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FULL SCALE VIBRATION TESTS ON A LONG SPAN TIMBER FLOOR

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ABSTRACT: Since January 2021, Biberach University of Applied Sciences has been working in cooperation with PIRMIN JUNG Deutschland GmbH, Remagen, on the development of a lightweight, vibration-optimized timber floor system for large spans. There is already research that deals with the vibration behaviour of wooden floors. The new focus in this project is primarily on size. Structures such as schools, administrative and office buildings require floors with very large column spacings and therefore very large spans. Existing approaches to serviceability design of timber floors reach their limits for long-span timber floors with spans over 8 m. Therefore, a physical test bench with an aera of 12.5 by 12.5 m² and the inclusion of flexible bearings was built. Various floor systems with spans of up to 12 m were measured and evaluated. As a result, the cooperation partners have received important input for new design rules for very large timber floor systems.

KEYWORDS: Vibration, Timber Floor, full scale tests, long span,

1 INTRODUCTION

Since 2021, Biberach University of Applied Sciences has been working in cooperation with PIRMIN JUNG Deutschland GmbH, Remagen, on the development of a lightweight, vibration-optimized timber floor system for large spans. There is already research that deals with the vibration behaviour of wooden floors. The new focus in this project is primarily on size. Structures such as schools, administrative and office buildings require floors with very large column spacings and therefore very large spans. Existing approaches to serviceability design of timber floors reach their limits for long-span timber floors with spans over 8 m. Therefore, a physical test bench with an aera of 12.5 by 12.5 m² and the inclusion of flexible bearings was built. Various floor systems with spans of up to 12 m were measured and evaluated. The vibrations are measured when people walk on the test floor, to evaluate the conditions with the best vibration properties.

This research project "Development of a lightweight, vibration-optimized flooring system with beams for large spans over 8 m" includes theoretical and practical considerations on the vibration and damping behaviour of timber floors with large spans and beams.

2 EXISTING DESIGN RULES IN CODES AND LITERATURE

2.1 EUROCODE 5

Eurocode 5 [1] 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 1.
3. The velocity v due to an impulse of 1 Ns should be less than the value according equation (3) (for b see figure 1).

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

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

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

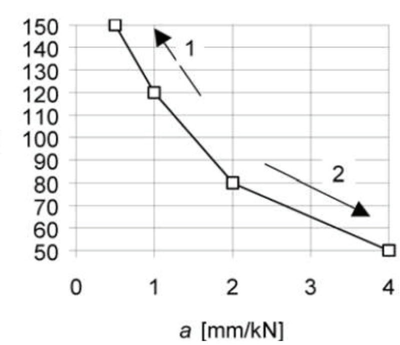

Figure 1: *Interrelation between the limit values a and b taken from Eurocode 5 [1]: Direction 1 means better behaviour, direction 2 means worse behaviour.*

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If equation (1) is neglected and the natural frequency is less than 8 Hz, a more precise investigation should be conducted. However, Eurocode 5 [1] does not provide any further information on this more detailed verification.

2.2 FORMER RESEARCH

To close this gap, a research project was carried out at the Technical University of Munich from 2007 to 2009 and published in [2]. 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.
The proof of acceleration is successful only in case of a heavy floor, such as timber-concrete composite systems or systems with wide spans.
The following flowchart (figure 2) shows the proof of vibrations according to [2].

