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Initial Results of the Research Project Sound and Vibration Protection for Long Span Timber Floors

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ABSTRACT

Long-span timber floors are usually designed with regard to the permissible deflection and/or position of the first natural frequency due to the serviceability requirements. Increasing the mass of the construction is often required to ensure sufficient impact sound insulation. In this research project, sound insulation and vibration measurements are carried out on floors, both during construction (without floating floors) and after completion. The focus is on the low-frequency airborne and impact sound transmission of the ceilings. In addition to classic building acoustics measurements, the influence of boundary conditions on the eigenmodes is to be clarified with the help of modal analyses of the floors. Inital results of the research project are reported here.

Keywords: *long-span timber floors, low frequencies, sound transmission, mode shapes.*

1. INTRODUCTION

Aesthetically designed and ecologically sustainable buildings are increasingly in demand. This requires the selection of construction methods and materials that are orientated towards these and future needs. Looking at CO_2 emissions in Germany, for example, the construction sector is responsible for a large percentage of these emissions. In order to reduce these CO_2 emissions, sustainable alternatives to CO_2 and energy-intensive building materials are being sought in the construction sector. Timber buildings are a viable solution due to their lower environmental impact. Lightweight construction has many positive aspects such as lighter foundations, lower transportation weight, storage of CO_2, etc., but other aspects such as the vibration behaviour of timber floors and sound insulation must also be considered. It is therefore essential to investigate the vibration behaviour and sound insulation in the low-frequency range of long-span floors in more detail.

2. PROJECT PRESENTATION

The "SchwallBe" project aims to investigate the vibration and sound behaviour of long-span timber and timber-concrete composite floors (TCC). The aim of the project is to refine the design methodology for the assessment of vibrations in long-span timber floors. Empirical studies have repeatedly shown that wooden floors exhibit better vibration properties under real conditions than predicted by calculations. This study deals with the analysis of constructed buildings to determine their actual vibration and sound insulation behaviour. In particular, it is investigated whether the measured first resonance frequency is higher in practice than expected by calculation using the existing prediction method due to boundary conditions.

This research project is a co-operation between Biberach University of Applied Sciences (HBC) and Stuttgart University of Applied Sciences (HFT). In Biberach, the main focus is on the design methodology for the evaluation of vibrations in long span wooden floors, while in Stuttgart the acoustic properties are being investigated, particularly in the low-frequency range. The project runs from May 2024 to December 2026. The analysed floors are mainly located in Germany, Switzerland and Austria. The research project is an EFRE project and is financially supported by the European Union and the state of Baden-Württemberg. This article only refers to the area of acoustics.

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3. TASK IN BUILDING ACOUSTICS

The requirements for airborne and impact sound insulation are specified in building regulations in DIN 4109-1 [1]. The weighted apparent building sound reduction index R'_w and the weighted apparent normalized impact sound pressure level $L'_{n,w}$ are the characteristic requirement values. These values cover the building acoustics frequency range of 100 Hz - 3150 Hz. There are no requirements for frequencies below 100 Hz (hereinafter referred to as "low frequencies"). However, studies (e.g. Holzbauhandbuch [2]) show that the subjective perception or the level of annoyance caused by the impact sound level of people walking does not correspond particularly well with the weighted standard impact sound pressure level. However, if the spectrum adaptaion term $C_{I,50\text{-}2500}$ is considered, there is a good correlation between the measured value, the impact sound level of the person walking and the subjectively perceived annoyance of the impact sound. In Germany, the proof of sound insulation required by building regulations is provided by calculation in accordance with DIN 4109-2 [3] with single-number quantities (SNQ) without taking the low frequencies into account.

As part of this research project, measurement data for airborne and impact sound insulation is to be determined for buildings with long-span timber floors. In particular, the frequencies in the frequency range between 20 Hz and 200 Hz are to be analysed separately, as very little data is currently available for this frequency range. In addition to the influence of the supporting structure (mass timber, timber-concrete composite, ribbed floors, etc.), the influence of mass per unit area, the influence of the resonance frequency of the screed and a possible influence of the support conditions on sound transmission in the low frequency range will be analysed.

4. MEASUREMENT PROCEDURES

Measurements are carried out both after construction of the supporting structure (timber floor) and after completion of the building (occupied). Measurements of the airborne and impact sound reduction in the receiving room are not possible before the building is finished, as the transmission via the door openings determines the overall transmission. However, by means of structure-borne sound measurements on the bare floor, it is possible to determine the velocity levels when excited with the standardised ISO tapping machine or with the ISO rubber ball. These measured values can then be used to estimate SNQs according to ISO 717-2: the weighted apparent normalized impact sound pressure level when excited with the tapping machine or the maximum level when the floor is excited with the rubber ball.

