Vibration-Based Serviceability and Acoustic Assessment of Timber Floors

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- a_{peak}: Peak acceleration response
- a_{rms}: Root mean square acceleration
- a_{rmq}: Root mean quad acceleration
- c: Damping coefficient
- $k_{e,1}$: Frequency factor in case of a double span floor on rigid supports. In case of a single span $k_{e,1} = 1.0$
- $k_{e,2}$: Frequency factor to consider the effect of the transverse floor stiffness. In case of a one-way spanning floor $k_{e,2} = 1.0$
- $(EI)_L$: Longitudinal bending stiffness of the floor per unit of length
- $(EI)_T$: Transverse bending stiffness of the floor span per unit of length
- μ: Resonant buildup factor, which may be taken as $\mu = 0.4$
- ζ: Modal damping ratio
- b: Floor width
- b_{ef}: Effective width
- c_f: Fourier coefficient of the dynamic load factor, which can be assumed equal to $c_f = 0.0714$
- F: Force applied in the point with greatest deflection

G. Fink et al. (Eds.): *Holistic Design of Taller Timber Buildings*, SPRTRCIENG, pp. 76–93, 2025.
https://doi.org/10.1007/978-3-032-02098-7_7

- F_p: Person weight walking on the floor equal to $F_p = 700$ N according to EC5
- F_{dyn}: Vertical dynamic force caused by a walking person, equal to $F_{dyn} = 50$ N according to EC5
- f_1: Fundamental frequency in Hz
- f_{lim}: Limit frequency between the resonant or a transient response in Hz
- f_w: Walking frequency in Hz
- h: Cross-section height
- $I_{mod,mean}$: Mean modal impulse, in N·s
- k_{black}: Reduction factor equal to $k_{black} = 0.7$ according to EC5
- k_{res}: Factor to account for higher modes of vibrations, according to EC5
- l: Floor span (the longest span in case of double span floor)
- m: Floor mass per unit of area
- M^*: Floor modal mass
- $v_{1,peak}$: Peak velocity response for the fundamental mode
- w: Load deflection
- K_p: Peak factor
- b_b: Width of the building
- h_b: Height of the building
- $q_{z,ref}$: Reference wind load
- c_{fw}: Force coefficient
- K: Dimensionless coefficient
- $\Phi_{1,x}(z)$: First mode shape
- M_1: Modal mass of the first mode
- R: Resonance response factor
- SEL: Sound exposure level
- VDV: Vibration dose value
- w_{1kN}: Load deflection under a concentrated 1kN load
- B: Floor width
- l_2: Shorter span of a double-span floor
- $(EI)_i$: Bending stiffness of the i-th member of a composite floor per unit of length
- $(EA)_i$: Axial stiffness of the i-th member of a composite floor per unit of length
- a_i: i-th member center of mass distance from the composite section center of mass
- γ_i: i-th member partial composite action factor
- S: Percentage of decrease in structural rigidity
- t: Elapsed time in years from timber bridge construction

1 Introduction

Timber floors are particularly susceptible to noise and vibration issues when compared to other construction methods, such as concrete floors. This is due to the relatively high stiffness-to-mass-density-ratio of timber floors, which enables so-called ‘lightweight’ floor constructions, in contrast to ‘heavyweight’ floor constructions consisting, for example, of concrete slabs and steel girders. Quantified, lightweight floors, as defined in ISO 10140-5:2021, are considered as floors whose area density is less than 150 kg/m^2 [1]. A heavyweight reference floor is specified in Annex C of ISO 10140-5:2021 [1]. The heavyweight reference floor is specified to be of reinforced concrete and have a minimum thickness of 100 mm, but preferably a thickness of 140 mm, meaning a lower bound mass density of 250 kg/m^2 and a preferred reference mass density of 350 kg/m^2. While timber floor constructions have the benefit of being relatively stiff and light, which is a positive from a static structural perspective, these lightweight structures are prone to higher vibration amplitude and noise transmission due to the reduced mass of the structure.

