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Comparison of vibrational comfort assessment criteria for design of timber floors among the European countries

Binsheng Zhang [a,*], Birgit Rasmussen [b], André Jorissen [c], Annette Harte [d]

[a] School of Engineering and Built Environment, Glasgow Caledonian University, Cowcaddens Road, Glasgow, UK
[b] SBi, Danish Building Research Institute, Aalborg University, Hørsholm, Denmark
[c] Department of the Built Environment, Technische Universiteit Eindhoven, Eindhoven, The Netherlands
[d] Civil Engineering, College of Engineering and Informatics, National University of Ireland, Galway, Ireland

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ABSTRACT

As part of the research work carried out by the Working Group 3 of COST Action FP0702, the need for vibrational comfort design for buildings and current regulations for comfort assessment of structural vibrations of timber floors in Europe have been summarised. Also the design practices of timber floors with respect to vibrational serviceability criteria, including those for fundamental frequency, unit point load deflection and unit impulse velocity, in up to thirteen European countries have been gathered and their differences been further assessed by analysing flooring systems constructed with three types of joists, i.e. solid timber joists, engineered I-joists and metal web joists. The unit point load deflection criterion is the most crucial one for structural design of timber floors with various types of joists and usually dominates the whole design. Finland tends to be the strictest, followed by Italy, the Netherlands, Austria and Norway, while Denmark, the UK and Ireland are the most generous. Even though EN 1995-1-1 has given general criteria for vibrational serviceability design of timber floors, the variations in the design equations and design limits are still large in the European countries, and hence further harmonisation is still needed.

1. Introduction

With the rapid development of modern construction technology, there is an increasing requirement for timber based lightweight components and buildings. This type of construction can largely reduce the negative effects caused by the global warning. In addition, it also allows an economic and very accurate industrial manufacturing.

In general the vibrational serviceability performance of buildings and components under structural and acoustic vibrations, in particular timber flooring systems, has become an important issue in Europe, and it is even more relevant for timber based lightweight components and buildings due to their natural frequencies of resonance and the low mass of building materials used for constructing these components.

Building acoustics on timber flooring systems concerns airborne and impact sound performances as well as sound from service equipment for mid-frequencies ranging from 200 Hz to 5000 Hz and high-frequency ranging from 5000 Hz to 20,000 Hz. Nowadays, much attention has been paid to low-frequencies ranging from 25 Hz to 100 Hz where timber-based lightweight buildings are likely to have less favourite performances than heavy buildings. Structural vibrations of timber flooring systems due to human activities and machinery produce low frequencies ranging from several Hz up to 50 Hz, which can cause significant annoyance and affect the occupant's comfort.

In the European countries, Eurocode 5 has been widely used for design of timber floors. A building or its component, e.g. timber floors, is generally designed to satisfy both ultimate limit state criteria and serviceability limit state criteria [1]. The former are set to ensure that the building or its component should be safe when subjected to bending, shear, axial loading, bearing and lateral stability under combined self-weight, imposed load, snow, wind and other possible loading, and include equilibrium, structural, geotechnical and fatigue designs. The latter are set to ensure that the building and its components are serviceable, i.e.

- provide acceptable human comfort,
- maintain functioning of the structure under normal use,
- uphold acceptable appearance of the construction works,

by controlling deformations, vibrations and damages adversely affecting durability. Acoustic and structural vibrations fall to the category of ensuring human comfort.

* Corresponding author. Tel.: +44 141 331 8660.
E-mail addresses: Ben.Zhang@gcu.ac.uk (B. Zhang), bir@sbi.aau.dk (B. Rasmussen), A.J.M.Jorissen@bwk.tue.nl (A. Jorissen), annette.harte@nuigalway.ie (A. Harte).

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Vibrational serviceability limit state criteria often dominate the design of timber floors, e.g. long span floors constructed with engineered timber joists. The vibrational parameters which need to be checked include the fundamental frequency, unit point load deflection and unit impulse velocity response. The methods for determining these parameters and the corresponding design limits are proposed in EN 1995 Part 1-1 [2] and the National Annexes of the European countries, which vary largely from country to country due to different design methods, fabrication procedures and construction techniques.

As part of the research work carried out by the Working Group 3 of COST Action FP0702, this paper summarises the need for vibrational comfort for buildings and current regulations for comfort assessment of structural vibrations of timber floors in Europe. The main design practices of timber floors on this aspect among the European countries and their variations are gathered and assessed by using some design examples of timber flooring systems constructed from various types of floor joists, and finally the recommendations on vibrational serviceability design of timber floors are proposed.

2. The need for vibrational comfort design for housing

Social surveys in several European countries have shown that the occupants of multi-storey light weight housing are considerably annoyed by the acoustic and structural vibrations caused by a number of sources [3–7]. Traffic noise alone is the top annoying source and harms the health of almost one-third population in the WHO European Region. It is followed by acoustic and structural vibrations caused by neighbouring residents. It is estimated that more than 50 million Europeans are subjected to the latter, which largely causes adverse effects on quality of life. The World Health Organisation (WHO) defines the health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" and this definition has not been amended since 1948 [8]. Based on this definition, the effects of acoustic and structural vibrations on health should not be simply understood as the adverse physical effects but also as disturbance of well-being, i.e. mental and psychological effects, which in long term will lead to adverse physical effect. In particular, excessive environmental noise seriously harms human health and interferes with people's daily activities at school, at work, at home and during leisure time [9]. It can disturb sleep, cause cardiovascular and psycho-physiological effects, reduce performance and provoke annoyance responses and changes in social behaviour.

Normally, annoying vibrations for occupants in lightweight buildings is divided into structural vibrations with low frequencies and acoustic vibrations with higher frequencies. Table 1 summarises the common sources and types of annoyance for both structural and acoustic vibrations. There is an increasing interest in timber based lightweight components and buildings because of some important requirements. The raw material wood has to be used effectively because of its quantitative limitation and needs to be bounded in buildings for a long time in respect of CO_2-storage regarding the global warming. This type of construction supplementarily allows an economic and very accurate industrial manufacturing. In general the acoustic and vibrational performance of buildings and elements is an important topic in Europe but also becomes even more relevant for timber based lightweight components and buildings. However, acoustic measurement procedures and characterisations of timber based components as well as the prediction of the acoustic performance in situ are research domains that still require further investigations.

For all of these, the COST Action FP0702 carried out the research on Net-acoustics for timber based lightweight buildings and elements, and its main aim was to improve the acoustic behaviour of timber based lightweight buildings and to develop effective prediction models and measurement schemes [10]. Airborne and impact sound performances as well as sound from service equipment were considered over a wide frequency range including low frequencies (50–100 Hz) where lightweight buildings are likely to have lower performances than heavy buildings. Vibrations with further lower frequencies (below 25 Hz) such as floor vibrations due to people walking were also considered, in particular on the subjective evaluation aspects. The following important topics were identified accordingly:

- prediction methods of building acoustic performances adapted to timber based lightweight constructions because the methods for heavy weight constructions do not work for lightweight buildings;
- low frequency vibrations of floors and the whole building because of the body perception of this type of vibration and its consequence on comfort;
- need for assessing comfort and defining proper requirements for this type of building;
- need for acoustic design taking also into account the other technical domains, e.g. thermal aspect in particular.

As a result, four working groups were created, and the Working Group 3 dealt with Comfort assessment for sound and vibration, with its intention to identify problems with classification of acceptability of floors from inhabitants' point of view and subjective evaluation on floor vibration and to review international design requirements related to low frequency sound and vibration performance [11]. The aim of the Working Group was to explore all aspects of low frequency sound and vibration in order to assess acoustic and vibrational comfort of timber based buildings. The results could be especially beneficial for design engineers, material and product manufacturers and acoustic scientists, and should be related to regulatory requirements regarding sound transmission and impact as well as structural vibrations. The following two topics were identified accordingly:

- rating of the annoyance associated to vibration in lightweight buildings, typically below 25 Hz;

Table 1
Sources and types of annoyance for comfort assessment.

Sources of annoyance	Structural vibrations		Acoustic vibrations	
	Type of annoyance	Frequency range	Type of annoyance	Frequency range
Walking people	Vibrations from neighbours, people in the same room or person himself	0–80 Hz	Noise from neighbours, people in the same room or person himself	>25 Hz (>50 Hz)
Jumping children	The same as walking people	0–80 Hz	The same as walking people	>25 Hz (>50 Hz)
Service equipment	Indoors vibrations	N/A	Indoors noise	>25 Hz (>50 Hz)
Domestic appliances	Indoors vibrations	N/A	Indoors noise	>25 Hz (>50 Hz)
Traffic	Outdoors vibrations	1–80 Hz	Outdoors noise	N/A
Wind	Outdoors vibrations	N/A	Outdoors noise	N/A

- rating of the annoyance associated with sound in lightweight buildings, especially at low frequencies, typically 50–100 Hz or even 25–100 Hz.

Two objectives in the WG3 were set to

- review national requirements related to low frequency sound and vibration performance;
- identify problems with classification of acceptability of floors from inhabitants' point of view and subjective evaluation of floor vibrations.

The expected outputs include the state of the art of the current assessment procedures related to low frequency acoustic and vibrational comfort and the recommendations for future standardisation development.

Within the Working Group 3, Rasmussen [6,7,12] summarised the current descriptors and regulatory requirements for sound insulation housing in Europe and confirmed the importance of the harmonisation of sound insulation requirements in Europe. Zhang et al. [13,14] extensively investigated the vibrational performance of lightweight timber floors constructed from various types of joists and also compared the test results with the current design codes for timber flooring systems. Labonnote [15] systematically investigated the damping in timber structures, including material damping and structural damping in timber members and structures. Several Short Term Scientific Missions (STSMs) were also carried out in the Working Group to enrich the Group's research activities and strengthen the cooperation between the European countries. Su [16] collected and compared current timber floor design codes and regulatory requirements for impact sound insulation and vibration control in the UK and the Nordic countries. De Klerk [17] tried to improve the predictability of low frequency vibration response in timber based floor structures. This paper only presents the research work carried out in the Working Group 3 on structural vibrations of timber floors.

3. Current regulations on comfort assessment for structural vibrations of timber floors in Europe

Table 2 summarises major design standards and codes which are currently used in Europe for comfort assessment of structural vibrations of timber floors, together with rating methods, frequency ranges, descriptors and available limiting values.

EN 1995-1-1 [2] has set three criteria

- the fundamental frequency f_1 of residential floors must be larger than 8 Hz otherwise a special investigation should be made but no indication is given about the investigation;
- the maximum instantaneous vertical deflection w caused by a vertical concentrated static force F applied at any point on the floor surface, taking account of load distribution, is smaller than its limit a but no value or equation is given for calculating a except that in Fig. 7.2 of the code a range of 0.5–4.0 mm is defined;
- the maximum vibration velocity v in m/N s^2 caused by an ideal unit impulse (1 N s) applied at a point of the floor should be smaller than its limiting value $b^{(f_1\zeta-1)}$ where b is a parameter depending on a, and ζ is the damping ratio, with the components above 40 Hz disregarded.

