WCTE
WORLD CONFERENCE ON TIMBER ENGINEERING
2010

Floor vibrations – new results

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ABSTRACT: A research project at the Technical University of Munich deals with the vibrations of timber floors. Measurements at real buildings (about 50 buildings and 100 floors) and in the laboratory have been carried out. The results (frequency, deflection, acceleration and velocity) have been compared and assigned to the subjective evaluation. The final results are rules and suggestions how to construct a timber floor in two different categories: A floor with lower demands, for example within a single-family house, or a floor with higher demands, for example in an apartment building or office building or another floor separating different users.

KEYWORDS: Floor vibrations, Timber floors, Heeldrop

1 INTRODUCTION

The serviceability of timber floors becomes more and more relevant due to the use of high strength materials and longer spans. Although the proof of floor vibrations is part of several codes, in many cases problems with floor vibrations arise. In order to look for the reasons for the complaints and to develop improved rules for design and construction a research project was carried out. The results are presented in this paper.

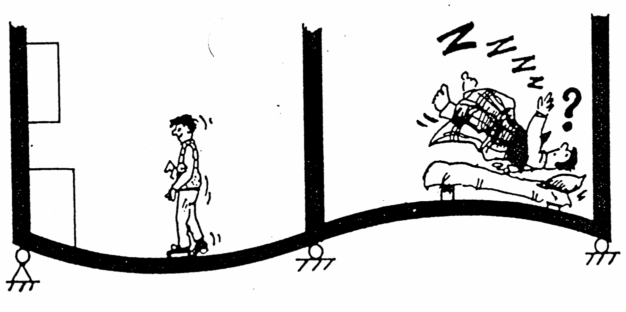

Figure 1: Floor vibrations as a serviceability problem, taken from [1]

2 EXISTING DESIGN RULES IN CODES AND LITERATURE

Many codes [2] – [9] and publications [10] deal with the vibrations of floors, not only timber floors [11] – [16], but also steel [17] or steel concrete composite systems [18] – [19], in some cases even concrete floors [20]. Two codes regarding the vibrations of timber floors are described as follows.

2.1 EUROCODE 5

Eurocode 5 [3] gives a suggestion how to proof the vibrations of floors.
It is divided in the following **three verifications**:

1. The natural frequency of the floor should be at least 8 Hz, see equation (1).
2. The deflections due to a single force should be less than a varying value a, see equation (2), values for a are given in figure 2.
3. The velocity v due to an impulse of 1Ns should be less than the value according equation (3) (for b see figure 2).

$$f_{e1} \geq 8\ Hz \tag{1}$$

$$\frac{w}{F} \leq a \quad [mm/kN] \tag{2}$$

$$v \leq b^{(fe1 \cdot D - 1)} \quad [m/(Ns^2)] \tag{3}$$

If equation (1) is neglected and the natural frequency is less than 8 Hz a more precise investigation should be

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conducted. But in Eurocode 5 [3] no more information is given regarding this more precise verification.

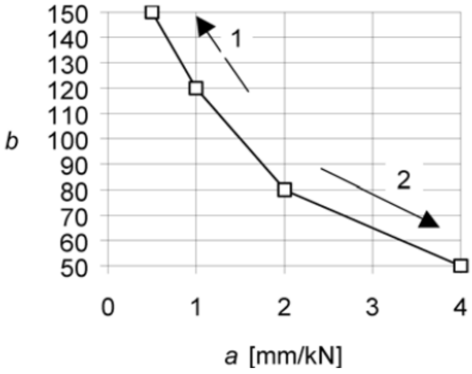

***Figure 2**: Interrelation between the limit values a and b taken from Eurocode 5 [3]: Direction 1 means better behaviour, direction 2 means worse behaviour*

2.2 DIN 1052

DIN 1052 [2] contains a proof of vibrations in form of a limit of deflection. The deflection due to the quasi steady load should be less than 6 mm, see equation (4):

$$w_{perm} \leq 6mm \tag{4}$$

The "quasi steady load" means that a certain part of the live load, defined in DIN 1055 [5], is added to the steady load.

$$w_{perm} = w_{steady\ load} + \psi_2 \cdot w_{live\ load} \tag{5}$$

ψ_2 is the combination factor taken from DIN 1055 [5]. In case of floors under flats or apartments it is taken as: $\psi_2 = 0{,}3$