The vibration and noise issues of timber floors may be divided into two parts based on the frequency range of consideration with some overlap between the two. Vibration-based serviceability of floors considers generally frequencies from 1 Hz to 80 Hz [2,3], while acoustics generally considers a frequency range from 50 Hz to nominally 5000 Hz [4–14]. However, research has suggested that acoustic frequencies as low as 20 Hz should be a consideration for lightweight constructions [15–17], indicating that a frequency range of 20 Hz to 5000 Hz should ideally be considered. Accordingly, this subsection is divided into two parts:

1. Vibration-based serviceability of floors
2. Acoustics of floors

2 Human-Induced Vibrations Issues

Timber floors are particularly susceptible to human-induced vibrations, which can give rise to various issues affecting their performance and occupant comfort. One significant issue is the potential discomfort experienced by occupants due to excessive vibrations. When timber floors are excited by walking or other human activities, floor vibration can be perceived by occupants, causing discomfort and even affecting the usability of the space. Excessive vibrations can lead to discomfort while walking, using furniture, or performing tasks that require stability [18]. It is crucial to address this issue to ensure the satisfactory serviceability of timber floors [19–24].

Human-induced vibrations in timber floors can also impact the functionality and performance of sensitive equipment and installations. In spaces where delicate instruments, equipment, or machinery are present, excessive vibrations can cause operational issues, measurement inaccuracies, or even damage to the equipment. This issue is particularly relevant in environments such as laboratories, healthcare facilities, and industrial settings where precise measurements and stable conditions are necessary [25].

Another concern is the potential fatigue and degradation of timber elements caused by prolonged exposure to excessive vibrations. Over time, repeated dynamic loading can lead to fatigue failure, and reduced strength, and durability of the timber floor system. This issue can compromise the long-term structural integrity of the floor and may require maintenance or strengthening interventions.

Additionally, the perception of vibrations in timber floors can vary among individuals, and some occupants may be more sensitive to vibrations than others. This issue highlights the importance of considering occupant comfort and wellbeing in the design and assessment of timber floors, as individual sensitivity can influence the acceptability of vibrations in different contexts [26].

Addressing these issues requires a comprehensive understanding of the dynamic behaviour of timber floors and the factors influencing human-induced vibrations. Experimental studies, such as impact tests and field measurements, play a crucial role in assessing the vibrational performance of timber floors and identifying potential mitigation strategies.

By considering these specific issues related to human-induced vibrations in timber floors, researchers and designers can develop effective design approaches, including appropriate damping measures, structural optimization techniques, and user guidelines, to ensure the satisfactory serviceability, occupant comfort, and long-term performance of timber floor systems [27–31].

3 Acoustics of Floors

The EU Environmental Noise Directive of 2002 specifically addresses the prevention of environmental noise pollution. The Directive focuses on noise to which humans are exposed, particularly in built-up areas. In 2008, the Directive was extended to include vibration as a form of pollution [32]. The Directive considers the direct or indirect influence of vibration, heat, or noise as pollution. However, despite the Directive, noise and vibration are often treated separately in the context of sustainable indoor comfort. International and national standards typically address these factors individually. In the literature and relevant standards, the perception of vibration in buildings has been extensively analyzed and studied over the past decades [33,34]. However, many authors suggest that the main discomfort experienced in buildings is related to a combined effect of noise and vibration. Noise and vibration co-occur in buildings, and even if the acoustic or vibration thresholds meet legal or standard limits, occupants can still report annoyance [35]. Nering et al. [36] proposed the evaluation of exposure to simultaneous events based on research by Howarth and Griffin [37]. They presented a graphical representation of the annoyance level as a function of sound exposure level (SEL) and vibration dose value (VDV). Physically, vibrations can be linked to the radiated sound power of a planar structure when expressed in terms of velocities. However, the sound power levels (W) emitted from a structure are linked to not just the structure's vibration levels, but also the so-called radiation efficiency of the structure. An expression for a planar element radiating into a fluid half-space is [38],

