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Evaluation of floor vibration properties using measurements and calculations

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Abstract

Timber floor constructions are very common in the Nordic countries, for instance in single- and multifamily buildings. But building with wood is increasing in popularity for other building categories and there is wider interest in increasing the span width of wooden joist floors. Static and vibrational performance become crucial for serviceability of timber floors and often limit the design; however, constructors and designers want to increase the floor span width. To meet these challenges, reliable design methods are required and have therefore become a focus in many countries.

This paper presents results from a number of measurements of different joist floor constructions. Parameters measured have also been calculated according to given equations and relevant methods. Both calculations and measurements include 17 laboratory objects and four field objects. The objects represent a huge variety of solutions and therefore a large spread of results. The main reason for the selection of floor solutions was to expand the possibilities and test the methods more than tuning current solutions into satisfactory floor vibration perception.

The data and resulting analysis in this paper highlight benefits and limitations concerning relevant parameters for evaluation of floor vibration perception. According to this work, it is not possible to verify the Eurocode method with respect to accuracy, and the link to perception of floor vibrations is rather low. Another method should be used or developed for the future. Results presented in this paper show that sufficient accuracy may be achieved using parameters from the Hu and Chui (2004) method. Experiences from Norway over the last five years are also promising regarding evaluation of floor vibration perception using this method. However, attention should be given to floors with significantly lower damping properties and/or significantly higher (modal) masses. Damping properties or an alternative parameter taking a longer time interval of the vibrations into account should be considered.

Keywords: Timber floor; Wooden joist floor; Vibration; Damping; Frequency; Deflection; Measurement; Calculation

1 Introduction

1.1 Objective

Constructions with wooden beams are very common in Norwegian single- and multifamily buildings both for vertical and horizontal partitions. For wooden joist floors, floor vibration properties have been an important topic for several decades and are the main focus of this paper. A lot of studies have been carried out in several countries, for example in [1–7]. Products, test methods, evaluation procedures and general understanding have improved very much in the last few decades. Static and vibrational performance have become crucial for serviceability of timber floors and often limits the design. However, constructors and designers want to increase the floor span width. To meet these challenges, reliable design methods are required and need to be in focus in many countries. With respect to standardization work, action has also been taken to revise Eurocode part 5 regarding floor vibration performance [8].

Since the end of the 1980s, research work and several studies have been carried out in Norway on floor vibration and serviceability of timber floors; examples include research work at the Norwegian Building Research Institute [9], thesis work by one of the author of this paper [11] and in the last decade research projects at SINTEF Building & Infrastructure. Except for [11], the results reported in [10–16] have only been published in Norwegian for the Norwegian Research Council and other project owners in the building sector. We recognize the need to analyse and compile results from the different projects. The aim of this article is therefore to summarize these results and present recommendations regarding methods and evaluation procedures. To substantiate the analysis, the paper will present results from numerous well-controlled measurements performed both in the laboratory and in situ.

1.2 Vibration properties

Timber floors need to meet requirements and expectations regarding structural performance, safety and serviceability in all aspects, for instance how people experience vibrations and springiness in timber floors where open-plan solutions with large span lengths are challenging. Due to their lightweight nature, timber floors are more sensitive to annoying vibrations induced by human activities than heavy concrete floors. The vibration performance of the floor structure itself is determined by the floor stiffness, mass and damping. The stiffness and mass properties of the floor determine the floor's natural frequencies. The damping affects the time it takes for an induced vibration to decay.

Measurements of dynamic and static properties of timber floors have been carried out in laboratories by many researchers. Results are available on parametric studies on floors and effects caused by natural frequencies, mode shape and damping ratio due to a number of parameters, both geometrical and product-related. The vibration performance of a floor changes as it is integrated into the structural system, adding parts like supplementary surface layers, partitions, fittings and fixtures. These added parts affect both floor mass and stiffness and consequently also the natural frequencies, mode shape and damping. Results presented in this article will contribute to the knowledge of this field.

2 Experimental investigations

2.1 Laboratory measurements

This paper presents results from four series of measurements performed in the laboratory from research projects listed below:

Lab-I: Norwegian Building Research Institute (NBI) measurements 1988

Lab-II: Thesis measurements 1999–2000

Lab-III: Web-joist project measurements 2003–2012

Lab-IV: Comfort Properties measurements 2007

Within each series, a number of objects have been investigated. Table 1 shows an overview of the different series including information regarding objects and parameters.

Table 1 Parameter overview, laboratory measurements of lightweight floor assemblies.

Series	Total number of objects investigated	Extract in this paper	Measurement parameters[a]	Project reference	Ref.
Lab-I	25	Lab-I a to Lab-I f	f_n (Hz), η (%), Δ (mm)	NBI	[9]
Lab-II	8	Lab-II a, b and c	f_n (Hz), η (%), h'_{max} (mm/s/Ns)	Thesis work, Homb	[11]
Lab-III	2	Lab-III an and b	f_n (Hz), η (%), Δ (mm), h'_{max} (mm/s/Ns)	Master's thesis and NBI research work	[10,11,16]
Lab-IV	17	Lab-IV a to Lab-IV f	f_n (Hz), η (%), Δ (mm)	Comfort Properties research project	[16]

[a] See Section 2.3 for explanation of the parameters.

