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Building acoustic analysis of doubly curved beam-like shell floors made of CFRP prestressed concrete and its integration into an interdisciplinary optimisation tool

Ahmad EIZ EDDIN*, Paul MERZ[a], Max DOMBROWSKI[b], Lucas HEIDEMANN[c], Steffi REINHOLD[c], Jamila LOUTFI[d], Berndt ZEITLER[c]

*TU Berlin, Institute of Civil Engineering, Chair of Conceptual and Structural Design
Federal Institute for Materials Research and Testing (BAM), Division 7.3 - Fire Engineering,
Unter den Eichen 87, 12205 Berlin, Germany
ahmad.eiz-eddin@bam.de

[a] ETH Zürich, Institute of Structural Engineering, Chair of Structural Engineering – Concrete Structures and Bridge Design
[b] TU Berlin, Institute of Civil Engineering, Chair of Conceptual and Structural Design
[c] University of Applied Sciences Stuttgart, Building Physics, Acoustics Unit
[d] Berlin University of the Arts, Department for Structural Design and Engineering

Abstract

An optimisation tool was developed to reduce the embodied carbon of floor systems. The considered system consists of a doubly curved beam-like shell made of carbon-fibre-reinforced polymer (CFRP) prestressed concrete and an infill layer. The thin-walled design of the system makes it susceptible to sound excitation. Therefore, the optimisation tool considers the static ultimate and serviceability limit states and the sound insulation aspect. Due to a lack of experience with the building acoustic properties of this floor system, it is, in practice, often simplified as a homogeneous floor. This paper aims to investigate its acoustic behaviour in more detail using numerical simulations and to integrate the gained knowledge into the optimisation tool. For this purpose, a simulation concept is set up and implemented. Simulations are carried out for different combinations of geometry and material parameters of the floor system. The data obtained is summarised into linear regression equations that estimate the weighted airborne sound reduction index and the weighted equivalent normalised impact sound pressure level of the system. The optimisation results based on these equations show a clear difference compared to those based on the above-mentioned simplified approach.

Keywords: building acoustic simulation, impact sound pressure level, airborne sound reduction index, doubly curved beam-like shells, optimisation tool, embodied carbon, parametric design, interdisciplinary optimisation

1. Introduction

The construction industry is responsible for a significant amount of man-made CO_2 emissions that contribute to climate change [1]. To reduce the harmful impact of the construction sector on the environment, much research is focused on finding environmentally friendly materials and elements. One approach is a floor system made of doubly curved beam-like hyperboloid shells (HP shells) used in Germany during the 1950s and 60s as roof elements [2]. In [3], it is proposed to adapt these shells as a resource-efficient floor system using carbon-fibre-reinforced polymer (CFRP) prestressed concrete. As shown in Figure 1, the system consists of a load-bearing concrete shell, an infill layer and a floating floor consisting of an

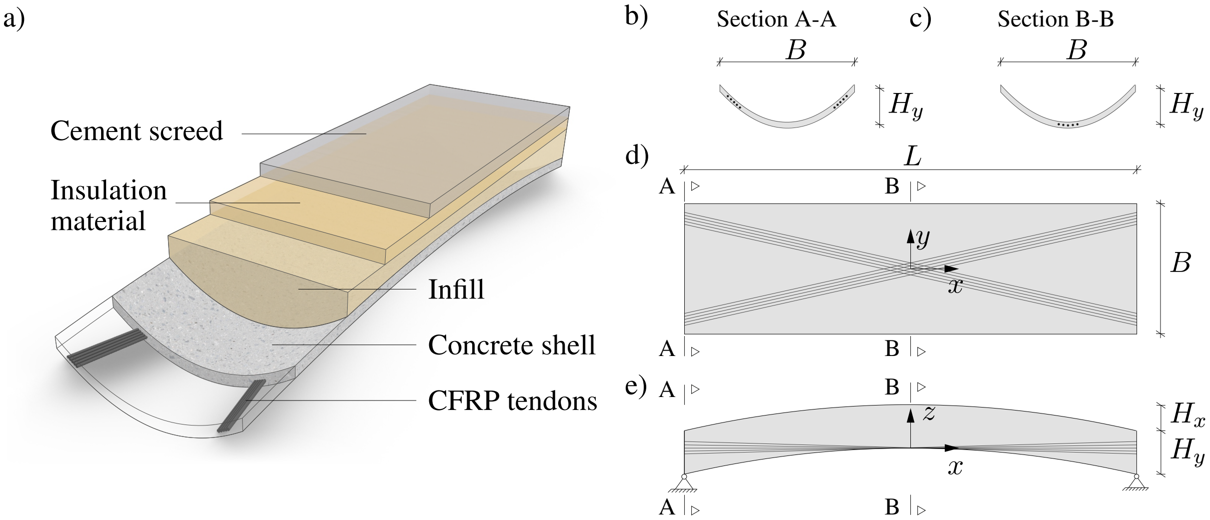

Figure 1: HP beam-like shell floor element: (a) rendering of HP floor element with its material layers, (b) cross-section at support and (c) at mid span, (d) top view and (e) side view [5]

