HUMAN-INDUCED VIBRATIONS IN COMPOSITE TIMBER FLOORS

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Abstract

The authors investigate the human induced vibrations in typical composite timber floors in residential buildings. Assessment methods given in different design codes and guidelines, such as the Eurocode, are discussed. A case study analysis based on the different methodologies is carried out to assess the acceptability of a specific timber floor. Two extreme cases are considered: full and non-composite action. It is shown that composite action improves the floor acceptability for general residential applications. The limitations of the different criteria given in the codes and guidelines for assessing floor vibrations in timber floor structures are discussed and, also, the possible improvement of these criteria.

1 Introduction

Composite timber floor constructions are used nowadays in many buildings all around the world due to their economical, environmental and structural advantages. However, the weakness of these structures is their dynamic behaviour. The problem of human-induced floor vibrations is, in general, related to the resonant or impulsive behaviour and/or local deflections. For timber structures, all of these problems are often at hand. Especially for large floor spans, timber structures possess relatively low natural frequencies. As orthotropic systems, the reaction of timber structures to low frequency resonant modes depends mainly on the bending stiffness of the structure and on the amount of total damping in the material. Natural modes are easily excited by the harmonics due to walking or rhythmic activities. These properties often give rise to perceptible vibration problems when walking or other traffic activities induce resonance of the floor system [1]. Walking and other human or rhythmic activities can also cause annoyance for people sitting in the room because of the "jolts" created by the sudden floor deflection produced by each footstep.

To assess the acceptability of human-induced floor vibrations, a number of guidelines and evaluation methodologies have been developed. In general, the design rules are based on frequency and stiffness criteria, and, in addition, on an evaluation of the acceleration or velocity of the floor system versus some prescribed values.

This paper investigates the footfall-induced vibrations in typical composite timber floors in residential buildings. In the first part of the paper, the analytical methods to assess the floor acceptability is presented as given by a number of commonly used European design guides and codes to predict human-induced floor vibrations in timber structures. These guides include the European design guidelines for floor vibration [2] and the European code for timber structures [3].

In the second part, these methods are applied to analyse a real composite floor structure in a residential building in order to assess its acceptability with respect to footfall-induced vibrations. The two extreme cases of full and non-composite action are considered. Full composite action is achieved if the decking etc. is glued to the joists. Ensuring composite action between the decking and the beams is generally a way of improving the vibration performance of floor systems.

The limitations of the different criteria of the codes and design guides for assessing floor vibrations in timber floor structures are discussed as well as the possible improvement of these criteria and their integration in modern design methodology.

2 Methods for assessing timber floor vibrations

To assess the acceptability of these human-induced floor vibrations, calculated values of the stiffness, frequency, velocity and/or acceleration of the floor system are usually used. These parameters are often combined or interrelated in the different design criteria. The calculated values are then compared to some prescribed limiting values.

In the following, the different criteria of footfall induced vibrations in composite timber floor systems are discussed.

2.1 Eurocode 5

Eurocode 5 (EC5) covers the design of timber structures [3]. In Section 7 “Serviceability limit states”, the issue of vibrations of timber floors is treated. The subsection covers the vibrations from machinery and vibrations in residential floors. For residential floors with a fundamental frequency (f_1) greater than 8 Hz, acceptable levels of deflection and unit impulse velocity are given. But for residential floors with $f_1 \leq 8$ Hz, the code states that a special investigation should be made. However, the details of such an investigation are not described.

Technically, the frequency requirement that the first natural frequency of the timber floor should exceed 8 Hz implies that the footfall-induced vibration corresponds to heel impacts made by a walker. Such timber floors may be classified as high-frequency floors in which the enforcing frequency on the floor from steps will be higher than 8 Hz. For low frequency floors ($f_1 \leq 8$ Hz), the frequency of the floor is low compared to the forcing frequency, and the steady-state part of the footfall-induced vibration response will be significant compared to the transient response, and the applied force will behave like a continuous function.