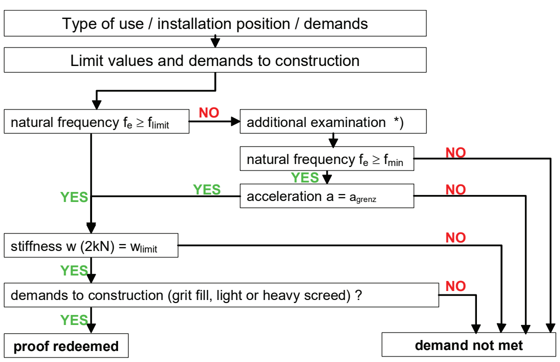

Figure 2: *Chart of rules for design and construction according to [2].*

2.3 DRAFT OF EUROCODE 5

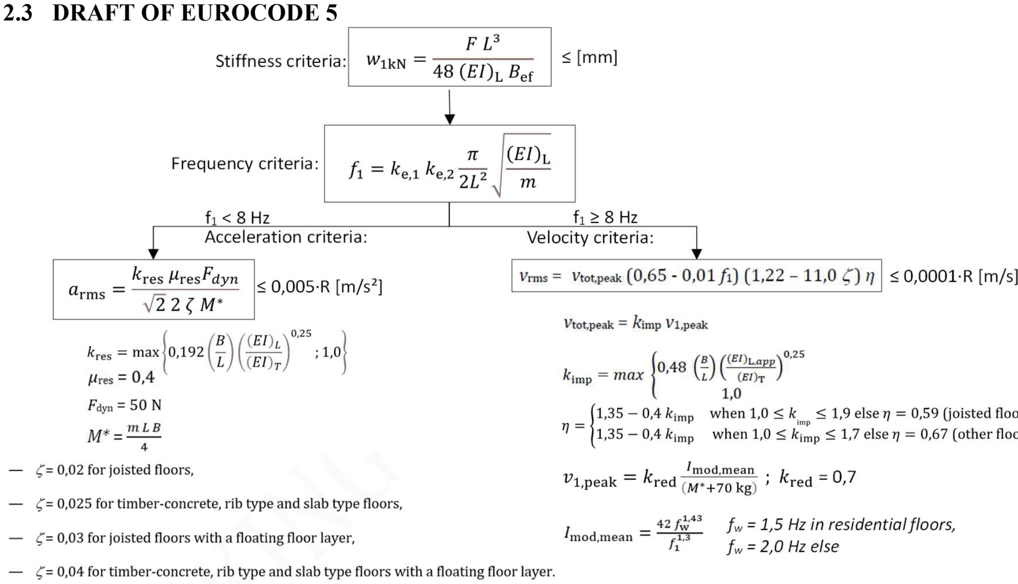

Figure 3. *Flowchart and equations according to [3].*

The basic idea of the new draft of Eurocode 5 [3] was to change the rules in a way, that the perception will be the most important value. Therefore, it was decided to introduce the response factor R. The perception depends on the first natural frequency, as shown below:

a_{rms} < Response factor × $a_{rms,base}$ when $f_1 < 8$ Hz
v_{rms} < Response factor × $v_{rms,base}$ when $f_1 \geq 8$ Hz

Figure 3 shows the principal way and the main equations of the proof, see also [4]. Table 1 contains the limit values of deflection due to point load and the response factors depending on the performance levels, taken from [3].

Table 1: *Limit values and response factor R according to performance level.*

	Floor performance levels					
Criteria	I	II	III	IV	V	VI
Response factor R	4	8	12	24	36	48
Stiffness criteria for all floors w_{1kN} [mm] ≤	0,25		0,5	1,0	1,5	2,0
Frequency criteria for all floors f_1 [Hz] ≥	4,5					
Acceleration criteria for resonant vibration ($f_1 < 8$ [Hz]) a_{rms} [m/s²] ≤	0,005 R					
Velocity criteria for transient vibration ($f_1 \geq 8$ [Hz]) v_{rms} [m/s] ≤	0,0001 R					