insulation layer and a cement screed. The system combines the advantages of efficient shell load-bearing behaviour and prestressing to allow for thin-walled and material-efficient floors. However, the low mass of the elements can pose challenges in terms of durability, fire protection, and sound insulation [4]. This paper examines sound insulation in detail. The objective is to determine the acoustic properties of the concrete HP shell floors using numerical building acoustics simulations.

Moreover, this paper pursues the second step of converting the simulation results into a regression model for the building acoustic quality of the floor system. This model is incorporated into the optimisation tool of Loutfi [5], which optimises a parametric model of the floor system to find a parameter combination with a minimum of global warming potential (GWP) and costs. The optimisation tool considers the design checks of static ultimate and serviceability limit state, and sound insulation. Penalty factors are applied to the GWP and cost values for designs that do not meet certain design checks to create a fitness value. This ensures that the optimum floor system found by the optimisation algorithm meets all considered requirements. All sound insulation verifications in this tool are carried out according to the requirements of DIN 4109-2:2018-01 without considering sound transmission via flanks.

So far, the HP floor system has been simplified to a flat floor in the optimisation tool to determine the building's acoustic properties. The mass per unit area of the concrete shell plus infill is used in the equations in DIN 4109-32:2016-07, which were initially developed to determine the airborne sound reduction index and weighted equivalent normalised impact sound pressure level of flat floors. In this paper, the results from this simplified approach are compared with those from the simulations.

2. Determining building acoustic floor properties according to standards

To quantify the acoustic quality of building elements, the relevant standards define the building acoustic properties as normalised impact sound pressure level L_n and airborne sound reduction index R. These building acoustic properties can be measured on-site with in-situ conditions or in a test facility under laboratory conditions. The basic principle of determination is based on the two-room method, as shown in Figure 2. In this method, the separating element is excited with an airborne or impact sound source in the source room. The sound level is measured in the receiving room as a function of frequency for at least the frequency range between 100 and 3150 Hz. The building acoustic properties for the separating element are calculated depending on the resulting sound level in the receiving room. The properties are

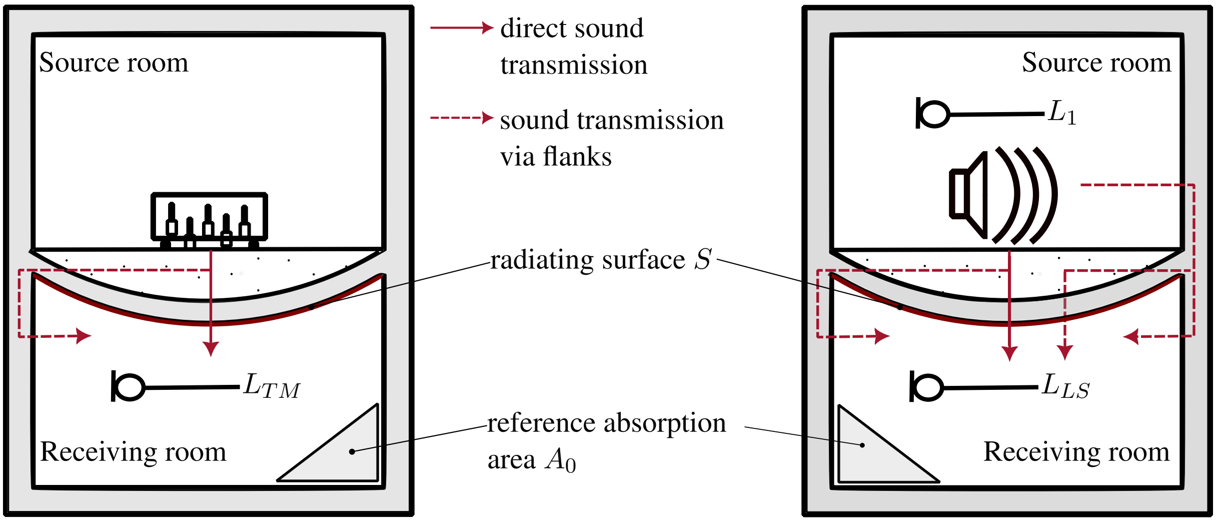

Figure 2: Two-room method with a tapping machine (left) and loudspeaker excitation (right)

then adjusted considering the influence of sound absorption in the receiving room. In the next step, the frequency-dependent values are weighted to a single value defined in ISO 717:2021-05. This simplifies the comparison of elements in terms of their acoustic quality.

