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Advancing Timber for the Future Built Environment

COMPARISON OF THE CALCULATED AND MEASURED VIBRATION BEHAVIOUR OF LONG-SPAN TIMBER FLOORS

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ABSTRACT: The demand for longer spans in timber floors is increasing steadily. Modern materials facilitated the construction of load-bearing systems, but serviceability concerns, particularly vibration analysis, remain crucial. Current design practises often result in over-designed cross-sections to mitigate perceived vibration issues, although in-situ floors typically surpass the calculations. The complete study aims to analyse up to 50 existing timber floors to empirically demonstrate this discrepancy between theoretical predictions and in-situ performance. By comparing measured data with computational models, this research seeks to refine design methodologies for more accurate vibration analysis, potentially reducing material usage without compromising structural integrity.

KEYWORDS: timber floor, vibrations, long-span, in-situ measurements, structural dynamics

1 – INTRODUCTION

The demand for aesthetically designed and ecologically sustainable buildings is constantly increasing. Fulfilling both criteria requires a thoughtful selection of construction methods and materials that are geared towards future needs. Looking at, for example, Germany CO_2 emissions, the construction sector is responsible for around 40 % of these emissions [17]. It is therefore imperative that the construction sector utilises sustainable alternatives to CO_2 and energy intensive building materials. Timber buildings appear to provide a practicable solution due to their lower environmental impact. The lightweight construction method has many positive aspects such as lighter foundations, less transport weight, storage of CO_2, etc., but other aspects such as the vibration behaviour of timber floors must be considered. A master's thesis has demonstrated that vibration analysis plays a pivotal role in the design of long-span timber floors. [1]. It is therefore essential to investigate the vibration behaviour of long-span floors in more detail. Various measurements have shown that real floors often show better vibration behaviour results than the calculated values. This discrepancy is analysed in this paper.

2 – BACKGROUND

Existing design methods [8], [7] and future design approaches [15] are often unable to accurately represent the real vibration properties of long-span timber floors. These calculations approaches always assume ideally supported systems. Consequently, these methods often lead to over-dimensioning, which unnecessarily increases the material cross-sections. In reality, clamping by walls at the bearings, non-load-bearing partition walls as well as additional stiffness due to friction, influence the natural frequencies. Especially for long-span floors ($l > 7m$), the natural frequency f_1 is decisive in determining whether resonance occurs or not. As shown in (1), the span l has a squared influence and emphasises this relevance [15].

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

With the frequency factor $k_{e,1}$ for double span floors and $k_{e,2}$ for the effect of the transverse floor stiffness different environmental conditions can be taken into account. The floor mass m and the bending stiffness along the floor span $(EI)_L$ are also required for the determination of the natural frequency. The calculated natural frequency is used to perform the verification procedure according to prEN 1995-1-1: 2024 [15].
In prEN 1995-1-1: 2024 [15] eight different floor performance levels with different limits (see Figure 1) are defined.

Figure 2 shows the first exclusion criterion for the verification is the natural frequency. Here, the minimum frequency of $f_1 \geq 4.5\ Hz$ must be complied with, especially for floor performance levels I to IV. For level V to VIII, the minimum frequency of $f_1 \geq f_{1,lim}$ must be observed. As shown in (2), $f_{1,lim}$ is four times the walking frequency f_w [15]. The walking frequency should be assumed to be at least $1.5\ Hz$ for residential floors and $2.0\ Hz$ for floors in other usage categories

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	Floor performance levels							
Criteria	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**
For all floors in the categories of use A, B, C1, C3 and D as defined in prEN 1991-1-1:2023								
Frequency criteria	$f_1 \geq 4{,}5$ Hz				$f_1 \geq f_{1,\text{lim}}$ [a]			
Stiffness criteria	$w_{1\text{kN}} \leq w_{\text{lim}}$ mm							
Deflection limit w_{lim} [b]	$w_{\text{lim}} = w_{\text{lim,max}}$			$w_{\text{lim}} = \max\left\{ w_{\text{lim,max}} \frac{3{,}6}{l} ; 0{,}5 \right\} \leq w_{\text{lim,max}}$				
Upper deflection limit $w_{\text{lim,max}}$	0,25		0,5	1,0	1,25	1,5	1,75	2,0
Velocity criteria	$v_{\text{rms}} \leq v_{\text{rms,lim}}$ m/s							
Limit of root mean square velocity response $v_{\text{rms,lim}}$	0,0004	0,0008	0,0012	0,0016	0,0024	0,0036	0,0042	0,0048
Additionally for floors with resonant response with fundamental frequency $f_1 < f_{1,\text{lim}}$ [a]								
Acceleration criteria	$a_{\text{rms}} \leq a_{\text{rms,lim}}$ m/s^2				Not applicable			
Limit of root mean square value of acceleration $a_{\text{rms,lim}}$	0,02	0,04	0,06	0,08				
[a] The fundamental frequency limit above which resonant response will not occur (see also Formula (9.12)), in Hz.								
[b] In the formula for calculating w_{lim}, l is the floor span being considered (see also 9.3.2.1(3)), in m.								

