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CROSS LAMINATED TIMBER ELEMENTS WITH FUNCTIONAL GRADING AND LOCALISED BALLAST TO IMPROVE AIRBORNE AND IMPACT SOUND INSULATION

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ABSTRACT

All over the world, Cross-Laminated Timber (CLT) elements are commonly used in the construction of multi-storey timber buildings due to their structural strength and relatively low weight. In some countries, to meet the stringent requirements for impact sound insulation at low frequencies, a common solution is to ballast the entire surface of the CLT floor with a gravel layer before a floating floor is installed on top. Hereby, the gravel doubles or even triples the mass of the bare CLT floor, reducing its benefits. In a recent research project, indentations were machined into the CLT floor to accommodate the gravel ballast. The depth profile of the indentations was functionally graded so that the localised gravel ballast inside attenuates structure-borne sound more efficiently and hence improves the sound insulation. The achieved performance and targeted frequency range crucially depend on the geometry (size, depth, and profile) and the location of the indentations. Laboratory experiments on a small-scale CLT plate with functional grading and localised gravel ballast demonstrated an excellent vibration reduction, while the total mass of the bare CLT floor was increased by only 50% to a reference CLT plate.

Keywords: *impact noise, sound insulation, timber construction, acoustic black holes, functional grading*

1. INTRODUCTION

The usage of wood for the construction of tall buildings is increasing worldwide with the rise of new engineered timber materials, such as Cross-laminated Timber (CLT). Besides the associated ecological benefits, such as the carbon storage of wood, this development was accelerated due to the structural strength and the relative low weight of these mass timber floors in comparison to traditional building elements. However, this property limits the airborne and impact sound insulation performance, especially in the low-frequency range. Low-frequency impact sound from floors caused by people walking or children jumping was found to be a major source of annoyance amongst the occupants of buildings [1].

This is a problem in countries with either stringent sound insulation requirements or a high demand for comfort and quality, like Switzerland. Even heavy floating floor systems, which are also necessary for the installation of hydronic floor heating systems, are not very efficient in reducing the impact sound level in this frequency range due to their inherent mass-spring-mass resonance. Therefore, concrete composite floors consisting of a concrete layer bonded to a thin engineered wood floor or the addition of gravel ballast is seen as a robust solution to overcome this problem [2]. Gravel layers with a thickness of around $12\,\mathrm{cm}$ are very common in Switzerland [3], which add a load of $200\,\mathrm{kg\,m^{-2}}$ to the floor system. Hereby, the weight of the base floor is tripled. For tall wooden buildings, the additional thickness of the floor system and additional dead load, which has to be supported by the load-bearing structure, adds up to a tremendous amount of additional weight. Consider a ten-storey building with a $500\,\mathrm{m^2}$ floor area: The total thickness of the gravel bal-

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last layers of all floors would be $1.2\,\mathrm{m}$ with a total weight of $1000\,\mathrm{t}$.

In a recent research project conducted at Empa, the feasibility of reducing additional weight due to ballasting glued engineered wood floors while maintaining or improving their impact sound insulation performance was investigated. The research project focused on applying functional gradings to the floors, whereby the ballast was localised to these functional gradings. Hereby, the principle of the so-called acoustic black holes was explored for this particular application.

In the following sections, the theory of the acoustic black holes is briefly outlined, challenges for identification of appropriate design parameters are reported, and experiments with a small-scale test specimen are presented.

2. ACOUSTIC BLACK HOLES

The theory behind the Acoustic Black Holes (ABHs) was first published for the one-dimensional case of a beam with a functionally graded end in the late 1980s [4]. Since then, different designs of the ABHs have been proposed and applied [5]. The general principle remains the same for all designs and applications: A local gradual reduction of the thickness of the plate or beam that follows a power law profile causes incident flexural waves to slow down while the amplitude increases. This effect is shown in Fig. 1 for an ideal profile with infinitely thin end. In theory, the bending wave-speed approaches zero and the wave is not reflected. This effect is broadband and, therefore, well suited for reducing random broadband noise, like impact sound.

In practice, the effect also occurs to some extent for truncated ABHs with a finite residual thickness due to damping of the waves in the ABH region, see Fig. 2. The ABH effect can be further enhanced if additional patches of visco-elastic damping material are placed in the ABH [6]. For a truncated ABH the effect occurs above a cut-on frequency. This cut-on frequency depends on the ABH geometry, while the vibration reduction performance of the ABH depends on damping measures. The most relevant developments for plate structures are the two-dimensional ABHs, as in Fig. 3.