2.2 Static deflection criteria

As human activities on the floor (e.g. footsteps) cause the floor to oscillate at a certain frequency, a static deflection under a point load can be a suitable criterion to assess the floor vibration. Thus, the stiffness of the structure should be designed so that the deflection due to a single static load is not exceeding a certain limiting value. The effect of the step load on the floor is here assumed to be the same as that caused by a corresponding static load. In EC5, it is stated that a deflection due to a single force should be less than a limiting value a:

$$\frac{w}{F} \leq a \quad \text{[mm/kN]} \tag{1}$$

where w is the maximum instantaneous vertical deflection caused by a vertical concentrated static force F applied at any point on the floor, taking account of the load distribution. For F = 1 kN, Eq. (1) may be rewritten as

$$w \le a \quad \text{[mm]} \tag{2}$$

The limiting value a depends on the span of the floor joist and is usually given in the national annex. In the UK National Annex to EC5 [4], the limiting value a is given as

$$\begin{aligned} a &\le 1.8\,\text{mm for floor spans} \le 4000\,\text{mm} \\ a &\le \frac{16500}{l^{1.1}}\,\text{mm for floor spans} > 4000\,\text{mm} \end{aligned} \tag{3}$$

where the values 1.8 and (16500 / $l^{1.1}$) represent the maximum allowable static deflection of the floor at the centre of the floor subjected to a static load of 1 kN at this point (simulating the foot force effect), and l [mm] is the span of the floor joist.
EC5 does not give any expression for calculating the actual deflection w. However, the UK National Annex to EC5 [4] present the following equation for calculating the deflection of the floor subjected to 1 kN point load at mid-span [4]

$$w = \frac{1000\, k_{\text{dist}}\, k_{\text{amp}}\, l_{\text{eq}}^3}{48\,(EI)_{\text{joist}}} \quad \text{[mm]} \tag{4}$$

where l_{eq} [mm] is the equivalent span length of the floor joists given by $l_{\text{eq}} = l$ for simply supported joists, $l_{\text{eq}} = 0.9\ l$ for end spans of continuous joists, and $l_{\text{eq}} = 0.85\ l$ for internal spans of continuous joists, where l is the design span of the floor joists, the parameter k_{dist} is the load sharing coefficient expressed as

$$k_{\text{dis}} = \max\left\{ k_{\text{strut}}\left[0.38 - 0.08\ln\left(\frac{14\,(EI)_{\text{b}}}{s^4}\right)\right] \ ; \ \ 0.30 \right\} \tag{5}$$

where k_{strut} is a factor that takes into account cross bridging or herringbone strutting (usually, $k_{\text{strut}} = 1$; for cross bridging according to BS 5268 [5], $k_{\text{strut}} = 0.97$), $(EI)_b$ [Nmm^2/m] is the bending stiffness of the floor perpendicular to the joists (E is the mean value of the modulus of elasticity of the floor decking; note that if ceilings with plasterboards attached directly to the joists are used, the bending stiffness of the plasterboard may be added), s [mm] is the joist spacing, the parameter k_{amp} is an amplification factor taking into account the effect of shear deformations ($k_{\text{amp}} = 1.05$ for simply supported solid timber joists; $k_{\text{amp}} = 1.45$ for continuous mechanically jointed floor trusses; for other boundary conditions one is referred to the UK National Annex to EC5 [4]), and $(EI)_{\text{joist}}$ [Nmm^2] is the bending stiffness of the joist (E is the mean value of the modulus of elasticity).
In Sweden, the limiting value, a = 1.5 mm, for a mid-point load of 1 kN is accepted [6].

2.3 Resonant fundamental frequency
The fundamental mode gives the lowest natural frequency and the largest amplitude. For rectangular orthotropic plates simply supported along all four edges, the fundamental frequency can approximately be expressed as

$$f_1 = \frac{\pi}{2}\sqrt{\frac{(EI)_l}{mL^4}}\sqrt{1 + \left[2\left(\frac{l}{b}\right)^2 + \left(\frac{l}{b}\right)^4\right]\frac{(EI)_b}{(EI)_l}} \tag{6}$$

where l [m] is the design span of the floor beams, m [kg/m^2] the mass per unit area of the floor including allowable imposed loads (note: based on permanent actions only without including partition loads), b [m] is the floor width, $(EI)_l$ [Nm^2/m] bending stiffness per unit width of the floor in the length direction of the joists (in case of non-composite action, only the joists are considered, and in case of full composite both decking and joists are included), and $(EI)_b$ [Nm^2/m] the bending stiffness per unit width of the floor in the cross direction of the joists. The E–value is the mean value of the modulus of elasticity. These bending stiffness values are approximations for the exact plate stiffness values, i.e. the Poisson's ratio is neglected here.
Alternatively, the fundamental frequency can also be calculated using the self-weight approach expressed as

$$f_1 = \frac{17.5}{\sqrt{\delta_{\max}}} \approx \frac{18}{\sqrt{\delta_{\max}}} \tag{7}$$

where $\delta_{\max}$ [mm] is maximum static deflection at the midspan due to the distributed floor mass m [N/m].
In EC5 [3], a simplified formula for predicting the fundamental frequency of timber floors is given as

$$f_1 = \frac{\pi}{2l^2}\sqrt{\frac{(EI)_l}{m}} \tag{8}$$

However, this equation sometimes gives too deviating results from the general formula according to Eq. (6), especially at low frequencies ($f_1 < 8$ Hz) [4].