Both nationally and internationally, progress has been made on measurements and calculations within this topic. From this, new standards and recommendations regarding relevant parameters to characterize floor vibration properties have been developed. As a result, there have been some changes in measured parameters shown in Table 1. All measurement series presented in Table 1 include results of the fundamental frequency and the damping properties. In almost all cases, the static deflection from a point load has also been measured.

2.2 Field measurements

This paper also includes field measurement results from the following studies and research projects:

Field-I: Thesis field measurements 2000–2002

Field-II: Web-joist field measurements 2005–2012

Within each series, a number of objects have been investigated. Table 2 shows an overview of the different series, including information regarding objects and parameters.

Table 2 Parameter overview, field measurements of lightweight floor assemblies.

Series	Total number of objects investigated	Extract in this paper	Measurement parameters[a]	Project reference	Ref.
Field-I	4	Field-I an and b	f_n (Hz), η (%), h'_{max} (mm/s/Ns)	Thesis work, Homb	[11]
Field-II	3	Field-II an and b	f_n (Hz), η (%), Δ (mm)	Comfort properties and Modern Wood Joist research project	[16,17]

[a] See Section 2.3 for explanation of the parameters.

All measurement series presented in Table 2 include results related to the fundamental frequency and damping properties. Moreover, the static deflection and the maximum impulse velocity response have been measured in one series.

2.3 Measurement methods

2.3.1 Point load deflection, Δ

The point load deflection of all objects is the measured deflection of the floor on the beam at the centre (weakest point) of the span width with a point load of 1.0 kN. It is also necessary to measure the deflection on the same beam at the support and on one or more neighbouring beams. The lateral positions of the beams have to be determined within an accuracy of approximately ±5 mm. When the floor has a rather high transverse stiffness (perpendicular to the main beam direction), it is recommended to take measurements on at least five beams with a centre distance of 0.6 m. It is necessary to establish a reference system for the deflection measurements to ensure that the values are independent of the load at the different measurement positions. The principle and procedure are fully described in [18], chapter 2. Electronic deflection transducers have been used with a resolution of 0.01 mm.

The deflection of the beam construction is the average of a number of point load deflection results when values from the support/reference system have been taken into account.

2.3.2 Fundamental frequency, f_o, and damping properties, η

Determination of the fundamental frequency and damping properties has been based on an impact source. An impact source is the most commonly used technique, since it is quick and easy. The convenience of this technique is attractive because it requires very little hardware and provides short measurement times. The only equipment needed is a proper impact source and one or more accelerometers. In addition, the measurement method is fully portable and therefore highly suitable for field measurements. In all objects except Lab-I, the Japanese rubber ball method for recording impact noise measurements on lightweight floors has been used. A mechanized impact source has been used for the Lab-I measurements. When the impact source hits the structure, a wide frequency range is quickly excited. Impacts from the rubber ball ensure high repeatability due to a constant falling height.

The number of vibration sensors differ from object to object, but in all cases accelerometers have been used. The accelerometers have been fixed to the structure via wax, magnetostatic forces or threaded stud. The single input, multiple output concept was used for the measurement setup. The measurement setup, equipment and procedure are fully described in [14], appendix B.

Determination of the fundamental frequency has been based on analysis of the Frequency Response Function (FRF) or FFT-spectra of the time domain signal. Due to relatively low damping (separated natural frequencies), the damping has been determined from half-power bandwidth, Δf of the FRF spectra. Assuming linear, viscous damping, the loss factors have been determined for each observed resonance frequency, f_n, according to:

$$\eta = \frac{\Delta f}{f_n} \quad (1)$$

For more details, see [11,14].

2.3.3 Impulse velocity response, h'_{max}

The impulse velocity response is a parameter in Eurocode 5; see [8] for evaluation of the floor vibration properties. A measurement procedure has been developed for comparison and verification of the prediction method given in [2]. The method is based on the use of rubber ball excitation, a force transducer and accelerometers. Signal processing tools have been developed in Matlab to simulate the impulse velocity response described in the method. A description of the method and calculation principles is given in [11].

3 Measurement results

3.1 Main results from laboratory and field measurements

Measurements of the different parameters have been carried out according to methods presented in Section 2.3. Tables 3 and 4 present the main results from the laboratory measurements and field measurements respectively. The tables also contain information on the type of beam, span width and mass per unit area. Evaluation of the different parameters and results will be given in Sections 3.2–3.5.

Table 3 Main results from laboratory measurements.