The airborne and impact sound insulation in the completed buildings is carried out in accordance with DIN EN ISO 16283-1 [4] and -2 [5]. The frequency range is extended to low frequencies of up to 20 Hz. For the airborne sound measurements, a subwoofer is used in addition to the usual dodecahedron to excite the low frequencies.

Binaural recordings are also made in the receiving room when walking on the floors, as well as during excitation with the standard tapping machine and the rubber ball. An evaluation of these measurements with regard to annoyance is planned.

5. ANALYSED BUILDINGS

5.1 Building description

The long-span timber floors with spans of over 7 metres are mainly found in school buildings as well as in office and workshop buildings. Spans of over 7 metres have not yet been investigated in residential buildings. The measured values are compared with the sound insulation requirements for classrooms and office buildings. In Germany and some other European countries, the apparent weighted sound insulation index R'_w or the weighted normalized impact sound pressure level $L'_{n,w}$ are used as SNQs. In Switzerland and other countries, reverberation time related parameters: the weighted standardized sound level difference $D_{nT,w}$ or the weighted apparent standardized impact sound pressure level $L'_{nT,w}$ are used as the required quantities.

The floor constructions analysed are mainly mass timber floors (with bulk filler), timber-concrete composite floors, timber beam floors, modular floors, etc.. Some of the measurements are carried out on the bare floor, while others are carried out on floors with a heavy screed.

5.2 Results of the analysed floors with airborne and impact sound measurements

The following Table 1 shows the component description and measured SNQ of the floors where airborne and impact sound measurements were carried out.

Table 1. Component description and determined weighted apparent sound reduction indices and weighted apparent impact sound pressure levels of the floors.

Nr.	Construction	R'_w dB	L'_{nw} dB	$L'_{nw} + C_{150\text{-}2500}$ dB	$L'_{nT,w}$ dB
D204	5 mm Linoleum flooring 60 mm cement screed 30 mm impact sound insulation board 60 mm Liapor weighting (20 kg/m²) 120 mm cross-laminated timber floor with glulam beams	52 53	61 61	62 62	54 54
D306	2 mm linoleum covering with 3 mm levelling adhesive 74 mm calcium sulphate flowing screed 22/20 mm impact sound insulation board 10 mm EPS insulation 30 mm calcium sulphate board 190 mm hollow floor system 120 mm concrete topping 200 mm glulam timber C24, partly as acoustic element	60 59	48 52	49 52	40 44
D205	5 mm linoleum flooring on 40 mm dry screed 22/20 mm impact sound insulation board 60 mm bulk filler 90 mm modular floor CLT plate 3-layer 50 mm mineral fibre boards 120 mm modular ceiling CLT plate 5-layer	57 55	55 56	58 58	48 48
D101	10 mm carpet floor covering 40 mm raised floor panel 600 mm x 600 mm 80 mm cavity floor with system floor supports 5 mm PU insulation boards 30 mm GF carrier board, 2-ply 30 mm impact sound insulation board 60 mm honeycomb fill 300 mm cross-laminated timber floor	52	45	53	42
D102	15 mm parquet flooring 70 mm cement screed 30 mm impact sound insulation 60 mm chippings fill 280 mm CLT	60	48	53	41
D203	7 mm linoleum flooring 70 mm cement screed 30 mm impact sound insulation 80 mm glulam board 60 mm chippings fill 400 mm glulam timber	66	56	60	48

5.3 Detailed Results for floor #D204

Construction measurement D204 is presented below as an example. This school building is a timber construction, with the separating floors consisting of timber beams with cross laminated timber (CLT) and floating screed, the exterior walls of timber stud walls and the interior walls of metal stud walls with plasterboard.