3 MOTIVATION

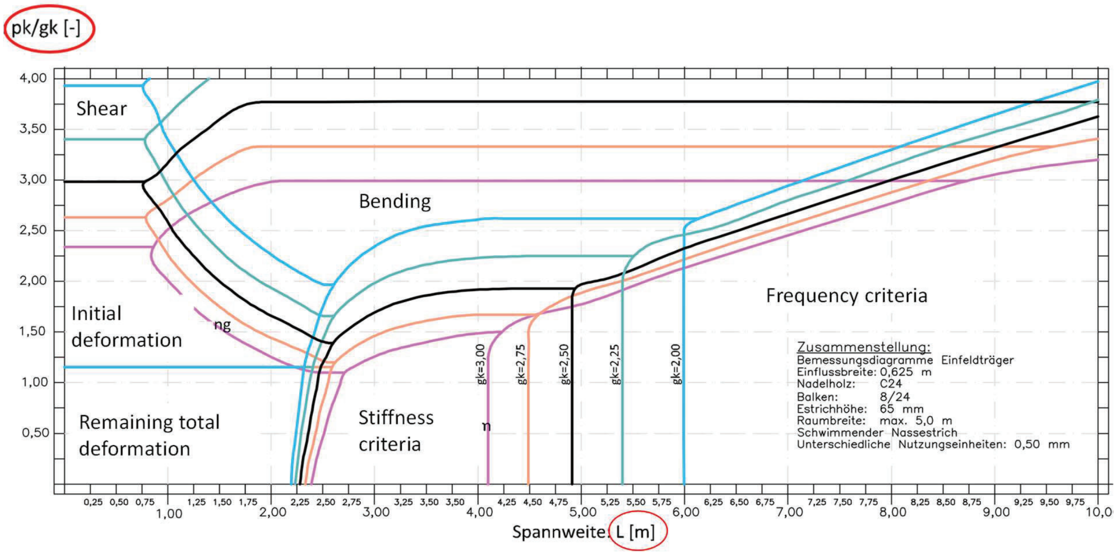

Figure 4. *Design relevant proof for a floor depending on span, based on [2], taken from [5].*

In [2] a possibility to handle low frequency floors is given. This “additional examination” has been adopted to [3] quite similar. Since this proof is based on mechanical laws, it works well.
The background is that low frequency floors are in resonance with one of the higher harmonics of the force that users exert to the floor when walking. Assuming resonance, the resulting acceleration can be calculated and compared to the limit value. To fulfil this proof, very heavy floors are needed.

On the other hand, resonance can be avoided. This means that the natural frequency of the floor must be greater than 8 Hz, see equation (1). In case of large spans, this proof would be relevant for designing the beams of the floor. Figure 4 shows the relevant proof depending on the span L (x-axes) and the relation of live load to steady load (y-axes). It can be seen that the proof of frequency criteria becomes relevant in case the spans are greater than 4-6 m.

For architectural reasons, long span floors are increasingly in demand. These floors would either be very heavy to fulfil the acceleration criteria or designed with very big dimensions to fulfil the frequency criteria.

In order to find out if this is really necessary or if the proofs can be modified and adapted for great spans, the research project mentioned above is carried out.

4 BUILDING UP THE TEST BENCH

The proof of vibration is a proof in the serviceability limit state. The most important thing is that the users of the floor feel safe and comfortable. To find out how people feel on the floor, the structure is built in scale 1:1.

The test bench is set up on a 1: 1 scale, so that all effects can be measured and felt. It has an area of 12.5 m x 12.5m and consists of box elements. The build-up of the test bench is shown in the figures 5 to 11. For detailed information regarding the planning and erection see [6].

Figure 5: *Beams are positioned.*

Figure 6: *Three-layer boards are glued on.*

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Figure 7: Beams are configured to elements.

Figure 8: The supporting wall is built.

Figure 9: Elements are turned and laid on the wall.

Figure 10: Raw floor without top planking.

Figure. 11: Raw floor with top planking, type 1a.

Figure 12: Test bench with mass and screed elements, type 3.

5 MEASUREMENTS ON TEST BENCH

5.1 MODIFICATION IN CONSTRUCTION

Working with the test bench it was possible to build up different types of construction. The following different types were built and measured, see figures 13, 14 and 18:

1. raw floor. The main construction are box elements.
2. raw floor with mass. Mass realized by paving stones.
3. raw floor with mass, sound insulation layer and heavy screed. Screed is made by concrete elements.
4. raw floor, sound insulation layer and screed