Series	Beam type	Dimension (mm)	Span width[a] (m)	Mass per unit area (kg/m²)	Lowest-resonance frequency, f_o (Hz)	Loss factor, η (%)	Static deflection Δ (mm) or h'_{max} (mm/s/Ns)
Lab-I a	Wood	48 × 198	4.2	22	13.7	1.5	$\Delta = 1.46$
Lab-I b	Wood	48 × 198	3.55	22	20.4	1.7	$\Delta = 1.00$
Lab-I c	Wood	48 × 198	3.55	22	19.3	3.8	$\Delta = 1.16$
Lab-I d	I-beam	h = 250	5.9	20	10.7	2.8	$\Delta = 2.32$
Lab-I e	I-beam	h = 400	7.2	21	12.4	1.6	$\Delta = 1.32$
Lab-I f	I-beam	h = 400	5.3	21	18.6	2.9	$\Delta = 0.77$
Lab-II a	I-beam	h = 400	7.0	21	12.5	7.4	$h'_{max} = 31$
Lab-II b	I-beam	h = 400	7.0	41	11.9	6.7	$h'_{max} = 27$
Lab-II c	I-beam	h = 400	7.0	72	9.4	5.1	$h'_{max} = 44$
Lab-III a	Web-joist	98 × 450	5.8	130	11.9	~12	$\Delta = 0.40$ $h'_{max} = 32$
Lab-III b	Web-joist	98 × 450	5.8	57	19.1	~4	$\Delta = 0.41$ $h'_{max} = 25$
Lab-IV a	Glue-lam	48 × 300	5.2	26	15.6	1.4	$\Delta = 1.15$
Lab-IV b	Web-joist	98 × 450	7.5 T	18	18.2	2.3	$\Delta = 1.00$
Lab-IV c	Web-joist	98 × 450	7.5 T	24	19.3	3.6	$\Delta = 0.90$
Lab-IV d	Web-joist	98 × 450	7.5 T	22	17.1	2.3	$\Delta = 0.71$
Lab-IV e	Web-joist	98 × 450	7.5 T	38	12.1	3.7	$\Delta = 0.63$
Lab-IV f	Web-joist	98 × 450	7.5	30	12.5	1.8	$\Delta = 1.12$

[a] T = transverse stiffener installed.

Table 4 Main results from field measurements.

Series	Beam type	Dimension (mm)	Span width (m)	Mass per unit area (kg/m²)	Lowest-resonance frequency, f_o (Hz)	Loss factor, η (%)	Static deflection Δ (mm) or h'_{max} (mm/s/Ns)
Field-I a	Wood	36 × 198	3.6 (+2.3)	23	20.6	~10	$h'_{max} = 55$
Field-I b	I-beam	h = 250	4 (+3.6)	62	13.4	>15	$h'_{max} = 28$
Field-II a	Web-joist	98 × 650	12.4	32	9.1	~2	$\Delta = 2.2$
Field-II b	Web-joist	98 × 400	6.3	40	18.0	–	$\Delta = 0.3–0.8$[a]

[a] Large spreading due to parquet underlayer deflection.

3.2 Fundamental frequency

All measurement results presented in Tables 3 and 4 have been carried out according to the procedure presented in Section 2.3.2. Considering all measurements, the fundamental frequency varies between 9 Hz and 21 Hz due to the variation of the objects and the involved parameters. The basic parameters determining the fundamental frequency are the beam stiffness, weight and span width. Unless measured specifically for each object, the beam stiffness will differ more or less from a classified or tabulated value. In addition, other stiffness components may contribute, for instance additional sheet layers, clamped support or transverse stiffeners. For some cases (especially field measurements), the determination of span width may also be inaccurate. For major cases, modal analyses have not been performed. Analyses of the lowest-resonance frequency have therefore been determined by peaks from a number of FRF spectra, but torsional modes have been rejected due to phase shift between simultaneous measurement points. Together with density variations, the measured fundamental frequency may therefore be higher or lower compared to a calculated value.

3.3 Damping

The basic parameters determining the damping properties of a floor are the sum of internal damping in the material, damping related to boundary conditions and coupling elements, and damping due to sound radiation. Tabulated values exist concerning internal damping of different materials based on experiments. There are also suggested equations on damping due to boundary conditions and sound radiation, but these equations have been developed for calculation of sound insulation at medium and high frequencies. Experience from a number of research studies shows that the observed damping of a floor at low frequencies to a high degree depends on boundary conditions and coupling elements including friction between layers of the floor. Therefore, it does not seem possible to calculate this with sufficient accuracy.

Evaluation of the damping property therefore needs to be based on experienced values. Results presented in Tables 3 and 4 show a large spread of the measured loss factors at the fundamental frequency. Measured objects from Lab-I and Lab-IV and object b from Field-II are relatively simple setups with beams and a sheet layer at the top or some transverse stiffening element. All these results show a loss factor between approximately 1.5% and 4%. Measured objects Lab-II, Lab-III, Field-I and object b from Field-II are more complex objects including additional layers, ceiling and or increased number of couplings to load-bearing walls. All these results show a loss factor between approximately 4% and 15%. Except object Lab-III a, all results above 7% are from objects with an additional load-bearing wall. From these results, we may conclude that a realistic loss factor of wooden floors is at least 4% in situ and may be at least 7% when additional support has been installed. As presented, tests on floors with a complex geometry give a very large scattering of the damping properties. The prediction of the damping properties is therefore a weak point in the design. Further evaluation of measurement results on damping properties will be carried out and published later.

3.4 Impulse velocity response

Results from the measurements and analysis considering the maximum impulse velocity responses are given in Tables 3 and 4. From the analysis, the “weakest point” is determined from the point where h'_{max} reaches its greatest value when considering excitation and measurement position on the beam with a force transducer. As seen in Tables 3 and 4, the number of impulse velocity results is rather limited. All results show h'_{max} values between 4 and 54 mm/s/Ns. The low value of 4 mm/s/Ns is from an object with an 80 mm concrete layer on top of a wooden joist floor. It means that the increased stiffness of the floor has a considerable influence on the impulse velocity response. From this data, it is not possible to give further evaluation of the results without considering other evaluation parameters or calculation results.