$$W = \frac{\sigma \rho c S \overline{|v|^2}}{2}. \tag{1}$$

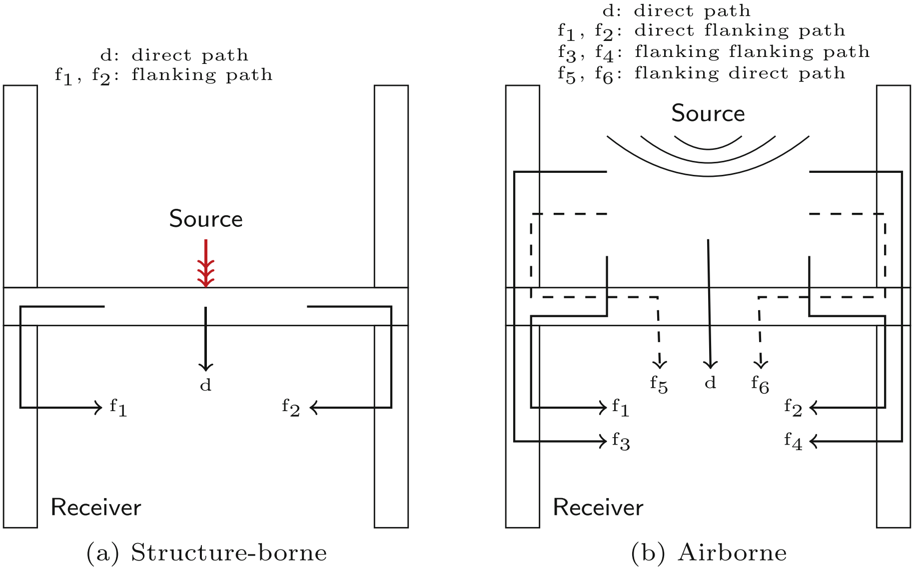
In the case of a floor radiating sound into the room above or below, S would be the surface area of the floor, ρ and c would respectively be the density and speed of sound in air, $\overline{|v|^2}$ would be the time- and spatially-averaged mean square velocity of the radiating surface, and σ would be the radiation efficiency of the floor. A noteworthy observation of Eq. 1, is that for a given floor, $W \propto \sigma\overline{|v|^2}$. This implies that reducing vibration levels may not necessarily equate to reduced radiated sound power levels if the radiation efficiency of the structure is increased in the process. The radiation efficiency of a vibrating structure is related to its response frequency and the vibratory velocity distribution on its surface. Typically, an element radiates with low efficiency below its critical frequency, $f < f_c$, where the critical frequency may be calculated according to Eq. (2) [38]

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{m''}{B}}. \tag{2}$$

m'' is the mass density and B is the bending stiffness of the element per unit width. For orthotropic plate elements, such as timber, two critical frequencies are calculated for each planar direction, i.e. $f_{c,x}$ and $f_{c,y}$. At the critical frequency, $f = f_c$ the radiation efficiency is at a maximum, and approaches a value of unity for $f > f_c$. A consequence of this, is that, while increasing the stiffness of a floor may shift problematic resonances from the human sensitive range of vibrations, this increase in stiffness can consequently increase the radiation efficiency of the floor, decreasing its acoustic performance. Care must also be given when treating undesirable noise and vibration levels by the addition of mass, that the vibration velocity distribution across the floor is not altered in such a way as to negate the effect of the additional mass on the radiated sound power levels of the structure.

Acoustic problems are prevalent in lightweight constructions [39–41]. Typical annoying sounds in buildings include people talking, television noise, footsteps. Transmission between rooms can occur through airborne or structure-borne paths. The paths themselves may be either direct path or flanking paths. An illustration of some potential flanking paths is illustrated in Fig. 1 for one room situated directly above another. For the case of a structure-borne sound source, there are three primary transmission paths, while for the case of an airborne sound source, there are 7 primary transmission paths. However, this schematic is for illustrative purposes, with the number of possible transmission paths depending on the structure and configuration. For example, there is a similar case for rooms adjacent to each other, when considering Fig. 1 as a top-down perspective. Accordingly, sound can reach the listener's room through various transmission paths, such as direct radiation from the separating wall, transmission of vibrations to adjacent walls, or transmission of vibrations from side walls of the source room to the partition or side walls of the listener room [42]. Flanking sounds refer to all sounds propagating through partition walls or floors, and solving flanking transmission problems is crucial for effective sound insulation.