Alternatively, in Germany, the acoustic parameters for specific elements can be read from the empirical values summarised in the element catalogues of parts 32 to 36 of DIN 4109 or calculated using the empirical formulas. For example, the weighted equivalent normalised impact sound pressure level $L_{\text{n,eq,0,w}}$ [dB] and the weighted airborne sound reduction index R_{w} [dB] for homogeneous floors according to DIN 4109-32:2016-07 can be determined depending on the mass per unit area m' [kg/m²] according to equations (1 and 2).

$$L_{\text{n,eq,0,w}} = 164 - 35 \cdot \log\left(\frac{m'}{1\,\text{kg/m}^2}\right) \tag{1}$$

$$R_{\text{w}} = 30.9 \cdot \log\left(\frac{m'}{1\,\text{kg/m}^2}\right) - 22.2 \tag{2}$$

3. Theoretical concept of the simulation

As the geometry and material properties of the HP shell floors differ from conventional elements, it is unclear how far the current standards are valid for these elements and parameter studies are crucial to understanding the acoustic behaviour of the system. These studies analyse how geometric and material properties affect the acoustic objective values, providing valuable insights to optimise the system's performance. Computer-aided simulations are ideal for this purpose in the early stages of development due to their relatively low cost compared to experimental investigations. The simulation results should be verified by measuring representative test specimens in the next step.

Numerical simulations are carried out to determine the sound insulation properties of the HP floor system. These simulations must represent the sound transmission through the floor system resulting from a normative excitation. Initially, the simulation was envisioned as a numerical simulation of the two-room method, which requires a lot of computing capacity. To avoid this, the implemented concept uses the structure-borne sound measurement approach, often used in building acoustics [6]. In this approach, the airborne sound reduction index and the weighted equivalent normalised impact sound pressure level are calculated using the vibration velocity of the floor system induced by normative sound sources. Sound transmission via flanks (see Figure 2) is not considered here, as this simulation aims to determine the sound properties of direct transmission through the separating floor system. Additionally, the simulation does not consider the floating floor, which is typically used to improve sound insulation. The simulation concept is based on three steps explained in the following subsections.

3.1. Modelling of sound sources

To determine the impact sound pressure level, the HP floor system is excited with a standard tapping machine according to DIN EN ISO 10140-3:2021-09 and DIN EN ISO 16283-2:2020-11. The structure of the standard hammer machine is described in DIN EN ISO 10140-5:2021-09. It consists of five hammers which are dropped one after the other during the operation of the tapping machine. According to Cremer's model [7], this excitation can be simplified as a point load. The effective value of the equivalent load in the frequency interval Δf is calculated according to Equation 3.

$$\tilde{F}_{\Delta f} = 2 \cdot m \cdot \sqrt{2 \cdot g \cdot h_{\mathrm{g}} \cdot \Delta f \cdot f_{\mathrm{s}}} \tag{3}$$

Here are:

$\tilde{F}_{\Delta \mathrm{f}}$	effective value of the equivalent excitation for the ISO tapping machine [N]
m	mass of an ISO tapping machine hammer [kg] ($m = 0.5$ kg)
g	gravitational acceleration [$\mathrm{kg\,m^{-2}}$] ($g = 9.81\ \mathrm{kg\,m^{-2}}$)
h_{g}	drop height of the hammer [m] ($h_{\mathrm{g}} = 0.04$ m)
f_{s}	impact frequency [Hz] ($f_{\mathrm{s}} = 10$ Hz)

To determine the airborne sound reduction index, the system should be exposed to a diffuse sound field (generated by a broadband, omnidirectional loudspeaker) according to DIN EN ISO 10140-5:2021-09. This load case can be modelled by applying distributed loads with different alignment angles over the system's surface. The average vibration response represents the response to diffuse field excitation and is used for further calculations.

3.2. Determining the vibration response of the structure

The finite element (FE) approach is used to numerically determine the vibration response of the HP floor system. The vibrating system can then be described using the equation of motion (Equation 4) [8]:

$$(-\omega^2 \mathbf{M} + i\omega \mathbf{D} + \mathbf{K}) \cdot \mathbf{u}(\omega) = \mathbf{f}(\omega) \tag{4}$$

Here are:

$\mathbf{M}$	diagonal mass matrix	$\mathbf{D}$	damping matrix	$\mathbf{K}$	stiffness matrix
$\mathbf{u}$	displacement vector	$\mathbf{f}$	external load vector	ω	circular frequency

The deformation from prestressing affects the vibrating system's potential energy. Using the Hamilton approach [9], the stiffness of the system can be determined, and the prestressing can be regarded as a "geometric stiffness" [10] in the simulation. To achieve this, the beam-like floor system's cross-section is subjected to a static axial force corresponding to the mean prestressing force. The resulting deformation is determined using the FE method and included in the vibration analysis. The infill is interpreted as an unevenly distributed mass, which adapts to the floor geometry. This can be incorporated by modifying the mass matrix in the equation of motion.