3.5 Point load deflection

All measurement results presented in Tables 3 and 4 have been carried out according to the procedure presented in Section 2.3.1. Considering all measurements, the results vary between 0.2 mm and 2.32 mm due to the variation of the objects and the involved parameters. The E-module of the materials, moment of inertia and span are of course of major importance, but the transverse stiffness and the coupling stiffness between components in the system (glued connections for instance) are also relevant. Further evaluation of the results needs to take all possible calculation parameters into account; see comparison of measurements and calculations in section 4.

4 Calculations

4.1 Fundamental frequency

Calculations of natural frequencies have been carried out according to equations presented in [14], annex D. If we simplify the object to an isotropic structure, the model from Leissa [19] should be used. An ordinary wooden joist floor is an orthotropic object and stiffness properties in both span direction and transverse direction are required. The general anisotropic model is recommended, but the principle is based on a simply supported floor on all four sides. The orthotropic model from Leissa takes different support conditions into account, but the correlation with measurements does not seem as good as the general orthotropic model. The following equations have therefore been used:

$$f_{mn} = \frac{\pi}{2 \cdot l^2} \cdot \sqrt{\frac{1}{g}} \cdot \sqrt{D_x \cdot m^4 + 2 \cdot D_{xy} \cdot m^2 \cdot n^2 \cdot \left(\frac{l}{b}\right)^2 + D_y \cdot n^4 \cdot \left(\frac{l}{b}\right)^4} \quad \textbf{(2)}$$

$$D_{xy} = \nu \cdot D_x + 2 \cdot D_k \quad (3)$$

$$D_k = \frac{G \cdot h^3}{12} \quad (4)$$

where l = span of floor (m); g = unit weight (kg/m^2); b = width of floor (m); h = depth of beam (m); and m and n = integers.

These are the same equations as given in [2]. Normally it is relevant to assume D_{xy} is equal to D_y.

4.2 Impulse velocity response

A calculation method concerning floor vibrations has been developed by Ohlsson; see [2]. From this, two different criteria are proposed concerning dynamic response due to people in motion: impulse load and continuous load. The criteria have to be applied to floors with a fundamental frequency higher than 8 Hz. Floors with a lower fundamental frequency will experience a more severe dynamic resonant response and must be designed in line with other principles. In conjunction with the impulse load criterion, there needs to be a limit to the initial vertical vibration velocity due to an idealized vertical force impulse, the impulse velocity response, h'_{max} (m/s)/Ns. Only contributions at frequencies below 40 Hz are taken into consideration. The h'_{max} value can be calculated according to

$$h'_{\max} = \sum_{n=1}^{N_{40}} \frac{\Phi_n^2(x_0, y_o)}{m_n} \left[\frac{\text{m/s}}{\text{Ns}}\right] \quad (5)$$

for the "weakest" point of application of the load (x_o, y_o). The term weakest point refers to the point where h'_{max} reaches its greatest value. This point is often situated at the midspan towards one of the short sides of the floor. In the general case, a dynamic analysis of the floor is therefore required. The majority of floor constructions can, however, be regarded as rectangular plates, simply supported around their edges. For these cases, the following simplified formula can be applied:

$$h'_{\max} = \frac{4 \cdot (0.4 + 0.6 \cdot N_{40})}{gBL + 200} \left[\frac{\text{m/s}}{\text{Ns}}\right] \quad (6)$$

where N_{40} is the modal number corresponding to 40 Hz and is obtained from calculations or from appendix A in [2].

Research results show that people tolerate a much higher initial vibration velocity if the vibration is rapidly damped. The parameter that determines how rapid a harmonic vibration is damped in the time domain is the damping coefficient, which can be written as a product of relative damping, ξ, and the frequency, f_1:

$$\sigma_0 = f_1 \cdot \zeta = f_1 \cdot \frac{\eta}{2} \ [\text{s}^{-1}] \quad (7)$$

For normal lightweight floor constructions, Ohlsson [2] generally proposes ξ = 1% in conjunction with the use of the design methods discussed here. This value refers to traditional floor constructions and is associated with the acceptance levels proposed in an evaluation diagram; see Fig. 13 and [2]. Whether or not the value of impulse velocity response is acceptable should depend on the magnitude of the damping coefficient.

For the calculation of the impulse velocity response, the BLAG software program has been used. Calculation results for a number of objects are presented in Tables 5 and 6, for laboratory and field objects respectively.

Table 5 Main results, calculation of laboratory objects.

Series	Beam type	Span width[a] (m)	Lowest-resonance frequency, f_o (Hz)	Static deflection Δ (mm)	h'_{max}[b] (mm/s/Ns)
Lab-I a	Wood	4.2	13.3	1.49	–
Lab-I b	Wood	3.55	18.6	1.06	–
Lab-I c	Wood	3.55	22.3	1.34	–
Lab-I d	I-beam	5.9	10.2	2.32	–
Lab-I e	I-beam	7.2	12.3	1.52	–
Lab-I f	I-beam	5.3	22.1	0.86	–
Lab-II a	I-beam	7.0	12.4	1.47	h'_{max} = 43 (69)

Lab-II b	I-beam	7.0	9.4	0.67	$h'_{max} = 23$ (31)
Lab-II c	I-beam	7.0	6.8	1.01	$h'_{max} = 23$ (26)
Lab-III a	Web-joist	5.8	9.6	0.42	$h'_{max} = 8$
Lab-III b	Web-joist	5.8	19.2	0.42	$h'_{max} = 23$
Lab-IV a	Glue-lam	5.2	16.0	1.16	–
Lab-IV b	Web-joist	7.5 T	18.1	1.02	–
Lab-IV c	Web-joist	7.5 T	19.0	0.89	–
Lab-IV d	Web-joist	7.5 T	19.3	0.65	–
Lab-IV e	Web-joist	7.5 T	13.9	0.52	–
Lab-IV f	Web-joist	7.5	12.8	0.98	–

[a] T = transverse stiffener installed.