Olsson [43] recently investigated the impact sound transmission of lightweight timber floors. The study focused on transmission and insulation without reverberation using fluid elements connected to reflection-free boundaries. The results



(a) Structure-borne (b) Airborne

Fig. 1. Sound transmission paths between two rooms (excluding indirect transmission) separated by a floor element. (a) Structure-borne sound transmission (b) Airborne sound transmission.

showed that a floor model with a hard screed surface exhibited higher impact force compared to a softer floor, although this effect was less pronounced at the lowest frequencies.

Reducing flanking transmission involves limiting the vibrations transmitted to the walls and floors in the source room. The goal is to minimize sound radiation from the walls and floors of the receiving room and reduce vibrations transmitted from the source room to the receiving room [44]. Achieving this requires a complete separation of the structural and non-structural parts of the adjoining apartments.

Separation is typically achieved using a layer more compliant than the timber of the structural elements that are to be connected. In the vertical direction, a compliant interlayer is used between overlapping walls, floors, and bearing walls, floors, and bearing walls. However, these layers are often subjected to static loads, so stiff layers should be used in the load-bearing structure. One drawback is that stiff layers can increase coupling and reduce the effectiveness of sound insulation [45,46]. Soundproof steel angle brackets can also be employed to prevent acoustic bridges, where rigid parts are separated by interlayers. Elastomers, such as closed cellular polyurethane (CCP) and mixed cellular polyurethane (MCP), are frequently used to reduce low-frequency noise [47,48].

A quantity known as the Vibration Reduction Index (K_{ij}) is a standardised quantity used in acoustics to characterise junction attenuation and determine the contribution of flanking sound transmission to the overall sound transmission into a space. The vibration reduction index is defined in the ISO 12354 series [13,14]. Schoenwald et al. experimentally demonstrated the efficacy polyurethane interlayers with a design frequency of $f_0 = 20\,\mathrm{Hz}$ for improving the vibration reduction index and flanking sound transmission performance of a mass timber structure with CLT walls and glulam floors. A best-case scenario showed an improvement of the vibration reduction index up to 17 dB when considering structure-borne sound transmission across a T-junction between vertically adjacent rooms. The best-case scenario compared a reference configuration (a): no elastic interlayers and steel angle brackets; and a best-case scenario configuration (b): no angle brackets and an elastic interlayer between the mass timber elements. The introduction of a third configuration (c), which contained an elastic interlayer between the mass timber elements and decoupled angle brackets with elastic interlayers showed an improvement of up to 12 dB. The vibration reduction improvements of configurations (b) and (c) resulted in 13 dB and 10 dB improvements of the airborne sound insulation of the floor system ($R_W^{'}$), respectively. The addition of decoupled angle brackets, required for structural supports, reduced the airborne sound insulation performance by 3 dB over the best-case scenario. This result indicates that further optimisation of the noise and vibration performance of the decoupled angle brackets for the investigated connection configuration is limited. However, this does not exclude the possibility of new decoupling techniques and technologies to further reduce flanking sound transmission [49].

There are alternative measures to reducing flanking sound transmission, however, these measures come with their own drawbacks. [50]

While separation is an effective solution for sound insulation, it can increase the overall deformability of the building, potentially compromising its stability. The influence of flexible sound insulation layers on the seismic performance of Cross-Laminated Timber (CLT) walls has been studied by Azinović et al. [48]. The study showed that the bedding insulation layer under the wall negligibly affected the load-bearing capacity under lower vertical loads. However, the stiffness of the wall decreased to less than 40% of the un-insulated wall due to additional lateral deformations caused by the insulation. Experiments also indicated that a higher vertical load substantially increased the lateral load bearing capacity and stiffness of the shear wall due to the associated increase in friction. The cyclic response of insulated steel angle brackets used for Cross-Laminated Timber (CLT) connections was assessed by Kržan et al. [51]. The tests revealed that insulation under the angle bracket had a marginal influence on the load-bearing capacity but significantly affected the stiffness characteristics, resulting in a reduction of effective stiffness by 22% and 45% in pure shear and tensile loading, respectively. Furthermore, the insulated specimens exhibited lower relative energy dissipation and equivalent viscous damping coefficient compared to the uninsulated samples, although this difference decreased with increasing displacements and repeated cycles.