Figure 1: Draft of EC5: Floor vibration criteria according to the floor performance level [15].

prEN 1995-1-1: 2024 [15].

$$f_{1,lim} = 4\ f_w \tag{2}$$

In addition to the frequency criteria of levels I to IV, an acceleration criterion must be carried out for the frequency below the limit frequency $f_{1,lim}$. Once this condition is met, the stiffness and velocity criteria can be carried out.

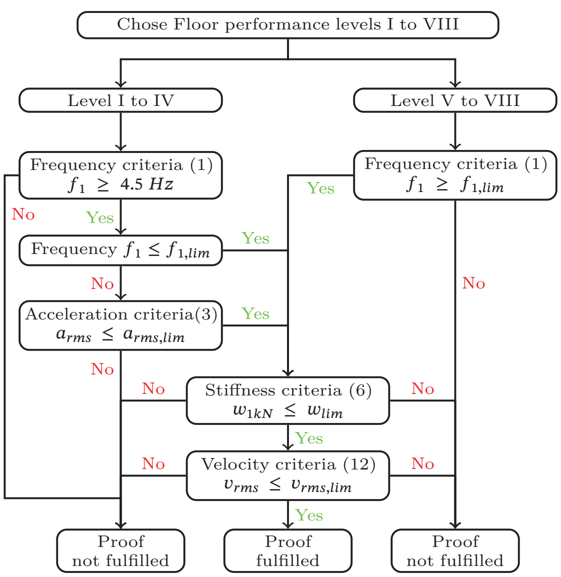

Figure 2: Procedure of the proof of vibration in the serviceability limit state according to [15].

The verification procedure [15] has become much more extensive compared to DIN 1052 [2], which means that significantly more influencing factors have to be taken into account, such as the modal mass M^* and damping ratio ζ.
The influence of damping in particular is included linearly in the design of acceleration in case of resonance (see (3) taken from [15]). In addition to damping, the factor that accounts for the effect of higher vibration modes k_{res} and the resonant build-up factor μ_{res} influences the vertical dynamic force F_{dyn}.

$$a_{rms} = \frac{k_{res}\ \mu_{res}\ F_{dyn}}{\sqrt{2}\ 2\ \zeta\ M^*} \tag{3}$$

In various studies such as Petersen et al. [14], Hamm et al. [8] and HIVOSS [10], damping ratio of the structural damping of timber from 1% to 6% can be found. In contrast, the range of damping values for floating screed is between 1% and 1.5%.
The draft prEN 1995-1-1: 2024 [15] givs damping ratios in the middle of the mentioned literature. These are described as follows:

- $\zeta = 0.02$
  for joisted floors
- $\zeta = 0.025$
  for timber-concrete floors, rib type floors and slab type (e.g. CLT, LVL, GLVL, GL) floors
- $\zeta = 0.03$
  for joisted floors with a floating floor layer
- $\zeta = 0.04$
  for timber-concrete floors, rib type floors and slab type (e.g. CLT, LVL, GLVL, GL) floors with a floating floor layer

In prEN 1995-1-1: 2024 [15] it is stated, that the damping values can alternatively be determined by testing on site using DIN EN 16929:2018 [5]. However, recent studies [9] have shown that the damping ratio of long-span floors under laboratory conditions is lower than mentioned above.
It is therefore necessary to refine and optimise this input data. In order to compare the real conditions and the calculation, it is essential to carry out comprehensive vibration analyses on in-situ buildings. By comparing measured vibration data and theoretical calculations, this study aims to harmonise the current design rules [7] with empirical results and thereby improve their accuracy and applicability to long-span timber floors.