[b] Result in parenthesis = calculation without 50 kg (modal) mass.

Table 6 Main results, calculation of field measurement objects.

Series	Beam type	Span width (m)	Lowest-resonance frequency, f_o (Hz)	Static deflection Δ (mm)	h'_{max} [a] (mm/s/Ns)
Field-II a	Wood	3.6 (+2.3)	17.1	1.57	$h'_{max} = 41$ (1 8 2)
Field-II b	I-beam	4 (+3.6)	11.8	0.75	$h'_{max} = 15$ (18)
Field-III a	Web-joist	12.4	6.9	0.74	–
Field-III b	Web-joist	6.3	15.3	0.59	–

[a] Result in parenthesis = calculation without 50 kg (modal) mass.

4.3 Static deflection

Research studies concerning evaluation of different methods to predict the point load deflection of a wooden joist floor construction have been carried out; see [15]. The work by Kolstad and Homb [15] also includes an evaluation of relevant software tools developed for this purpose. The following methods and tools have been evaluated:

- BTAB: Software tool developed from the fundamental equations in [2]
- KAN based on AIII-design method: Calculation tool based on the Canadian method from Forintek; see [6]
- Tresving: Calculation tool developed by JJJConsult; see [20]

4.3.1 BTAB

This software enables calculation of the point load deflection at midspan on each beam, due to a point load at midspan of a chosen beam. The method is based on the shell and plate theory, where the plate (sub-floor) is modelled as a shell supported by beams; see [21]. The connection between the plate and beams has been assumed to be an elastic support (spring-type connection) resisting relative motions in the span direction of the beams. The beams have been assumed to be simply supported. The bending stiffness in the transverse direction of the beam direction and possible torsion of the beams have been neglected. At the edges of the joist floor (perpendicular to the beam direction), no support has been assumed.

The software tool does not take the transverse stiffness into consideration automatically, but it is possible to manually increase the stiffness parameters of the plate. The contribution from a possible transverse beam can therefore be modelled as an evenly distributed stiffness in the whole width of the floor. The stiffness contribution from a ceiling is taken into consideration in the same way. The stiffness input parameters need to be evaluated due to possible discontinuities of joints. A matrix (Element) method forms the tool’s basic routines, but it is limited to calculations of a floor with no more than seven beams.

4.3.2 KAN

At Forintek, a calculation procedure and a software tool have been developed. The tool can calculate the point load deflection at midspan on each beam, when there is a 1 kN point load in the same position and the lowest natural frequency of the wooden floor. The method is based on the general ribbed plate theory. It is similar to BTAB where the plate (sub-floor) is modelled as a shell supported by beams and the connection between the plate and beams has been assumed to be an elastic support (spring-type connection). The wooden floor has been assumed to be simply supported on all four sides. To take additional elements into consideration, for instance ceiling or transverse stiffeners, additional expressions and equivalent values from typical Canadian solutions have been included. Tabulated values have been based on material properties and experimental investigations. The calculation tool can therefore consider the beams, sub-floor, top-floor, transversal stiffeners and ceiling. The method is further described in [15].

4.3.3 Tresving

For investigation and determination of floor vibrations, Jensen [20] has developed this software tool. The software tool may calculate the point load deflection (and some dynamic parameters) of either the plate, simply supported on all four sides, or the beam, simply supported with one, two or three spans. The limitations of the method mean that the tool is not able to calculate wooden joist floors. Therefore, calculations based on this method using this method have not been carried out in this project.

4.3.4 Evaluation of BTAB and KAN

A comparison of calculation results according to these methods has been carried out; see [15]. Fig. 1 presents the results together with the measurement results of six objects.

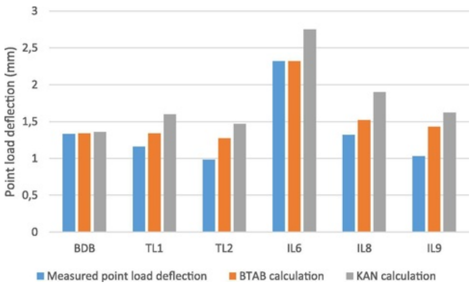

Fig. 1 Measured and calculated deflection from 1 kN point load at midspan.

All calculation results show conservative values, i.e. higher point load deflection compared to measurement values. From BTAB, the deviation is between 0 and 39% with an average deviation (conservative compared to measurements) of approximately 17%. From KAN, the deviation is between 3 and 57% with an average deviation (conservative compared to measurements) of approximately 35%. For wooden joist floors without ceiling and transverse stiffening beams, BTAB calculations give results closer to the measurement results compared to KAN calculations. Both methods give results close to measurement results for joist floors with transverse stiffening beams. The influence of a ceiling is larger than both methods take into account, with the highest deviation compared to measurement results. As it had the best performance compared to measurement results, BTAB has been used for calculation of objects presented in Tables 5 and 6.