The challenge for the design of ABHs is the identification of geometrical design parameters and damping measures that are appropriate for the frequency range of interest. The ABH profile parameters are the coefficient a and exponent m that describe the power law profile

$$h(x) = h_0 + a x^m \tag{1}$$

and the size of the ABHs

$$x_r = \left(\frac{h_1 - h_0}{a}\right)^{\frac{1}{m}} . \tag{2}$$

x_r is the length in the one-dimensional case or the radius of the ABH in the two-dimensional case. Two additional design parameters are the residual thickness h_0 of the ABH, and the thickness of the plate h_1. All parameters are illustrated in Fig. 2. For two-dimensional ABHs, the location of the ABHs must also be taken into account.

For homogeneous materials, like steel or aluminium, the stiffness gradient within the ABH is only a function of material thickness, which can be either calculated analytically or numerically with efficient models using state-of-the-art Finite Element Method (FEM) software packages.

The application of ABHs was explored in many industrial sectors; however, the manufacturing of ABHs in thin plates, which are very common in many lightweight structures, presents challenges [5]. To date, the only industrial application of ABHs is for vibration damping of turbine blades [7].

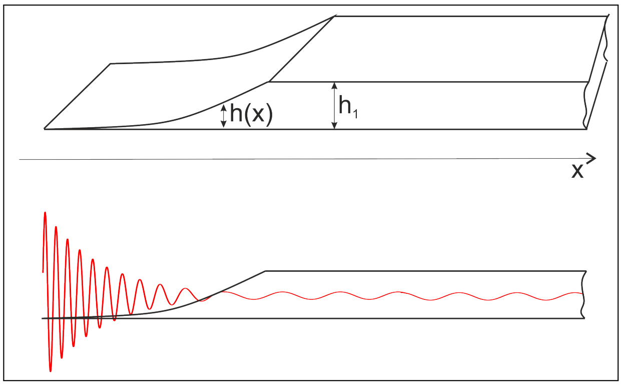

Figure 1. Illustration of a perfect one-dimensional ABH implemented at a plate edge.

3. CROSS-LAMINATED TIMBER FLOORS WITH ACOUSTIC BLACK HOLES

Engineered wood floors, more specifically CLT, consist of multiple layers of wooden beams or laminae that are glued together to form a composite material. The fibres of adjoining layers are usually oriented at an right angle to each other. The global mechanical properties of a CLT panel crucially depend on the material properties, as well as on the number, the thickness and the orientation of the

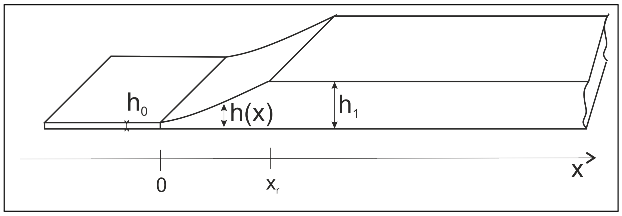

Figure 2. Illustration of an imperfect one-dimensional ABH with finite residual thickness at a plate edge.

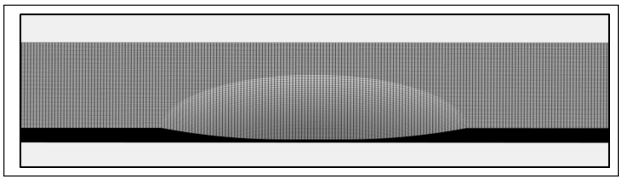

Figure 3. Cross section of a two-dimensional ABH implemented at the centre of a plate.

layers. Softwood species, like pine or spruce, which are usually used for CLT, are orthotropic, where the stiffness is an order of magnitude higher in the direction parallel to the fibres than in the normal or tangential directions.

At the ABHs, plies are gradually removed from the CLT. The local mechanical engineering properties within this area depend on the number of remaining plies, their orientation and their remaining thickness. Numerical FEM calculations were applied to consider all these factors in the dimensioning process of the ABHs. The goal was to identify ABH geometries suitable for reducing impact sound radiated from a CLT floor. Unfortunately, the layered composition of CLT and the geometry of the ABHs require a very fine FEM mesh in the vicinity of the ABHs to achieve a spatial resolution that accurately captures the ABH phenomena. As a result, common FEM models based on volume elements become computationally expensive.