3 – PROJECT DESCRIPTION

The project 'SchwallBe' [16] is designed to investigate precisely this problem. The project investigates the vibration and sound insulation behaviour of long-span timber and timber concrete composite (TCC) floors. The aim of this project is to refine the design methodology for the assessment of vibrations in long-span timber floors in order to increase the efficiency of serviceability calculation. The current practice often leads to oversized cross-sections and increased material consumption.
Empirical evidence repeatedly shows that timber floors exhibit better vibration properties under real conditions than predicted by calculations. This study focuses on the analysis of constructed buildings to determine their real vibration and sound insulation behaviour. In particular, it investigates whether the

observed first resonant frequency is higher than expected in practice due to boundary conditions and recessed corners of the floor plate. The aim of the project is to confirm or disprove the assumption that these structural properties contribute to a better vibration behaviour of timber floors compared to theoretical methods.
This research project is a cooperation between Biberach University of Applied Science (HBC) and Stuttgart University of Applied Sciences (HFT). The HFT is primarily investigating the acoustic properties, which are not included in this paper. The project duration is from May 2024 to December 2026, which explains why the full scope of measurements is currently not complete. The tested floors are mainly in Germany, Swiss and Austria.
The research project is an European Regional Development Fund project (EFRE: Europäischer Fonds für regionale Entwicklung) and is financially supported by the European Union and the state of Baden-Württemberg (see Figure 3).

Kofinanziert von der Europäischen Union

Baden-Württemberg

Figure 3: EFRE supporter.

4 – EXPERIMENTAL SETUP

The test program begins with the selection of various floors to be tested.

4.1 FLOORS

As part of the project, 50 floors should be analysed. At the time of this publication, 18 floors have been measured and most of them have been compared with the calculation. The following floor types are analysed (see Figure 4).

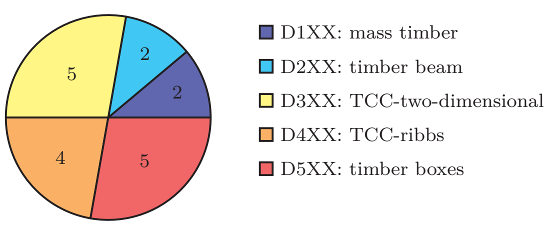

Figure 4: Different types of tested floors.

It is obvious that Timber Concrete Composite (TCC) floors make up a large proportion of the analysed floors, especially with long-spans. In addition to the significant difference between the materials, it is also clearly recognisable that flat floors usually have smaller spans than ribbed floors. This can be attributed to the effective use of materials.
The span distribution can be seen in Figure 5. As can be clearly seen, TCC floors are particularly common with long-spans.

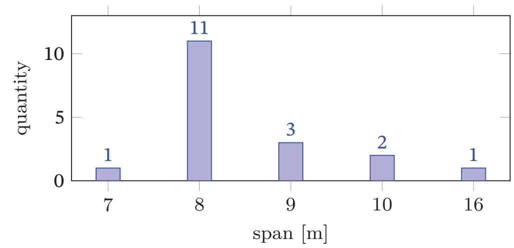

Figure 5: Spans of the measured floors.

Figure 6 shows the type of building where the measured floors are installed.

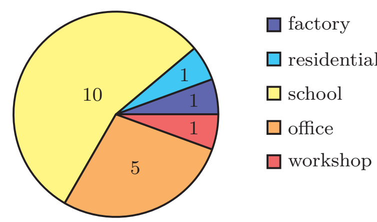

Figure 6: Category of buildings of the measured floors.

As can be seen, that long-span floors are mainly installed in public and office buildings. This can be attributed to the use of space. In residential buildings, for example, floors with a span of less than 7 metres are usually used.

4.2 MEASUREMENT SETUP

Sensor

The vibration measurements are carried out in compliance with [5]. The position of the sensors is selected analogously to DIN 45669-2:2005 [3] and DIN EN 16929:2018 [5] in the centre of the field at the largest expected vibrations. The other sensors are positioned in the quarter points of a floor. All sensors are placed on the structure with docking plates. As accelerations of less than 3 m/s^2 are expected, a free positioning of the accelerometers is possible [3].
Piezoelectric acceleration sensors are used to measure the vibrations. The signal is amplified and analysed using a measuring card controlled by the software *DASYLab* and *FlexPro*.