The limitation of deflection is also a limitation of the natural frequency. In case of a single span girder there is a direct relationship between the deflection due to an uniformly distributed quasi steady load and the natural frequency of the girder under quasi steady load $f_{e,perm}$ as shown in equation (6).

$$f_{e,perm} = \frac{5}{\sqrt{0{,}8 \cdot w_{perm}\,[cm]}} \tag{6}$$

A 6 mm deflection corresponds to a frequency of 7,2 Hz.

$$f_{e,perm} = 7{,}2Hz = \frac{5}{\sqrt{0{,}8 \cdot 0{,}6\,[cm]}} \tag{7}$$

3 MOTIVATION

Although these rules to avoid annoying vibrations are published, regular problems with floor vibrations arise. While searching for the reasons of these annoying vibrations it can be proofed that the above-mentioned rules are satisfied in most cases. This leads to the assumption that these rules are not sufficient and there must be one or more additional rules to avoid uncomfortable floor vibrations.
On the other hand the frequency / deflection limits are very severe criteria which lead to larger dimensions of the timber floor beams.

4 MEASUREMENTS IN SITU

To provide clarification and to get a trustable pool many measurements at existing buildings have been carried out. 57 timber beam floors, 42 with heavy screed, 8 with light screed and 7 without any floor finish were observed, in addition 4 floors with elastic bearings, 6+12 special constructions, 16 timber concrete composite systems and 38 floors made of massive wood, 20 of them with heavy screed, 7 with light screed and 11 without any floor finish, see figure 3.

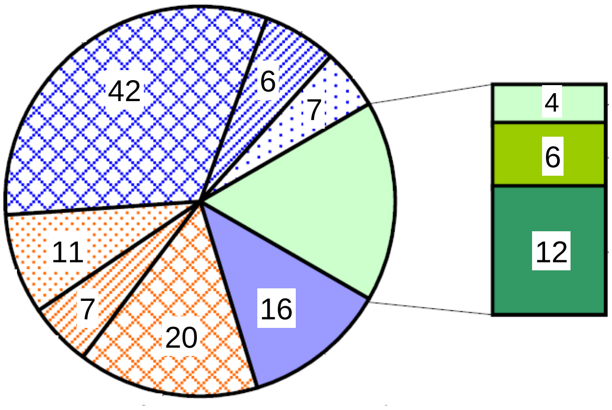

***Figure 3**: Complete picture of all measured systems*

4.1 EQUIPMENT

Figure 4 shows the equipment used for the measurements in situ. It is a measurement device MR2002 CE Standard-Plus from SYSCOM Instruments SA, Zürich, Switzerland with a recorder for three acceleration sensors MS2004+.

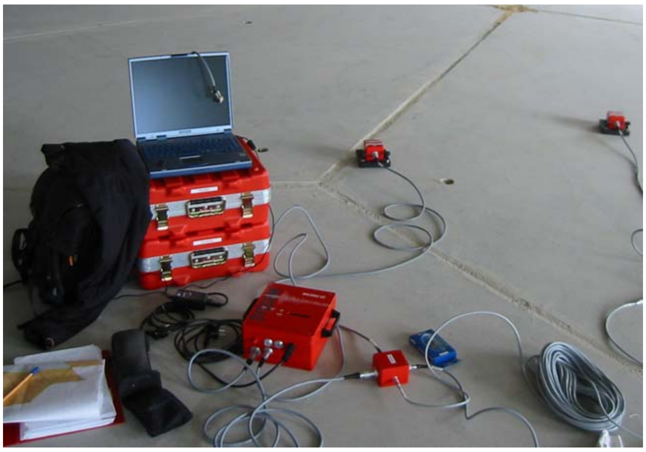

***Figure 4**: Measurement device with recorder (middle) and acceleration sensors (right)*

4.2 MEASURED VALUES / RECORDED DATA

The measured values are:

- the natural frequency of the floor after a jump or a heeldrop
- the acceleration of the floor due to walking, if possible walking with a step frequency half or one third of the natural frequency
- the velocity due to a heeldrop
- the damping of the floor after a heeldrop

With help of plots of the floors the following values were calculated:

- the natural frequency of the floor
- the acceleration of the floor due to walking in resonance with the second or third harmonic part of the Fourier decomposition [10]
- the velocity due to a heeldrop
- the static deflection due to a single load

4.3 COMPARISON BETWEEN MEASURED AND CALCULATED VALUES

Figure 5 shows the comparison between the measured and the calculated natural frequencies of all measured floors. The straight line in the figure shows the ideal case: measured frequency is equal to calculated frequency. But in nearly all cases the measured frequencies are clearly greater than the calculated ones.