4. EXPERIMENTS ON SMALL-SCALE PROTOTYPE

4.1 Small-Scale Prototype

For the experiments, two nominally identical small-scale CLT plates were purchased. One was kept as a reference, and the other was machined to obtain the small-scale ABH prototype. Two ABHs were machined into one of its planar surfaces with a CNC router. The geometrical parameters of the ABH were determined from FEM calculations using the commercial FEM code Ansys. Pre- and post-processing methods were applied to reduce the size of FEM for computational efficiency. A detailed description of the methods is out of the scope of this paper and will be published elsewhere. Initially, the experiments on the small-scale ABH prototype were only intended for the validation of the FEM model. Therefore, the ABH geometry was not extensively optimised at this point. However, results demonstrate the ability of ABHs to reduce vibrations and hence their suitability for impact sound reduction. The ABHs of the prototype were filled with sand/gravel to increase the damping.

4.2 Experimental Set-Up

The reference CLT plate as well as the small-scale ABH prototype were placed on three airbags in Empa's lightweight construction laboratory. The airbags in the experiment were utilised to approximate free boundary conditions that were considered in the FEM model. The set-up was equivalent to that used in a previous study which is described in more detail in [8].

In a first experiment, the plates were excited consecutively at three excitation points on their respective undersides with an electrodynamic inertial shaker, Type Data Physics IV40, driven by a swept sine signal. A photo of the experimental set-up is presented in Fig. 4. Two of the points were located close to the corners along the respective short sides of the plates, and the third was approximately in the middle of the opposite short edges, as in [8]. At the excitation point, the force and acceleration signals were measured as reference signals with a PCB 288D01 impedance head mounted in-between the shaker and the test specimen. The vibration response of the plate was measured on the top surface with a Polytec Scanning Laser Vibrometer PSV-400. The measurement grid had 189 points in a rectangular 9×21 grid. From the measured vibration response signal and the force reference signal, the transfer mobilities were determined at all measurement points for comparison with FEM results. For this first experiment, the ABH plate was placed upside down with ABHs on the bottom in order to scan the whole surface and see the effect of the ABHs on the mode shapes.

In a second experiment, the ABH plate was turned such that the ABHs were on top and subsequently filled with sand/gravel, as shown in Fig. 5. The plate was excited with an ISO standard tapping machine from Sources

Figure 4. Measurements of mode shapes with the scanning Doppler laser vibrometer on the small-scale ABH prototype with shaker excitation at bottom.

Line, Type EOS and the vibration response was measured again in a reduced grid between and around the ABHs. The same measurement was also conducted with an equivalent reduced grid for the reference plate without ABHs. From the vibration response signal at the the measurement points, the spatially averaged surface velocity level was calculated in one-third octave bands. The difference between the average velocity level of the reference plate and the small-scale ABH prototype gives an estimate of the impact sound pressure level reduction that can be achieved with the ABHs for this plate.

Figure 5. Experimental set-up for measurement of velocity level reduction with the scanning doppler laser vibrometer on the small-scale plates; excitation with an ISO tapping machine.

4.3 Plate Vibrations

The results of the first measurement set-up agreed very well with the plate vibrations from the FEM analysis. However, the predicted eigenfrequencies of the small-scale ABH prototype and the reference plate without ABHs were systematically about $5\,\%$ higher than the ones in the experiment. In this study, input data from [8] was used for the CLT plates. However, the CLT in both studies is from two different producers based in different countries. Therefore, it is likely that the CLT in the simulations was assumed to be slightly stiffer than the actual CLT in the experiment.

Nevertheless, besides the systematic shift, an inspection of the average transfer functions and the mode shapes exhibited a very good agreement of simulation and experiment. In Fig. 6 a mode shape of the small-scale ABH prototype is shown. The simulated results agree very well with measured plate vibrations. In the area of the ABHs, high vibration amplitudes occur since the ABHs were empty for this first experiment.