3.3. Determining the sound properties

The frequency-dependent velocity field $\boldsymbol{\nu}$ of the surface of the vibrating structure facing the receiving room can be derived from the solution of the equation of motion. Then, this velocity field is averaged to obtain a mean value of the vibration velocity ν_{mean} [m/s]. Assuming that the radiation coefficient in the entire frequency range is $\sigma = 1$ and the diffuse field condition prevails, the building acoustic properties can be determined using the mean value of the vibration velocity, as shown in Figure 3.

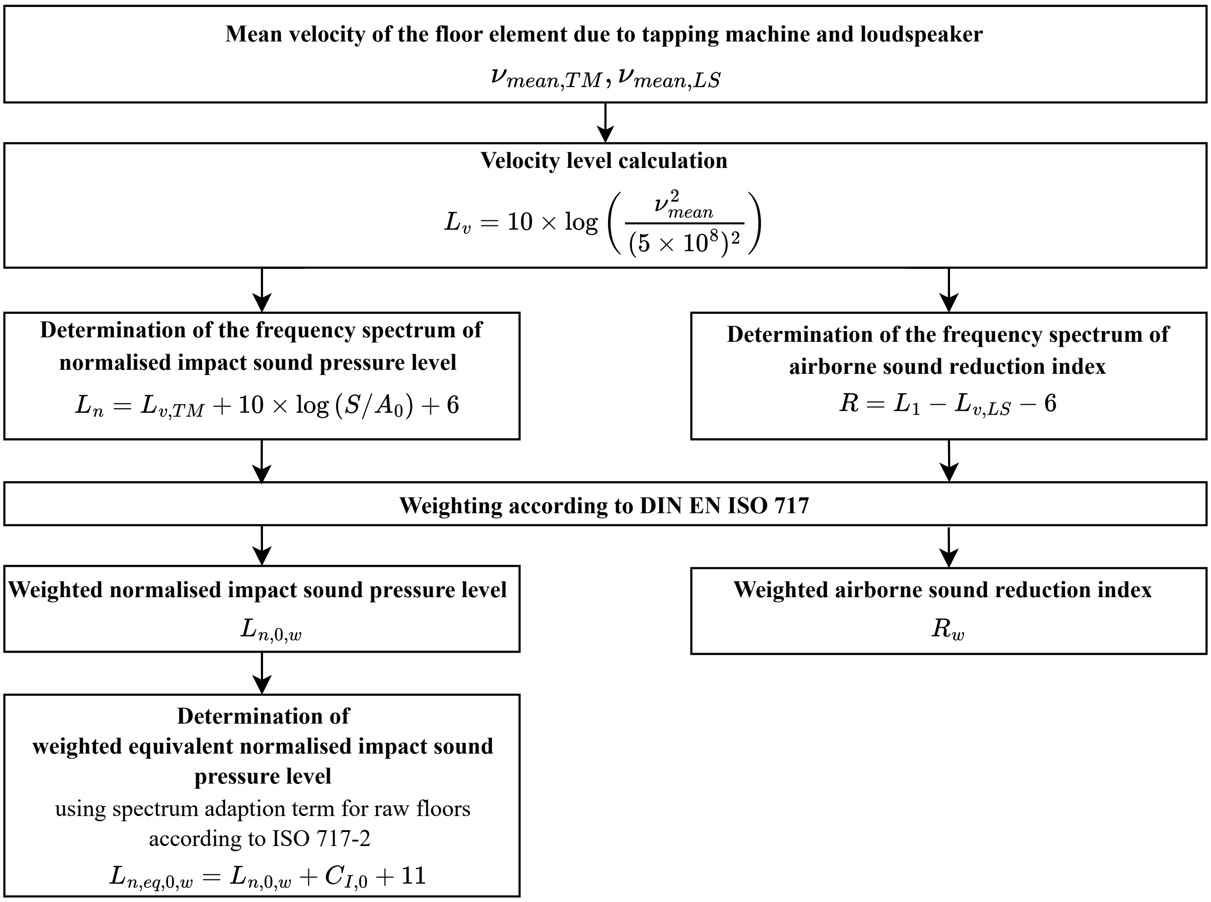

Figure 3: Calculation concept to determine the sound properties by using the vibration velocity