Shaker

In addition to human-induced force excitation and excitation by a rubber ball, a stationary force is also injected by a shaker (see Figure 7). This shaker is used to apply a force at the resonance frequency and thus compare the calculated values with the measured values. The electrodynamic shaker is set up in the centre of the floor [11] and excites the floor with a moving mass of 13.2 kg. The shaker can be used to generate frequencies from 1 Hz to 200 Hz, although only frequencies up to 80 Hz are investigated in the experiments [12].

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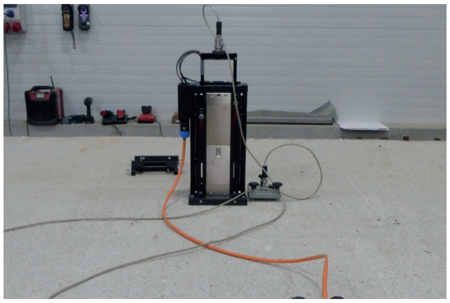

Figure 7: Shaker on top of a element.

Deflection

The deflection is measured using a micrometer with a margin of tolerance within $0.01\ mm$. The static load is applied within three load cycles by a person (approx. $80\ kg$) or by defined masses ($100\ kg$).

4.3 MEASURING THE FLOOR PROPERTIES

Different impacts are required for different measured values. The determination of the different data is explained below.

Fundamental frequency

To determine the fundamental frequency of the floor, a force impulse is applied to the floor using a heeldrop or/and a rubber ball. During the measurement, both a heeldrop and the dropping of a rubber ball with $4\ kg$ are carried out. The impulse is repeated three times close to each accelerometer. This impulse deflects the floor and allows it to vibrate at the natural frequency. Using Fast Fourier Analysis (FFT) on the measured time signal the different natural frequencies of the floor can be evaluated. An exemplary FFT is shown in Figure 8.

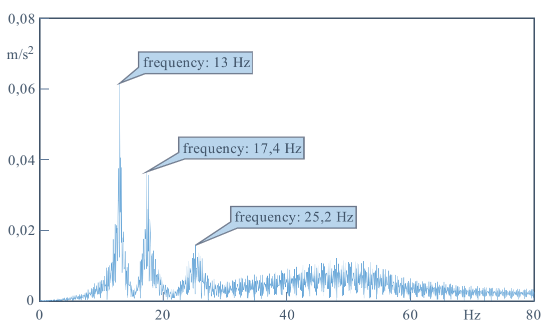

Figure 8: FFT of the excitation with ball - Measured acceleration at the centre of the floor in building D506.

Damping

The damping is evaluated according to the transient excitation with heeldrop/ ball or stationary excitation with the shaker. The logarithmic decrement λ is used for the calculation. This is described (see (4)) by the deflection curve with a start W_i and end W_{i+n} value and the number of amplitudes n [14][5].

$$\lambda = ln\frac{W_i}{W_{i+1}} \quad or \quad \lambda = \frac{\left(ln\frac{W_i}{W_{i+n}}\right)}{n} \tag{4}$$

In Figure 9 the acceleration of a ripped floor excited by the shaker, is shown when the excitation is switched off. The vibration reduction of the floor is clearly recognizable.

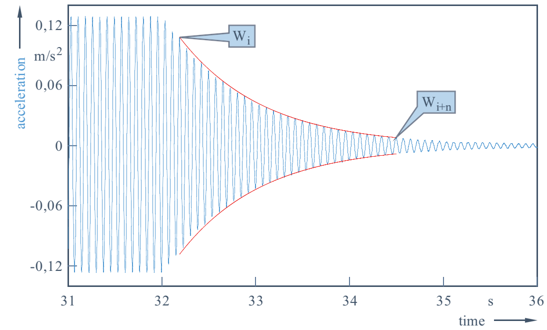

Figure 9: Time signal of the acceleration when the shaker is switched off. Using (4) the damping can be evaluated.

The literature often refers to the damping ratio ζ, which is related to logarithmic decrement λ as follows:

$$\zeta = \frac{\lambda}{2\pi} \quad for \quad \zeta < 0.2 \tag{5}$$

As previous research shows [9] that people have an influence on the damping behaviour. Both the damping after the heeldrop and the ball are analysed in Section 5.