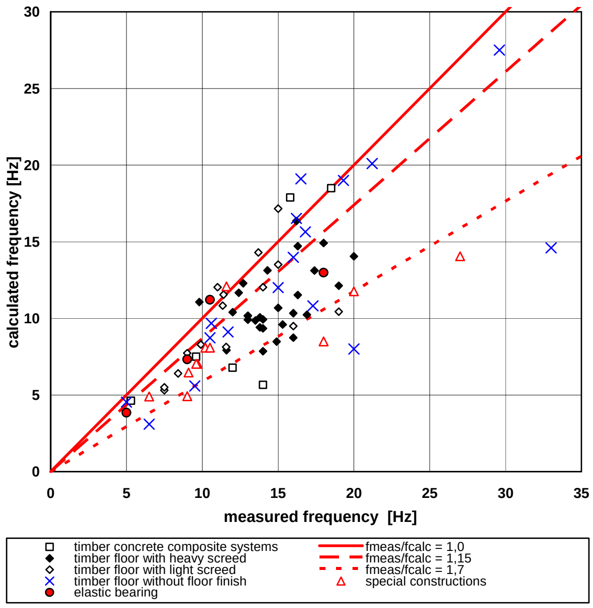

***Figure 5**: Comparison between measured and calculated natural frequencies divided into the type of screed*

4.4 SUBJECTIVE EVALUATION OF BEHAVIOUR

Another very important point is the subjective evaluation of the floor vibration. The floor was evaluated by the test takers Patricia Hamm or Antje Richter and - if the floor was already in use – also by the users. The used marks follow the research report done by Kreuzinger/Mohr [13]: Rate 1 (no vibration problem) to rate 4 (heavy vibration problem). Afterwards a correlation between measured or calculated values and the subjective evaluation of behaviour was searched, for example the correlation between measured frequency and subjective evaluation (figure 6) or calculated frequency and subjective evaluation of behaviour (figure 7).

As a result it can be mentioned that there is no sufficient correlation between the natural frequency and the subjective evaluation of behaviour, neither for the measured nor for the calculated one. There is no doubt that the natural frequency is an important criterion. But beside the frequency criterion additional criteria are needed to proof the vibration behaviour.