4. Implementation concept of the simulation

Figure 4 shows the implementation concept of the building acoustics simulation. During the preprocessing stage, the parametric model of the floor system is created using the visual programming environment ”Grasshopper 1.0.0007”. At this stage, the necessary boundary conditions and settings for the building acoustics analysis are determined. The objective is to generate input files for the FE vibration analysis and the deformation resulting from prestressing. These files contain all the properties of the HP floor system and can be analysed using the chosen simulation software. In the processing stage, the acoustic simulation software ”Actran 19” is used to conduct vibration analysis and determine the deformation caused by prestressing. Additionally, Actran is used to extract the relevant simulation results for the further process, such as the velocity at the bottom side of the floor. This process is automated by writing scripts, which are executed to simulate multiple parameter combinations of the investigated floor system.

The analysis results are evaluated in Grasshopper during the postprocessing stage as shown in Figure 3 to obtain the relevant acoustic properties of the HP floor system.

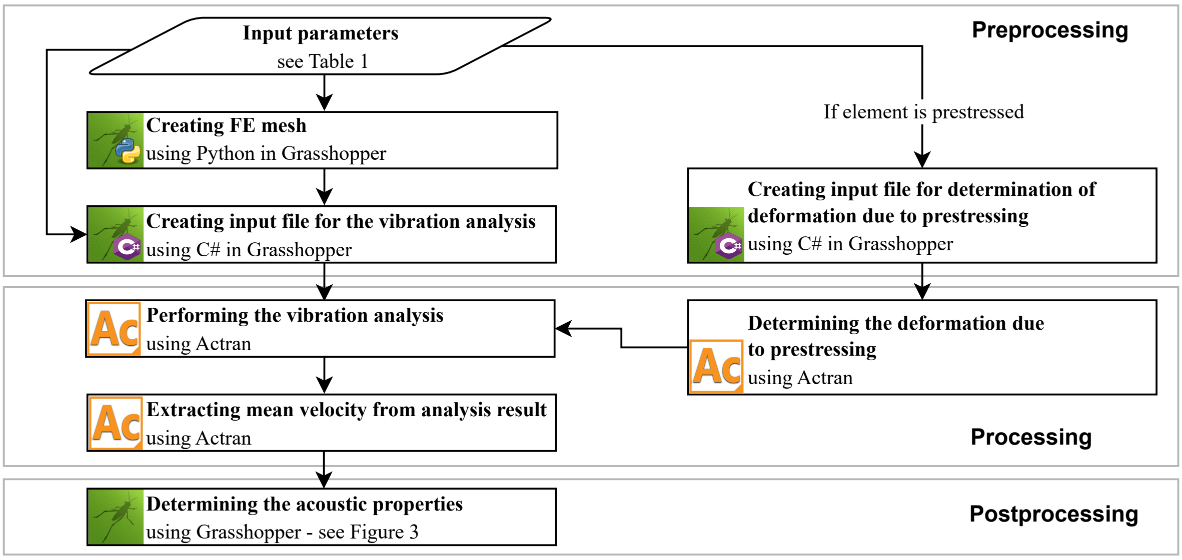

Figure 4: Implementation concept subdivided into preprocessing, processing and postprocessing

5. Validation of the simulation

As already mentioned, the HP floor system is currently in the development stage and no physical prototype has been produced. Therefore, laboratory measurements of reinforced concrete slabs are used to validate the FE simulation. A comparison of simulation results and laboratory results of a 140 mm [11] and a 180 mm [12] thick reinforced concrete floor are depicted in Figure 5. The simulation results are in good agreement with the measurements.

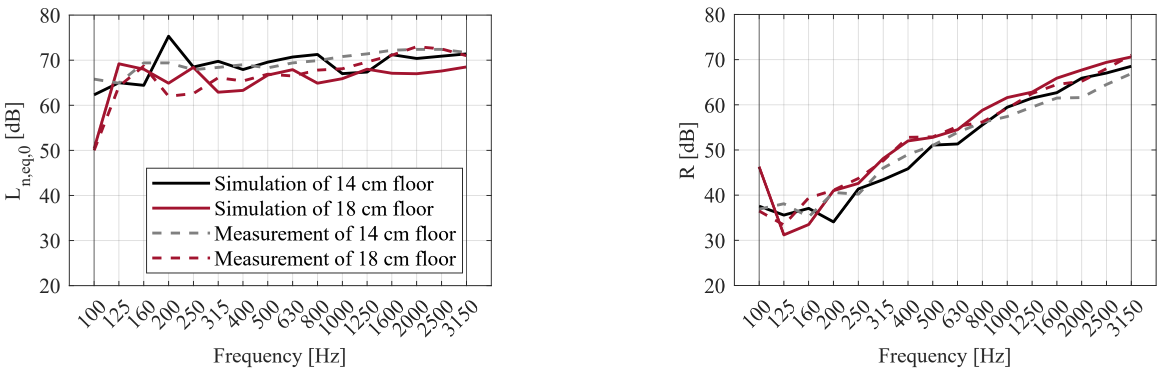

Figure 5: Validation of the FE simulations with laboratory measurements of reinforced concrete slabs