Feldmann et al. [18] in a JRC scientific and technical report have suggested the use of a single response parameter to reflect both the comfort perception of users and the dynamic response of the floor structure. This first needs a weighting function $B(f)$ for the spectrum of vibration velocities, and the root mean square values (the RMS values) are used as effective response values by evaluating a time window T_s. The one step-root mean square values (the OS-RMS values) with certain fractile, e.g. 90%, can be defined for further establishing the perception curves for vertical vibrations (W_b curves) and for horizontal vibrations (W_d curves) so as to assess the vibrational comfort of floors. The working frequency f ranges from 1 to 80 Hz, and the OS-RMS$_{90}$ has a limit ranging from 0.1 to 3.2 mm/s for residential buildings depending on the building class categorised from Class A to Class D.

ISO 2631 Part 1 [19] and Part 2 [20] also suggest the perception curves for vertical vibrations (W_b curves) and horizontal vibrations (W_d curves) to assess the vibrational comfort of floors with the working frequency f ranging from 1 to 80 Hz. The proposed parameters include the weighted root-mean-square velocity v_{rms} and acceleration a_{rms} but no limits are given.

ISO 10137 [21] suggests the perception curves for vertical vibrations (W_b curves) and horizontal vibrations (W_d curves) to assess the vibrational comfort of floors with the working frequency f ranging from 0.5 to 80 Hz. The vibration dose values for vertical and horizontal vibrations, VDV$_b$ and VDV$_d$, are used here, and their limits for different levels of adverse comment within residential buildings are largely dependent on day time or night time. BS 6472-1 [22] suggests the same perception curves for W_b and W_d curves by using the parameters VDV$_b$ and VDV$_d$, with similar limits for different levels of adverse comment within residential buildings.

DIN 4150 Parts 1–3 [23–25] use the maximal weighted vibration strength KB to assess the structural related low frequency vibrational perception for human beings. KB is dimensionless and is related to the peak particle velocity v_i in mm/s, the reference frequency f_0 = 5.6 Hz, and the vibrational frequency f in Hz. The limit for KB in residential buildings ranges between 0.15 and 0.3.

Table 2
Design standards for comfort assessment of structural vibrations of timber floors.

Standards	Rating methods	Frequency range (Hz)	Descriptors	Limiting values
EC5-1-1 [2]	f_1, w and v	8–40	f_1 (Hz)	>8 Hz
			w (mm/kN)	a = 0.5–4.0 mm/kN, depending on NAs
			v (m/N s^2)	$b^{(f_1\zeta-1)}$ m/N s^2, depending on NAs
JRC report [18]	W_b and W_d curves	1–80	OS-RMS$_{90}$ (mm/s)	0.1–3.2 mm/s
ISO 2631-1 and 2 [19,20]	W_b and W_d curves	1–80	v_{rms} (m/s)	N/A
			a_{rms} (m/s^2)	N/A
ISO 10137 [21]	W_b and W_d curves	0.5–80	VDV (m/s$^{1.75}$)	Varied with day or night
BS 6472-1 [22]	W_b and W_d curves	0.5–80	VDV (m/s$^{1.75}$)	Varied with day or night
DIN 4150-1 to 3 [23–25]	KB values	1–80	KB	0.15–0.3 for residential buildings
NS 8176 E [26]	W_b and W_d curves	0.5–160	$v_{w,95}$ (mm/s)	Varied with Class A–D
		(0–80)	$a_{w,95}$ (mm/s^2)	Varied with Class A–D
SBR Deel B [27]	Nuisance degree	1–80	V_{max}	Varied with day, evening or night
			V_{per}	

NS 8176 E [26] suggests the perception curves for vertical vibrations (W_b curves) and horizontal vibrations (W_d curves) to assess the vibrational comfort of floors with the working frequency f ranging from 0.5 to 160 Hz compared with the original range from 1 to 80 Hz. The proposed parameters include the 95% fractile weighted velocity $v_{w,95}$ in mm/s and acceleration $a_{w,95}$ in mm/s^2, and the corresponding limits are largely dependent on the categorised classes from A to D.

SRB Directive Part B [27] uses the 95% fractile maximum vibration strength V_{max} and the mean vibration strength V_{per} to evaluate the degree of nuisance to human beings caused by the structural vibrations. Both parameters are dimensionless but the former is actually the maximum value of the latter and is used as the main parameter. The target values of V_{max} are normally controlled over three assessment periods: (i) Day from 07.00 to 19.00, (ii) Evening from 19.00 to 23.00, and (iii) Night from 23.00 to 07.00. Five categories are proposed for V_{max}.

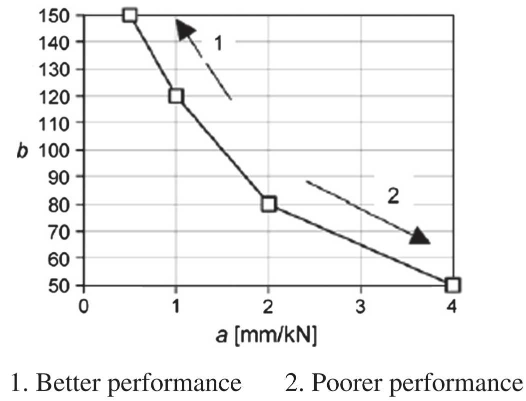


Fig. 1. Recommended range for b and a and the relationship between b and a.

4. Criteria for vibrational serviceability limit state design of timber floors to Eurocode 5

Vibrational serviceability design for timber floors in EN 1995-1-1 is largely based on Ohlsson's early research work [28]. Human beings are regarded as the critical sensors of vibration and their discomfort to structural vibrations of timber floors becomes great concern to many professionals. For building design, human activities and machinery are the two most important internal sources of vibration in timber based lightweight buildings (TBLBs). Human activities include footfall from normal walking and children's jumping, which can cause human discomfort due to footfall-induced vibrations. Human discomfort can also be caused by machine-induced vibrations.

From Ohlsson, the human sensitivity and perception to structural vibrations is regarded to be

- related to vibration acceleration for frequencies which are lower than 8 Hz,
- related to vibration velocity for frequencies which are higher than 8 Hz,
- increased by the duration of vibration,
- decreased by proximity to or awareness of the vibration source,
- decreased by physical activities.

Based on those facts, Ohlsson systematically carried out experimental testing and numerical analysis on structural vibrations of timber floors and proposed several parameters for controlling the vibrational serviceability design of timber floors, including the fundamental frequency f_1, the maximum deflection w of the floor under unit point load applied at the floor centre, and the maximum velocity response v under unit impulse. These three parameters have been adopted in EN 1995-1-1 for vibrational serviceability design of timber floors.

4.1. Fundamental frequency

EN 1995-1-1 requires that the fundamental frequency of residential floors, i.e. the first first-order modal frequency f_1 in cycles per second or Hz, should satisfy the following equation

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}} > 8\ \text{Hz} \tag{1}$$

where m is the mass per unit area in kg/m^2, L is the floor span in m, and $(EI)_L$ is the equivalent plate bending stiffness of the floor about an axis perpendicular to the beam direction in N m^2/m.

4.2. Unit point load deflection

For residential floors with f_1 > 8 Hz, the maximum instantaneous vertical deflection caused by a unit point load, w, in mm/kN, should satisfy the following equation

$$w \leqslant a(\text{mm/kN}) \tag{2}$$

where a is the design limit of the deflection of the timber floor under unit point load.

4.3. Unit impulse velocity response

For residential floors with f_1 > 8 Hz, the unit impulse velocity response, or the maximum initial value of the vertical floor vibration velocity (in m/s) caused by an ideal unit impulse (1 N s) applied at the point of the floor which gives maximum responses, v, should satisfy

$$v \leqslant b^{(f_1\zeta-1)}\ (\text{m/N s}^2) \tag{3}$$

For a rectangular floor with an overall dimension of $L \times B$, simply supported along all four edges, the value of v may be taken as

$$v = \frac{4(0.4+0.6n_{40})}{mBL+200}\ (\text{m/N s}^2) \tag{4}$$

where B is the floor width in m, n_{40} is the number of first-order modes with natural frequencies up to 40 Hz, given as

$$n_{40} = \frac{B}{L}\left\{\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\frac{(EI)_L}{(EI)_B}\right\}^{1/4} \tag{5}$$

and $(EI)_B$ is the equivalent plate bending stiffness of the floor about an axis parallel to the beam direction in N m^2/m. The parameter b for assessing v is dependent on the deflection limit a and can be directly obtained from Fig. 7.2 of EN 1995-1-1 (see Fig. 1). ζ is the modal damping ratio, recommended as ζ = 0.01.

5. Current national annexes to EN 1995-1-1 in the european countries

The National Annexes (NAs) to EN 1995-1-1 have been collected from thirteen European countries, including

- Austria (AT) [29]
- Belgium (BE) [30]
- Denmark (DK) [31,32]
- Finland (FI) [33]
- France (FR) [34]
- Germany (DE) [35]

- Ireland (IE) [36]
- Italy (IT) [37]
- Netherlands (NL) [38]
- Norway (NO) [39]
- Spain (ES) [40]
- Sweden (SE) [41]
- United Kingdom (UK) [42]

5.1. Fundamental frequency

Eq. (1) for calculating the fundamental frequency f_1 is a simplified design equation which is actually applied for two-side supported floors and the effect of the transverse stiffness is omitted because the errors caused are not large. EN 1995-1-1 does not clearly indicate how the participating mass should be calculated and whether the composite effect of floor joists and deck in the floor direction should be considered. Table 3 summarises the design equations and the corresponding limits for the fundamental frequency f_1 proposed from EN 1995-1-1 and the National Annexes.

The majority of the European countries have directly adopted Eq. (1) for determining the fundamental frequency and the limit of 8 Hz specified in EN 1995-1-1 except Austria and Finland. Austria adopts Eq. (1) for two-side supported floors and provides a fairly accurate equation for four-side supported floors by including a quadratic term about L/B to reflect the effect of transverse stiffness [29]. The equation, however, omits a term about $(L/B)^2$. Finland provides a more accurate equation for four-side supported floors by including both second-order and fourth-order terms about L/B for the transverse stiffness effect [30]. The frequency limit is also raised to 9 Hz. Spain specifies the limiting values for the fundamental frequency f_1 for all construction materials including timber: $f_1 > 8$ Hz for gymnasiums and sport buildings, $f_1 > 7$ Hz for public spaces without fixed seats, and $f_1 > 3.4$ Hz for public spaces with fixed seats [40].

Austria and Finland specify that the floor mass m should be determined using quasi-permanent combination of dead and imposed loads, as specified in Eq. (6.16b) of EN 1990 [1]

$$m = m_{Gk} + \psi_2 m_{Qk} \tag{6}$$

where m_{Gk} is the mass due to the characteristic dead load G_k, and m_{Qk} is the mass due to the characteristic imposed load Q_k. ψ_2 is the factor for quasi-permanent value of a variable action, e.g. imposed load, and its values for different building categories can be taken from Table A1.1 of EN 1990 or the corresponding tables of the National Annexes to EN 1990. In general, ψ_2 can be taken as 0.3 for domestic residential buildings and office buildings, 0.6 for congregation areas and shopping malls, and 0.8 for storage areas.

Table 3
Design criteria for fundamental frequency f_1.