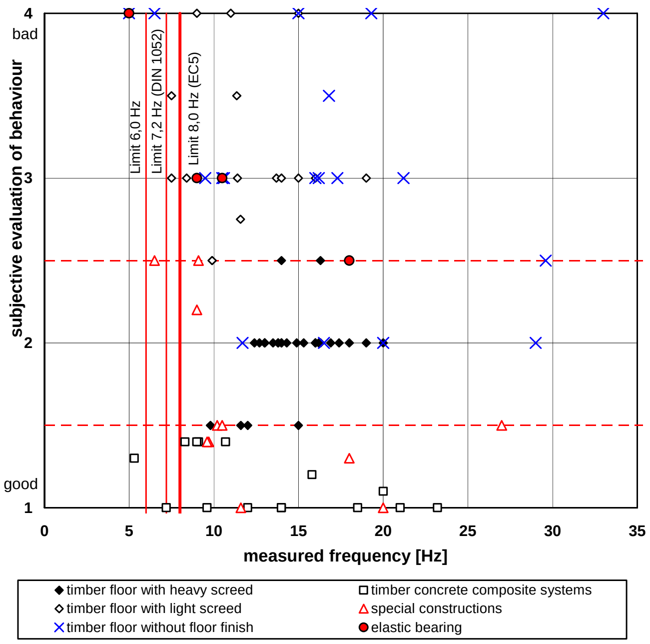

***Figure 6**: Correlation between measured natural frequencies and subjective evaluation of behaviour*

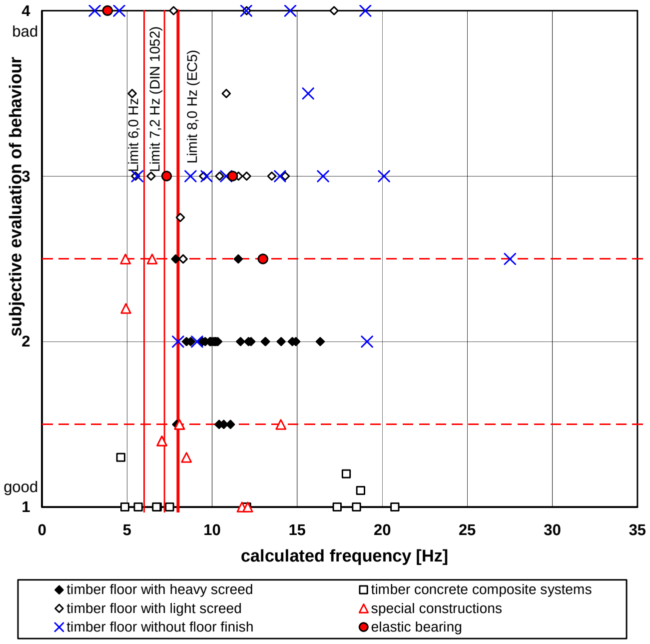

***Figure 7**: Correlation between calculated natural frequencies and subjective evaluation of behaviour*

5 MEASUREMENTS IN LABORATORY

Figure 5 shows that the measured and calculated frequencies of the floors do not fit very well. The reasons were found in wrong assumptions for the calculations. E.g. in the calculation the bearing was set pin ended, in situ a torsional spring act due to the walls in the above storeys or the roof loads.

Another point with big influence on the measured frequencies is the partition wall. These walls are set as non load bearing walls in the static calculation but they act stiffening – and therefore positive regarding the vibrations.

To eliminate all the not calculable influences laboratory tests were conducted.

5.1 TEST STATION – TIMBER BEAM FLOOR

Figure 8 shows one of the 1:1 scale test stations: a timber beam floor without any floor finish. The span and the width are 5,0m. After the measurements of the pure floor different screeds and floors, as well as walls on the sides were added. The corresponding measured frequencies are shown in table 1.

Figure 8*: 1:1 scale test station with timber beam floor and no floor finish*

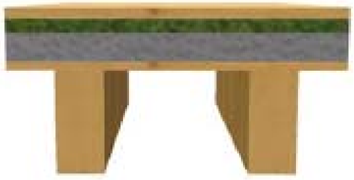

Figure 9: *Light floor made of (from top):*
one layer OSB as a light screed
30 mm foot fall sound-damping on 60 mm grit

Figure 10: *Heavy floor made of (from top):*
60 mm anhydrite screed
30 mm foot fall sound-damping on 60 mm grit

Table 1: *Test series with the timber beam floor and some of the results: first natural frequency and damping*

VA		mass [kg/m²]	f_1 [Hz]	D_1 [%]
1	no floor finish, elastomer bearing	41	14,85	4,52
4	no floor finish, timber bearing	41	15,00	3,59
5	only 60 mm grit	122	10,40	-
6	light floor, bearings on 2 sides	140	10,30	2,99
7	light floor, bearings on 4 sides	140	10,15	3,47
8	like VA 6, add. lower deck	151	9,75	3,16
9	like VA 8, lower deck on springs	151	10,35	2,15
10	like VA 9 with carpet	154	10,30	2,39
11	heavy floor add. lower deck	278	9,75	2,85
12	heavy floor (no lower deck)	267	9,55	2,91
13	like VA 12 with carpet	270	9,62	3,16
14	heavy floor bearings on 4 sides	267	10,35	4,57

5.2 MEASUREMENT DEVICES

In addition to the devices used for measurements in situ in laboratory a second device system DIAdem was used: 1 recorder typ Spider 8, HBM Messtechnik Darmstadt, with 8 acceleration sensors typ ARF-20A, Fa. Tokyo Sokki Kenkyujo Co. Ltd.

5.3 EXCITATION

The following methods were used to excite the structure:

- punching with the fist against the bottom of the structure to get the natural frequencies, figure 11
- heeldrop to measure the natural frequencies, the damping and the velocity, figure 12
- dropping a sandbag to measure the damping, figure 13
- walking in resonance to measure the acceleration
- using a shaker to have a defined excitation (see figure 8)

Figure 11: *Excitation by punching with the fist*

Figure 12: *Position of the feet before a heeldrop*

5.4 MORE TEST STATIONS

After these tests with the timber beam floor was removed and two different massive timber constructions were built.

A construction made of nailed up slabs and a constructions made of cross laminated timber (CLT). The last mentioned tests have been carried out costlier, even as continous beams (see figure 13), and are described in [21] and [22].