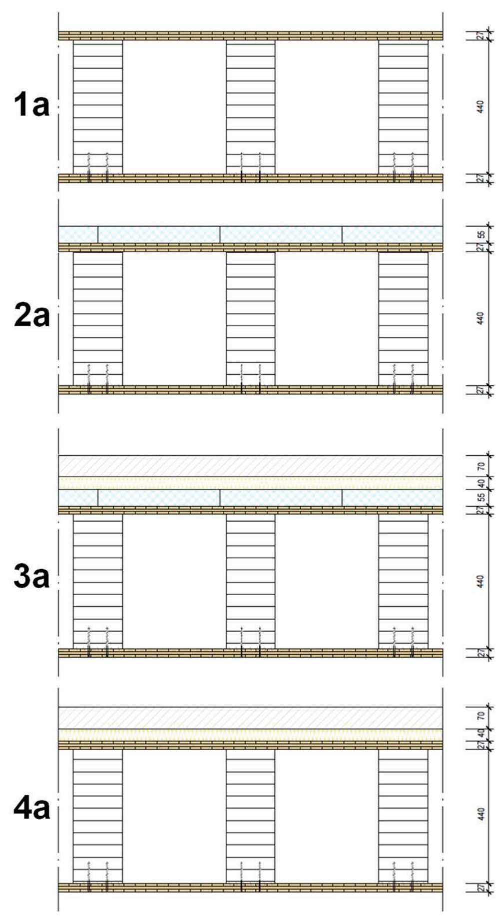

Figure 13: Different constructions on the floor. Type 1a to 4a.

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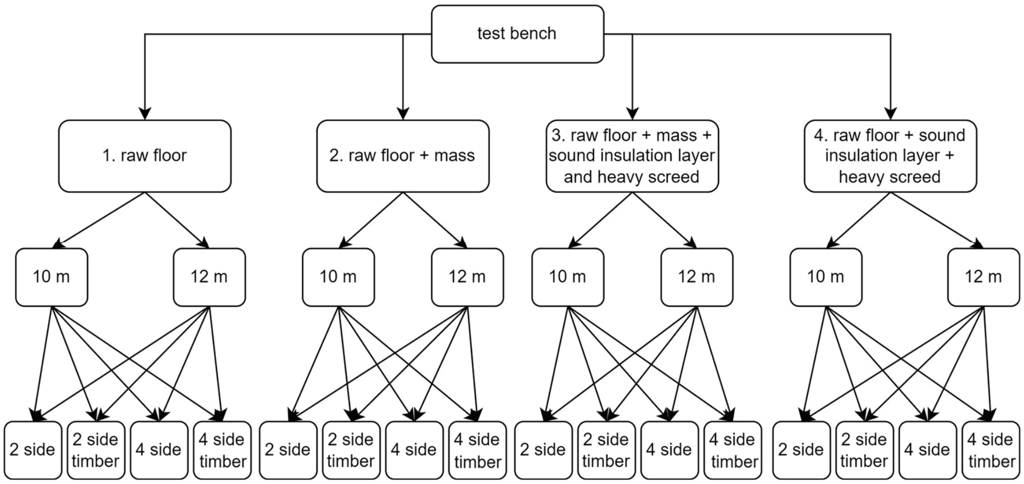

Figure 14: *Modifications in construction, spans and bearings.*

5.2 MODIFICATION IN SPAN AND BEARINGS

By using the test bench, the span could be varied. Spans from 8 m to 12 m were tested.
Another feature was to modify the bearing situation:

- stiff bearings (walls) on two sides
- stiff bearings (walls) on four sides
- elastic bearing (timber beam with two different widths) replacing one stiff bearing
- elastic bearing (steel beam)

Figure 14 shows the tested combinations.

5.3 EXCITATION

The following methods were used to excite the structure:

- heeldrop, to measure the natural frequencies, damping and velocity (see figure 15)
- a person walking around, to simulate the user and measure the velocity (v_rms)
- a group of people walking around
- walking or running in resonance in the centre of the structure, to measure the acceleration
- using a shaker, to have a defined excitation (see figure 16)