Country	Design equations for f_1 (Hz)		Limit
EC5-1-1	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}$	For 4-side supported	>8 Hz
AT	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}$	For 2-side supported	EC5-1-1
	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}\sqrt{1+\left(\frac{L}{B}\right)^4\frac{(EI)_B}{(EI)_L}}$	For 4-side supported	
BE	EC5-1-1		EC5-1-1
DK	EC5-1-1		EC5-1-1
FI	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}$	For 2-side supported	>9 Hz
	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}$ $\sqrt{1+\left(2\left(\frac{L}{B}\right)^2+\left(\frac{L}{B}\right)^4\right)\frac{(EI)_B}{(EI)_L}}$	For 4-side supported	
FR	EC5-1-1		EC5-1-1
DE	EC5-1-1		EC5-1-1
IE	EC5-1-1		EC5-1-1
IT	EC5-1-1		EC5-1-1
NL	EC5-1-1		EC5-1-1
NO	EC5-1-1		EC5-1-1
ES	EC5-1-1		EC5-1-1
SE	EC5-1-1		EC5-1-1
UK	EC5-1-1		EC5-1-1

5.2. Unit point load deflection

Eq. (2) provides the criterion for checking the vertical deflection of the timber floor under the unit point load of 1 kN but does not provide the detailed equations for calculating the deflection of the floor and the limiting values. Table 4 summarises the design equations and the corresponding limits for the vertical deflection w, quoted from EN 1995-1-1 and the corresponding National Annexes.

The equations for calculating the vertical deflection w are established based on the beam bending theory by considering the contribution of the transverse stiffness to the longitudinal stiffness in the floor direction. In general, the deflection limiting values largely vary, with Finland and Norway being the strictest, Italy and the Netherlands the next, Ireland, the UK and Denmark the most generous and other countries in-between.

Austria introduces a modification factor of b_F to consider the effect of the transverse stiffness on the vertical deflection w [29] and proposes the limiting value a as 1.5 mm/kN for normal floors and 1.0 mm/kN when the adjacent structures are disturbed. Belgium [30] and Sweden [41] define the limiting value $a = 1.5$ mm/kN, while Italy [37] and the Netherlands [38] defines a lower limiting value $a = 1.0$ mm/kN. Denmark earlier proposed the limiting value $a = 4.0$ mm/kN [31] but has later revised to a reasonable value $a = 1.7$ mm/kN [32] for the normal timber joists in residential buildings with spans up to 6.0 m. Finland introduces a modification factor of k_F to consider the effect of the transverse stiffness on the vertical deflection w and also includes the effect of the timber joist spacing s. A strict value $a = 0.5$ mm/kN is proposed for floors with

Table 4
Design criteria for unit point load deflection w.

Country	Design equations for w	Limit a (mm/kN)
EC5-1-1	N/A	0.5–4.0
AT	$w = \frac{FL^3}{48(EI)_L b_F}$ where $b_F = \frac{L}{1.1}\sqrt[4]{\frac{(EI)_B}{(EL)_L}}$	1.5 normal floors 1.0 when adjacent structures are disturbed
BE	N/A	1.5
DK	N/A	1.7 for timber joists with $L \leqslant 5000$–6000 mm
FI	$w = \min\left\{\begin{matrix} FL^2/[42k_\delta(EL)_L] \\ FL^3/[48s(EL)_L] \end{matrix}\right\}$ where $k_\delta = \sqrt[4]{(EI)_B/(EI)_L}$ and $k_\delta \leqslant B/L$ for 4-side supported	$0.5k$ for $L \leqslant 6000$ mm k depends on span 0.5 for $L > 6000$ mm Additional 0.5 mm allowed for floating and raised floors
FR	N/A	1.3 ± 0.3
IE	$w = \frac{1000\ k_{dist}\ L_{eq}^3\ k_{amp}}{48\ (EI)_{joist}}$ where $k_{dist} \geqslant 0.30$ and $k_{amp} = 1.05$–1.45	1.8 for $L \leqslant 4000$ mm $16{,}500/L^{1.1}$ for $L > 4000$ mm
DE	N/A	N/A
IT	N/A	1.0
NL	N/A	1.0
NO	N/A	0.9 for normal stiff 0.6 for high stiff only for $L \leqslant 4500$ mm
ES	N/A	N/A
SE	N/A	1.5
UK	$w = \frac{1000\ k_{dist}\ L_{eq}^3\ k_{amp}}{48\ (EI)_{joist}}$ where $k_{dist} \geqslant 0.30$ and $k_{amp} = 1.05$–1.45	1.8 for $L \leqslant 4000$ mm $16{,}500/L^{1.1}$ for $L > 4000$ mm

$L > 6$ m. For small rooms with $L \leqslant 6$ m, the limiting value can be increased to $a = 0.5k$ mm/kN [33], where k is an increasing factor of the floor span L and can be determined from Fig. 2. An extra 0.5 mm is permitted for skin plate or floating floors. France defines $a = 1.3 \pm 0.3$ mm/kN but does not indicate when the variation of ± 0.3 mm/kN is applied [34]. Germany [35] and Spain [40] do not provide any design equations or limiting values for deflection. Norway defines the limiting value $a = 0.9$ mm/kN for floors with normal stiffness but $a = 0.6$ mm/kN for floors with high stiffness [39].

Ireland [36] and the UK [42] define a complex but philosophical design equation for calculating the vertical floor deflection w. A factor k_{dist} is introduced first to justify the point load acting on a single joist as

$$k_{dist} = \max \begin{cases} k_{strut}\{0.38 - 0.08\ln[14(EI)_B/s^4]\} \\ 0.30 \end{cases} \quad (7)$$

where $k_{strut} = 0.97$ for single or multiple lines of strutting otherwise $k_{strut} = 1.0$. An amplification factor k_{amp} is then introduced to account for shear deflection in solid timber and glued thin-webbed joists or joint slip due to use of mechanical connections and it can take

- 1.05 for simply-supported solid timber joists,
- 1.10 for continuous solid timber joists,
- 1.15 for simply-supported glued thin-webbed joists,
- 1.30 for continuous glued thin-webbed joists,
- 1.30 for simply-supported mechanically-jointed floor trusses,
- 1.45 for continuous mechanically-jointed floor trusses.

If the lateral floor stiffness is contributed from the timber floor deck, roof ceiling and strutting, the overall equivalent plate bending stiffness of the floor about an axis parallel to the beam direction, $(EI)_B$, can be obtained by simply superpositioning the stiffnesses of individual components and ignoring the composite effect as follows

$$(EI)_B = (EI)_{B,deck} + (EI)_{B,ceiling} + (EI)_{B,strut} \quad (8)$$

An equivalent floor span L_{eq} is used for calculations, which can take the following values

- L for simply supported single span joists,
- $0.9L$ for the end spans of continuous joists,
- $0.85L$ for the internal spans of continuous joists.

The limiting value a for the floor deflection w in Ireland and the UK is regarded as a decrease function of the floor span L in mm if L is larger than 4 m otherwise defaulted as 1.8 mm/kN. When L increases from 4 m to 10 m, a will decrease from 1.8 mm/kN to 0.66 mm/kN, down by 1.14 mm/kN or 63.5%, with the largest variation among the European countries.

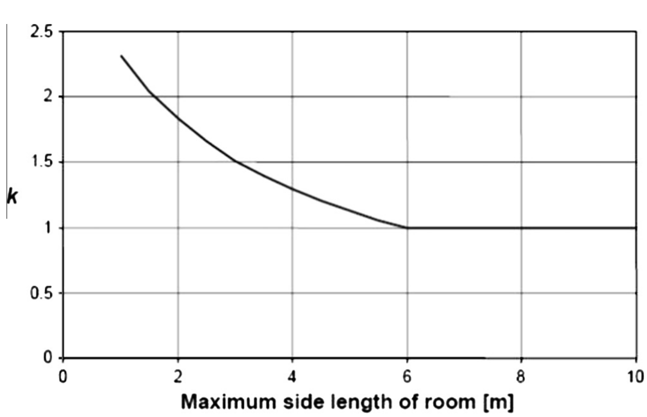


Fig. 2. The increasing factor k for the deflection limit.

Figs. 3–5 further show the comparisons of the values of the deflection limit a among the European countries for the floor span $L = 3$ m, 6 m and 10 m, respectively, together with the average values for a.

For $L = 3$ m, the average value of the deflection limit, a_{av}, is 1.34 mm/kN among the eleven European countries that define the limit a. Six countries have the limits higher than a_{av}, with Denmark, Ireland and the UK having the highest values of 1.70 mm/kN,

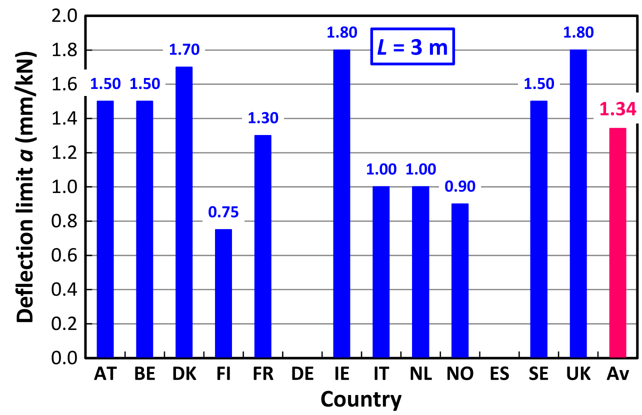


Fig. 3. Deflection limit a in European countries for $L = 3$ m.

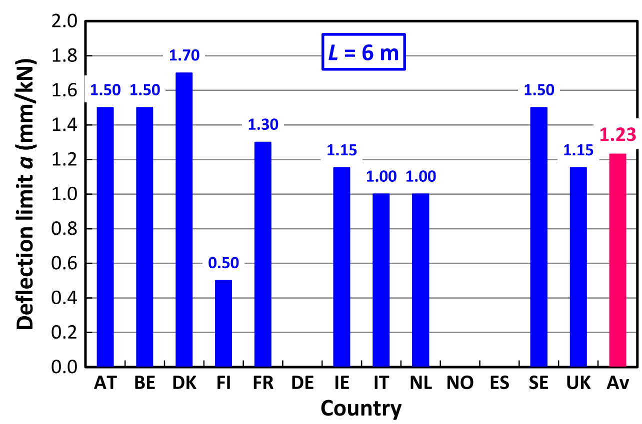


Fig. 4. Deflection limit a in European countries for $L = 6$ m.

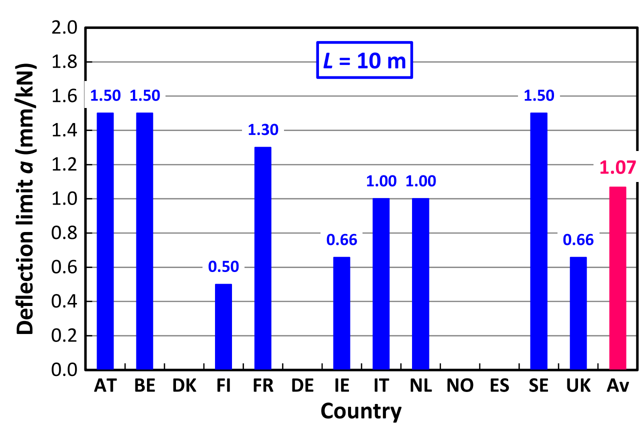


Fig. 5. Deflection limit a in European countries for $L = 10$ m.

