that vibrations of timber floor structures repaired with lightweight concrete are not being researched enough. Based on the research carried out in the world and in our country, some of them already being applied in everyday engineering practice for reconstruction of numerous buildings, it is apparent that available knowledge makes it possible for composite timber-concrete floor structures to be properly designed and constructed for static loads. On the other hand, special research of dynamic stresses, vibrations caused by human live loads in particular, which can significantly influence the exploitation reliability of the structure, have not been discussed enough and their design is insufficiently numerically verified although this type of structure could be more sensitive to vibrations due to its reduced weight when compared to structures with normal weight concrete.

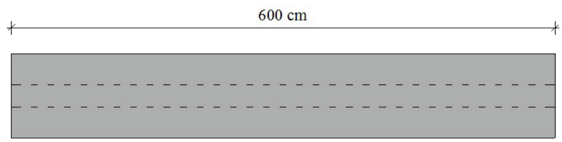
This paper deals with numerical analysis of dynamic behavior of timber floor structures repaired with lightweight concrete. Advantages and possible shortcomings will be pointed out when using lightweight concrete for strengthening timber floor structures subjected to dynamic loads i.e. human live loads.

MATERIAL AND METHODS

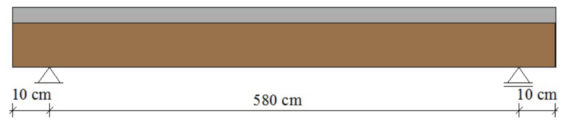
Four composite floor structures have been analyzed. The structures have identical cross sections and dowels, but are made of different types of concrete. Girders have length of 6 m while the distance between supports is 5.8 m. The distance between each timber beam is 60 cm. Cross section of the girder has "T" shape with flange made form cast in place lightweight concrete and full timber web, Fig. 1.



a) Cross section



b) Top view



c) Boundary conditions of the model

Fig. 1: Geometrical characteristics of the girder.

Concrete slab 7.5 cm high and 60 cm wide is casted over wooden beams that are 24 cm high and 16 cm wide. Concrete is poured directly onto existing structure. Four types of girders are analyzed that have concrete slabs made of lightweight concrete of the same strength class but with different density. Short overview of the physical-mechanical properties (density and elastic modulus) according to Eurocode 2 (2004) of the lightweight concrete from which slabs were made is given in Tab. 1. Obtained results are compared to results calculated for the beam G5 which is made with normal weight concrete, class C25/30.

Tab.1: Physical–mechanical properties of concrete slabs according to Eurocode 2 (2004).

Beam	ρ (kg.$^{-3}$)	$\eta E=(\rho/2200)^2$	E_{cm} (GPa)	$E_{lcm}=E_{cm}\bullet\eta_E$ (GPa)
G1	1150	0.27324	31	8.47
G2	1350	0.37655	31	11.67
G3	1550	0.49638	31	15.38
G4	1750	0.63275	31	19.61
G5	2400	/	31	/

According to Eurocode 2 (2004), the value of Poisson's ratio for concrete without cracks is 0.2.

Composite floor structure is constructed from full timber beams from fir tree (*Abies alba*) strength class C16.

In the case of free vibrations of the partial composite beam, Girhammar and Pan (1993) derived the following two ordinary differential equations, considering that the dynamic response is summation of specific shapes $\phi_n(x)$ with time-dependent amplitudes $f_n(t)$:

$$\frac{d^2 f_n}{dt^2} + \omega_n^2 f_n = 0 \tag{1}$$

$$\frac{d^6 \emptyset_n}{dx^6} - \alpha^2 \frac{d^4 \emptyset_n}{dx^4} - \omega_n^2 \frac{m}{(EI)_0} \frac{d^2 \emptyset_n}{dx^2} + \omega_n^2 \alpha^2 \frac{m}{(EI)_\infty} \emptyset_n = 0 \tag{2}$$

where:

$$\alpha^2 = k \left(\frac{1}{E_1 A_1} + \frac{1}{E_2 A_2} + \frac{r^2}{(EI)_0} \right) \tag{3}$$

$$(EI)_0 = E_1 I_1 + E_2 I_2 \tag{4}$$

$$(EI)_\infty = E_1 I_1 + E_2 I_2 + \frac{r^2 E_1 A_1 E_2 A_2}{E_1 A_1 + E_2 A_2} \tag{5}$$

and k = slip modulus(Nm^{-2}), $E_i\, I_i$ = bending stiffness of the i^{th} subelement, $(EI)_0$ = bending stiffness of the non-composite section (k→0), $(EI)_\infty$ = bending stiffness of the fully composite section (k→∞), $E_i\, A_i$ = axial stiffness of the ith subelement, r = distance between the two centroids, $m = m^1 + m^2$ (kg.m^{-1}) is the sum of the mass per unit length of each subelement, ω_n = radian frequency.