Figure 13: *Test taker on CLT plate dropping a sand bag*

6 CALCULATIONS WITH FINITE ELEMENT METHOD

The 1:1 scale test station shown in figure 8 has been modelled and calculated with help of the Finite Element Software ANSYS. Figure 14 shows the first eigenform with a corresponding first frequency of about 16 Hz and the eigenform with a double wave with a natural frequency of about 64 Hz.

To fit the measured natural frequencies, parameters like elastic modulus and mass have been varied. Another test was to model the lost of one or more bearings, as the beams under the (light) plate without any floor finish did not fit the bearings in every case. Figure 15 shows the results of varying the elastic modulus and figure 16 the results of lost of bearings.

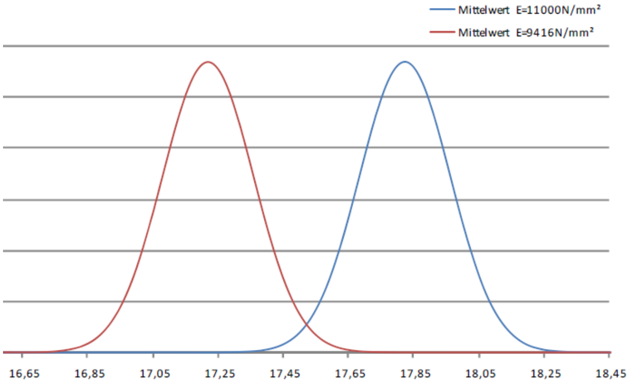

Figure 15: *Distribution of the first natural frequency by varying the elastic modulus*

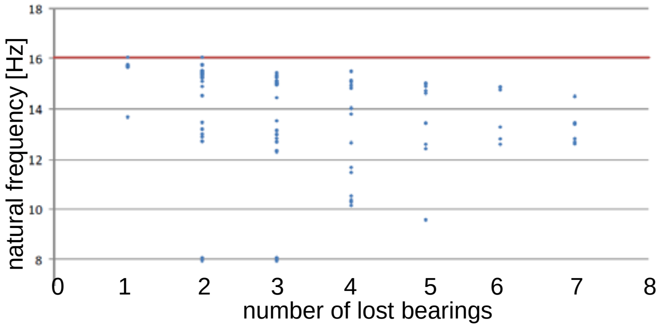

Figure 16: *Distribution of the first natural frequency due to lost of bearings*

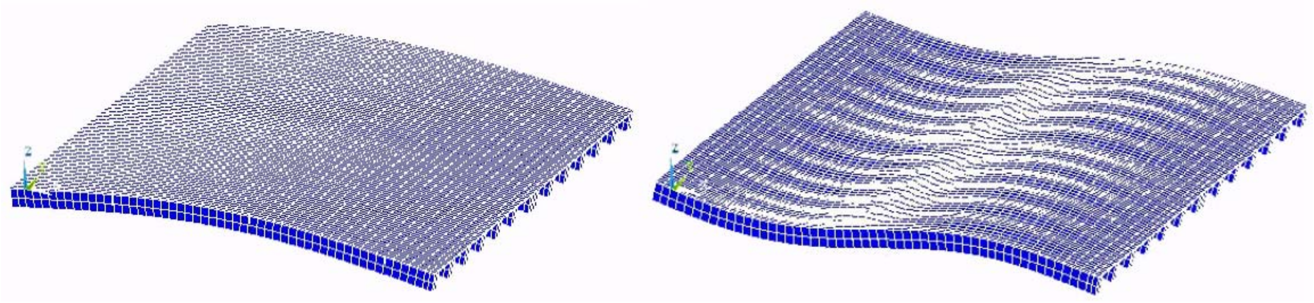

Figure 14: *Results of FE calculation: two eigenforms of 1:1 scale test station*

7 RESULTS

The results of the research project are rules for design and construction, how to construct a timber floor without any annoying vibrations. A chart of the rules is shown in figure 17. The first step is to decide whether there are higher demands or lower demands. Table 2 will help.