The mainstream research on sound insulation of timber buildings focuses on two aspects:

- Modelling approaches. See the recent papers by Fox et al. [52], Paolini et al. [53], De Santis et al. [54], ~~and~~ Wang et al. [55], and Vallely et al. [56]. Fox et al. [52] developed a composite model structure for predicting low-frequency vibration in light timber floors, considering the coupling via air cavity. Paolini et al. [53] proposed a method for avoiding hexahedral meshing for the thin elastomer layer. De Santis et al. proposed an analytical model for the stiffness prediction of screw connection with deformable interlayers [54]. Wang et al. [55] implemented state-of-the-art approaches for predicting impact forces, structural vibration and radiated sound power of timber joist floors. Vallely et al. [56] proposed a homogenisation method for Cross-Laminated Timber (CLT) elements. The method is based on first-order shear deformation theory and allows for determination of broadband frequency-independent bending, extensional, shear, and bending-extensional material stiffness matrices. From the material stiffness matrices, effective orthotropic engineering constants can be derived, however, with the assumption that the behaviour of the bending and extensional deformation of the elements remained uncoupled. This limitation is generally not an issue, as Cross-Laminated Timber (CLT) elements are typically composed of symmetric stacking sequences and flexural vibrations dominate the acoustic response of the structure [57]. In cases where the coupled bending-extensional behaviour of CLT elements would be considered non-negligible, the full material stiffness matrices should be implemented, as considered in Vallely et al. [58]. The homogenisation method has been validated against experimental measurements for both modal and forced-response models up to 5500 Hz [56,58].
- Experimental investigations, especially on the role of the floor coverings, see Lietzen [59], who studied the effect of floor coverings on impact sound insulation.

Regarding the experimental investigations on floor coverings, Huang et al. [60] investigated the performance of three kinds of elastic cushion materials for timber floors: Portuguese cork, foam, and polypropylene plastic foam board. They found that foam boards exhibit the highest performance. More details about the studies on acoustic issues will be detailed when addressing specific aspects of different floor typologies in the following paragraphs.

4 Serviceability Criteria

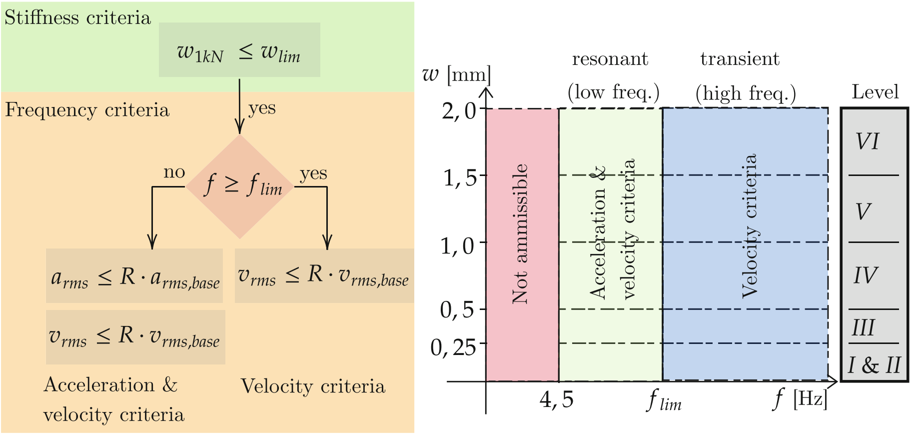
Serviceability requirements for timber floors specifically focus on the performance of lightweight floor systems. Standards and guidelines in this regard consider parameters such as velocity and acceleration to assess floor response. The root mean square values (v_{rms} and a_{rms}) are commonly used as they provide an average measure of the response, accounting for the excitation duration. Another metric, known as root-mean-quad (a_{rmq}), is employed for cumulative measurements, particularly in the analysis of vibration dose values (VDVs) according to standards like BS 6472 and ISO 2631 [3,61].