Eq. 1 implies that free vibration is a harmonic motion. Eq. 2 can be solved in the usual way by solving first the following characteristic equation:

$$(\lambda_n^2)^3 - \alpha^2(\lambda_n^2)^2 - \omega_n^2 \frac{m}{(EI)_0}\lambda_n^2 + \omega_n^2\, \alpha^2 \frac{m}{(EI)_\infty} = 0 \tag{6}$$

where: λ_n - the characteristic root corresponding to the nth vibration shape $\phi_n(x)$.

Solving the cubic Eq. 6 it can be easily shown that $\lambda_{1,n}^2<0$, $\lambda_{2,n}^2 > 0$ and $\lambda_{3,n}^2 > 0$, i.e. the roots are given as $\pm i\lambda_{1,n}$, $\pm\lambda_{2,n}$ and $\pm\lambda_{3,n}$. The general solution can then be written as:

$$\emptyset_n(x) = C_1 \sin(\lambda_{1,n}x) + C_2 \cos(\lambda_{1,n}x) + C_3 \sinh(\lambda_{2,n}x) + C_4 \cosh(\lambda_{2,n}x) + \\ + C_5 \sinh(\lambda_{3,n}x) + C_6 \cosh(\lambda_{3,n}x) \tag{7}$$

where: C_i (i = 1 to 6) - constants, to be determined from the boundary conditions at the two ends of the partial composite beam.

The boundary conditions for a single-span simply supported beam of length l can be written as follows:

$$\begin{aligned} &w(0) = w(l) = 0 && \rightarrow && \emptyset_n(0) = \emptyset_n(l) = 0 \\ &w''(0) = w''(l) = 0 && \rightarrow && \emptyset_n''(0) = \emptyset_n''(l) = 0 \\ &w''''(0) = w''''(l) = \frac{q}{(EI)_0} && \rightarrow && \emptyset_n''''(0) = \emptyset_n''''(l) = 0 \end{aligned} \tag{8}$$

Eq. 8 gives six homogeneous equations, of which the determinant of the coefficient matrix must be equal to zero, in order to get a set of non-zero solution for the coefficients C_i (i = 1 to 6). The determinant can be expressed as:

$$(\lambda_{1,n}^2 + \lambda_{2,n}^2)^2 (\lambda_{1,n}^2 + \lambda_{3,n}^2)^2 (\lambda_{2,n}^2 - \lambda_{3,n}^2)^2 \sin(\lambda_{1,n}l)\sinh(\lambda_{2,n}l)\sinh(\lambda_{3,n}l) = 0 \tag{9}$$

which can be satisfied only when

$$\begin{aligned} &\sin(\lambda_{1,n}l) = 0 \\ &\lambda_{1,n} = \frac{n\pi}{l} \end{aligned} \tag{10}$$

Substituting Eq. 10 back into Eq. 6 with $\lambda_{1,n}^2 < 0$, the radian frequency can be solved as:

$$\omega_n^2 = \frac{(n\pi)^4 (EI)_\infty}{ml^4} \times \left[\frac{(EI)_0 (n\pi)^2 + \alpha^2 l^2 (EI)_0}{(EI)_\infty (n\pi)^2 + \alpha^2 l^2 (EI)_0}\right] \tag{11}$$

The first term on the right-hand side of Eq. 11 is equal to the square of the radian frequency for the full composite beam ($k \rightarrow \infty, \alpha^2 \rightarrow \infty$):

$$\omega_n^2 = \frac{(n\pi)^4 (EI)_\infty}{ml^4} \tag{12}$$

In the case of non-composite action ($k \rightarrow 0, \alpha^2 \rightarrow 0$) square of the radian frequency is:

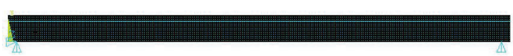
$$\omega_n^2 = \frac{(n\pi)^4 (EI)_0}{ml^4} \tag{13}$$

Finite element method (FEM) is applied by using Ansys (2011) software. The girder is designed as a 2D model made out of 2 layers, upper concrete slab from lightweight concrete and lower layer which is monolithic timber beam. Concrete slab is subjected to compressive stresses so that the presence of minimum reinforcement is neglected in its numerical modelling. Similar was done by Davison (2003) and Rijal (2013).

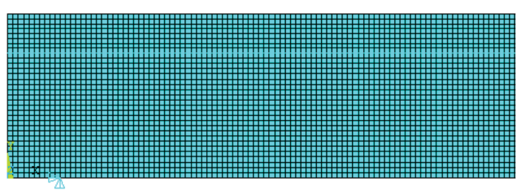
Timber beam modelling is done by using elements from the Ansys library. Concrete slab and timber beam are modeled using 4-node two-dimensional element PLANE42. It is used as a 2D element with biaxial stress and thickness. Element is defined with 4 nodes having 2 degrees of freedom at each node, translations in the nodal x and y directions. Basic input data for his element are: elastic modulus, Poisson's ratio and the density of wooden beam and concrete slab.