4.4 Main calculation results from laboratory and field objects

Calculations of the relevant parameters have been carried out according to methods presented in Sections 4.1–4.3. Tables 5 and 6 present the main results from the laboratory and field objects. The tables also contain information on the type of beam, span width and mass per unit area.

The overview presented in Tables 5 and 6 shows a big scattering of results; to a high degree, this scattering depends on the span width distances from 2.3 to 12.4 m. From the different objects, we have results on the lowest fundamental frequency from 6.8 to 22.3 Hz and the point load deflection from 0.42 to 2.32 mm. The objective of the measurements was not to fulfil some criteria level, but to investigate the floor vibration properties, develop methods and verify criteria. Generally, the results are therefore not typical for common Norwegian wooden floor constructions.

5 Comparison of results

5.1 Fundamental frequency

A comparison between measured and calculated fundamental frequencies, f_o, is presented in Figs. 2 and 3, including objects from laboratory and field studies.

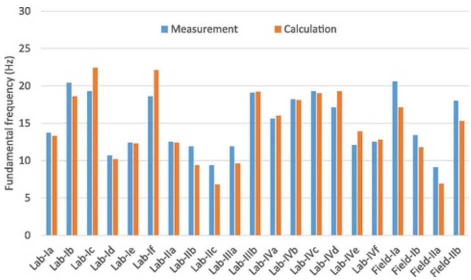

Fig. 2 Comparison of calculated and measured fundamental frequency.

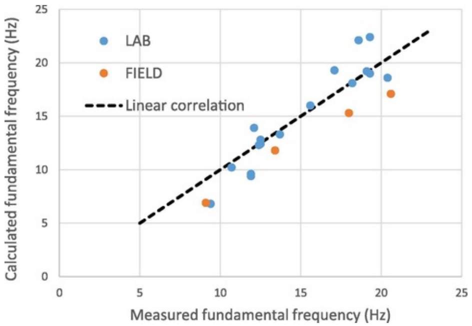

Fig. 3 Comparative analysis of calculated and measured fundamental frequency.

The average deviation between calculated and measured fundamental frequency is approximately 9% for the laboratory objects and approximately 17% for the field objects. All field objects and three of the laboratory objects show measurement values between 12 and 28% above calculated values. For these objects, the calculations underestimate the fundamental frequency, which means a conservative estimate with respect to the perceived floor vibrations. Four out of 17 laboratory objects show measurement values between 13 and 19% below calculated values. In these cases, the calculations overestimate the fundamental frequency. The consequence of this is a non-conservative estimate with respect to the perceived floor vibrations. Results from this comparison generally show that calculations of the fundamental frequency according to Eqs. (2)–(4) in Section 4.1 combined with accurate input data give reliable calculation results.

5.2 Impulse velocity response

A comparison between measured and calculated maximum impulse velocity response, h'_{max}, is presented in Figs. 4 and 5, including objects from laboratory and field studies.

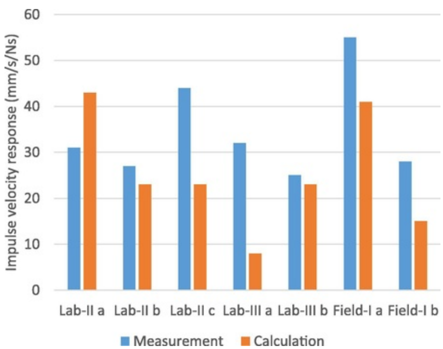

Fig. 4 Comparison of calculated and measured maximum impulse velocity responses.

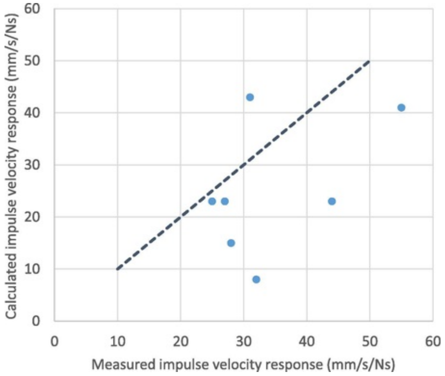

Fig. 5 Comparative analysis of calculated and measured maximum impulse velocity responses.

The comparison shows that the calculations correlate poorly with the measurement results. The deviation between calculated and measured maximum impulse velocity response is between 9 and 300%. Only three out of seven objects show a deviation less than 30%. Except for one object, the calculations underestimate the h'_{max} value compared with the measured ones. On the one hand, this means that, according to this comparison, the calculation is far too optimistic with respect to floor vibration perception. On the other hand, the procedure to measure the impulse velocity response and the accuracy of the results may be uncertain with this comparison. In summary, these results show that it is not possible to verify the calculation procedure or the measurement results from this study. Evaluation with respect to floor vibration perception is given in Section 6.

5.3 Point load deflection

A comparison between measured and calculated point load deflection (1 kN point load at midspan) is presented in Figs. 6 and 7, including all objects from laboratory studies.

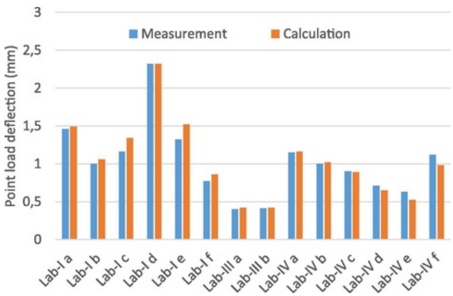

Fig. 6 Comparison of calculated and measured point load deflection.