6. Results

The results are organised in two studies. In parameter study I, a reference model with fixed material specifications and geometric properties is established. Then, one parameter is varied while the rest remain constant. In parameter study II, all parameters are varied simultaneously to record interaction effects between the parameters. Table 1 lists the reference values of the used parameters and the variation ranges of both parameter studies. Parameter study II uses a maximum mesh width of 100 mm due to

Table 1: Parameters considered in the studies with their reference value and variation ranges

Parameter	Parameter study I reference value	Parameter study I variation range	Parameter study II variation range
Span L [m]	8	[4, 12]	[4, 12]
Cross-section width B [m]	1.2	[0.6, 1.2]	[0.5, 2.5]
Rise in longitudinal direction H_x [m]	0.08	[0.04, 0.12]	[0.05, 0.15]
Rise in transverse direction H_y [m]	0.32	[0.26, 0.38]	[0.10, 0.50]
Shell thickness h [m]	0.05	[0.03, 0.07]	[0.03, 0.15]
Infill thickness Δs [m]	0.01	[0.01, 0.06]	[0, 0.1]
Young's modulus E [kN/mm²]	37	[33, 40]	[33, 41]
Prestressing Force F_p [N/mm²]	0	[0, 20]	[0,20]
Damping ξ [-]	0.01	[0.005, 0.02]	[0.005, 0.03]

software constraints. This width corresponds approximately to half of the floor element's bending wavelength. However, in acoustics a mesh width of less than one-sixth of the wavelength is recommended. Therefore, the results of parameter study II should be interpreted with caution. For parameter study I, a finer mesh with a maximum width of 50 mm is used, leading to more precise results.

Figure 6 shows how the simulated results of the weighted equivalent normalised impact sound pressure level and the weighted airborne sound reduction index depend on individual parameters. The thickness of the shell and the degree of damping have the greatest influence on reducing the normalised impact sound pressure level. Similarly, the infill thickness also has a negative influence, but to a lesser extent. The rise in transverse direction has a slightly reducing influence on the normalised impact sound pressure level. Additionally, the cross-section width slightly reduces it. The results also indicate a negative correlation between the normalised impact sound pressure level and Young's modulus of the concrete. The weighted airborne sound reduction index decreases with increasing shell thickness, while it increases with increasing the degree of damping and infill thickness. A positive correlation between the cross-section width and the sound reduction index can be observed.

The acoustic properties of the element depend on its vibration behaviour. Therefore, the normalised impact sound pressure level and the airborne sound reduction index are expected to depend on the damping, which reduces the amplitudes of the vibration response [8]. The normalised impact sound pressure level primarily depends on the structure's mass, which is determined by the shell and infill thickness. It has already been established that there is a negative correlation between the normalised impact sound pressure level and the shell thickness, as well as the thickness of the infill. This is consistent with the typical behaviour of conventional floor constructions - see Equation (1).

It has been observed that the airborne sound reduction index increases with the thickness of the infill material. Greater thickness results in higher mass and greater sound reduction. This observation is consistent with the behaviour of conventional floors as described in Equation (2). However, it is noteworthy that the airborne sound reduction index does not follow the same relationship with the shell thickness but seems to decrease with increasing shell thickness. This is because the shell thickness not only affects the mass but also the stiffness. When combined with the finding from the simulation that the sound reduction index increases with increasing cross-section width, a negative correlation between the sound reduction index and stiffness in the transverse direction can be inferred.

The data obtained from both parameter studies is combined into a database. This database is then split into two sets: the training data set, which comprises 80% of the database, and the test data set, which