These serviceability requirements are defined by threshold values expressed using the response factor R. The response factor R serves as a multiplier applied to the base curve value, indicating the level of vibration perceptible to an average human. Different multiples of R, such as 4, 8, and 48, establish various performance levels for the floor system [2].

In the assessment of timber floors, the literature proposes different approaches, considering these parameters individually or in combination. Basaglia [62] distinguishes two main approaches for serviceability assessment based on the floor's intended use:

- Residential Timber Floors: these floors are typically characterized by smaller spans and lighter loads, resulting in higher frequencies. Basaglia suggests employing a pass-fail criterion that considers various parameters such as static deflection, peak velocity, root-mean-quad acceleration, or a combination of these factors.
- Office Timber Floors: these floors generally have larger spans and heavier loads, leading to lower frequencies compared to residential floors. For low-frequency office floors, more detailed procedures have been proposed.

Chang et al. [63] introduced an approach that combines the Response Factor and Vibration Dose Value (VDV) methods to assess the performance of these floors. Additionally, rules developed by Hamm et al. [64,65] and Abeysekera et al. [66], which are currently incorporated in the draft of Eurocode 5 (EC5), provide further guidance. The synoptic table in Table 1, Fig. 2, and Table 2 summarize these criteria.



(a) (b)

Fig. 2. (a) Pass/fail design approach for limiting vibration in timber floor according to Eurocode 5 draft; (b) Floor classification based on the serviceability criteria.

The verification is based on two sequential criteria, stiffness-based and frequency-based. The first step, see Fig. 2a, is a stiffness-based verification: the designer must verify the floor deflection under a concentrated 1 kN load (w_{1kN}), is below a given threshold. If this criterion is satisfied, the designer must also prove that the first natural frequency of the floor is beyond a certain threshold f_{lim}, representing the limit between the resonant and the transient response. The typical human walking pace has a dominant frequency (f_w) ranging between 1.5 to 2.5 Hz. Still, to account for the contribution of the higher harmonics, f_{lim} is typically set as four times the walking frequency [67].

Suppose the inequality in frequency is not satisfied. In that case, the designer must verify that the root mean square acceleration and velocity are below the thresholds defined in terms of the response factor R (see Table 2). The verification can be limited to a velocity check if the inequality is satisfied. The first two verification steps, stiffness and frequency-based, are illustrated in the diagram in Fig. 2(b) where the y and x-axes show the floor deflection and the first natural frequency and three regions are identified. If the first natural frequency of the floor is below 4.5 Hz, the floor behaviour is not admissible (red). For low-frequency floors, with the first natural frequency between 4.5 Hz and f_{lim} (green region), the designer must satisfy both acceleration and velocity criteria. Only the velocity criterion must be verified in the case of high-frequency floors (light blue region). In the absence of more accurate predictions, EC5 provides simplified expressions of the main parameters (f_1, w_{1kN}, a_{rms} and $v_{1,peak}$) needed to verify the vibration performance of a timber floor.

The synoptic Table 1 summarises all the expressions provided by the current EC5 draft to verify the vibration performance of a timber floor. Equation (3) and Eq. (5) present the simplified formulations for estimating the first natural frequency and vertical deflection. Table 3 provides the values for the $k_{e,1}$ factor used to calculate the fundamental frequency in case of a double-span floor on rigid supports. The remaining equations estimate the simplified acceleration and velocity responses in the absence of more accurate predictions.

Empirical design criteria for lightweight floors, shown in Table 1 based on static displacement and the fundamental natural frequency, were not validated against the dynamic response of CLT floors [68]. So far, no specific serviceability criteria have been proposed with a particular reference to CLT floors under multiple occupancy classifications. While traditional lightweight timber floors are prevalent in one-way systems, CLT floors exhibit a plate-like behaviour, being supported on all four sides. The scientific literature highlights two relevant aspects.