Static Deflection under 1 kN

For static deflection, a load of $100\ kg$ ($1\ kN$) is applied in the centre of the field. If the defined force cannot be applied for logistical reasons, the load is applied by the persons present. Two load stages are carried out to interpolate the deflection due to $1\ kN$.

Acceleration

According to [5], there are two ways to apply load for acceleration. A force can be applied to the floor either by resonant jogging or with the shaker. In order to achieve a defined force, the shaker is primarily used as part of the project. This is done for three times $20\ sec.$ action times and a break of $10\ sec.$ between the excitation (see Figure 10).
During the measurements, different forces should be imitated with the shaker.

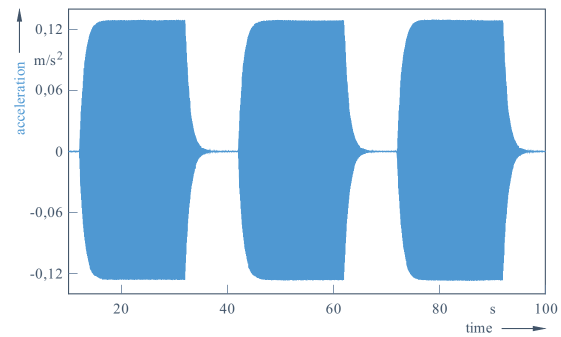

Figure 10: Acceleration of the floor D506 when the shaker excites the floor 3 times for 20 s with a 10 s break.

Velocity

No loads are listed in DIN EN 16929:2018 [5] for the verification criterion of velocity according to [15]. As this value cannot be determined on the basis of the standard. Randomised walking on the floor is carried out. Here, the test subjects present walk on the floor for 20 *sec.* to 60 *sec.* on the whole floor. However, only an interval of 4 *sec.* with one maximum peak of the measured time is analysed (see Figure 11).

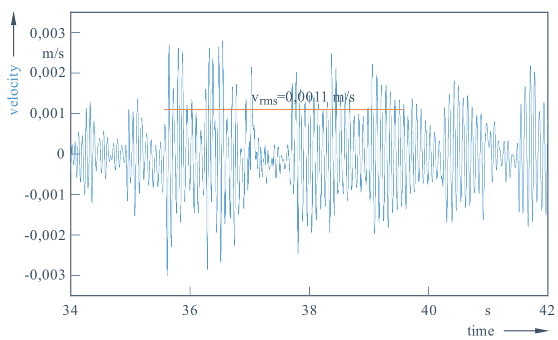

Figure 11: v_{rms} as a result of random walking on the building D506.

5 – RESULTS

The results of the calculation and measurement are compared and listed below.

5.1 FREQUENCY

As can be seen in Figure 12, all calculated natural frequencies are higher or close to the minimum frequency of $f_e = 4.5\ Hz$. This confirms that the cross-sections reach their calculation limits and often lead to larger dimensions.

Comparing the calculated frequencies and the measured frequencies (see Figure 12), certain tendencies can be recognised. With exception of two floor, all measured frequencies are higher than the calculated frequencies. This confirms the supposition that the measured floors still have reserves in the frequency. However, the corresponding measurement data is still missing in order to determine a clear tendency.

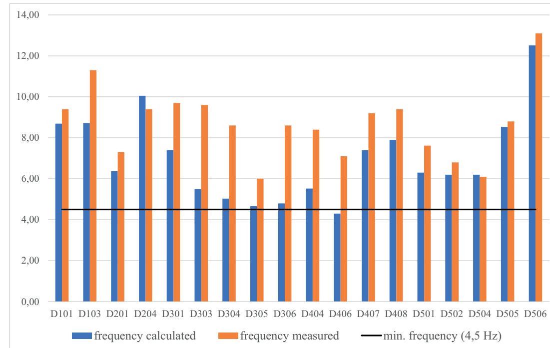

Figure 12: Calculated and measured first resonance frequencies of the investigated floors so far.

5.2 DAMPING

As can be seen in Section 2, different damping values are assumed for the calculation. Since most of the verification methods are based on [8], the applied damping values similar for the floor. As shown in Figure 13, the variation in damping is quite high. However, in contrast to the frequency, there is no clear tendency to recognise that the assumptions or reality is better.