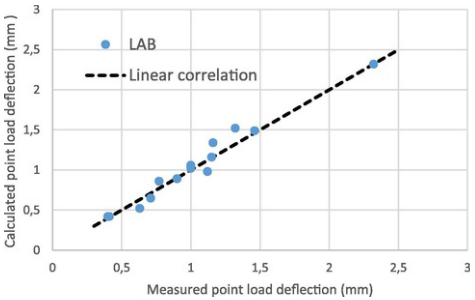

Fig. 7 Comparative analysis of calculated and measured point load deflection.

The average deviation between calculated and measured fundamental frequency is approximately 7% for these laboratory objects. Four out of 14 objects show deviation between measurements and calculations in the range from 10 to 21%. The results show an evenly distributed correlation between overestimation and underestimation of the point load deflection. Regarding the point load deflection, results from this comparison generally show that calculations using BTAB tools presented in Section 4.3 combined with accurate input data give reliable results. Evaluation with respect to floor vibration perception is given in Section 6.

6 Evaluation procedures

6.1 Eurocode 5, Ohlsson method

Evaluation of lightweight floors in Eurocode 5 [8] is based on research work from Ohlsson [2]. The original reference has been used for the evaluation of floors in this study. Fig. 8 shows the evaluation of results according to [2] based on measurement and calculation results from Section 5. In all cases, a loss factor of 2% has been used in line with the Ohlsson method.

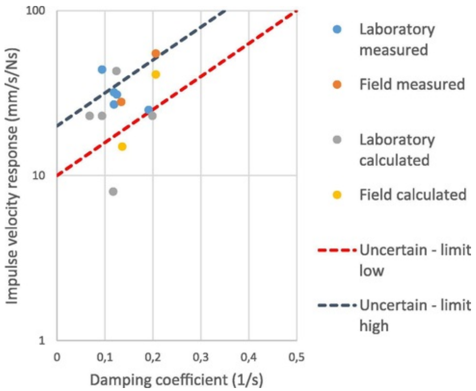

Fig. 8 Evaluation of floor vibration properties according to [2].

Table 7 shows an overview of the evaluations when categorized into intrusive, uncertain and satisfactory floor vibration properties according to suggestions from [2]. The first column of Table 7 presents evaluations based on measurements and the second column presents evaluations based on calculations.

Table 7 Evaluation of floor vibration properties according to Ohlsson [2].

Object	Evaluation based on	
	Measurement	Calculation
Lab-II a	Intrusive	Intrusive
Lab-II b	Uncertain	Uncertain
Lab-II c	Intrusive	Uncertain
Lab-III a	Intrusive	Satisfactory
Lab-III b	Satisfactory	Satisfactory
Field-I a	Intrusive	Uncertain
Field-I b	Uncertain	Satisfactory

When we compare the evaluations based on calculations versus measurements, we recognize that the evaluation agrees for three objects: Lab-II a, Lab-II b and Lab-III b. On the other objects, the evaluation is better based on calculations compared with measurements. For object Lab-II a, the evaluation actually changes from intrusive (based on measurement) to satisfactory (based on calculation).

From this comparison, the overall experience is that the parameters given for an evaluation of the vibration perception cannot be verified with satisfactory accuracy from measurements. Use of this criterion therefore relies on trust in the calculation procedure. The method involves damping properties of the floors. However, according to Eurocode, this is more or less a “sleeping” parameter because only internal damping properties should be used. The effect of increased damping (from boundary conditions and coupling elements) totally changes the evaluation in the diagram.

6.2 The Canadian method from Hu and Chui

The evaluation method developed by Hu and Chui is well documented in [6]. The criteria curve dividing the floor vibration properties into satisfactory or not satisfactory properties has been based on more than one hundred test objects and statistical analysis. The method is based on the calculation of the point load deflection and the fundamental frequency of the wooden floor structure.

Different prediction methods and evaluation criteria regarding floor vibration perception were investigated in the “Comfort Properties” research that took place in 2006 and beyond [12]. Results and experiences from Sweden, Finland, the United States, Canada and Norway were taken into account for this study. One part of the study was to compile measurement results and subjective evaluation of floors using the same criterion as those used for the Canadian research; see [12]. Both results from [5,9] correlated well with the suggested criteria curve from [6]. Later on, SINTEF Building & Infrastructure decided to use these criteria for recommendations of span width of wooden floor constructions. This has been named the “Comfort criteria”.

Fig. 9 shows the results of the evaluation according to [6] based on measurement results from Tables 3 and 4. Fig. 10 shows a similar evaluation based on calculation results from Tables 5 and 6.

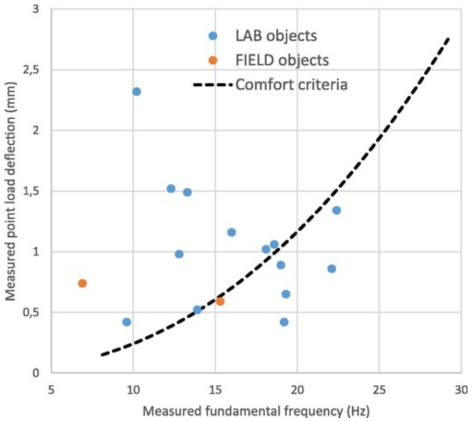

Fig. 9 Evaluation of floor vibration properties from measurement results.