Some scholars affirm that using the current vibration criteria for the CLT floor design leads to conservative estimates; see Zhang et al. [69] and Hu et al. [70]. In this sense, Hu et al. [70] proposed a serviceability design criterion based on experimental tests on CLT strips behaving like simply-supported beams. According to Hu et al. [70], CLT strips can be considered the worst scenario since they neglect the effect of four-side support, see the recommendations of the CLT Handbook sponsored by the Canadian forest industry [71].

On the other hand, the human-induced dynamic response of CLT panels is associated with a significant contribution of higher modes, neglected by the EC5 formulation [72–75]. If all sides of the panel are supported, the number of participating modes can increase significantly up to 100 Hz [76]. This phenomenon is magnified by semi-rigid support conditions, intra-slab joints and a plan aspect ratio close to one. Recently, Milojevic et al. [77] numerically assessed the effect of connections, proving their stronger influence on high-frequency floors rather than low-frequency floors. Also, the effect of multiple people activities appears crucial for CLT floors. Wang [78] showed that the vibration amplitude of CLT floors under multi-person loadings was almost double that under single-person.

Table 1. Synoptic table of the mathematical formulation enclosed in the Eurocode 5 draft for assessing the serviceability of timber floors.

Serviceability criteria according to the new Eurocode 5 draft

Frequency

$$f_1 = k_{e,1} k_{e,2} \frac{\pi}{2l^2} \sqrt{\frac{(EI)_L}{m}} \tag{3}$$

with

$$k_{e,2} = \sqrt{\left(1 + \frac{\left(\frac{l}{b}\right)^4 (EI)_T}{(EI)_L}\right)} \tag{4}$$

Deflection

$$w_{1kN} = \frac{Fl^3}{48\,(EI)_L\, b_{ef}} \tag{5}$$

with:

$$b_{ef} = \min\left\{0,95 \left(\frac{(EI)_T}{(EI)_L}\right)^{0{,}25}; b\right\} \tag{6}$$

Acceleration

$$a_{rms} = \frac{k_{res} \mu F_{dyn}}{\sqrt{2} \cdot 2\zeta M^*} \tag{7}$$

with

$$k_{res} = \max\left\{0,192 \left(\frac{b}{l}\right) \left(\frac{(EI)_T}{(EI)_L}\right)^{0{,}25}; 1\right\} \tag{8}$$

and

$$F_{dyn} = c_f F_p \tag{9}$$

Velocity

$$v_{1,peak} = k_{black} \frac{I_{mod,mean}}{(M^* + 70kg)} \tag{10}$$

with

$$I_{mod,mean} = \frac{42 f_w^{1,43}}{f_1^{1,3}} \tag{11}$$

and

$$M^* = \frac{m \cdot l \cdot b}{4} \tag{12}$$

Table 2. Floor vibration criteria according to the floor performance level.

	Floor performance level					
Criteria	I	II	III	IV	V	VI
Response factor R	4	8	12	24	36	48
Upper deflection limit $w_{1kN} \leq w_{lim}$ [mm]	0.25		0.5	1	1.5	2
Stiffness criteria for all floors	$w_{1kN} \leq w_{lim}$ [mm]					
Frequency criteria for all floors	$f_1 \geq 4.5$ Hz					
Acceleration criteria for resonant vibration design situations ($f_1 < f_{1,lim}$)	$a_{rms} \leq 0.005\text{R m/s}^2$					
Velocity criteria (for all floors)	$v_{rms} \leq 0.0001\text{R m/s}$					

Table 3. Factor $k_{e,1}$ to calculate the fundamental frequency in case of a double span floor on rigid supports. l is the longer span, l_2 is the shorter span of a double span floor in m.

l_2/l	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
$k_{e,1}$	1	1.09	1.16	1.21	1.25	1.28	1.32	1.36	1.41

Thus, multi-person activities are more likely to cause the occupants discomfort, although the serviceability criteria in Table 2 are satisfied. Kozar et al. [79] explored the vibrations caused by human action on five-layer Cross-Laminated Timber (CLT) panels with a height of 14 cm by considering different combinations of thicknesses and spans. The authors discussed the serviceability requirements, highlighting that if the minimum required natural frequency of the CLT panel is 8 Hz, the spans could go up to 6 m.

