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ECOLOGICALLY MOTIVATED APPROACHES FOR IMPROVING LOW-FREQUENCY SOUND AND VIBRATION PERFORMANCE IN MULTISTORY TIMBER BUILDINGS

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ABSTRACT

In order to use the potential of the natural resource wood for sustainable and resource-efficient buildings, timber constructions have to address various requirements, such as those from architecture, structural design and building physics. While most of the requirements for use can be met, the suboptimal sound transmission and vibration behavior in the low-frequency range is a weakness from an acoustic point of view. Conventional improvement measures consist of a large number of complex systems that result, for example, from the use of various materials in the form of mineral filling or additional concrete weights. The resulting combination of materials affects the environmental performance of the structures.
In order to achieve the contemporary demand regarding the ecological quality of buildings, constructions have to be developed, planned and executed reasonably from both an acoustic and an ecological point of view, in addition to structural design. This paper presents integrative acoustic solutions, enabling wood-based constructions to be realized that reduce low-frequency impact sound transmission and improve the overall vibration behavior.

Keywords: *timber construction, sustainable construction, wood-based acoustic design, building acoustics, vibration behavior*

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1. INTRODUCTION

Timber has been used as a building material for centuries, but advances in technology and construction have led to a resurgence in its popularity in recent years. As a natural and renewable resource, its use offers a sustainable and environmentally friendly alternative to traditional building materials, also with regard to multi-story buildings. [1–3]

The acoustic quality at low frequencies in multi-story timber buildings is challenging due to the unique properties of timber as a building material. Timber is a porous material and has lower density and stiffness than other building materials such as concrete, masonry or steel. These characteristics result in lower sound reduction at low frequencies, which can lead to sound transmission problems and noise disturbances resulting in impairing user comfort [4, 3].

The propagated low-frequency sound is mostly resulting from impact sound. To address this issue, several design strategies are used to enhance the acoustic quality of timber buildings. Typically, acoustic improvements are achieved through the addition of mass elements and layered structures. These structures may include the incorporation of mineral materials like gravel, concrete, and mineral wool, which are used to create mass-loaded floor constructions and suspended ceilings. These approaches derive from experience with solid construction to date. Furthermore, this generates a correlation between the acoustic behavior of ceiling constructions and the environmental profile of the entire system [3].

In addition, there is a lack of suitable digital design tools that support the achievement of sound insulation requirements already at an early state in the overarching design process. Digital methods of interdisciplinary planning between the fields of architecture, civil engineering, engineering geodesy, production, etc. (co-design) are available but are not yet sufficiently established and coordinated to ensure the necessary integration and sustainability regarding design, fabrication and construction [5]. However, in terms of acoustics and dynamics, the co-design methodology offers the possibility to consider the dynamic load-bearing behavior early in the design process. In combination with structural design, innovative designs and solution concepts can be realized in the interdisciplinary planning process that consider the entire vibration behavior from both an acoustic and a structural point of view [6].

Such approaches are being investigated within the framework of the Cluster of Excellence IntCDC (Integrative Computational Design and Construction for Architecture) [7] at the University of Stuttgart in Germany. The creation of sustainable timber building architecture is one of the core objectives, pursuing the development and realization of resource-efficient structures in an interdisciplinary process (co-design). In order to achieve this, digital technologies are essential to fully exploit the potential of integrative and multidisciplinary building design. [5]

2. CONCEPTS FOR VIBRATION DAMPING AND INTEGRATIVE SOUND DECOUPLING

The acoustic performance of timber ceiling constructions in terms of impact sound transmission and vibration behavior is considered in practice as a subsequent step to structural design. As a result, timber ceiling systems are supplemented by mass-loaded layers. In addition to increasing the cross-section, this also results in an increase in weight. Furthermore, such improvement measures represent suboptimal solutions, since they do not show any improvement in impact sound transmission in the relevant low-frequency range [3]. For a specific improvement of the sound transmission behavior, it is necessary to analyze the frequency-dependent characteristics of the structures in exchange with the global statics of the system.

The work presented in this article constitutes interim results of research conducted within the Cluster of Excellence IntCDC to improve low-frequency sound transmission and vibration behavior of timber ceiling constructions.