1.80 mm/kN and 1.80 mm/kN, respectively. Five countries have the limits lower than a_{av}, with Finland having the lowest value of only 0.75 mm/kN.

For L = 6 m, the average value of the deflection limit, a_{av}, slightly decreases to 1.23 mm/kN among the ten European countries that give the limit a. Five countries have the limits higher than a_{av}, with Denmark still having the highest values of 1.70 mm/kN. The remaining five countries have the limits lower than a_{av}, with Finland still having the lowest value of only 0.5 mm/kN and both Italy and the Netherlands having the second lowest value of 1.00 mm/kN.

For L = 10 m, the average value of the deflection limit, a_{av}, further decreases to 1.07 mm/kN among the nine European countries with the available limit a. Four countries have the limits higher than a_{av}, with Austria, Belgium and Sweden having the highest values of 1.50 mm/kN. The remaining five countries have the limits lower than a_{av}, with Finland still having the lowest value of 0.5 mm/kN, and Ireland and the UK having the second lowest value of 0.66 mm/kN.

Table 5
Design criteria for unit impulse velocity v.

Country	Design equations	Limit (m/N s^2)
EC5-1-1	$v = \frac{4(0.4+0.6n_{40})}{mBL+200}$	$b^{(f_1\zeta-1)}$, ζ = 1%
AT	EC5-1-1	$b \geqslant 100$ normal floors $b \geqslant 120$ when adjacent structures are disturbed
BE	EC5-1-1	EC5-1-1 and b = 100
DK	EC5-1-1	EC5-1-1 and b = 80
FI	N/A	N/A
FR	EC5-1-1	EC5-1-1 and b = 108, from Fig. 7.2 but a < 3 mm/kN
DE	EC5-1-1	N/A
IE	EC5-1-1	EC5-1-1 and b from Fig. 7.2 But not applicable to Category A1 (areas of domestic activities)
IT	EC5-1-1	EC5-1-1 and b = 120
NL	EC5-1-1	EC5-1-1 and b = 120
NO	N/A	N/A
ES	N/A	N/A
SE	EC5-1-1	EC5-1-1, b = 100
UK	EC5-1-1	EC5-1-1, ζ = 2%, $b \geqslant 88$ for $a \leqslant 1.8$ mm/kN

5.3. Unit impulse velocity response

Before the variations of the unit impulse velocity as a vibrational serviceability design criterion are assessed, the meaning of the parameter b is discussed. Fig. 6 shows the relationship between the design limit of the unit impulse velocity, $b^{(f_1\zeta-1)}$, and the parameter b over the range from 50 to 150 suggested by EN 1995-1-1. The fundamental frequency f_1 is assumed to be 10 Hz with the damping ratio ζ = 0.01.

The design limit $b^{(f_1\zeta-1)}$ for v monotonically decreases with the increased b. Also by comparing the relationship between b and the deflection limit a, it can be seen that the higher the value of b, the lower the values of a and $b^{(f_1\zeta-1)}$. This indicates that a higher b value corresponds to a more strict design limit for the unit impulse velocity.

Several countries have disregarded the unit impulse velocity as the vibrational parameter for serviceability limit state design due to its theoretical complexity and measuring difficulty. The limit values largely vary from country to country as well, with main changes in the parameters b and ζ. Table 5 summarises the design criteria for the unit impulse velocity v.

Most European countries have fixed the values for b when determining the design limit of unit impulse velocity except Ireland and the UK which link b to the deflection limit a by following the trend given in Fig. 7.2 of EN 1995-1-1. It can also be seen that the parameter b varies from country to country. Fig. 7 shows the values of the parameter b proposed by nine European countries for L = 6 m. The average value of the parameter, b_{av}, is 106.20. Five countries have the proposed values of b higher than b_{av}. Italy and the Netherlands have the highest value of 120, and Ireland and the UK have the second highest value of 113.91, which indicates that these countries are stricter. The remaining four countries have the values of b lower than b_{av}. Denmark has the lowest value of 80, which is the most generous, and Austria, Belgium and Sweden have the second lowest value of 100, which tends to be generous.

Fig. 8 shows the values of the design limit of the unit impulse velocity, $b^{(f_1\zeta-1)}$, calculated based on the values of b proposed by the nine European countries for L = 6 m. Here f_1 is assumed to be 10 Hz together with ζ = 0.01 except for the UK where ζ = 0.02 is adopted to make this criterion redundant.

The average value of the design limit for the unit impulse velocity, $b^{(f_1\zeta-1)}$, is 0.0161 m/N s^2. Now only two countries have the design limit values higher than the average, with the UK having the highest value of 0.0226 m/N s^2 and Denmark having the second highest value of 0.0194 m/N s^2, which indicates that these two countries are more generous. The remaining countries all have the design limit values lower than the average value. Italy and the Netherlands have the lowest value of 0.0135 m/N s^2, which is the strictest. Ireland has the second lowest value of 0.0141 m/N s^2, France has 0.0148 m/N s^2, and Austria, Belgium and Sweden have the design limit value of 0.0158 m/N s^2.

It should be pointed out that damping is an important parameter which significantly influences the response of occupants to

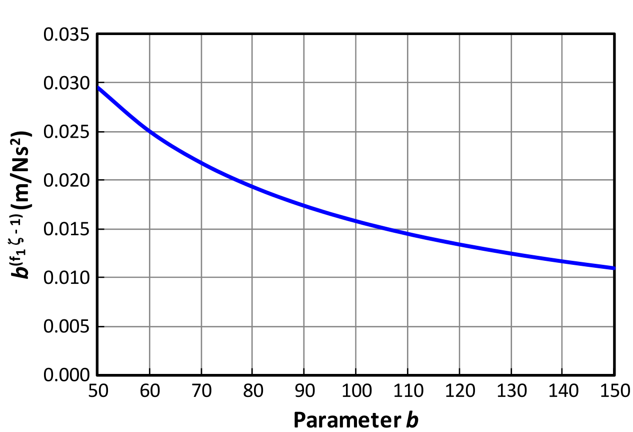


Fig. 6. Relationship between $b^{(f_1\zeta-1)}$ and b.

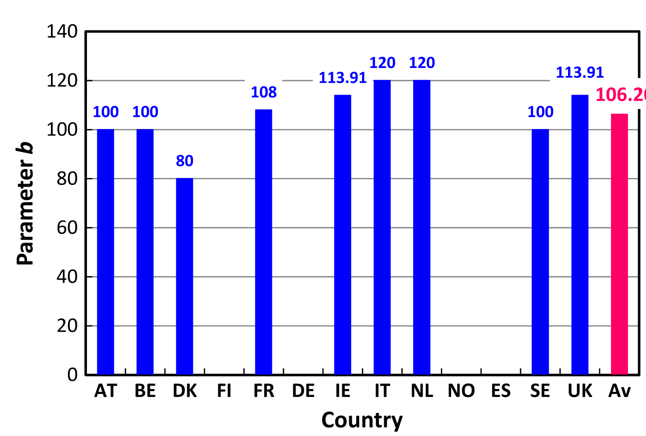


Fig. 7. Parameter b in the European countries for L = 6 m.

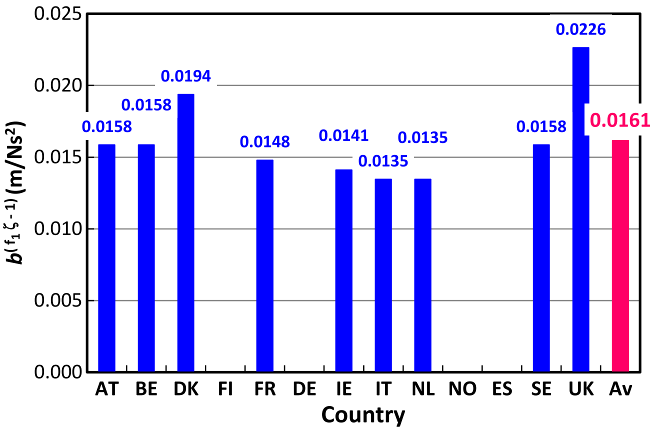


Fig. 8. Design limit $b^{(f_1\zeta-1)}$ in the European countries for $L = 6$ m.

floor vibrations even though it hardly affects the fundamental frequency f_1. Previous research has shown that the timber floors constructed with engineered I-joists had a damping ratio $\zeta = 2–4\%$ [43] while the floors with metal-webbed joists only had a very low damping ratio $\zeta = 0.86\%$ which is below 1% [44]. This indicates that the design damping ratio $\zeta = 1\%$ proposed in EN 1995-1-1 [1] may not cover all timber floor types but a damping ratio $\zeta = 2\%$ proposed in the corresponding UK National Annex [42] may cover most practical cases.

6. Vibrational design of floors with solid timber joists, engineered I-joists and metal web joists

The floors for this study are assumed to be constructed with solid timber joists, engineered I-joists and metal web joists and are presented to show the variations in the vibrational serviceability design of timber floors among the European countries.

6.1. Floors constructed with solid timber joists

Two floors are designed for a domestic timber frame building and are constructed with solid timber joists, see Fig. 9. Floor 1 has a dimension of $L \times B = 3.0$ m $\times$ 3.0 m and is constructed with 47 mm $\times$ 147 mm C24 solid timber joists at a spacing $s = 450$ mm, and Floor 2 has a dimension of $L \times B = 5.0$ m $\times$ 5.0 m and is constructed with 75 mm $\times$ 220 mm C24 solid timber joists at $s = 400$ mm. The P5 particleboard with a thickness of 22 mm is chosen for the decking, and the Gyproc plasterboard with a thickness of 12.5 mm is chosen for the ceiling. The total self-weight of the flooring system including the timber joists is assumed to be 50 kg/m², and Service Class 2 is assumed. The imposed load is taken as $Q_k = 1.5$ kN/m² from EN 1991-1-1 [45].

Table 6 presents the geometric dimensions and materials properties of the two floors. The materials properties are quoted from EN 338 [46]. Table 7 lists the calculated values of the fundamental frequency f_1, the design limits $f_{1,\text{limit}}$ and the ratios of $f_{1,\text{limit}}/f_1$ for the floors using the National Annexes of the European countries (see the detailed formulae in Table 3) and EN 1995-1-1. The results show that the design for Floor 1 has passed all National Annexes with respect to the fundamental frequency and the design for Floor 2 has passed almost all National Annexes except that the design has marginally failed in Finland.

Table 8 lists the calculated values of the deflection w, the limit values of a and the ratios of w/a (see the formulae in Table 4). The results also show that the design for Floor 1 has only passed the criterion in Denmark, Ireland and the UK with respect to the unit point load deflection and the design for Floor 2 has passed the criterion in six countries, i.e. Belgium, Denmark, France, Ireland, Sweden and the UK. The fact that the designs for both floors have failed to pass the criterion in majority of the European countries indicates that the unit point load deflection criterion is more crucial than the fundamental frequency criterion.

Table 6
Basic properties of floors constructed with solid joists.