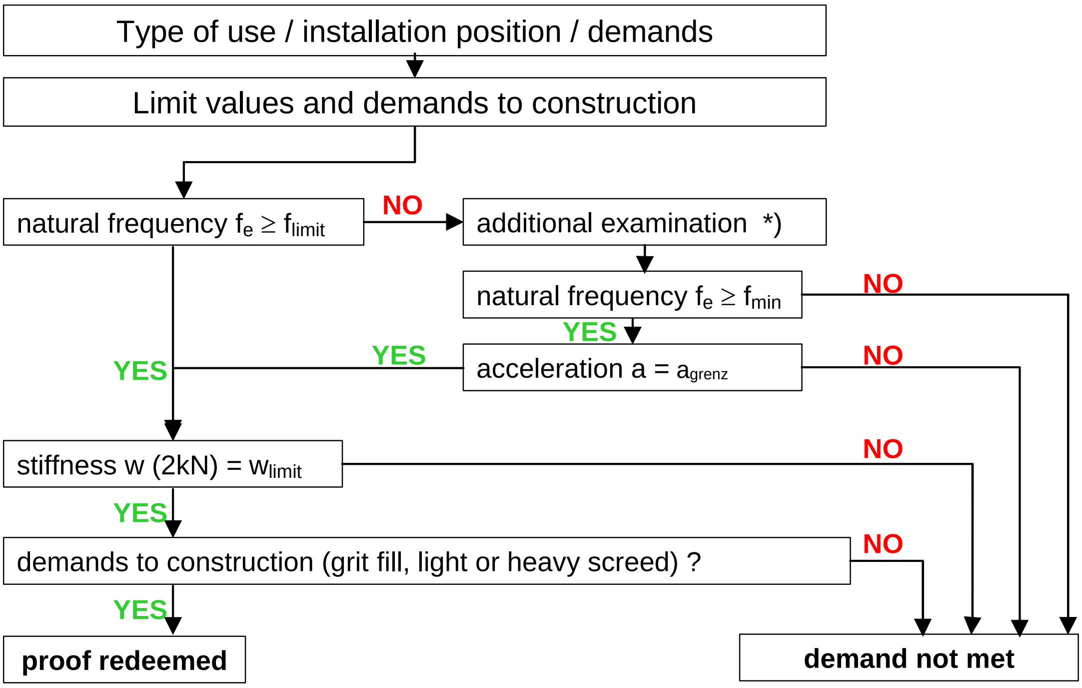

***Figure 17:** Chart of rules for design and construction.*
**) The additional examination of acceleration is successful only in case of timber concrete composite systems or other heavy systems with wide spans.*

***Table 2:** Test series with the timber beam floor and some of the results: first natural frequency and damping*

demands regarding the vibrations	floors with higher demands	floors with lower demands	floors without demands
evaluation	1,0 to 1,5	1,5 to 2,5	2,5 to 4,0
installation position	floors between different units of use	floors between one unit of use	
during the research project examined type of use	e.g. corridors with low spans, e.g. floors between different users, floors in apartment buildings or floors in office buildings	e.g. floors within a single-family house, floor in existing buildings or with agreement of the owner	e.g. floors under not used rooms or in not developed attic storeys
description of perception of vibrations	Vibrations are not perceptible or only perceptible when concentrating on them. Vibrations are not annoying.	Vibrations are perceptible but not annoying.	Vibrations are clearly perceptible and sometimes annoying.
frequency criterion $f_e \geq f_{limit}$	$f_{limit} = 8\ Hz$	$f_{limit} = 6\ Hz$	-
stiffness criterion / deflection due to single load $w(2kN) \leq w_{limit}$	$w_{limit} = 0{,}5\ mm$	$w_{limit} = 1{,}0\ mm$	-
additional examination / acceleration, if $f_e < f_{limit}$	$f_{min} \leq f_e < f_{grenz}$ where $f_{min} = 4{,}5\ Hz$ and $a_{limit} = 0{,}05\ m/s^2$	$f_{min} \leq f_e < f_{grenz}$ where $f_{min} = 4{,}5\ Hz$ and $a_{limit} = 0{,}10\ m/s^2$	-
demands on construction	set up of floating screed, heavy screed or light screed on grit fill or not, see table		-

7.1 FREQUENCY CRITERION

The natural frequency of the floors with steady loads should be high enough to avoid resonance with walking persons. The limit frequencies are dependent on the installation position and the demands (see table 2). The natural frequency can be determined by calculation or measurement.

When calculating the natural frequency the following aspects should be regarded:

For the mass of the floor live load may be neglected, in contradiction to DIN 1052.

The stiffness of screed may be regarded and added to the stiffness of the construction, see table 4.

If exist, bearings on more than two sides may be regarded.

If the floor is a continuous beam this may be regarded.