2.1 Vibration damping by tuned mass damper elements

Achieving and realizing large spans of up to 11.0 m is a challenge in timber construction, especially from a structural engineering point of view related to serviceability. The normative requirements specify that the first natural frequency should be above 8 Hz [8]. However, the acoustic performance of timber ceiling systems and the perception of users is affected by the eigenfrequencies in the range of 50 to 100 Hz. Both the deformation-related and acoustically relevant types of vibrations should be damped or modified to occur outside the ranges perceived by users. The use of tuned passive timber dampers to influence the eigenfrequencies of timber ceilings in the range of 50 Hz to 100 Hz is part of the investigation in the research project. For this, the analytical approach with Simcenter 3D [9] as digital design tool was used in a first step.

The ongoing research to date has shown that tuned absorbers can improve the vibration behavior of (timber) ceiling systems [6]. For this purpose, a timber plate was examined for its vibration behavior using the modal analysis methodology. This method allows for the determination of fundamental acoustic characteristics, including the eigenfrequencies and corresponding modes of vibration. The slab had the dimensions of 4 x 5 m and was punctually supported with a distance to the edge of the slab of 600 mm on each side. The material is assumed to be a 5-ply cross-laminated timber (CLT) panel with 40 mm thick plies, giving a total panel thickness of 200 mm. The material parameters for softwood (spruce, C24) according to [10] are used for the investigation. [11]

To evaluate the effect of an additional mass as a tuned damper on the system, an eigenfrequency in the acoustically relevant range between 50 Hz and 100 Hz is initially selected. The 9th eigenfrequency at 69 Hz, calculated with Simcenter 3D, is set as the target value for damping. This is based on the characteristic mode in this range also having a deflection in the center of the plate. The oscillation is forced by a dynamic excitation with a frequency of 2 Hz and the load value of 2 kN.

For the damping of the slab system, an additional mass-spring system is added. In this context, it is important to ensure that the mass ratio μ of the absorber to the undamped ceiling system is between 0.020 and 0.067 [12]. This leads to a mass of 40 kg and a spring stiffness of 9338.4 kN/m, calculated according to [12] and [13].

Figure 1 shows the simulated results obtained from the case study on vibration damping by a tuned vibration damper. The results in the diagram refer to the transfer functions evaluated at the local position in the middle of the system. It can be seen that the application of additional mass changes the response of the structure. This is proven by the shift in the peak values of the mass-spring system curve. Especially at the frequency of 69 Hz chosen for damping, the tuning of the damping elements becomes apparent. In contrast, the curves in the lower frequency ranges at around 20 Hz and 35 Hz are almost aligned. This is because the damper elements have not been tuned to this range and are therefore inactive.

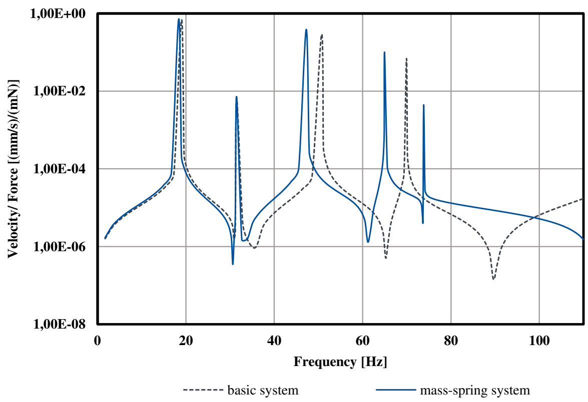

Figure 1. Simulative evaluated transfer function of a punctually supported timber slab with and without tuned mass damping element

As the project progresses, consideration will also be given to the contextual parameters for the structural design. By using absorbers with different tuning configurations, multiple frequencies can be targeted within the ceiling system, allowing synergies between vibration solutions for both acoustic and structural design aspects. In addition, measurements are planned to validate the simulations and evaluate the effectiveness of wood-based dampers.

2.2 Integrative timber-based acoustic solution for sound decoupling

In contrast to single-shell constructions, double-shell wood ceiling constructions provide the cavity between the two shells that can be used for acoustic improvement. Common solutions achieve a reduction of structural vibrations by filling the cavity with fillings or weights usually in combination with mass-loaded build-up layers or suspended ceilings [3]. However, structurally necessary connecting elements between the shells, such as beams in timber beam construction, consequently act as acoustic bridges and must also be decoupled. Research into multiple functions for structural elements has been limited in the construction industry so far. This represents a previously unexplored opportunity to integrate sound-decoupling functionalities into ceiling systems. Achieving this goal requires a comprehensive understanding of structural behavior and force distribution within the system, as well as an interdisciplinary approach to the planning and design phases.