Parameters	Floor 1	Floor 2
L (m)	3.0	5.0
B (m)	3.0	5.0
s (mm)	450	400
b (mm)	47	75
h (mm)	147	220
t_{deck} (mm)	22	22
t_{ceiling} (mm)	12.5	12.5
$E_{0,\text{mean, C24}}$ (N/mm²)	11,000	11,000
$E_{\text{mean,P5}}$ (N/mm²)	3000	3000
$E_{\text{mean,plaster}}$ (N/mm²)	2000	2000
G_k (kN/m²)	0.491	0.491
Q_k (kN/m²)	1.5	1.5
m (kg/m²)	50	50
ψ_2	0.3	0.3
$(EI)_L$ (N m²/m)	304122.67	1830125.00
$(EI)_B$ (N m²/m)	2987.52	2987.52

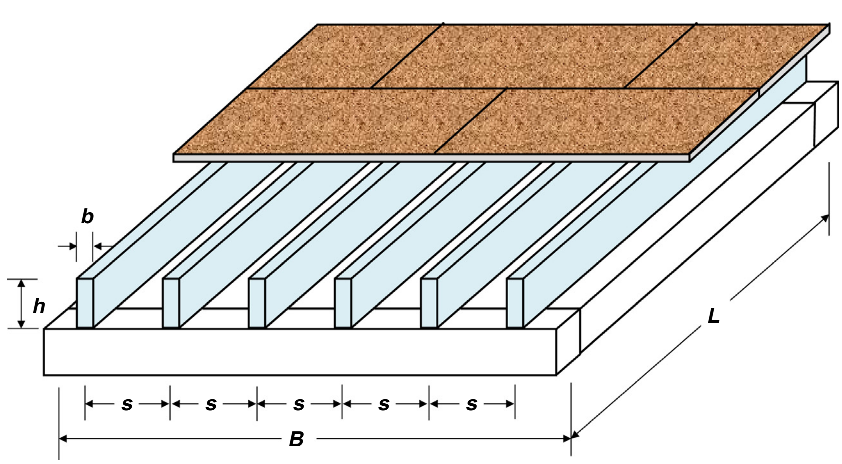


Fig. 9. A typical floor constructed with solid timber joists.

Table 7
Calculated fundamental frequency f_1 and limit $f_{1,limit}$ for solid timber joist floors.

Floor	Floor 1 ($L = 3$ m)			Floor 2 ($L = 5$ m)		
Country	f_1 (Hz)	$f_{1,limit}$ (Hz)	$f_{1,limit}/f_1$	f_1 (Hz)	$f_{1,limit}$ (Hz)	$f_{1,limit}/f_1$
AT	9.88	8.0	0.81	8.69	8.0	0.92
BE	13.61	8.0	0.59	12.02	8.0	0.67
DK	13.61	8.0	0.59	12.02	8.0	0.67
FI	9.97	9.0	0.90	8.70	9.0	1.03[a]
FR	13.61	8.0	0.59	12.02	8.0	0.67
DE	13.61	8.0	0.59	12.02	8.0	0.67
IE	13.61	8.0	0.59	12.02	8.0	0.67
IT	13.61	8.0	0.59	12.02	8.0	0.67
NL	13.61	8.0	0.59	12.02	8.0	0.67
NO	13.61	8.0	0.59	12.02	8.0	0.67
ES	13.61	8.0	0.59	12.02	8.0	0.67
SE	13.61	8.0	0.59	12.02	8.0	0.67
UK	13.61	8.0	0.59	12.02	8.0	0.67

[a] Indicates that the design fails.

Table 8
Calculated deflection w and limit a for solid timber joist floors.

Floor	Floor 1 ($L = 3$ m)			Floor 2 ($L = 5$ m)		
Country	w (mm/kN)	a (mm/kN)	w/a	w (mm/kN)	a (mm/kN)	w/a
AT	2.15	1.50	1.44[a]	1.56	1.50	1.04[a]
BE	1.63	1.50	1.09[a]	1.27	1.50	0.85
DK	1.63	1.70	0.96	1.27	1.70	0.75
FI	2.24	0.75	2.98[a]	1.62	0.57	2.84[a]
FR	1.63	1.30	1.26[a]	1.27	1.30	0.98
DE						
IE	1.63	1.80	0.91	1.27	1.41	0.90
IT	1.63	1.00	1.63[a]	1.27	1.00	1.27[a]
NL	1.63	1.00	1.63[a]	1.27	1.00	1.27[a]
NO	1.63	0.90	1.82[a]	1.27	0.90	1.41[a]
ES						
SE	1.63	1.50	1.09[a]	1.27	1.50	0.85
UK	1.63	1.80	0.91	1.27	1.41	0.90

[a] Indicates that the design fails.

Table 9 lists the calculated values of the unit impulse velocity v, the limiting values of $b^{(f_1\zeta-1)}$, and the ratios of $v/b^{(f_1\zeta-1)}$ (see the formulae in Table 5). If the ratio for any of the three vibrational serviceability parameters is smaller than 1.0, the design can be regarded to be satisfactory with respect to the criterion for that parameter. The results show that the design for Floor 1 has only passed the design criterion in Austria, Denmark, Ireland and the UK with respect to the unit impulse velocity, but the design for Floor 2 has passed the design criterion in seven out of nine European countries except Italy and the Netherlands. This indicates that the unit impulse velocity criterion is less crucial than the unit point load deflection criterion but is still more crucial than the fundamental frequency criterion.

Fig. 10 shows the cohort ratios of all three vibrational parameters calculated based on the National Annexes of the European countries for Floors 1 and 2, respectively. It can be seen that the design for Floor 1 with a span of 3 m has passed all three vibrational serviceability criteria only in Denmark and the UK and has either partially or fully failed to pass the design criteria in the rest European countries. Finland has the strictest design criteria and is then followed by Norway, Italy, the Netherlands, Austria and France. The failure of the floor design in Belgium, Ireland and Sweden is only marginal. For Floor 2 with a span of 5 m, more countries have now passed all three vibrational serviceability criteria, including Belgium, Denmark, France, Ireland, Sweden and UK.

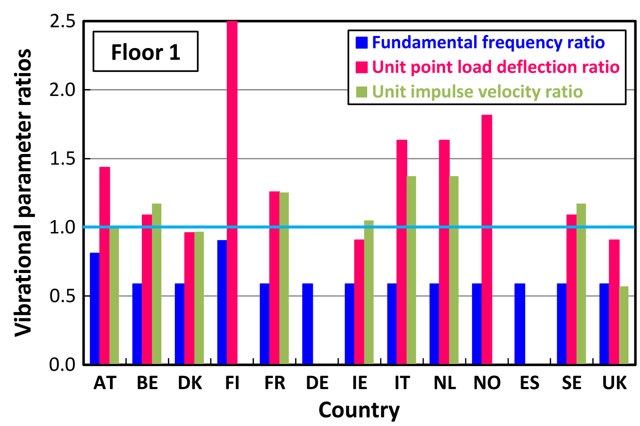
6.2. Floors constructed with engineered I-joists

Floors 3 and 4 are designed for a domestic timber frame building and are constructed with the engineered I-joists (JJI-Joists) produced by James Jones & Sons Ltd. in the UK [47], see Fig. 11. The top and bottom flanges are manufactured from C24 solid timber with

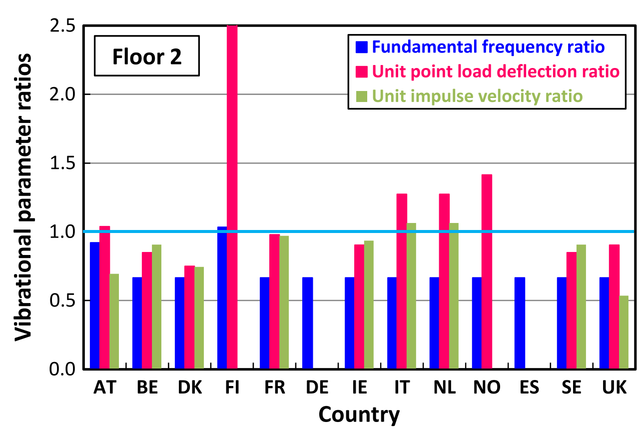
Table 9
Calculated unit impulse velocity v and limit $b^{(f_1\zeta-1)}$ for solid timber joist floors.

Floor	Floor 1 ($L = 3$ m)			Floor 2 ($L = 5$ m)		
Country	v (10^{-2} m/N s^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/N s^2)	$v/b^{(f_1\zeta-1)}$	v (10^{-2} m/N s^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/N s^2)	$v/b^{(f_1\zeta-1)}$
AT	1.571	1.576	1.00	1.036	1.492	0.70
BE	2.196	1.872	1.17[a]	1.577	1.740	0.91
DK	2.196	2.270	0.97	1.577	2.117	0.75
FI						
FR	2.196	1.751	1.25[a]	1.577	1.626	0.97
DE						
IE	2.196	3.845	0.57	1.577	2.944	0.54
IT	2.196	1.599	1.37[a]	1.577	1.482	1.07[a]
NL	2.196	1.599	1.37[a]	1.577	1.482	1.07[a]
NO						
ES						
SE	2.196	1.872	1.17[a]	1.577	1.740	0.91
UK	2.196	3.845	0.57	1.577	2.944	0.54

[a] Indicates that the design fails.



(a) Floor 1 with $L = 3$ m



(b) Floor 2 with $L = 5$ m

Fig. 10. Vibrational parameter ratios for Floors 1 and 2.

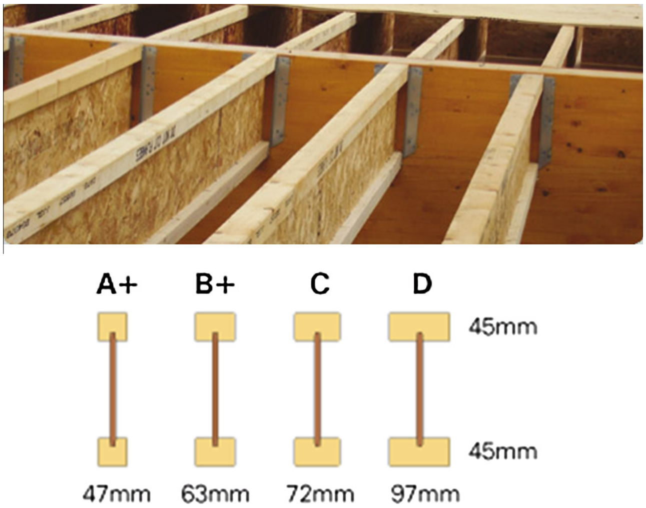


Fig. 11. Engineered I-joists (JJI-Joists).

the width b ranging from 47 mm to 97 mm (A–D) and a constant height of $h_f = 45$ mm. The web is manufactured from 9 mm OSB3 which is embedded into the flanges by 12 mm. The 22 mm P5 particleboard is chosen for the decking, and the Gyproc plasterboard with a thickness of 12.5 mm is chosen for the ceiling. The total self-weight of the flooring system including the engineered I-joists is assumed to be 75 kg/m^2, and also Service Class 2 is assumed. The imposed load is taken as $Q_k = 1.5$ kN/m^2 [45]. Floor 3 has a dimension of $L \times B = 5.4$ m $\times$ 5.0 m and is constructed with the JJI 300B Joists at $s = 400$ mm, and Floor 4 has a dimension of $L \times B = 7.3$ m $\times$ 6.0 m and is constructed with the JJI 400D Joists at $s = 300$ mm.