2.4 Velocity criteria

To simulate the effect of heel impact on timber floors (high-frequency effects), the vertical floor vibration velocity (v) due to an impulse of 1.0 Ns is evaluated. For a rectangular floor with overall dimensions $b \times l$ and simply supported along all four sides, an approximate unit impulse velocity response of the floors structure can be obtained as [3]

$$v = \frac{4(0.4 + 0.6 n_{40})}{m\,b\,l + 200} \quad [\text{m/Ns}^2] \tag{9}$$

where b [m] is the floor width, l [m] the design span of the floor, m [kg/m^2] the mass per unit area of the floor (based on permanent actions only without including partition loads), and n_{40} is the number of first-order vibration modes with natural frequencies up to 40 Hz, and is expressed as

$$n_{40} = \left\{ \left[\left(\frac{40}{f_1}\right)^2 - 1 \right] \left(\frac{b}{l}\right)^4 \frac{(EI)_l}{(EI)_b} \right\}^{0.25} \tag{10}$$

where $(EI)_l$ and $(EI)_b$ [Nm^2/m] are the bending stiffnesses of the floor in the two directions (cf. above). Components of the first-order vibration modes above 40 Hz are disregarded.
The calculated value for the unit impulse response is then compared to a maximum allowable unit impulse velocity according to

$$v \le b^{(f_1 \varsigma - 1)} \qquad [\text{m/Ns}^2] \tag{11}$$

where f_1 [Hz] is the fundamental frequency of the floor obtained from Eq. (6) or (7), ζ is the modal damping ratio [dimensionless] (UK National Annex to EC5 [4] suggests a value of 2%), and b is a parameter controlling this maximum allowable value for the unit impulse velocity and is related to the limiting value a for the floor deflection according to Eq. (1). EC5 gives the following recommended range, $50 \le b \le 150$, and provides a diagram for the relationship between a and b (these values are subject of National choices). The parameter b can also be expressed as

$$\begin{aligned} b &= 180 - 60w \quad \text{where } w \le 1\,\text{mm} \\ b &= 160 - 40w \quad \text{where } w > 1\,\text{mm} \end{aligned} \tag{12}$$

where w [mm] is the actual deflection of the floor subjected to a mid-point load of 1 kN, see Eq. (4).

2.5 The OS-RMS method

The one-step root mean square (OS-RMS) method is developed for evaluating the acceptability of floor vibrations [2]. The OS-RMS_{90}-value represents the response of a floor brought into harmonic vibrations due to a person walking on that floor. The index 90 indicates that 90 % of the steps on the floor are covered by this value. The OS-RMS_{90}-value is obtained for different weights and walking speeds (or step frequency) of persons and should be checked against recommended values given in the guideline.

In general the excitation and response points are selected where the largest vibration amplitudes are expected (in regular floors this is usually in the middle of the floor span). In calculating the OS-RMS_{90}-value, the excitation and response points do not necessarily have to coincide. Further, it is assumed that the excitation point is kept fixed, i.e. the walking path is not taken into consideration.

In general, the method is semi-probabilistic and the results lead to a determination of the vibration response of sensitive floors with a reasonable accuracy. The first step in the design procedure is to determine the basic floor characteristics, which are

(1) natural frequency;
(2) modal mass; and
(3) damping.

Using these characteristics and a set of graphs, the OS-RMS_{90}-value characterizing the floor response due to walking is obtained. This value is then compared to recommended values for different tabulated floor classes. Floor vibrations are classified into six classes (A to F) and the guidelines also give recommendations for the assignment of classes with respect to the function of the considered floor.

This method is originally developed for analysing vibrations in composite floor structures of steel and concrete. But since the main criterion of assessment is the use of OS-RMS_{90}-values, the response of timber floor systems can also be evaluated by this method.

The evaluation of the natural frequency is discussed in Section 2.3 above and that of modal mass; and damping is discussed below.