At IntCDC, this aspect of research, among others, is coming into focus, encompassing the integration of structural behavior and robotic manufacturing processes in the design and development of acoustic solutions. This interdisciplinary approach allows acoustic functionality to be incorporated into structural design essentials. By incorporating acoustic analysis in conjunction with global structural analysis, targeted measures can be implemented to improve sound radiation. Through the utilization of computational analysis, ceiling systems can be examined in detail with respect to their vibration behavior and the resulting effects on sound radiation. [6]

The structural timber system, which was developed in the course of this interdisciplinary project [2, 7], is distinguished from conventional timber ceiling structures by a number of special characteristics, hence innovative solutions for sound decoupling were developed. By means of column-based support and multi-directional spans of the double-shell ceiling system, a span distance of up to 11 m can be realized [2].

In order to improve the acoustic quality of the developed raw ceiling construction in the low-frequency range, targeted robotic processing (CNC milling) of the beam elements is performed. This extends their structural function to include an acoustic decoupling function by giving them a vertically acting elastic property. However, the modification preserves the transmission of shear forces in the horizontal plane. In order to achieve an improvement of the impact sound transmission behavior, according to the operating principle of a bending resonator, the spring elements are tuned to low frequencies. [6, 11, 14]

The resulting impact sound transmission in the double-shell ceiling system with beams as spring elements is shown schematically in Figure 2.

Figure 2. Schematic representation of the impact sound transmission of the double-shell ceiling element decoupled by wooden spring elements; © ICD, IABP, University of Stuttgart [6]

The eigenfrequencies were determined through the modal analysis method using Simcenter 3D software. The structure consists of a 160 mm thick slab as the bottom slab, on which 200 mm high beam or spring elements are positioned. On top of these, an 80 mm thick upper floor slab is installed. All components are constructed from cross-laminated timber (specifically softwood C24) and are bonded together. The material parameters were defined based on the provided data from source [10]. [6]

Figure 3 and Figure 4 depict the underlying operational principle as determined by modal analysis conducted with Simcenter 3D, showcasing vibration modes within the 100 Hz range. Figure 3 illustrates the expected vibration behavior of the ceiling structure using a beam structure. The system shows vibration characteristics similar to those of a single-shell structure, since the vibration modes of both shells are aligned with each other. To effectively decouple the two slabs, the spring elements were tuned to resonate at 100 Hz. The improved performance can be seen in Figure 4, where the decoupling of the top and the bottom plates can be visually seen due to the different vibration characteristics. In contrast to the top plate, the bottom plate has a smaller deflection. [6]

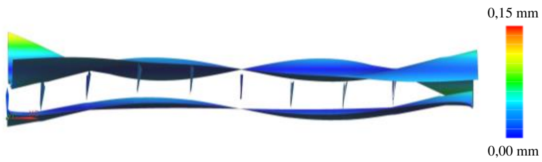

Figure 3. Eigenmode of the ceiling system with beam elements at 103 Hz calculated with Simcenter 3D [6]

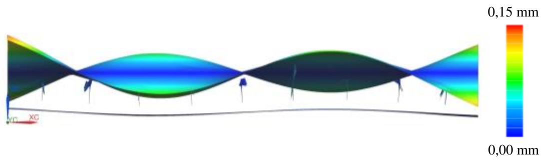

Figure 4. Eigenmode of the ceiling system with wooden spring elements at 104 Hz calculated with Simcenter 3D [6]

The principle of operation was determined by measurement on the basis of the Weighted Standard Impact Sound Level $L_{n,w}$ and the frequency weighting value C_I as a parameter for the low-frequency range according to DIN EN ISO 10140-3 [15]. The construction was realized according to the specifications for the simulation on an area of 5 x 4 m. Due to the demountability, the components were screwed together.

The results obtained from the measurements are presented in Figure 5 and Table 1. These measurements involved the evaluation of the relevant parameters for the three various ceiling configurations. The initial measurement was conducted with the lower plate only, to facilitate a comparison between double-shell and single-shell constructions made of CLT. In the next step, the ceiling structure with beam elements as well as with wooden spring elements was measured for impact sound.