Table 10 presents the geometric dimensions and materials properties of the floors constructed with JJI-Joists. Table 11 presents the calculated values of the fundamental frequency f_1, the design limits $f_{1,limit}$ and the $f_{1,limit}/f_1$ ratios for the floors using the National Annexes of the European countries and EN 1995-1-1. The results show that both Floors 3 and 4 have passed almost all European National Annexes with respect to the fundamental frequency except that the design for Floor 3 has marginally failed in Austria and Finland, and the design for Floor 4 has only marginally failed in Finland.

Table 10
Basic properties of floors constructed with JJI-Joists.

Parameters	Floor 3	Floor 4
L (m)	5.4	7.3
B (m)	5.0	6.0
s (mm)	400	300
b (mm)	63	97
h (mm)	300	400
h_f (mm)	45	45
t_w (mm)	9	9
t_{deck} (mm)	22	22
$t_{ceiling}$ (mm)	12.5	12.5
$E_{0,mean,C24}$ (N/mm^2)	11,000	11,000
$E_{mean,P5}$ (N/mm^2)	3000	3000
$E_{mean,OSB3}$ (N/mm^2)	4930	4930
$E_{mean,plaster}$ (N/mm^2)	2000	2000
G_k (kN/m^2)	0.736	0.736
Q_k (kN/m^2)	1.5	1.5
m (kg/m^2)	75	75
ψ_2	0.3	0.3
$(EI)_L$ (N m^2/m)	2606249.39	10393003.99
$(EI)_B$ (N m^2/m)	2987.52	2987.52

Table 11
Calculated fundamental frequency f_1 and limit $f_{1,limit}$ for JJI-Joist floors.

Floor	Floor 3 (L = 5.4 m)			Floor 4 (L = 7.3 m)		
Country	f_1 (Hz)	$f_{1,limit}$ (Hz)	$f_{1,limit}/f_1$	f_1 (Hz)	$f_{1,limit}$ (Hz)	$f_{1,limit}/f_1$
AT	7.92	8.0	1.01[a]	8.65	8.0	0.93
BE	10.04	8.0	0.80	10.97	8.0	0.73
DK	10.04	8.0	0.80	10.97	8.0	0.73
FI	7.93	9.0	1.14[a]	8.65	9.0	1.04[a]
FR	10.04	8.0	0.80	10.97	8.0	0.73
DE	10.04	8.0	0.80	10.97	8.0	0.73
IE	10.04	8.0	0.80	10.97	8.0	0.73
IT	10.04	8.0	0.80	10.97	8.0	0.73
NL	10.04	8.0	0.80	10.97	8.0	0.73
NO	10.04	8.0	0.80	10.97	8.0	0.73
ES	10.04	8.0	0.80	10.97	8.0	0.73
SE	10.04	8.0	0.80	10.97	8.0	0.73
UK	10.04	8.0	0.80	10.97	8.0	0.73

[a] Indicates that the design fails.

Table 12
Calculated deflection w and limit a for JJI-Joist floors.

Floor	Floor 3 (L = 5.4 m)			Floor 4 (L = 7.3 m)		
Country	w (mm/kN)	a (mm/kN)	w/a	w (mm/kN)	a (mm/kN)	w/a
AT	1.39	1.50	0.93	0.90	1.50	0.60
BE	1.23	1.50	0.82	0.90	1.50	0.60
DK	1.23	1.70	0.73	0.90	1.70	0.53
FI	1.45	0.53	2.73[a]	0.94	0.50	1.88[a]
FR	1.23	1.30	0.95	0.90	1.30	0.69
DE	1.23			0.90		
IE	1.23	1.29	0.95	0.90	0.93	0.97
IT	1.23	1.00	1.23[a]	0.90	1.00	0.90
NL	1.23	1.00	1.23[a]	0.90	1.00	0.90
NO	1.23	0.90	1.37[a]	0.90	0.90	1.00
ES	1.23			0.90		
SE	1.23	1.50	0.82	0.90	1.50	0.60
UK	1.23	1.29	0.95	0.90	0.93	0.97

[a] Indicates that the design fails.

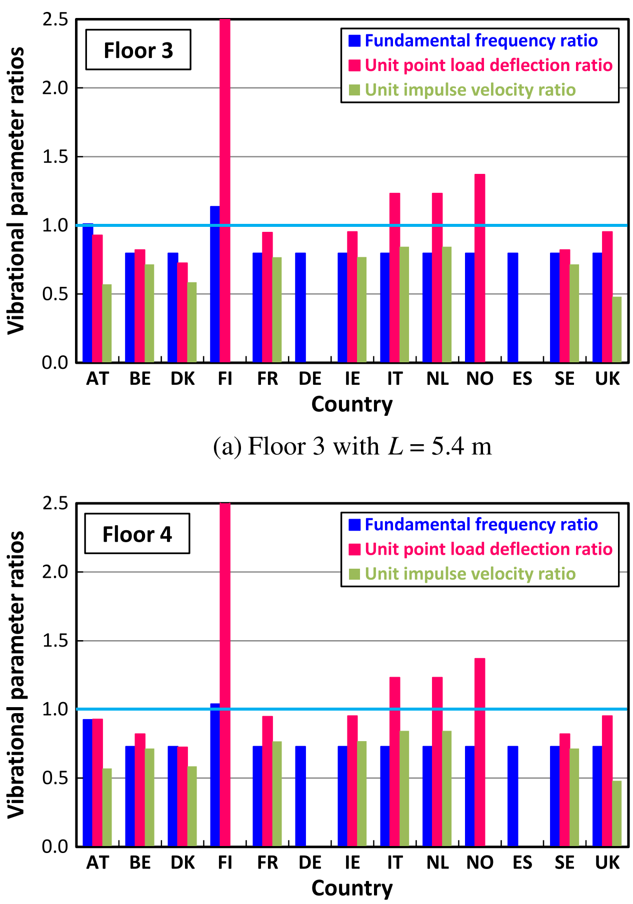
Table 12 lists the calculated values of the deflection w, the limit values of a and the w/a ratios. The design for Floor 3 has only failed in Finland, Italy, the Netherlands and Norway with respect to the unit point load deflection. The design for Floor 4 has passed the criterion in almost every country except Finland, but it has a marginal pass in Ireland, Norway and the UK. This indicates that Finland has given the strictest criterion on the deflection and is followed by Norway, Italy and the Netherlands. Belgium, Denmark and Sweden become more generous than other European countries.

Table 13 lists the calculated values of the unit impulse velocity v, the limiting values of $b^{(f_1\zeta-1)}$, and the $v/b^{(f_1\zeta-1)}$ ratios. Both designs for Floors 3 and 4 have passed the criterion in all European countries included with respect to the unit impulse velocity. In general, the unit point load deflection criterion is more crucial than other two criteria.

Fig. 12 shows the cohort ratios of all three vibrational parameters calculated based on the National Annexes of the European countries for Floors 3 and 4, respectively. Fig. 12a shows that the design for Floor 3 with a span of 5.4 m has passed all three vibrational serviceability criteria in Belgium, Denmark, France, Ireland, Sweden and the UK and has either partially or fully failed to pass the design criteria in other European countries. Finland has the strictest design criteria and is followed by Italy, the Netherlands and Norway. The failure of the floor design in Austria is only marginal. Fig. 12b shows that the design for Floor 4 with a span of 7.3 m has followed a similar trend as the design for Floor 3. All three vibrational serviceability design criteria

Table 13
Calculated unit impulse velocity v and limit $b^{(f_1\zeta-1)}$ for JJI-Joist floors.

Floor	Floor 3 (L = 5.4 m)			Floor 4 (L = 7.3 m)		
Country	v (10^{-2} m/N s^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/N s^2)	$v/b^{(f_1\zeta-1)}$	v (10^{-2} m/N s^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/N s^2)	$v/b^{(f_1\zeta-1)}$
AT	0.822	1.440	0.57	0.615	1.489	0.41
BE	1.138	1.588	0.72	0.860	1.658	0.52
DK	1.138	1.941	0.59	0.860	2.0218	0.43
FI						
FR	1.138	1.482	0.77	0.860	1.548	0.56
DE						
IE	1.138	1.479	0.77	0.860	1.380	0.62
IT	1.138	1.348	0.84	0.860	1.409	0.61
NL	1.138	1.348	0.84	0.860	1.409	0.61
NO						
ES						
SE	1.138	1.588	0.72	0.860	1.658	0.52
UK	1.138	2.367	0.48	0.860	2.340	0.37



(a) Floor 3 with $L = 5.4$ m

(b) Floor 4 with $L = 7.3$ m

Fig. 12. Vibrational parameter ratios for Floors 3 and 4.

have been satisfied in Austria, Belgium, Denmark, France, Ireland, Sweden and the UK while the design criteria have not partially or fully been satisfied in Finland, Italy, the Netherlands and Norway.

6.3. Floors constructed with metal web joists

Two floors are designed for a domestic timber frame building and are constructed with the metal web joists (Posi-Joists) produced by Mitek Industries Ltd. [48], see Fig. 13. The top and bottom flanges (chords) are manufactured from TR26 solid timber [49] with the width b ranging from 72 mm to 147 mm (PS8 to PS16) and a constant height of h_f = 47 mm. The engineered V shaped galvanised steel webs of 203 mm (8″) to 406 mm (16″) are fixed to the top and bottom chords via the nail-plated zones. The 22 mm P5 particleboard is chosen for the floor decking, and the Gyproc plasterboard with a thickness of 12.5 mm is chosen for the ceiling. Floor 5 is laterally stiffened using a TR26 solid timber strongback of 47 mm × 147 mm in the transverse direction at the mid-span, while Floor 6 is stiffened using two TR26 strongbacks of the same sizes at two-thirds spans. The previous experimental research confirms that both cases produced the same stiffening effect [44], which has been included in the latest version of the UK National Annex to EN 1995-1-1 [42]. The total self-weight of the flooring system including the Posi-Joists and the strongbacks is assumed to be 75 kg/m^2, and also Service Class 2 is assumed. The imposed load is taken as Q_k = 1.5 kN/m^2 [45]. Floor 5 has a dimension of $L \times B$ = 5.0 m × 5.0 m and is constructed with PS10 Joists at s = 600 mm, and Floor 6 has a dimension of $L \times B$ = 7.5 m × 6.0 m and is constructed with PS16 Joists at s = 400 mm.

Fig. 13. Metal web joists (Mitek Posi-Joists).

Table 14 presents the geometric dimensions and materials properties of the floors constructed with Posi-Joists. Table 15 presents the calculated values of the fundamental frequency f_1, the design limits $f_{1,\text{limit}}$ and the $f_{1,\text{limit}}/f_1$ ratios for the floors using the National Annexes of the European countries and EN 1995-1-1.

Table 14
Basic properties of floors constructed with Posi-Joists.