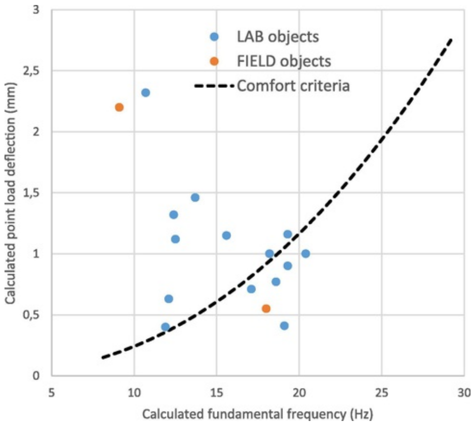

Fig. 10 Evaluation of floor vibration properties from calculated results.

The evaluation of results from measurements shows five objects clearly below the criteria curve, four objects close to the curve and seven objects far above the criteria curve. When we look at the same evaluation from calculated results, we can see that there is only a change in one of the field objects, moving from being clearly below the curve to being close to the curve. The other field objects have moved much closer to the criteria curve based on calculations compared with measurements.

From this comparison, the overall experience is that the parameters given for an evaluation of the vibration perception can be verified with satisfactory accuracy from measurements. It means that measurements may be used in combination with calculations when developing new solutions or for verification of installed floors. The method does not involve the damping properties of the floors. Therefore, results from field measurements must be used with caution, especially when the damping is increasing. The comparison also highlights the necessity to calculate the point load deflection and fundamental frequency using reliable methods.

7 Conclusions

This paper has presented results from a number of well-controlled measurements of floor vibration parameters given in the Ohlsson [2] and Hu and Chui [6] methods. The same parameters have been calculated according to given equations and relevant methods. Both calculations and measurements include 17 laboratory objects and four field objects. The objects represent a huge variety of solutions and therefore a similar large spread of results. An important reason for choosing solutions has been to expand the possibilities of increased span width and test the methods more than tuning current solutions into satisfactory floor vibration perception.

Use of Ohlsson [2] and Eurocode [8] involve calculation of the impulse velocity response, fundamental frequency and point load deflection. In addition, tabulated values of the damping properties should be used. Use of the Hu and Chui [6] method involves calculation of the fundamental frequency and point load deflection. The method does not involve the damping properties of the floors.

Calculation of the fundamental frequency is based on equations from Ohlsson [2]. Results from comparison of calculations and measurements generally show that calculations of the fundamental frequency give reliable and sufficiently accurate results when quality-assured input data has been used.

Different methods and procedures have been used to calculate the point load deflection. From our comparison of the methods, our recommendation is to use the principles given in the BTAB equations. This involves stiffness in two directions from a setup of seven beams and a plate. Results from this comparison show that calculations according to BTAB tools combined with appropriate input data give rather high accuracy of results.

Calculation of the maximum impulse velocity is based on equations from Ohlsson [2]. Comparisons between calculations and measurements show a huge scattering. According to this comparison, the calculation is far too optimistic; however, the procedure to measure the impulse velocity response and the accuracy of the results may be uncertain. In summary, these results show that it is not possible to verify the calculation procedure or the measurement results from this study.

The link between the evaluation method in the Eurocode [8] and human perception studies is very weak. The use of the Eurocode evaluation is fully dependent on input data given in national annexes to the standard. Such values are not given in Norway due to insufficient documentation of correlation to human perceptions. The effect of damping properties achieved in real buildings with respect to the evaluation is also not verified.

The link between the evaluation method from Hu and Chui [6] and human perception is strong, because the method is based on experiences from more than one hundred real floors.

In a former research study [12], different evaluation criteria regarding floor vibration perception was investigated. In that study, results from both [5,9] correlated well with the suggested criteria from Hu and Chui [6], later called the “comfort criteria”. The method does not involve the damping properties of the floors; however, it is based on physical and subjective evaluations of real wooden floors with certain damping properties, probably similar to comparable Norwegian wooden floors. Therefore, the method should be used carefully if the damping properties are significantly lower than experiences from the Canadian study.

The collection of data and resulting analysis in this paper highlights benefits and limitations concerning relevant parameters for evaluation of floor vibration perception. According to this work, it does not seem possible to verify the Eurocode method with respect to accuracy, and the link to perception of floor vibrations is rather low. Another method should be developed and used in future. Results presented in this paper show that sufficient accuracy may be achieved using parameters from the Hu and Chui method. Experiences from Norway in the last five years are also promising regarding evaluation of floor vibration perception using this method. However, care should be taken when dealing with floors with significantly lower damping properties and/or significantly higher (modal) masses. Damping properties or an alternative parameter taking longer time intervals for the vibrations should be investigated in future, for instance using the a_{RMS} value suggested in [1,5].

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.engstruct.2018.07.091.

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Appendix A. Supplementary material

Multimedia Component 1

Supplementary data 1

Highlights

- Comparison of measurement and calculation results regarding floor vibration properties.
- Evaluation of the serviceability of wooden joist floors.
- Results indicate that it not is possible to verify the Eurocode method with respect to accuracy.
- Results presented in the paper show that sufficient accuracy may be achieved using parameters from the Hu and Chui method.

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