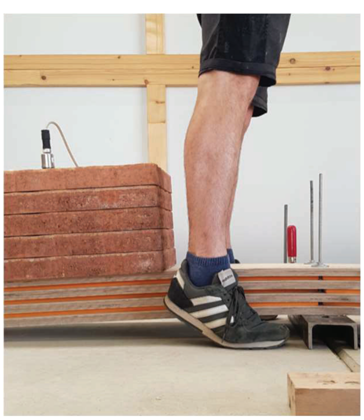

Figure 15: *Person doing a heeldrop.*

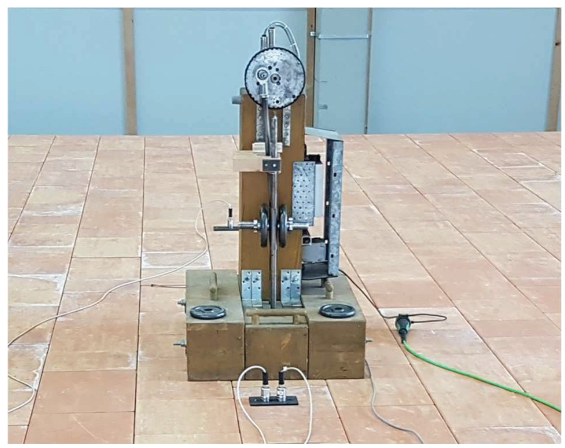

Figure 16: *Mechanical shaker placed on the floor, type 2b.*

5.4 MEASUREMENT DEVICE

The measuring equipment consists of

- 8 accelerometers (MMF Accelerometer KF48C)
- measuring amplifier (MMF Charge Amplifier M68D1 Ver. C)
- measurement card (Geitmann Siconn USB2-basic),

see figure 17.

The measurement, control and simulation tasks were carried out with the software DASYLab 2013.

Figure 17: *Measuring amplifier, accelerometers and measurement card.*

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5.5 SUBJECTIVE EVALUATION

One of the most important points is the subjective evaluation of the floor vibration. The floor was evaluated by the test takers Johannes Ruf and Valentin Knöpfle, always in coordination with the other authors. Sometimes groups of students or other interested people visited the test bench. They were asked to evaluate the vibration behaviour, too. The used marks follow the research report [2] and Kreuzinger/Mohr [7]: Rate 1 (no vibration problem) to rate 4 (heavy vibration problem).

6 RESULTS OF MEASUREMENT

The combination of different types of construction and bearing conditions leads to many measurement situations.

Table 2: *Overview of combinations, frequency, damping ratio.*

construction	span [m]	bearings	elastic beam	measured frequency [Hz]	damping ratio incl. person [%]	v_rms [mm/s]
1a	9	2 side	steel	5,4	1,0	2,11
1a	10	4 side		9,3	1,7	1,00
1a	10	4 side	timber	7,5	1,3	1,24
1a	10	2 side		9,1	1,3	1,40
1a	10	2 side	timber	7,4	1,4	1,20
1a	12	4 side		7,2	1,4	1,48
1a	12	4 side	timber	6,1	1,6	1,21
1a	12	2 side	timber	6,0	2,4	1,38
2a	10	4 side		7,2	1,2	1,51
2a	10	4 side	timber	5,7	1,6	1,03
2a	10	2 side		7,0	1,1	2,33
2a	10	2 side	timber	5,5	1,3	1,18
2a	12	4 side		5,3	1,4	2,43
2a	12	2 side		5,1	1,1	2,13
2a	12	2 side	timber	4,4	1,3	1,20
2a	12	2 side	steel	4,0	1,0	1,35
3a	10	4 side		6,2	1,8	0,61
3a	10	4 side	timber	4,9	1,8	0,90
3a	10	2 side		5,8	1,7	0,49
3a	10	2 side	timber	4,8	1,7	0,60
3a	10	2 side	steel	4,1	1,3	0,64
3a	12	4 side		4,6	2,2	0,54
3a	12	4 side	timber	4,1	1,8	0,48
3a	12	2 side		4,4	1,7	0,51
3a	12	2 side	timber	3,9	1,6	0,50
4a	10	4 side		6,8	1,9	1,37
4a	10	4 side	timber	5,2	1,9	2,20
4a	10	2 side		6,6	1,6	1,03
4a	10	2 side	timber	5,2	1,7	2,01
4a	12	4 side		5,2	1,7	2,54
4a	12	4 side	timber	4,3	1,7	0,75
4a	12	2 side		4,9	1,4	1,15
4a	12	2 side	timber	4,2	1,5	0,61

6.1 FREQUENCY, DAMPING, VELOCITY

Table 2 shows some of the combinations, the natural frequency of the first vibration mode, the damping ratio and the velocity v_rms. This v_rms value is measured due to one walking person. It is the average of several steps.

The natural frequency is clearly influenced by the mass of the construction, the span and the elastic bearings.