Parameters	Floor 5	Floor 6
L (m)	5.0	7.5
B (m)	5.0	6.0
s (mm)	600	400
b (mm)	97	97
h (mm)	254	421
h_f (mm)	47	47
b_{strut} (mm)	47	47
h_{strut} (mm)	147	147
t_{deck} (mm)	22	22
t_{ceiling} (mm)	12.5	12.5
$E_{0,\text{mean,TR26}}$ (N/mm^2)	11,000	11,000
$E_{\text{mean,P5}}$ (N/mm^2)	3000	3000
$E_{\text{mean,plaster}}$ (N/mm^2)	2000	2000
G_k (kN/m^2)	0.736	0.736
Q_k (kN/m^2)	1.5	1.5
m (kg/m^2)	75	75
ψ_2	0.3	0.3
$(EI)_L$ (N m^2/m)	1821467.40	11086227.89
$(EI)_B$ (N m^2/m)	30358.56	21234.88

Table 15
Calculated fundamental frequency f_1 and limit $f_{1,\text{limit}}$ for Posi-Joist floors.

Floor	Floor 5 ($L = 5$ m)			Floor 6 ($L = 7.5$ m)		
Country	f_1 (Hz)	$f_{1,\text{limit}}$ (Hz)	$f_{1,\text{limit}}/f_1$	f_1 (Hz)	$f_{1,\text{limit}}$ (Hz)	$f_{1,\text{limit}}/f_1$
AT	7.78	8.0	1.03[a]	8.48	8.0	0.94
BE	9.79	8.0	0.82	10.74	8.0	0.75
DK	9.79	8.0	0.82	10.74	8.0	0.75
FI	7.90	9.0	1.14[a]	8.50	9.0	1.06[a]
FR	9.79	8.0	0.82	10.74	8.0	0.75
DE	9.79	8.0	0.82	10.74	8.0	0.75
IE	9.79	8.0	0.82	10.74	8.0	0.75
IT	9.79	8.0	0.82	10.74	8.0	0.75
NL	9.79	8.0	0.82	10.74	8.0	0.75
NO	9.79	8.0	0.82	10.74	8.0	0.75
ES	9.79	8.0	0.82	10.74	8.0	0.75
SE	9.79	8.0	0.82	10.74	8.0	0.75
UK	9.79	8.0	0.82	10.74	8.0	0.75

[a] Indicates that the design fails.

The results show that the design for Floor 5 has passed almost all National Annexes with respect to the fundamental frequency except those in Austria and Finland, and the design for Floor 6 has only failed to satisfy the fundamental frequency criterion in Finland.

Table 16 lists the calculated values of the deflection w, the limit values of a and the w/a ratios. The design for Floor 5 has only failed to pass the criterion in Finland and Norway with respect to the unit point load deflection. The design for Floor 6 has passed the criterion in almost every country except Finland. This again indicates that Finland has set the strictest criterion on the deflection and is followed by Norway, Italy and the Netherlands. Austria, Belgium, Denmark, France, Ireland, Sweden and the UK are more generous.

Table 17 lists the calculated values of the unit impulse velocity v, the limiting values of $b^{(f_1\zeta-1)}$, and the $v/b^{(f_1\zeta-1)}$ ratios. The designs for both Floors 5 and 6 have passed the criterion in all European countries considered with respect to the unit impulse velocity. This confirms again that in general, the unit point load deflection criterion is more crucial than other two criteria.

Fig. 14 shows the cohort ratios of all three vibrational parameters calculated based on the National Annexes of the European countries for Floors 5 and 6, respectively. Fig. 14a shows that the design for Floor 5 with a span of 5 m has passed all three vibrational serviceability criteria in almost all countries and only marginally failed in Austria and Norway but largely failed in Finland. Finland has the strictest design criteria and is followed by Austria and Norway and then by Italy and the Netherlands. Similarly Fig. 14b shows that the design for Floor 6 with a span of 7.5 m has passed all three vibrational criteria in most European countries and only failed in Finland and Norway.

6.4. Summary of the floor design results

Table 18 summarises the design results of all six timber floors constructed with various types of floor joists for the vibrational

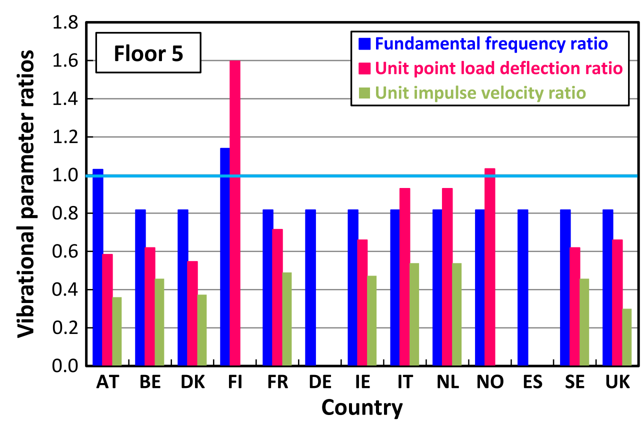
Table 16
Calculated deflection w and limit a for Posi-Joist floors.

Floor	Floor 5 ($L = 5$ m)			Floor 6 ($L = 7.5$ m)		
Country	w (mm/kN)	a (mm/kN)	w/a	w (mm/kN)	a (mm/kN)	w/a
AT	0.88	1.50	0.58	0.56	1.50	0.37
BE	0.93	1.50	0.62	0.77	1.50	0.52
DK	0.93	1.70	0.55	0.77	1.70	0.46
FI	0.91	0.57	1.60[a]	0.58	0.50	1.16[a]
FR	0.93	1.30	0.71	0.77	1.30	0.60
DE						
IE	0.93	1.41	0.66	0.77	0.90	0.86
IT	0.93	1.00	0.93	0.77	1.00	0.77
NL	0.93	1.00	0.93	0.77	1.00	0.77
NO	0.93	0.90	1.03[a]	0.77	0.90	0.86
ES						
SE	0.93	1.50	0.62	0.77	1.50	0.52
UK	0.93	1.41	0.66	0.77	0.90	0.86

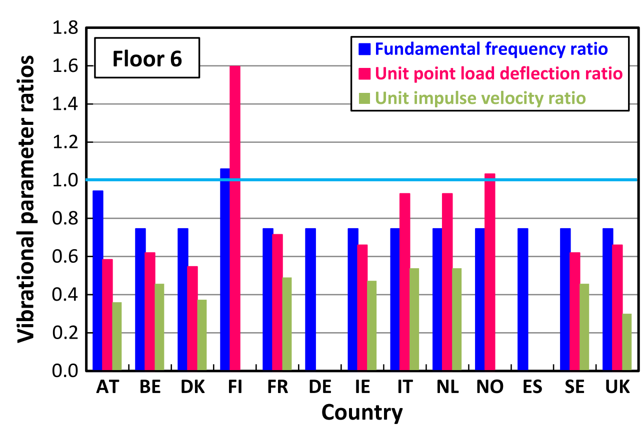
[a] Indicates that the design fails.

Table 17
Calculated unit impulse velocity v and limit $b^{(f_1\zeta-1)}$ for Posi Joist floors.

Floor	Floor 5 ($L = 5$ m)			Floor 6 ($L = 7.5$ m)		
Country	v (10^{-2} m/N s^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/N s^2)	$v/b^{(f_1\zeta-1)}$	v (10^{-2} m/N s^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/N s^2)	$v/b^{(f_1\zeta-1)}$
AT	0.515	1.431	0.36	0.378	1.478	0.26
BE	0.718	1.570	0.46	0.531	1.640	0.32
DK	0.718	1.920	0.37	0.531	2.001	0.27
FI						
FR	0.718	1.465	0.49	0.531	1.531	0.35
DE						
IE	0.718	1.519	0.47	0.531	1.335	0.40
IT	0.718	1.332	0.54	0.531	1.393	0.38
NL	0.718	1.332	0.54	0.531	1.393	0.38
NO						
ES						
SE	0.718	1.570	0.46	0.531	1.640	0.32
UK	0.718	2.394	0.30	0.531	2.243	0.24



(a) Floor 5 with $L = 5$ m



(b) Floor 6 with $L = 7.5$ m

Fig. 14. Vibrational parameter ratios for Posi joist floors.

Table 18
Summary of floor design to EN 1995-1-1 among the European countries.

Country	Floor 1			Floor 2			Floor 3			Floor 4			Floor 5			Floor 6			Ave ratio	Pass rank
	f_1	w	v	f_1	w	v	f_1	w	v	f_1	w	v	f_1	w	v	f_1	w	v		
AT	P	F	P	P	F	P	F	P	P	P	P	P	F	P	P	P	P	P	0.77	10
BE	P	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.72	6
DK	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.65	1
FI	P	F	N	F	F	N	F	F	N	F	F	N	F	F	N	F	F	N	1.62	13
FR	P	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.77	8
DE	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	0.72	3
IE	P	P	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.77	5
IT	P	F	F	P	F	F	P	F	P	P	P	P	P	P	P	P	P	P	0.88	11
NL	P	F	F	P	F	F	P	F	P	P	P	P	P	P	P	P	P	P	0.88	11
NO	P	F	N	P	F	N	P	F	N	P	P	N	P	F	N	P	P	N	0.99	9
ES	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	0.72	3
SE	P	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.72	6
UK	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.67	2

Note: P stands for Pass, F stands for Fail, and N stands for Not Available (N/A).

serviceability criteria with respect to the fundamental frequency f_1, the unit point load deflection w and the unit impulse velocity v in all thirteen European countries included. Thus, there are a total of eighteen cases which need to be checked for each country. Here Pass (P), Fail (F) and Not Available (N) are classified to indicate whether the design for each floor has passed or failed the vibrational design requirements. The average values of those vibrational parameter ratios listed in Tables 7–9, Tables 11–13, and Tables 15–17 are also included in the table. From all of these results, these European countries can be ranked from the most generous to the strictest. First consideration is the number of Fails and a country with the fewest number of Fails will be ranked at the top. If the numbers of Fails are the same, the numbers of Passes will be considered. The country with more Passes will stay in front. If the numbers of Passes are still the same, the average values of the vibrational parameter ratios will be compared and countries with lower average values will be ranked at higher positions.

Four countries have no Fails, e.g. Denmark, Germany, Spain and the UK. Both Denmark and the UK have gained 18 out of 18 Passes but Denmark has only an average of 0.65 which is smaller than the value for the UK. Hence, Denmark is ranked as the most generous country for the design of timber floors and is then followed by the UK. Both Germany and Spain only have six Passes and the remaining are all Not Availables so they are ranked at the equal third. However, the ranking for these two countries is quite subjective and may not be very convincing. Ireland has 17 Passes and only one Fail so it is ranked at the fifth. Belgium, Sweden and France all have 16 Passes and 2 Fails but France has a higher average of 0.77 compared with 0.72 for Belgium and Sweden. Hence, Belgium and Sweden are ranked at the equal sixth and France ranked at the eighth. Norway has 8 Passes, 4 Fails and 6 Not Availables and is ranked at the ninth. Austria has 14 Passes and 4 Fails so it is ranked at the tenth place. Both Italy and the Netherlands have 13 Passes and 5 Fails with an equal average of 0.88 so they are ranked at the equal eleventh, as the second strictest countries. Finally, Finland has only 1 Pass, 11 Fails and 6 Not Availables and is ranked at the last, as the strictest country.