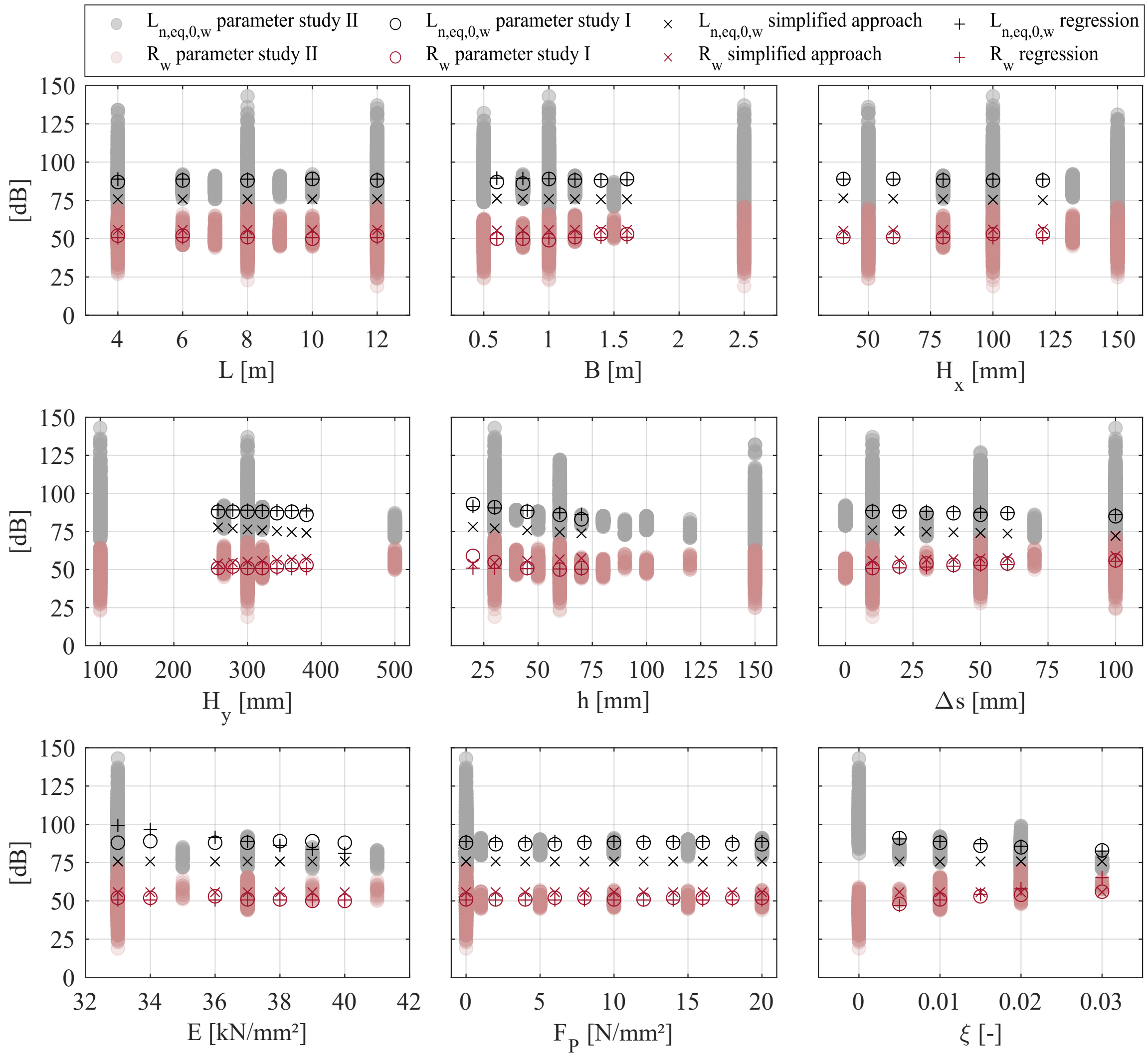

Figure 6: Weighted equivalent normalised impact sound pressure level and weighted airborne sound reduction index for different parameters and comparison of the simplified and regression approach with FE simulated data

accounts for 20% of the database. The training data is used to determine regression coefficients, which are then used to create models to predict the weighted equivalent normalised impact sound pressure level (Equation 5) and the weighted airborne sound reduction index (Equation 6). The test data was utilised to evaluate the accuracy of its predictions. The average prediction error (Root Mean Square Error) for the normalised impact sound pressure level is 4.29 dB and 4 dB for the airborne sound reduction index.

$$L_{\text{n,eq,0,w}} = 260 - 108\,h - 6607\xi - 1.07B - 41\Delta s - 6.35H_y - 0.0043E + 264h\Delta s + 0.17\xi E \quad (5)$$

$$R_{\text{w}} = 42 + 727\xi + 54\Delta s + 1.51B - 11.5Bh \quad (6)$$

Figure 6 summarises the results obtained from the two approaches for calculating the building acoustic properties of the HP shell floors in parameter study I. The simplified approach uses the standard´s