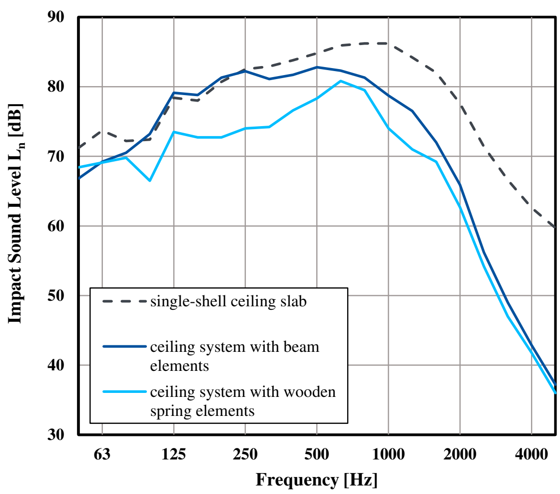

Figure 5. Measured Impact Sound Level of the three examined ceiling system configurations

Table 1. Weighted Standard Impact Sound Level with the respective Frequency Weighting Value for the investigated ceiling systems [6]

Ceiling System	Weighted Standard Impact Sound Level	Frequency Weighting Value	
	$L_{n,w}$ [dB]	$C_{I,100\text{-}2500}$ [dB]	$C_{I,50\text{-}2500}$ [dB]
Single-shell ceiling slab	85	-5	-5
ceiling system with beam elements	79	-3	-2
ceiling system with wooden spring elements	75	-3	-3

It is apparent that the impact sound behavior of the single-shell system is improved by the application of an additional second shell. However, the double-shell construction with the beams as connecting elements behaves like the single-shell system in the frequency range from 100 to 250 Hz and there is no improvement in the impact sound level that occurs in this range. This corresponds to the expectations resulting from the calculation according to Figure 3. Replacing the beam elements with wooden spring elements shows a significant improvement of the impact sound level in the frequency range below 500 Hz. Particularly at the point of the tuned frequency at about 100 Hz, the resonator effect is evident from the indentation in the curve.

The reduction of the Weighted Standard Impact Sound Level underlines the effect of decoupling. This is also apparent from the Frequency Weighting Values in Table 1. The Weighted Standard Impact Sound Level of the double-shell construction is reduced by 4 dB by replacing the beam elements with the wooden spring elements.

Currently, measurements are underway on prototypes at the Materials Testing Institute of the University of Stuttgart to establish the connections between mechanical strength and acoustic effectiveness. The aim is to enable integrative solutions to be realized in timber construction which requires a precise knowledge of the mechanical properties. In the ongoing progression of the project, the optimization of wooden spring elements in terms of geometry and acoustic effectiveness will be pursued, particularly in connection with robotic manufacturing.

3. CONCLUSION

In this article, two approaches to improve the low-frequency sound transmission and vibration behavior of timber ceiling systems are presented. The results shown indicate intermediate progress in the current research being pursued. Integrative approaches are directly related to one of the core objectives of the Cluster of Excellence IntCDC. The early consideration of the dynamic structural behavior in the interdisciplinary planning and design process enables targeted solutions that can improve the acoustic behavior of the overall system while substituting the use of mineral materials for acoustic improvement with timber.

The use of tuned vibration dampers can reduce the deflection of ceiling systems in a selective manner and attenuate particular natural vibrations. In timber construction, they affect the transmission of impact sound in the frequency range between 30 and 100 Hz. By applying differently tuned dampers, this effect can also be used in the structurally relevant frequency range below 10 Hz. Particularly in the case of systems with large spans, this can be advantageous and is subject of further investigation in the research project.

A novel integrative solution approach was presented that focuses on structure-borne sound decoupling using wooden spring elements as structural components within ceiling systems. These spring elements are precisely tuned to the vibration characteristics of the entire ceiling system and influence the sound transmission behavior in the targeted frequency range. Initial results on the examined timber ceiling constructions confirm the basic concept. The extent to which the Weighted Standard Impact Sound Level can be further reduced is the aim of ongoing investigations. Moreover, it is in the interest of the project to further develop sustainable and natural-substance-based system solutions of this kind so that they are suitable for a wide range of building typologies and also represent efficient solutions for the extension of existing buildings.

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