2.6 The modal mass

In the OS-RMS method, the modal mass is one of the parameters that are used to determine the acceptance class of floor response. For orthotropic floors with simply supported beams and one direction bending of the decking between the beams, the modal mass is given by [2]

$$M = m_{\text{tot}} \left[\frac{\delta_{\text{beam}}^2 + \delta_{\text{deck}}^2}{2\delta_{\text{max}}^2} + \frac{8}{\pi^2} \frac{\delta_{\text{beam}}\delta_{\text{deck}}}{\delta_{\text{max}}^2} \right] \tag{13}$$

where δ_{beam} is the deflection of the beams, δ_{deck} the deflection of the decking (under the assumption that the deflection at the supports is zero), δ_{max} the maximum total deflection of the floor, i.e. $\delta_{\text{max}} = \delta_{\text{beam}} + \delta_{\text{deck}}$, and m_{tot} [kg] the total mass of floor slab including finishing and representative variable loading (from experience, the value of the quasi-permanent part of the imposed loads for residential and office buildings is 10 – 20 % of their characteristic values). Also, it is recommended that for lightweight floors the mass of one person with a minimum mass of 30 kg is added on top of the mass of the structure.

If the floor structure essentially behaves as simply supported beams, the modal mass can approximately be expressed as $M = 0.5\ ml$, where l is the floor length and m [kg/m] the mass of the floor structure including self-weight, finishing, furniture and 10% of the full live load.

2.7 Damping

In case of damping, e.g. due to friction and slip at joints, the vibration energy in the floor construction is dissipated. The total damping consists of material and structural damping (e.g. the coupling loss factor), damping from furniture and finishing (e.g. false floor), and geometrical radiation (propagation of energy through and out of the structure) [1].

Different design guides recommend appropriate values for damping (in percentage of the critical damping) for various floor types. Normally, damping caused by human occupation is neglected in the design stage.

In the OS-RMS method [2], tabulated system damping values for vibrating floors are presented divided into three types of damping: (1) structural damping (D_1) (due to the floor materials); damping due to furniture (D_2); and (3) damping due to finishing (D_3). For timber floors, D_1 = 6 %, for furniture in residential buildings, D_2 = 1 %, and for floor finishing, D_3 = 1 %. The total damping is $D = D_1 + D_2 + D_3$.

In EC5, a modal damping ratio of ζ = 1% for timber floors is assumed unless other values are proven more appropriate. This value is relatively small compared to other guides, indicating that it might neglect the effect of damping due to furniture and finishing, and, also, possible damping due to partitions. In the UK National Annex to EC5 [4], a value of 2 % is given.

2.8 Intermittent vibrations and minimum floor frequency

Assessment with respect to intermittent vibrations and using the concept of vibration dose value (VDV) developed for steel floors could well be adapted also to timber floors, but no specific VDV limiting values exist as yet for timber floors.

Also, a minimum floor frequency value (f_1) should be proposed for timber floors. They should be designed with a frequency, say $f_1 \geq 3$ Hz, because the fundamental walking harmonic gives considerably larger amplitude than the higher harmonics. By making the fundamental natural frequency of the floor sufficiently high, the off-resonant response (i.e. the response at frequencies between the natural frequencies) of the floor from this first harmonic will be avoided.

3. Application of assessment methods to a composite timber floor structure

3.1 Assumptions

The vibration response of a composite timber floor in a residential building is analysed in this section. A floor spanning 6 m × 4.8 m with a cross-section according to Figure 1 is studied. The timber floor structure consists of a decking of 22 mm particle board (ρ = 650 kg/m^3; E =

2900 MPa), timber joists 70 × 220 mm of quality C30 spanning 4.8 m at 600 mm spacing (m = 7.1 kg/m; E = 12000 MPa), 220 mm mineral wool (ρ = 50 kg/m^3; $E_{dynamic}$ = 0.1 MPa), plastic film (ρ = 0.01 kg/m^2), and a gypsum plasterboards of 13 mm attached to the underneath side of the joists (ρ = 700 kg/m^3; E = 2000 MPa).

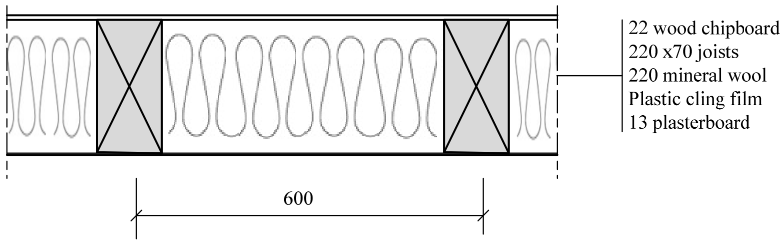

Figure 1. Timber floor structure in a residential building [dimensions in mm].

The composite timber floor structure is modelled as an orthotropic plate with a distributed floor mass, m = 78.5 kg/m^2 (including 10 % of the imposed load and other service loads). The decking and timber joists are supposed to act either as a full or non-composite section.

3.2 Assessment of the floor

The calculated parameters are presented in Table 1.