DIN 4109-1 specifies the following minimum requirements for the airborne sound insulation of floors between classrooms for schools: weighted apparent sound reduction index $R'_w \geq 55$ dB, weighted normalized impact sound pressure level $L'_{n,w} \leq 53$ dB. The floor construction has a span of 7.5 m, with CLT-elements with a thickness of 120 mm laid on glulam beams (spacing of 3000 mm). A bulk filler of 90 kg/m² was planned on these. However, at the insistence of the building contractors, a lighter bulk filler

with only 20 kg/m² was used. The floating screed with 60 mm was applied on an insulation layer with s' = 16 MN/m³. The floor covering (5 mm linoleum) was also present in the measurement. The measurements were carried out in two pairs of classrooms of different sizes, one above the other. Figure 1 shows the frequency curve of the sound reduction index for one measurement. Here the drop in the sound reduction curve at 125 Hz is presumably caused by the mass-spring-mass resonance of the floating screed. R'_w = 52 dB / 53 dB are determined as SNQs for the weighted apparent sound reduction index.
This means that the required values are not achieved. The weighted apparent normalized impact sound pressure level of $L'_{n,w}$ = 61 dB measured in both pairs of rooms also does not fulfill the minimum requirement of DIN 4109-1. For the maximum A-weighted impact sound level $L'_{iA,Fmax}$ when excited with a rubber ball in accordance with DIN EN ISO 16283-2, measured values of $L'_{iA,Fmax,50\ -\ 630\ Hz}$ = 47 and 52 dB are determined. Due to the low surface mass of the mass timber floor in combination with the reduced mass of the fill, the available data results in a resonance frequency of approx. 100 Hz with relatively high impact sound levels in the frequency range from 100 Hz to 500 Hz.

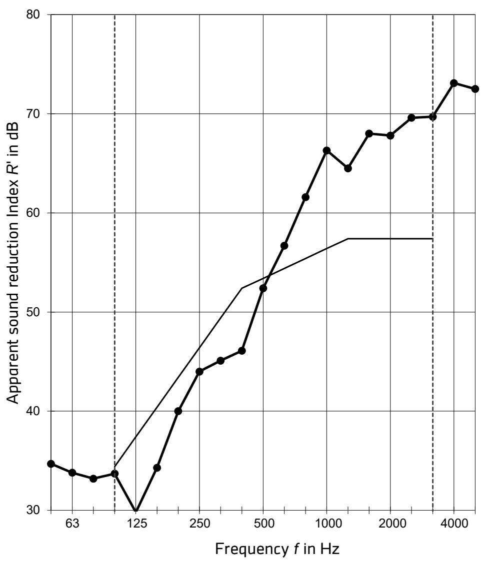


Figure 1. Measured sound reduction index of the analysed floor construction D204.

The following figure 2 shows the measured impact sound pressure level by the tapping machine and the maximum sound pressure level due to the impact of the rubber ball for two different floors in the building.

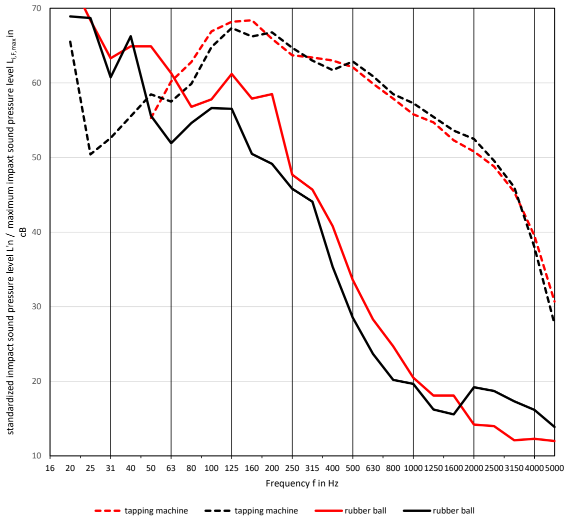


Figure 2. Measured sound pressure level due to excitation by tapping machine (solid lines) and rubber ball (dashed lines).