Contact surface between the timber beam and the concrete slab is modelled using contact elements CONTA171 and TARGE169. CONTA171 element is used for the lower edge of the concrete slab and TARGE169 is used for upper edge of the wooden beam. Applied contact elements are one-dimensional and set between the nodes of 2D elements, in this case element PLANE42. In this model, contact elements are firstly allowed to slide during deflection, but separation is prevented. After that, the same model is analyzed but this time with prevented sliding and separation of the contact elements during deflection. First analysis corresponds to repaired timber-concrete ceiling without dowels at contact surface, while the second corresponds with a ceiling with full composite action between the lightweight concrete and wooden beams at the contact surface.

Finite element size for timber beam is 10×10 mm while, for the concrete slab it is 10×9.375 mm, Fig. 2. The model, including contact elements, consists of 20400 finite elements.



a) Finite element model network



b) Left part of the model enlarged

Fig. 2: Arrangement of nodes and finite elements of the model.

Natural frequencies of the first three modes of analyzed beams are shown in Tab. 2.

Tab. 2: Natural frequencies (Hz) of analysed beams (A – no composite action, B – full composite action).

Beam	Analytical						FEM					
	Mode 1		Mode 2		Mode 3		Mode 1		Mode 2		Mode 3	
	A	B	A	B	A	B	A	B	A	B	A	B
G1	7.39	13.93	29.57	55.73	66.53	125.39	7.36	13.64	29.20	50.64	64.64	88.12
G2	7.07	13.78	28.29	55.12	63.67	124.02	7.05	13.46	27.96	49.62	61.97	85.88
G3	6.83	13.55	27.34	54.22	61.51	122.01	6.81	13.22	27.03	48.45	59.96	83.69
G4	6.65	13.29	26.61	53.19	59.89	119.69	6.63	12.95	26.33	47.26	58.45	81.57
G5	6.16	12.22	24.64	48.89	55.46	110.00	6.14	11.88	24.41	43.03	54.26	74.30

RESULTS AND DISCUSSION

First three natural frequencies of the model and corresponding characteristic vibration mode shapes are calculated with modal analysis in Ansys software. Fig. 3 illustrates first three mode shapes for the beam G1.

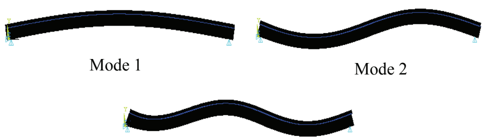


Fig. 3: First three characteristic mode shapes of the beam G1.

Based on the results of this research the following can be observed:

Fundamental natural frequency of beams is increased by applying lightweight concrete for the upper concrete slab of the ceiling. Floor structures repaired with lightweight concrete of lesser density have more rigidity and less added weight making them a good solution for seismic retrofitting of building, reparation and reconstruction of timber floors from the aspect of dynamics. Obtained results show that timber floor structure repaired by lightweight concrete of 1150 kg.m^{-3} density, without dowels, has fundamental frequency close to the minimal requirement of 8 Hz, Eurocode 5 (2004). Smith and Chui (1988) recommended that floors fundamental frequency should exceed 8 Hz. By choosing and arranging mechanical dowels correctly, lightweight concrete slab can achieve full composite action with existing timber beams and reach fundamental frequency of even 13.64 Hz which corresponds to the recommendations of Allen and Pernica (1998). They proposed a more stringent fundamental frequency limit for light-frame floors depending on the load activity. The minimum floor frequency for dancing/dining is 10 Hz and for aerobics 13 Hz. By increasing bulk density of the concrete, the sensitivity of the floor structure to the vibrations is also increased.

Rijal (2013) analyzed the dynamic performance of timber-concrete composite floor structural systems with normal bulk density concrete. There are no papers on the dynamic performance of wooden floors repaired using lightweight concrete. This paper gives the basic dynamic characteristics of wooden floors repaired using lightweight concrete of various bulk densities. The results indicate the benefit of using lightweight concrete from the dynamic aspect, considering that the fundamental frequency of the floor structure increases with decreasing the bulk density of lightweight concrete. In this case, lightweight concrete absorbs vibrations caused by human action, and although the weight of the structure is reduced, the structure is more resistant to vibrations compared to those repaired using normal bulk density concrete.

All analytical results obtained for Mode 1 match well with the FEM results. There is also a good match of the results for Mode 2 and Mode 3 in case of no composite action. However, for full composite action there is a significant deviation of the results for Mode 3. But since Mode 1 represents the most important criterion in assessing the sensitivity of the structure to the vibrations caused by human activity, research within this paper was not focused on detailed analysis of the results for Mode 2 and Mode 3 in the case of full composite action. Further research will be invested into analysis of these modes and will include experimental verification of the obtained results for the analyzed beams.

CONCLUSIONS

Presented results of analyzed floor structures made by joining existing timber beams with lightweight concrete slab show that this method can, among other benefits, be successfully applied for strengthening timber floor structures from the aspect of vibrations caused by human live load. Rigidity of the structure is increased by improving composite action of these two materials i.e. by an adequate choice of dowels for shear force transfer. Future research into vibration of floor structures made with composite timber and lightweight concrete will include the analysis of the effects that type, number and arrangement of mechanical dowels have on their dynamic behavior.

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