If the construction is laid out of an elastic bearing (e.g. a beam below), this must be regarded, see [12].

For a single span beam the natural frequency can be calculated with help of equation (8).

$$f_{e,1} = \frac{\pi}{2\cdot\ell^2}\cdot\sqrt{\frac{EI}{m}} = f_{beam} \qquad (8)$$

$$I = \frac{b_{beam}\cdot h^3}{12} \qquad (9)$$

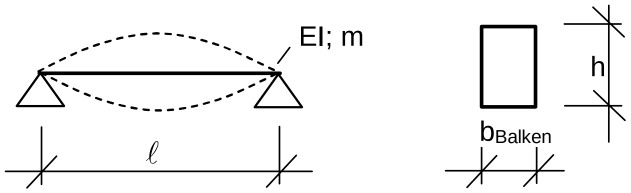

Figure 18: Single span beam

If there are bearings on 4 sides, the frequency of a plate can be calculated by equation (10).

$$f_{Platte} = f_{Balken}\cdot\sqrt{1+1/\alpha^4} \qquad (10)$$

$$\alpha = \frac{b}{\ell}\cdot\sqrt[4]{\frac{EI_\ell}{EI_b}} \qquad (11)$$

b is the width of the floor.

EI_ℓ is the effective stiffness in longitudinal direction (stiffness construction and stiffness screed).

EI_b is the effective stiffness in transverse direction (stiffness construction and stiffness screed), where $(EI)_\ell > (EI)_b$.

7.2 STIFFNESS CRITERION / DEFLECTION

In this research project and in [13] it was recognized that the stiffness criterion is at least that important as the frequency criterion. Figures 6 and 7 verify that the frequency criterion alone is not sufficient.

The stiffness of the construction should be chosen in a way, that the deflection due to a single static load of 2 kN is less than the limit value w_{limit}. The limit values of deflection are dependent on the installation position and the demands (see table 2).

The deflection due to a single static load of 2 kN should be determined by respect to the following:

Independent of the original system this deflection should be calculated based on a substitute system of a single span beam with pin ended supports on both sides (figure 18). The span of the substitute system should be taken as the greatest span of the original system.

If the construction is supported by an elastic bearing (e.g. a beam below), this must be regarded.

The stiffness of screed may be regarded and added to the stiffness of the construction, see table 4.

$$w(2kN) = \frac{2\cdot\ell^3}{48\cdot EI_\ell\cdot b_{w(2kN)}} \leq w_{limit} \qquad (12)$$

$$b_{w(2\,kN)} = min\left\{\begin{matrix} b_{ef} \\ b\ (width\ of\ floor) \end{matrix}\right\} \qquad (13)$$

$$b_{ef} = \frac{\ell}{1{,}1}\cdot\sqrt[4]{\frac{EI_b}{EI_\ell}} = \frac{b}{1{,}1\cdot\alpha} \qquad (14)$$

If there are bearings on four sides, the deflection of the construction may be calculated as a beam grid.

In literature and in Eurocode 5 [3] the deflection due to a static load of 1 kN is used. Why is 2 kN used here? And why is it not allowed to use the original system but a substitute system like figure 18?

The proposal is based on the good correlation between the values of deflection calculated by equation (12) and the subjective evaluation of behaviour, see figure 19.