The damping ratio is measured during the decay curve after excitation in resonance. The measured values are mostly smaller than 2%. Usually, damping ratios for timber floors are taken from [1], [2] or [3] as

- 2% for joisted floors
- 2,5% for rib type floors (type 1a or 1b)
- 3 % for joisted floors with a floating floor layer (type 3 or 4)

As a main result, it can be mentioned that the vibrations are perceptible and sometimes annoying, in spite of the great mass of the test bench (50 – 60 to). One of the reasons may be found in the small damping ratio. Therefore, the possibility to instal tuned mass dampers will be examined.

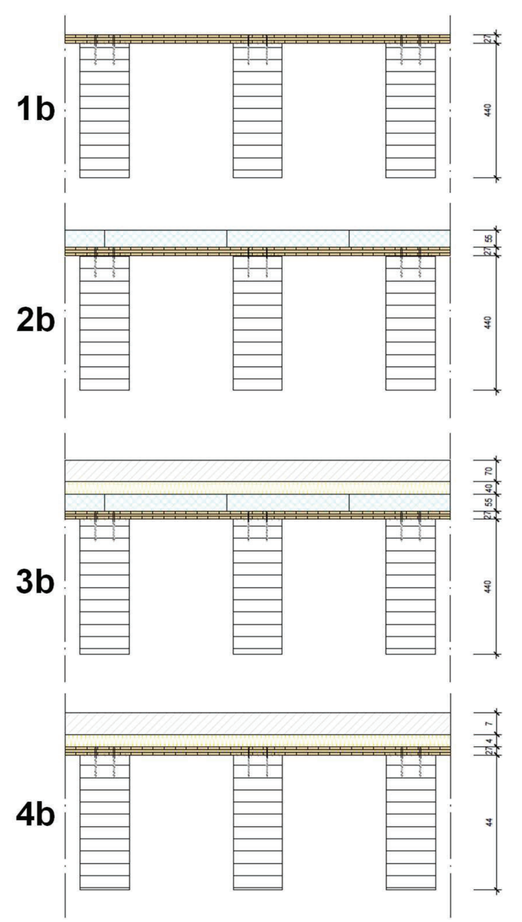

Figure 18: *Different constructions on the floor. Type 1b to 4b.*

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6.2 MODIFIED CONSTRUCTION

In addition to the modifications in construction (type 1a to 4a) one of the three-layer panels was removed. This led to the following modifications type 1b to 4b shown in figure 18. Table 3 shows the results of the measurements and a comparison of the damping ratio including a person standing on the floor and no person on the floor. In this case the floor was excited by the shaker.

Comparing table 2 and table 3, one can see the influence of the second three-layer panel on the natural frequency. The construction with one three-layer panel only is less stiff. This results in reduced values of natural frequencies.

Table 3: *Overview of combinations, frequency and damping.*

construction	span [m]	bearings	elastic beam	frequency [Hz] measurement	damping ratio incl. person [%]	damping ratio without person [%]	v_rms [mm/s]
1b	12	2 side		6,20	1,9%		
2b	12	2 side		4,56	1,2%		2,62
3b	12	2 side		4,20	1,5%		0,73
3b	12	4 side		4,0	1,8%	1,3%	0,73
3b	12	4 side	timber	3,6	1,7%	1,2%	1,14
3b	12	2 side		4,0	1,6%	1,2%	0,69
3b	12	2 side	timber	3,6	1,6%	1,2%	1,48

From table 3 one can see the influence of the exciting person on the damping ratio: the damping ratio with one person standing on the floor is always higher.

7 CALCULATIONS WITH FINITE ELEMENT METHOD

To transfer the measurement results to calculations of future long span timber floors, it must be ensured that the measured values agree with the calculation. This was done with the help of a FE model (see figures 19 and 20). The model was built up step by step, analogue to the test bench. By this all the individual conditions like E-modulus, mass etc. could be taken into account.

The modelling was done with the program "Mechanical APDL" of the company "Ansys Inc.". The advantage of this program is that data can be entered using the company's own script language. This ensures that the parameters entered are used and not standardizes parameters from a database. At the same time, automation is possible without major effort. All parameters used are stored as variables and linked to each other. When a parameter is changed, most of the values adapt immediately.