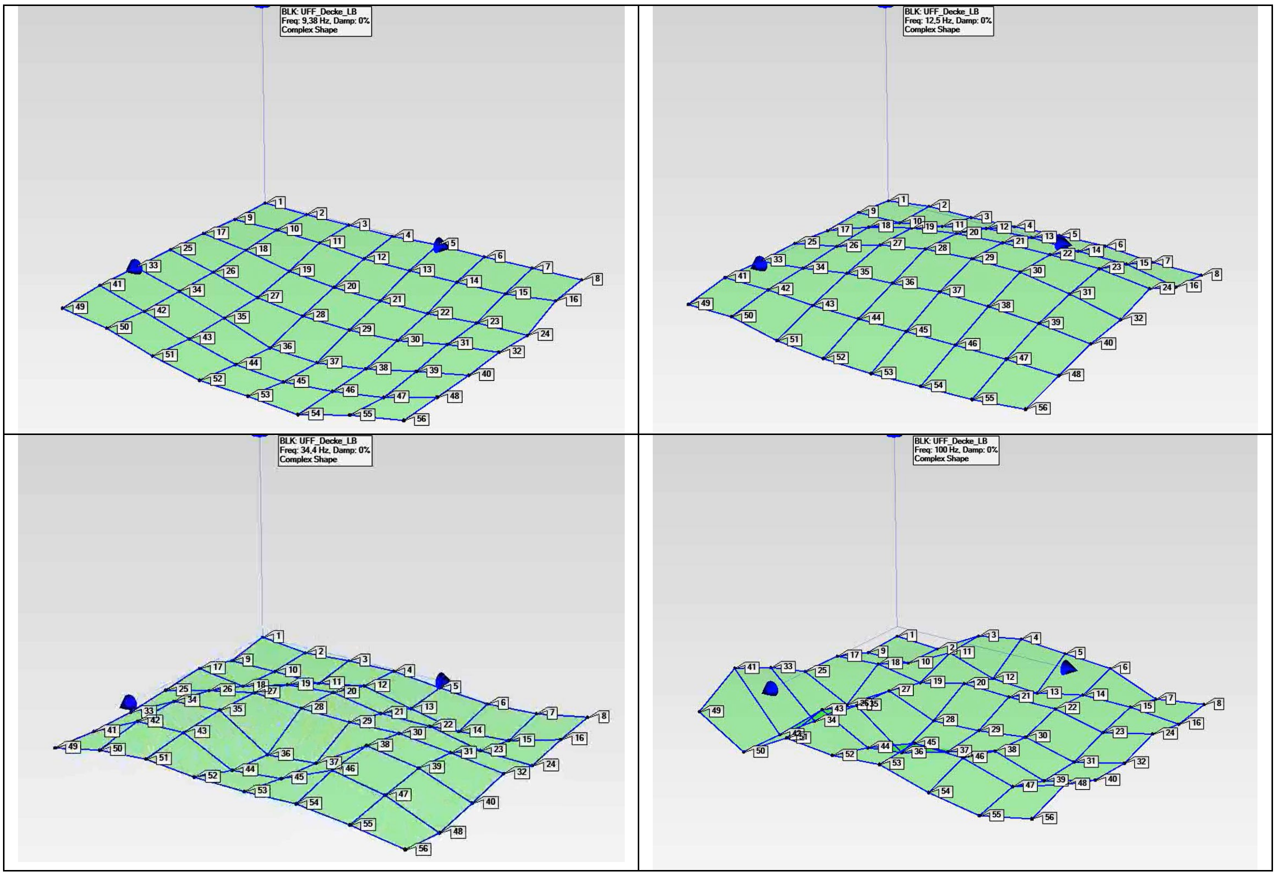
In the frequency curves from the measurements, at 125 Hz a local maximum can be recognised for both excitation with the tapping machine and with the rubber ball. However, while the level decreases towards lower frequencies with the hammer excitation, the level continues to increase towards lower frequencies with the rubber ball. The relatively large reverberation time correction of the measured impact sound level is particularly striking. With a room volume of approx. 200 m³ and a reverberation time of T = 0.5 s, which is common in classrooms today, a correction of 7.5 dB results due to the reference to an equivalent absorption area of A_0 = 10 m². This correction results in a very high weighted apparent normalized impact sound pressure level of $L'_{n,w}$ = 61 dB (weighted apparent standardized impact sound level $L'_{nT,w}$ = 54 dB).
Although the minimum requirements stipulated by the building authorities are clearly not met, the teaching staff rated the sound insulation as very good. Presumably, particularly in primary schools, the background noise levels present during lessons are higher than the impact noise from the classrooms above.

5.4 Modal Analysis

In addition to the building acoustics measurements, measurements of the vibration modes are also carried out on this object. Furthermore, the natural vibrations and eigenmodes of the solid floor are measured in selected buildings with the reciprocal roving hammer technique. The force F is measured using an impulse hammer, which is used to excite corresponding points in a fixed grid. The acceleration is measured at a point slightly outside the center of the field. The transfer function acceleration/force is formed for each of the measuring points from the force applied and the resulting acceleration. Using the modal analysis software ME'scope, the vibrations are analysed, the first natural frequencies of the floor are determined and the corresponding vibration images are created. Due to the rough grid, it is only possible to visualise the first natural vibration modes. Even at a frequency of approx. 50 Hz, it is usually no longer possible to clearly recognize the vibration patterns of the floor.