4.4 Impact Noise Reduction

The second experiment with the ISO tapping machine demonstrates the impact noise reduction capability of the ABHs when filled with gravel. The level difference $\Delta L_{|\hat{v}|^2}$ of the space- and time-averaged velocity levels measured on the reference plate and on the small-scale ABH prototype are shown in Fig. 7 for the octave bands from $125\,\mathrm{Hz}$ to $2\,\mathrm{kHz}$. Assuming the ABHs do not affect sound radiation, this level difference is a direct estimate

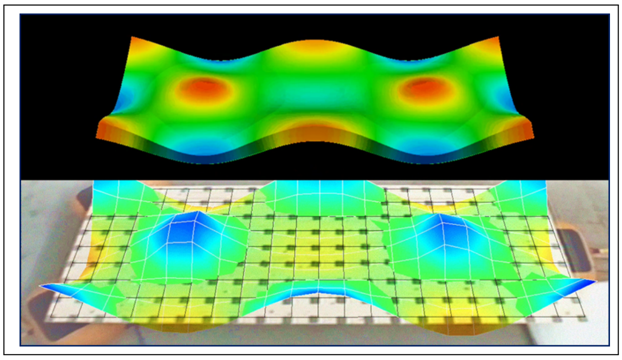

Figure 6. A mode shape of the small-scale prototype plate with ABH active. Top: FEM calculation. Bottom: Experimental measurement.

of the impact sound level reduction that can be achieved with the ABHs.

The improvement is more than $5\,\mathrm{dB}$ for the whole frequency range. The cut-on frequency of the ABH was found to be around $100\,\mathrm{Hz}$. In the $125\,\mathrm{Hz}$ and $250\,\mathrm{Hz}$ octave bands just above the cut-on frequency of the ABHs, the vibration level improvement is approximately $10\,\mathrm{dB}$.

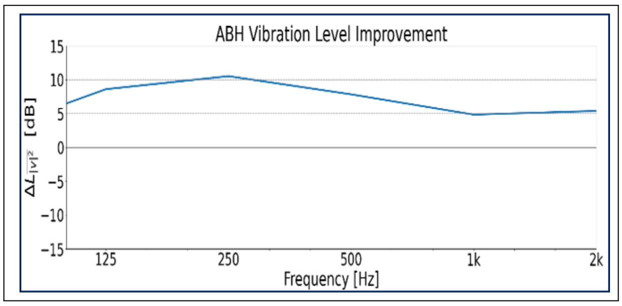

Figure 7. Measured velocity level difference $\Delta L_{|\hat{v}|^2}$ between the reference plate and small-scale ABH prototype for excitation with ISO tapping machine.

The total mass of the small-scale ABH prototype with gravel was only about $50\,\%$ higher than the reference plate. The achieved vibration reduction clearly exceeds the mass effect, which theoretically is expected to be about $3.5\,\mathrm{dB}$. Thus, the results demonstrate that ABHs are suitable for impact noise reduction. Unfortunately, due to time restrictions during the production of the small-scale ABH prototype, no optimisation of the ABH geometry was conducted to lower the cut-on frequency. A further reduction of the impact sound also at lower frequencies, which are very important for the perception of impact noise, seems to be achievable with further optimisation of the ABH geometry.

5. CONCLUSIONS AND OUTLOOK

A study is presented that demonstrates the application of Acoustic Black Holes (ABHs) for impact noise reduction in engineered wooden floors, such as Cross-Laminated Timber (CLT). This technology could be a viable alternative to current measures, such as full gravel ballast layers that increase the mass of the base floor assembly by up to $200\,\%$. In the presented study, the vibration level of a CLT panel was reduced by about $10\,\mathrm{dB}$ by using ABHs . The maximum improvement occurred in the frequency range just above the cut-on frequency of the ABH at $100\,\mathrm{Hz}$. Only the two ABHs of the prototype were filled with gravel, which increased the mass of the base floor by only $50\,\%$. This demonstrates that ABHs are a viable alternative technology for impact noise reduction of CLT floors. With the smaller height and significantly less weight required by the ABH technology compared to current state-of-the-art solutions for impact noise control of engineered timber floors, the technical, economic and environmental benefits of engineered timber floors could be further advanced with the application of ABH technology.

In the meantime, a full-scale CLT floor with ABHs was produced. The ABH geometry was further adjusted to lower the cut-on frequency by using efficient finite element based numerical simulations. Standard airborne and impact sound insulation tests were conducted according to EN ISO 10140 in Empa's floor laboratory. However, the results have not yet been released due to contractual reasons. In a further step to bring the technology to market, research and development is necessary on other multidisciplinary aspects, such as structural stability, serviceability, fire safety, and production processes.

6. ACKNOWLEDGMENTS

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