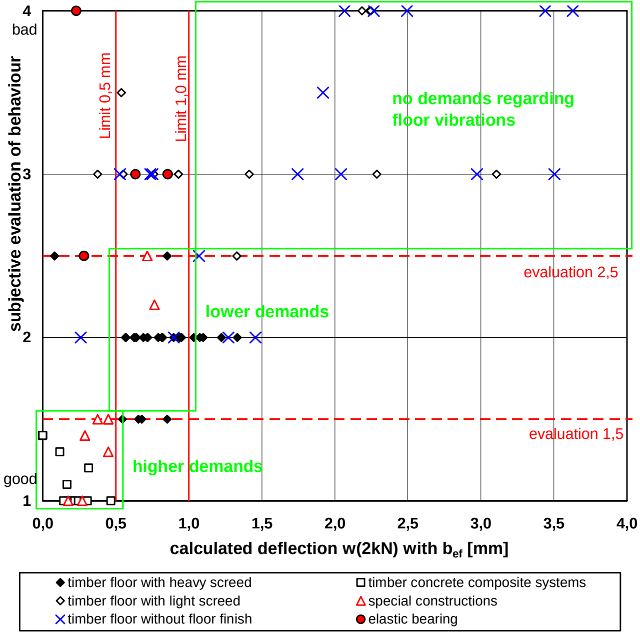

***Figure 19:** Correlation between stiffness and subjective evaluation of behaviour*

7.3 ADDITIONAL EXAMINATION / PROOF OF ACCELERATION

Especially in case of wide spans the frequency criterion is very severe. The research project showed that floors with natural frequencies less than the limit frequency work if two conditions are given: The frequency must be greater than the minimum frequency of 4,5 Hz and the acceleration due to walking in resonance with half or third the natural frequency is less than a limit acceleration, see table 2.
The proof of acceleration is successful only in case of a heavy floor, such as timber concrete composite systems, or systems with wide spans.

$$a\left[\frac{m}{s^2}\right] = \frac{F_{dyn}}{M^{*}\cdot 2D} = \frac{0,4\cdot F(t)[N]}{m[kg/m^2]\cdot 0,5\ell[m]\cdot 0,5b[m]\cdot 2D} \qquad (15)$$

$$F_{dyn} = 0,4\cdot F(t) \qquad (16)$$

M^{*} is the modal mass of the floor.
b is the width of the floor, but b should be less than $b \le 1,5\cdot\ell$.
D is the damping of the structure. See table 3.
F_{dyn} is the total dynamic force. 0,4 is a factor to consider, that the force is acting during a limited time and not always in the middle of the span, see [13]. $F(t)$ are the harmonic parts of the force on the floor (see [10]). They depend on the natural frequency and can be taken from figure 20.

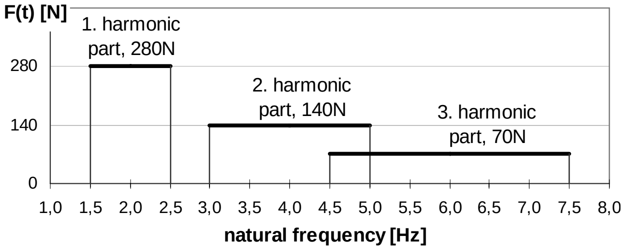

Figure 20: *Force F(t) depending on the natural frequency of the floor*

Table 3: *Values of modal damping ratios, taken from [4] and [6]*

Type of floor	Damping D [ ]
timber floors without any floor finish	0,01
plain glued laminated timber floors with floating screed	0,02
girder floors and nail laminated timber floors with floating screed	0,03

Table 4: *Values of elastic modulus of different types of heavy screed used in the research project*

Type of heavy screed	E Modulus [MN/m²]
cement screed	25000
anhydrite screed	14000
mastic asphalt screed	10000

7.4 DEMANDS ON CONSTRUCTION

Regarding the floor vibrations floating heavy screeds are always better than floating light screeds. This is related to their increased mass and stiffness. A (if possible heavy grit) fill improves the vibration behaviour. A heavy fill in table 5 is at least 60 kg/m², e.g. a 40 mm grit fill.

Table 5: *Demands on construction depending on subjective evaluation of behaviour:*
rate 1: no vibration problem; rate 4: heavy vibration problem

	floors between different units of use	floors between one unit of use
Type of construction	evaluation 1,0 to 1,5	evaluation 1,5 to 2,5
Timber concrete composite systems	no more demands	no more demands
Massive timber floors, e.g. cross laminated timber or nail laminated timber floors	heavy floating screed on a light or heavy fill	heavy floating screed (fill not necessary)
	light floating screed on a heavy fill	light floating screed on a heavy fill
timber beam floors	heavy floating screed on a heavy fill	heavy floating screed (fill not necessary)
	probably not possible	light floating screed on a heavy fill

8 CONCLUSIONS

To improve the proofs of floor vibration and develop rules for the design and construction of timber floors a research project has been carried out. The rules for design are the frequency criterion, the stiffness criterion and an additional examination of acceleration if the frequency is less than the limit value. The demands on construction regard the kind of floating screed and the fill has been evaluated. It has been seen that also the non bearing partition walls have influence on the vibration behaviour. This influence is always positive. But as the proof should be as simple as possible and as these walls can be removed, they do not appear in the proofs.

ACKNOWLEDGEMENT

The research project has been carried out at the Technical University of Munich from 2007 to 2009. It was financed by the Federal Ministry of Education and Research and supported by AiF and DGfH.

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