Parameters	**Non-composite action**	**Full composite action**	**Comments**
Bending stiffness	$(EI)_l$ = 1.24 MNm^2/m $(EI)_b$ = 3.03 kNm^2/m	$(EI)_l$ = 2.02 MNm^2/m $(EI)_b$ = 0.46 kNm^2/m	
Fundamental frequency,(f_1)	8.59 Hz 8.69 Hz	10.94 Hz 11.08 Hz	Eq. (6) Eq. (7)
Limiting deflection (a)	1.47 mm		Eq.(3)
Floor deflection (w)	1.53 mm	1.24 mm	Eq.(4)
Maximum allowable unit impulse velocity	0.022 m/Ns^2	0.025 m/Ns^2	Eq. (11) ζ = 2 % [4]
Actual unit impulse velocity (v)	0.012 m/Ns^2 (n_{40} = 11.99)	0.019 m/Ns^2 (n_{40} = 19.08)	Eq. (9) (Eq. (10))
	OS-RMS		
Damping	6% (timber)+1% (houses)+1% (false floor) = 8%		Section 2.7
Modal mass	1130 kg		Eq. (13)
OS-RMS$_{90}$-value	3.6 mm/s (Class E)	2.0 mm/s (Class D)	

Table 1. Calculated parameters for the assessment of the timber floor structure. With respect to the OS-RMS$_{90}$-value, Class D is acceptable and Class E is not acceptable.

With respect to the deflection criteria, only the full composite section is acceptable, but concerning the unit impulse velocity criteria, both full and non-composite sections are acceptable.

Regarding the OS-RMS$_{90}$ methodology, the floor with non-composite action belongs to Class E with an expected OS-RMS$_{90}$-value of approximately 3.6 mm/s. Floors in perception Class E is considered critical and not suitable for residential buildings. This result agrees approximately with the EC5-criteria concerning deflection. The floor with full composite action is classified as Class D with the an expected OS-RMS$_{90}$-value of approximately 2.0 mm/s. Perception class D is acceptable for residential buildings. Also, this result agrees with the previous results based on the EC5. If the damping ratio is decreased to 4 %, the full composite section is still acceptable, but not if it decreases to 2 %.

In cases where full composite action cannot be achieved, the floor structure can be improved by increasing the bending stiffness of the joists, e.g. by choosing a higher strength class. For example, by increasing the strength class to C35 and C40, the fundamental frequency becomes, f_1 = 8.9 Hz and 9.3 Hz, respectively, the deflection w = 1.41 mm and 1.29 mm, respectively. In both cases, the floor structure with non-composite action will be acceptable with respect to human-induced floor vibrations.

4. Concluding remarks

The fundamental frequency of a floor system is mainly influenced by the transverse bending stiffness since it controls the effective floor mass. Increasing the primary bending stiffness increases the fundamental frequency of the floor system. Attaching e.g. a gypsum plasterboard ceiling adds mass to the floor structure and reduces the fundamental frequency and deflection.

The assessment of the vibration of timber floors is usually critical. Timber floor systems with large spans have often low stiffness and mass resulting in low natural frequencies and increased ratio between the exciter mass and the excited mass. Moreover, the timber floor systems usually have highly orthotropic stiffness ratios.

Designing timber floor structures with composite action increases considerably the acceptability for human-induced vibrations. An interacting composite structure has greater bending stiffness, higher load resistance and a lower vibration level.

The OS-RMS methodology gives approximately comparable results with that of EC5. Thus, this method can be considered a simple tool for designers to assess the human-induced floor vibrations, especially for floor systems where sufficient information of the dynamic properties is not available.

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References

[1] Hassan O.A.B. *Building acoustics and vibration – Theory and practice*. World Scientific Publishing Co. Pte. Ltd., Singapore (2009).

[2] Feldmann M., Heinemeyer C., Butz C., Caetano E., Cunha A., Galanti F., Goldack A., Hechler O., Hicks S., Keil A., Lukic M., Obiala R., Schlaich M., Sedlacek G., Smith A. and Waarts P. *Design of floor structures for human induced vibrations*. Joint Report, EUR 24084 EN (2009).

[3] Eurocode 5, EN 1995-1-1: *General – Common rules and rules for buildings*. (November 2004).

[4] UK National Annex to Eurocode 5 (BS EN 1995-1-1): *Design of Timber Structures*. British Standards Institution (2004).

[5] TRADA. *Vibration in timber floors (Eurocode 5)*. Timber Engineering Guidance Document GD 6 (2009).

[6] Ohlsson S. *Springness and human induced vibrations – A design guide*. Swedish council for building research, Stockholm (1988).