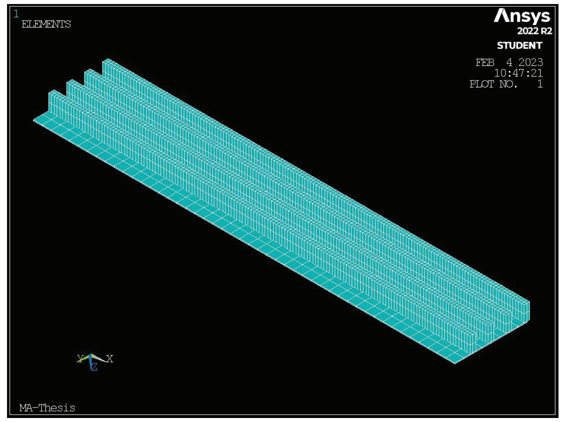

Figure 19: *One element for the step by step construction.*

In order to be able to transfer the subjective behaviour of people to other long span timber floors, the prevailing computational values must be known, at which the sensation of the persons was examined. By calibrating the model based on the measurement results, realistic predictions of new situation are possible through the model.

Table 4: *Comparison measured and calculated frequencies, first 3 modes.*

Construction	measured frequencies [Hz]			calculated frequencies [Hz]		
	mode 1	mode 2	mode 3	mode 1	mode 2	mode 3
one beam	7,32	-	-	7,32	-	-
one element	6,85	14,45	19,42	6,79	14,45	19,44
raw floor type 1b	6,20	7,43	8,62	6,24	7,43	8,65
type 2b	4,56	5,23	6,15	4,07	5,04	5,75
type 3b	4,20	4,95	5,09	4,35	4,64	5,20

It was shown that a simulation of the structural behaviour by using FE models, especially under special boundary conditions, can be carried out very accurately (see table 4). In the first step, the calibration was performed on the natural frequencies (see figure 19). However, to use this model for an assessment of the vibrations of timber floors, further investigations are necessary. For example, the velocities and accelerations due to walking and running persons will be considered, too.

Nevertheless, it is subsequently possible to determine the vibrations behaviour of the timber floor in the model without the need for costly on-site construction or modification of the floor and to subsequently investigate this behaviour by measurements. For detailed information on the FE model and the calibration see [8].

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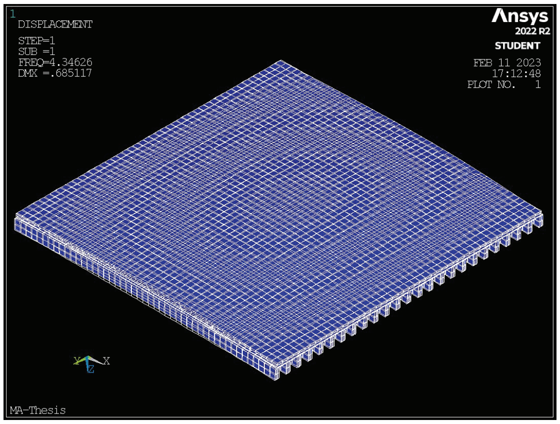

Figure 20: *Finite element model showing the first mode.*

8 RESULTS AND OUTLOOK

The result will be an extended design concept for long span timber floors. As the evaluation of measurement data and further measurements are going on, the concept will be presented during the oral presentation in Oslo.
As an outlook it can be stated that long span timber floors are likely to vibrate in spite of their great mass. The possibility to instal tuned mass dampers will be examined.

CONCLUSIONS: ZIM Research Project Pirmin Jung – Biberach University

A ZIM research project is being carried out in cooperation with Pirmin Jung Deutschland GmbH and the Institute for Timber Construction at Biberach University of Applied Sciences. It is precisely these wide-span floors that are being examined.
The aim of the research project is to develop a standardized and vibration-minimizing design system for wooden floors with beams and large spans of more than 8 m - based on theoretical and practical considerations.
For this purpose, a test stand for a timber floor with approx. 12.5 m x 12.5 m is set up, which is constantly being rebuilt. As a result, the cooperation partners have received important input for new design rules for very large timber floor systems.

ACKNOWLEDGEMENT

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