The transfer function for the floor #D204 is determined in a grid of 1 m x 1 m at 56 points on one half of the floor (but over the entire span direction). The following Table 2 shows the maximum acceleration at different resonance frequencies.

Table 2. Measured maximum deflection of the analysed half of the floor for f = 9.4 Hz (top left) f = 12.5 Hz (top right), 34.4 Hz (bottom left) f = 100 Hz (bottom right).



The first natural frequency of the floor at 9.4 Hz is clearly recognisable and distinct in Table 2 (top left half ceiling). The second natural frequency shows a pronounced oscillation transverse to the direction of tension. Moving to higher frequencies and higher mode orders, it becomes increasingly difficult to identify the individual modes. At significantly higher frequencies (f = 100 Hz Table 2 bottom right), the modes can no longer be identified. However, it can be seen that the edges in particular experience a large acceleration. This is due to the fact that the screed slab is now decoupled from the floor slab because of the mass-spring-mass resonance. As the edges of the screed are free, they show a relatively large acceleration in the area of the resonance frequency and above, in contrast to the edges of the bare floor.

6. CALCULATION OF THE SOUND INSULATION OF TIMBER FLOORS

In Germany, airborne and impact sound insulation is verified in accordance with DIN 4109-2. However, there is currently no calculation method for calculating the direct airborne and impact sound insulation of timber floors. It is still unclear to what extent findings from solid construction can be transferred to timber construction e.g. dependence of the equivalent standard impact sound level on the mass per unit area, impact sound reduction of screeds can be described by resonance frequency. Furthermore, there are major differences between elementised load-bearing structures such as beam or ribbed floors and more homogenised structures such as timber-concrete composite floors. Here, reference is made to table values in the component catalogue for timber and lightweight construction (DIN 4109-33 [6]) or in other publications such as "Holzbauhandbuch" [2]. These table values come from laboratory measurements in accordance with ISO 10140, whereby the dimensions of the floors in the laboratories are generally only 4 - 5 metres. It is unclear to what extent this measurement data can be transferred to floors with spans of over 7 meters.
Due to the large number of new load-bearing structures (modular floors, timber-concrete composite elements on glulam beams, timber beam or timber ribbed floors, etc.) and different additional layers to the load-bearing structure (suspended ceilings, floating screeds, suspended or acoustic ceilings), it is usually difficult, if not impossible, to calculate or estimate the expected sound insulation from the values in the standard. Planners then rely on their experience or plan appropriate safety measures, usually in conjunction with an increased use of materials.
The modal analyses carried out can be used to visualise the vibration pattern of the floors. Particularly in the edge areas of the floor, it is then possible to draw conclusions about the boundary condition (hinged or nevertheless restrained to a certain extent). Initial results show, on the one hand, large deflections in mass timber floors in the area of the panel joints and, on the other hand, an influence of non-load-bearing partition walls on the vibration behaviour. An additional evaluation with the determined transfer functions with regard to the boundary conditions is planned here, as has already been successfully carried out with a bending beam [7].

7. SUMMARY

In the project described, the sound and vibration properties of long-span timber floors were and are still being measured in realised buildings. When possible, these properties are compared with mathematical approaches and the results of verification procedures. The first results of the vibration analyses will be presented at the WCTE 2025 (World Conference on Timber Engineering) in Brisbane [8]. The first results regarding the sound insulation of the analysed floor constructions are presented here. Most of the tested floors meet or even highly exceed the minimum requirements for airborne sound insulation. However, in one case, the requirements are not achieved due to the incorrectly carried out back filler, in another case due to the cavity floor used.
A different picture emerges for impact sound insulation. Here, many floors don't come close to meeting the minimum requirements. The reason for this is actually that the single number quantity, $L'_{nw,}$ prescribed in the DIN 4109 is not suited for large class rooms. It normalises to a reference absorption area of 10 m², which is much higher for the investigated and most class rooms. It should be replaced by the standardized impact sound level $L'_{nT,w}$, which is normalised toT = 0.5 s reverberation time common in class rooms.
With the visualisation of the vibration shapes using modal analysis, it was possible to clarify the initial effects with regard to the boundary conditions. Further measurements still to be carried out will provide the basis for calculating the acoustic properties in the low frequency range.

8. ACKNOWLEDGMENTS

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