5 Conclusions

Timber floors present unique challenges in the built environment due to their distinctive physical properties. With a high stiffness-to-mass-density ratio, these lightweight structures offer considerable structural advantages but simultaneously face significant performance issues related to vibration and sound transmission when compared to heavyweight alternatives like concrete floors.

Lightweight timber floors, whose area density is typically below 150 kg m^{-2} [1], have become a key contributor to low-carbon construction. Their reduced mass, however, makes them more susceptible than heavyweight alternatives to both human-induced vibrations in the 1–80 Hz band [2,3] and airborne or impact sound in the 20–5000 Hz band [4,6]. A central theme of this chapter has been the relationship between these phenomena: increasing stiffness to push fundamental modes above the dominant walking range may simultaneously raise radiation efficiency, so that radiated sound power does not fall even as vibration amplitudes diminish, as implied by Eq. (1). Conversely, adding mass can lower both vibration and noise but may be impractical at floor–wall junctions or may compromise the carbon footprint advantage of timber.

The sequential stiffness–frequency–vibration checks in the draft Eurocode 5 (EC5) offer a pragmatic design route, yet experimental and numerical studies on plate-like Cross-Laminated Timber (CLT) panels indicate that these rules can be conservative because they neglect higher-order modes that contribute significantly up to at least 100 Hz [73,76]. Although some researchers report that current criteria over-predict occupant discomfort for CLT floors [69,70], others show that multi-person activities can nearly double vibration amplitudes relative to single-person excitation and thus trigger complaints even when EC5 limits are met [78]. At the same time, field surveys confirm that occupants often perceive combined noise–vibration annoyance even when each parameter separately satisfies its guideline value [36], underscoring the need for unified metrics that merge sound-exposure level and vibration dose value.

Modelling capabilities continue to advance: efficient CLT homogenisation [56], hybrid finite-element/statistical-energy-analysis schemes for joist floors [55] and contact-free air-cavity coupling techniques [52] now permit broadband predictions to 5 kHz within practical time frames, provided that connection stiffness and damping are characterised accurately. Mitigation solutions such as resilient interlayers, elastomeric angle brackets and floating screeds can trim flanking transmission by 6–12 dB, but they simultaneously reduce in-plane stiffness by up to 45 % and may affect seismic performance [48,51]. Tuned floor coverings, for example foam-based boards, have demonstrated impact-sound improvements of up to 15 dB with negligible influence on global floor dynamics [60].

Looking ahead, research should converge on four priorities: first, the formulation of a harmonised limit state that spans 20–5000 Hz and reflects combined noise–vibration perception; second, the development of stochastic multi-person and rhythmic load models suitable for assembly and educational buildings; third, standardised high-frequency characterisation of semi-rigid connections and interpanel gaps; and fourth, lifecycle-aware mitigation strategies that balance acoustic comfort with embodied-carbon targets. For practitioners, an integrated workflow that pairs rapid early-stage analytical models with detailed vibro-acoustic simulations and prototype testing remains essential; response-factor limits can guide preliminary sizing, but plate-like floors should always be checked with modal superposition or time-history methods that capture higher modes. Combining modest mass additions with resilient detailing at floor–wall interfaces typically provides the best trade-off between vibration control, impact-sound insulation and structural efficiency, provided that long-term creep of isolators is considered and that floor performance is verified post-occupancy with wireless accelerometers and sound-level meters.

As sustainable building practices continue to drive increased adoption of timber construction, these serviceability and acoustic considerations will remain crucial for ensuring acceptable levels of occupant comfort, particularly as regulations and standards evolve to better address the complex interaction between vibration and acoustic performance in lightweight floor systems.

Acknowledgments. The CA20139 - Holistic design of taller timber buildings (HELEN) is gratefully acknowledged for networking support.

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