7. Discussion and recommendations

For vibrational serviceability design of timber floors constructed with various types of joists, human activities including walking people and jumping children are still the primary annoyance sources, which cause structural vibrations with frequencies ranging from 0 to 80 Hz and acoustic vibrations with frequencies above 25 Hz (50 Hz). For structural vibrations, various standards and design codes have been proposed, together with different rating methods, descriptors and limits, as indicated in Table 1.

All design practices, except EN 1995-1-1, use the perception curves to assess people's comfort to structural vibrations on timber floors, with the frequency ranging from 0.5 to 80 Hz except Norway which has expanded the range up to 160 Hz. The descriptors used are related to either weighted velocity, e.g. OS-RMS$_{90}$, v_{rms}, KB, $v_{\mathrm{w,95}}$, $V_{\max}$ and V_{per}, or weighted acceleration, e.g. a_{rms}, VDV and $a_{\mathrm{w,95}}$. Not all of these descriptors can be obtained analytically but they need to be determined, directly or indirectly, through site experimental testing. This nevertheless requires expertise from acoustic scientists but also causes difficulties for structural design engineers because the latter do not have enough knowledge on these complex comfort perception design curves. Hence, completely satisfactory vibrational serviceability design for structural vibrations indeed needs cooperation between acoustic scientists and structural design engineers.

The vibrational parameters proposed in EN 1995-1-1, i.e. the fundamental frequency, unit point load deflection and unit impulse velocity, have clear physical meanings to various professionals and can reflect people's comfort to structural vibrations on timber floors even though they cannot be used to directly assess perception levels of structural vibrations. All three parameters can be determined either analytically or experimentally and are easily accepted by structural design engineers so they still have their advantages over other comfort perception descriptors.

As mentioned above, Eq. (1) for calculating the fundamental frequency f_1 is largely applicable for two-side supported floors and may underestimate the frequency for four-side supported floors. The difference in f_1 may be no more than 1 Hz, so EN 1995-1-1 and majority of National Annexes to the code in the European countries have adopted Eq. (1) for calculations. However, this small difference can be crucial when f_1 is close to 8 Hz and lead the design to fail. Therefore the contributions of the lateral stiffness $(EI)_{\mathrm{B}}$ from floor decking, roof ceiling and struts should be included. In this way, the formulae used in Austria and Finland are more rational. The following question is how these individual lateral stiffnesses should be combined. The UK National Annex suggests to superposition these stiffnesses by simply adding them together, which is generally conservative. However full composition of floor decking, roof ceiling and struts with floor joists will overestimate the global stiffness because the connections of these components with floor joists are not perfectly rigid and there always exist slips which unavoidably reduce the overall stiffness of the floor. Some stiffness values in-between should be adopted for calculating f_1. So far no such amendments have been found among the European countries studied. Another issue is how to calculate the participating floor mass. Based on the design philosophy in EN 1990 [1], for serviceability limit design, quasi-permanent load should be used, i.e. certain proportion of imposed load, e.g. furniture, partitions, etc., should be added onto dead load for calculating the design load. Vibrational design of timber floors is indeed a serviceability issue and it is more reasonable to include certain proportion of imposed load for calculating the mass *m*. Again both Austria and Finland adopt the quasi-permanent combination for determining *m*. The final issue on the fundamental frequency f_1 is its limit. The threshold of 8 Hz seems to be well accepted by almost all European countries except Finland which requires 9 Hz. If both the composition effect on the global stiffness $(EI)_B$ of the timber floor and the quasi-permanent combination for the mass *m* are considered, the limit of 8 Hz should still be reasonable because the two effects cancel each other.

EN 1995-1-1 only gives a general design criterion expression for the unit point load deflection *w* as illustrated in Eq. (2) but has failed to provide with the detailed formulae for calculating *w* because Eurocodes assume that these formulae are regarded as common knowledge and should be found from normal textbooks. There are a number of factors which influence the deflection. First shear will add extra deflection to the bending deflection, and connections between floor members also contribute the overall deflection due to slips between the connectors and the surrounding timber materials. However, the applied unit point load can be redistributed to neighbouring joists due to lateral stiffness contributed by floor decking, roof ceiling and struts so that the actual deflection can be largely reduced. Joist spacing also largely influences the vertical deflection. The smaller the joist spacing, the smaller the mid-span deflection. Austria, Finland, Ireland and the UK consider the stiffening effect from transverse floor members. Finland, Ireland and the UK include the effect of floor joist spacing, and Ireland and the UK also consider the shear effect in the formulae for calculating the deflection *w*. Hence the formulae proposed in Ireland and the UK are more comprehensive. EN 1995-1-1 only gives a permitted range for the deflection limit *a* which largely varies from country to country. As discussed above, for short floor span floors below 3 m, Denmark, Ireland and the UK are more generous than other European countries. For long floor span up to 6 m, Austria, Belgium, Denmark and Sweden have set more relaxed limits. For extra long floor span up to 10 m, Austria, Belgium and Sweden remain the most generous. It can be seen that the current National Annexes among the European countries use largely different formulae for calculating the deflection *w* and set different limits. Hence there is an urgent need to harmonise the formulae for calculating the deflection and the corresponding limits.

The unit impulse velocity response v is the most mysterious parameter for vibrational serviceability design of timber floors in EN 1995-1-1. The formula Eq. (4) for determining v cannot be easily deduced and its physical meanings are difficult to understand because it is more empirical rather than analytical or theoretical. Unlike the fundamental frequency and unit point load deflection, the unit impulse velocity response is difficult to be determined numerically and experimentally. Occasionally, this parameter influences design of timber floors in a funny way by failing to give any practical solutions or even producing singular solutions. Thus, several countries have disregarded this design criterion, e.g. Finland, Germany, Norway and Spain. The UK has deliberately increased the damping ratio to 2% to make this criterion redundant. Some parameters in the formulae are also defined in an arbitrary way, e.g. the upper limit of 40 Hz for the included modal frequencies, the extra participating mass of 50 kg, etc. Most European countries have adopted the formulae for determining the unit impulse velocity response but largely different values have been proposed for the parameter *b* for calculating the design limit. The larger the value of *b*, the stricter the floor design. In general, Denmark and the UK are more generous than other European countries while Italy and the Netherlands are stricter. The design value of damping ratio is also an issue because it covers for timber floors constructed with most types of joists but fails to cover for some other types of joists, e.g. metal web joists. Therefore it is suggested that a varied damping ratio for various types of timber flooring systems should be used to reflect practical situations.

As for the influencing order of the three vibrational serviceability design criteria, the unit point load deflection criterion is no doubt the most crucial one for timber floor design but it is difficult to tell which one will be the next most crucial criterion, with respect to the fundamental frequency or to the unit impulse velocity response. From the given six design examples, it is interesting to observe that for the floors constructed with solid timber joists, the unit point load deflection criterion is the most crucial one and is followed by the unit impulse velocity response criterion, while the fundamental frequency criterion has become the least crucial one. For the floors constructed with engineered I-joists, the unit point load deflection dominantly controls the vibrational serviceability design, and is followed by the fundamental frequency criterion, while the unit impulse velocity response criterion has become the least crucial. Finally, for the floors constructed with metal web joists, the unit point load deflection criterion remains the predominant one in some countries but the fundamental frequency criterion seems no less important on average while the unit impulse velocity criterion is far less crucial. For other types of floor joists, different trends may be observed.

8. Conclusions

As part of the research work carried out within the Working Group 3 of COST Action FP0702, sources of annoyance, types of annoyance for both structural and acoustic vibrations and the corresponding frequency ranges have been summarised and evaluated. Human activities including walking people and jumping children remain the predominant annoyance sources. For structural vibrations, various standards and design codes have been collected, and the comfort rating methods, descriptors and their limiting values have been discussed in detail. Most codes use the perception curves for assessing people's comfort to structural vibrations on timber floors. The used descriptors which are related to either weighted velocity or acceleration cannot be obtained analytically but need to be determined experimentally. Completely satisfactory vibrational serviceability design of timber floors with respect to structural vibrations needs cooperation between acoustic scientists and structural design engineers.

Eurocode 5 Part 1-1 has provided structural engineers for design of timber floors with three vibrational serviceability design criteria, with respect to the fundamental frequency, unit point load deflection and unit impulse velocity response, respectively. The first two parameters are physically clear and easily determined with analytically or experimentally. The third parameter is slightly mysterious. The national design practices of timber floors among thirteen European countries have been summarised, and their similarities and differences have been further discussed by realistically designing the flooring systems constructed with three different types of joists, i.e. solid timber joists, engineered I-joists and metal web joists.

For calculating the fundamental frequency, the composite effect of floor decking, ceiling and struts on the global stiffness in the floor joist direction should be included so as to make the design formulae applicable for both two-side supported and four-side supported floors. It is more rational to use the quasi-permanent combination for calculating the participating mass because during the design life there are always certain proportions of imposed loads acting on the floors together with dead loads. Among the thirteen European countries dealt with in this study, only Austria and Finland consider the lateral composite effect and quasi-permanent combination of loads for design of timber floors. Further harmonisation on these issues among the European countries is needed.

EN 1995-1-1 only gives a general design criterion for the unit point load deflection but has failed to provide with detailed formulae for calculating the deflection and also failed to set the design limits. Ireland and the UK have considered more influencing factors than other countries when determining the mid-span deflection of the floor under unit point load, e.g. shear induced deflection, stiffening and composite effect of floor decking, ceiling and struts, joist spacing, etc. Austria and Finland have considered the contribution of these transverse components to the global stiffness. Finland has also included the effect of joist spacing. The remaining European countries have failed to provide with detailed formulae in their National Annexes for calculating the mid-span deflection under unit point load. The design limit for the unit point load deflection also varies largely between the European countries. In general, Denmark, Ireland, Sweden and the UK are more generous than others, while Finland is the strictest and is followed by Austria, Italy and the Netherlands. Hence there is also an urgent need to harmonise the formulae for calculating the deflection under unit point load and setting up the corresponding limits.

The design criterion for unit impulse velocity response remains as a trickiest one for many design engineers due to the difficulty to understand its physical meanings and to physically measure it. Some parameters used for determining the unit impulse velocity are also very arbitrary. This criterion occasionally stops engineers obtaining meaningful solutions so some countries have disregarded this design criterion like Finland, Germany, Norway and Spain, or made it redundant like the UK. On the other hand, the differences in the design limit also remain large between the European countries. In general, Denmark and the UK are more generous than other European countries while Italy and the Netherlands are stricter. It is also suggested that a varied damping ratio should be adopted for timber flooring systems with various types of joists.

In general, the unit point load deflection criterion is the most crucial one for timber floor design, but to be followed by which criterion will largely depend on practical situations. For the floors constructed with solid timber joists, the unit impulse velocity response criterion is more crucial than the fundamental frequency criterion. For the floors constructed with engineered I-joists, the fundamental frequency criterion is more crucial than the unit impulse velocity response criterion. For the floors constructed with metal web joists, the fundamental frequency criterion seems no less important than the unit point load deflection criterion while the unit impulse velocity criterion becomes far less crucial than the other two criteria.

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