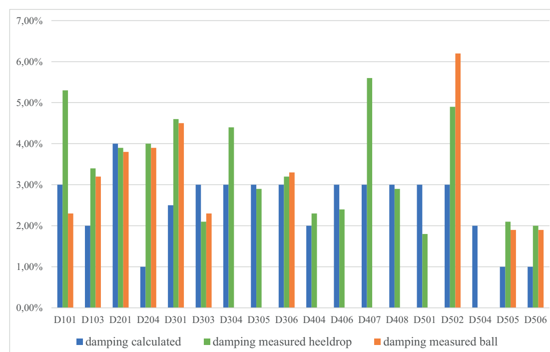

Figure 13: Assumed and measured damping from floors with the impact from heelrop and ball.

If a closer look is taken at Figure 13, it can be seen that around 30% of the damping has smaller values than assumed. If the research [13] on the damping behaviour of long-spans is also considered, the tendency for long-spans to have smaller damping values can be confirmed. However, how large the damping values actually are, can be determined at the end of 'SchwallBe' project.

5.3 STATIC DEFLECTION DUE TO 1 KN

The proof of static deflection can be calculated either due to 1 *kN* [15] or 2 *kN* [8]. However, as it is a linear calculation, all of the complete deflections are scaled to 1 kN.
Figure 14 shows the calculated and measured deflections with (6) [15] under an single static load of $F = 1\ kN$. For the calculation, the bending stiffness along the floor $(EI)_L$ is used from the statics of the

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floor. The effective width b_{ef} is calculated according to (7).

$$w_{1kN} = \frac{F\ l^3}{48\ (EI)_L\ b_{ef}} \tag{6}$$

Clear tendencies can be recognised in Figure 14.

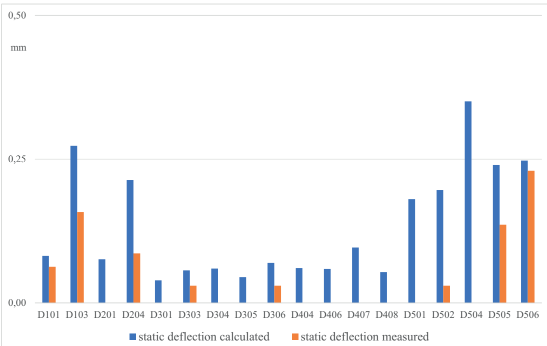

Figure 14: Calculated and measured static deflection due to 1 kN.

The measured deflections are predominantly lower than the calculated deflections. This may be due to better material properties and also stiffer composite connections in combined cross-sections. Therefore, a clear influence of the construction and the bending stiffness along the floor $(EI)_L$ can be seen. TCC floors in particular have a very low deflection. This can be attributed to the high transverse bending stiffness $(EI)_T$. The transverse bending stiffness has a big influence to the effective width b_{ef}. This is calculated with (7)[15].

$$b_{ef} = min\left\{0,95\ l\ \left(\frac{(EI)_T}{(EI)_L}\right)^{0,25};b\right\} \tag{7}$$

If the panelling of a timber beam floor is compared with the concrete layer of an TCC floor, clear differences can be seen. For example, the modulus of elasticity of timber GL24h with $11\ 500\ N/mm^2$ [4] is only one third of the modulus of elasticity of concrete C20/25 with $30\ 000\ N/mm^2$ [6]. So this might be one reason for the smaller deflection due to $1\ kN$.

5.4 ACCELERATION

There is still too little comparable measurement data available for acceleration. Jogging in resonance [5] can excite the floor, but the force from excited by jogging is undefined and therefore cannot be used to comparisons to the calculated values. As shown in (3) the force $F_{dyn} = 50\ N$ is used for the calculation for the acceleration. Only shaker induced (see Chapter 4.2) vibrations can be compared. Till now, only three floors in-situ and two floors in test setups were measured. Therefore, no results are listed yet.