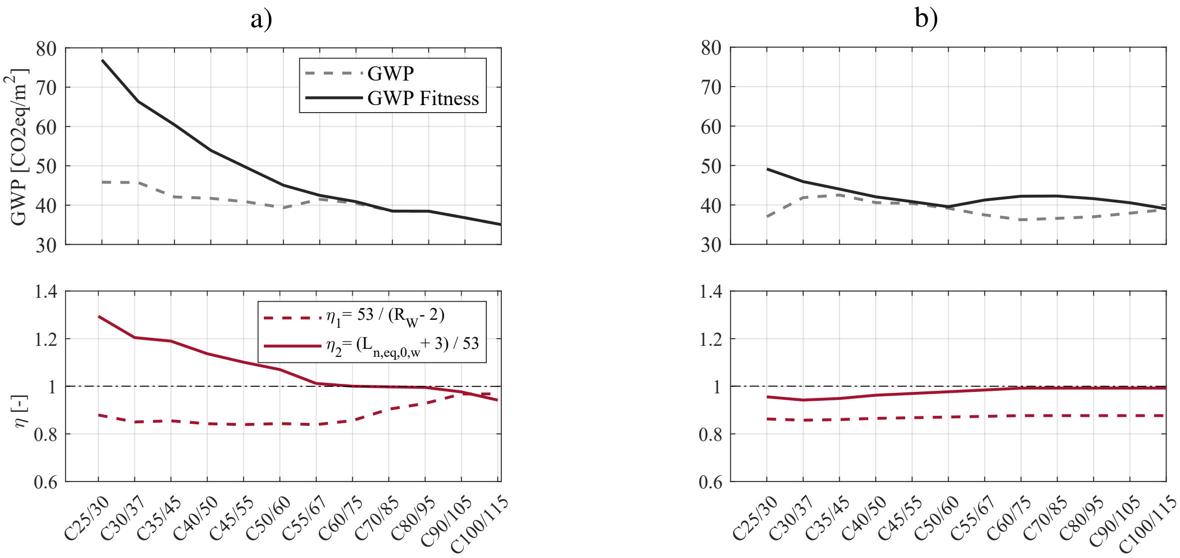

Figure 7: Comparison of optimisation results with (a) regression approach and (b) simplified approach

formulae (Equations 1 and 2), while the regression approach uses the regression model´s equations (5 and 6). The regression models produce more accurate results with regard to the simulated data. This demonstrates the advantages of using regression models over the simplified approach.

The regression models can be easily integrated into the optimisation tool from [5], allowing for interdisciplinary optimisation with a more precise approach to sound insulation. Figure 7 shows results from the interdisciplinary optimisation model for an exemplary parameter set and a range of concrete qualities using both approaches. Since it was found in [5] that optimising the HP floor system for GWP and costs is not a Pareto problem, only GWP optimisation results are considered here. It can be seen that the two approaches lead to different optimisation results. The simplified approach does not include Young‘s modulus of the concrete and, therefore, can not capture its influence on the building acoustic quality of the floor system. This results in the mostly constant value of both GWP values and utilisation in Figure 7 b). The regression approach, on the other hand, shows the influence of the different concrete grades and their respective Young‘s moduli (see Figure 7 a)). This example understates the importance of considering sound insulation in the optimisation.

7. Conclusion and outlook

The present paper proposes an FE simulation concept to assess the building acoustic properties of a material-efficient floor system made of CFRP prestressed concrete HP shells and an infill layer. The simulation concept is used to derive the normalised impact sound pressure level and airborne sound reduction index from the vibration response of the system to excitation. A validation of the simulation model with laboratory measurements shows good agreement. Extensive parameter studies are conducted to understand the structural dynamic behaviour of the system. The results from these studies are used to develop two regression models to determine the weighted equivalent normalised impact sound pressure level and the weighted airborne sound reduction index. These regression models pose an alternative to the coarse implemented simplified sound insulation approaches used in current standards.

It was shown that the regression approach enables a more precise consideration of various material and geometry parameters, like Young’s Modulus of the concrete and the shell thickness, leading to more favourable acoustic properties than the simplified approach for specific parameter combinations. Due to their simple mathematical expression, the regression models can be easily incorporated into other tools like the interdisciplinary optimisation tool for HP shell floors [5]. As a part of the optimisation tool, the regression models led to different optimal designs regarding GWP and costs. This approach offers the possibility to expand conventional structural optimisation models with relevant acoustic parameters like the thickness and specific weight of the infill layer and the thickness of the cement screed.

In future work, the availability of more computing capacity can enable the creation of high-resolution models for more accurate regression models that provide deeper insight into the influence of various parameters on the acoustic properties. Moreover, a more sophisticated formulation of the regression function, such as the logarithmic approach, may provide more accurate predictions.

The properties of the described floor system are influenced by a complex interaction of different parameters, making the optimisation step essential. To optimise effectively, one must understand the relationship between the parameters and the various performance criteria. This paper outlines a procedure for establishing the relationship between input parameters and acoustic performance. Furthermore, the method can be used to obtain data for other performance criteria, e.g. fire resistance and durability of thin-walled structures.

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