5.5 VELOCITY

In order to compare the velocity, the calculated values from the structural analysis are missing, as this design criterion is only included in prEN 1995-1-1: 2024 [15]. However, the input parameters from the respective structural analysis are used and the calculation is carried out according to the design. To calculate the root mean square value of velocity v_{rms} different values are necessary. The first is the mean modal impulse $I_{mod,mean}$ with the chosen walking frequency from $f_w = 2.0\ Hz$ and the first fundamental floor frequency f_1.

$$I_{mod,mean} = \frac{42\ f_w^{1,43}}{f_1^{1,3}} \tag{8}$$

Using this value along with the modal mass $M^* = \frac{m\ l\ b}{4}$, the peak velocity $v_{1,peak}$ can be calculate with:

$$v_{1,peak} = k_{red} \frac{I_{mod,mean}}{(M^* + 70)} \tag{9}$$

The reduction factor k_{red} is chosen as 0.7. To consider the peak velocity $v_{tot,peak}$ the factor k_{imp} is required for the higher modes, and this is calculated according to (10).

$$k_{imp} = max\left\{0,48\left(\frac{b}{l}\right)\left(\frac{(EI)_L}{(EI)_T}\right)^{0,25};1,0\right\} \tag{10}$$

$$v_{tot,peak} = k_{imp}\ v_{1,peak} \tag{11}$$

The root mean square velocity v_{rms} can be calculated using this peak velocity.

$$v_{rms} = v_{tot,peak}\,(0,65 - 0,01\ f_1)\,(1,22 - 11,0\ \zeta)\,\eta \tag{12}$$

with

$$\eta = \begin{cases} 1,35 - 0,4 \cdot k_{imp}\ (for\ joisted\ floors) \\ \text{when } 1,0 \leq k_{imp} \leq 1,9 \text{ else } \eta = 0,59 \\ 1,35 - 0,4 \cdot k_{imp}\ (for\ all\ other\ floors) \\ \text{when } 1,0 \leq k_{imp} \leq 1,7 \text{ else } \eta = 0,67 \end{cases} \tag{13}$$

The calculated root mean square velocity v_{rms} with (8) to (12) and measured values are shown in Figure 15.

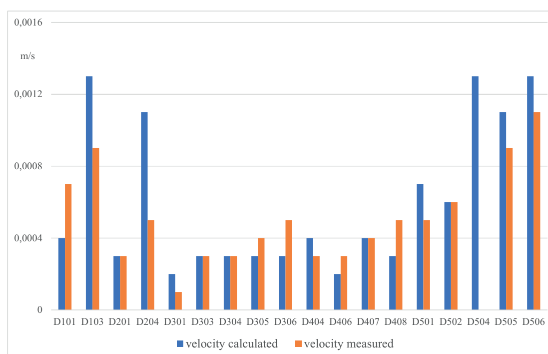

Figure 15: Calculated and measured velocities of the different floors measured so far.

As can be seen in Figure 15, the calculated velocity is higher than the measured velocity in most cases. This means, that the real floors shows better behaviour regrading to velocity.

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6 – CONCLUSION

Looking at the results, the significance of the project is clearly recognisable. The most important conclusions are summarised below.

As part of the 'SchwallBe' [16] research project, timber or timber concrete composite floors with long-spans $l > 7\ m$ are examined regarding to their vibration behaviour. The measured data is compared with the calculated data and then evaluated. Most of the floors have better measured values than the calculated values.

The frequency of the floor slabs is mostly higher than the calculated frequency, provided that the boundary conditions ("beam") have been taken into account. The calculation is therefore on the conservative side. Exact influencing factors still need to be discussed or verified by further measurements.

The measured damping values are not always higher than the assumed values. Therefore, acceleration behaviour can be underestimated if the damping values are too low. For this reason, conservative damping values for the calculation of long-span timber floors should be used.

Looking at the static deflection, there is a similar tendency as at the resonance frequency is shown. Especially floors with floating floor layer have less deflection than the calculated ones. If the sound insulation is very soft, it can also have an influence on the static deflection. This can be attributed to the load above the screed and the measurement on the underside of the floor. However, looking at the results, the above-mentioned limit ranges can be utilised and safety margins are not necessary.

As can be seen in the Section 5.4, more measurements must be carried out for a conclusion on acceleration. The comparison is planned as part of the project 'SchwallBe' [16] .

As the frequency shows, a clear trend can be seen for the velocity. The measured data is below the calculated values and leads to a positive classification of the floor.

7 – OUTLOOK

However, what is not yet being taken into account in the project is subjective perception. This is to be examined even more intensively as part of further measurements.

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