Sound insulation of double masonry exterior walls

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Summary
Masonry is commonly used for the construction of buildings in Germany. Due to energy efficiency the masonry facades are more and more often constructed of two shells sandwiching thermal insulation. The inner shell, typically with a thickness of 150 mm to 240 mm and mass per area of 200 kg/m^2 to 480 kg/m^2 respectively, ensures the structural safety, whereby the outer shell, typically a brick lining with a thickness of 75 mm to 115 mm and mass per area of 120 kg/m^2 to 220 kg/m^2 respectively, ensures the environmental protection (e.g. from wind and rain). The cavity is typically filled with 120 mm to 250 mm of thermal insulation material, such as mineral wool or polystyrene. Due to wind and seismic loads the outer shell is connected to the structural inner shell by 5 to 10 tie-bars per square meters, typically 4 mm in diameter. Further anchors are located above openings (e.g. windows and doors) where the outer shell is fastened to brackets. The quantity and location of the anchors changes the dynamic coupling between the two shells and could diminish the sound insulation of the wall.
In this paper the sound insulation and vibration patterns of such a wall is investigated in the laboratory. Besides standard airborne measurements, a modal analysis of the wall was carried out to visualize the vibration pattern of the wall in the low frequency range. These results are compared with FEM-calculations, in which different types and quantity of the connections between the walls were investigated. The presented results are the first of a series of investigations planned with heavy masonry inner shells and various outer shell types.

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1. Introduction

Masonry facades are more and more often constructed of two shells sandwiching thermal insulation. The inner shell, typically with a thickness of 150 mm to 240 mm and mass per area of 200 kg/m^2 to 480 kg/m^2 respectively, ensures the structural safety, whereby the outer shell, typically a brick lining with a thickness of 75 mm to 115 mm and mass per area of 120 kg/m^2 to 220 kg/m^2 respectively, ensures the environmental protection (e.g. from wind and rain). The cavity is typically filled with 120 mm to 250 mm of thermal insulation material, such as mineral wool or polystyrene.
Due to wind and seismic loads the outer shell is connected to the structural inner shell by 5 to 10 tie-bars per square meters, typically 4 mm in diameter. Further anchors are located above openings (e.g. windows and doors) where the outer shell is fastened to brackets.

The sound reduction index SRI of double masonry exterior walls can be defined as the SRI of the inner shell and the sound reduction improvement of the additional lining. The quantity and location of the tie-bars changes the dynamic coupling between the two shells and could diminish the sound insulation of the wall.
In this paper the sound insulation and vibration patterns of such a wall is investigated in the laboratory. Besides standard airborne measurements, a modal analysis of the wall was carried out to visualize the vibration pattern of the wall in the low frequency range. These results are compared with Calculations, in which different types and quantity of the connections between the walls were investigated. The presented results are the first of a series of investigations planned with heavy masonry inner shells and various outer shell types.

2. Measurement Setup

Four different wall systems are investigated in this study, including the inner shell, base wall (IS), a 175 mm thick calcium-silicate blocks masonry wall. Its masonry blocks have a nominal bulk density of around 1900 kg/m^3 and are referred to as KS_R P 20-2.0-6 DF 175. The other three wall systems are comprised of the IS, plus 200 mm of mineral wool cavity insulation, and an external outer shell (OS) constructed of 115 mm thick calcium-silicate blocks brickwork (see **Fehler! Verweisquelle konnte nicht gefunden werden.**). The blocks of the OS, referred to as KS Vb 12-1.8-2 DF, were fastened to the IS three different ways.

Figure 1: Constuction of exterior wall in wall sound transmission facility of the HFT Stuttgart.

Firstly, it was fastened, with five 4 mm-thick tie-bars per square meter (IS+OS5), secondly with nine tie-bars per square meter (IS+OS9), and finally with the nine tie-bars and four threaded rods (each 12 mm in diameter) to simulate the console bracket used to support the blocks above, e.g. window openings (IS+OSC).

3. Modal Analysis

To better understand the sound transmission of the wall systems, a reciprocal modal analysis was performed, firstly, on the IS walls using a 21 cm by 21 cm grid. The grid spacing was slightly less at the edges of the wall, resulting in 294 excitation positions with the impulse hammer. A reference accelerometer was placed at a height of 0.56 m and 2.39 m from the left edge of the wall. The same procedure was repeated for the wall system IS+OS5, yet with double the amount of excitation points, half of which were on the IS and the other half mirrored on the OS5. A second reference accelerometer was added to the OS5 opposite the one on the IS.

Due to reciprocity, the modal analysis can be viewed as exchanging the excitation and response locations. In other words, as exciting the walls at the reference location, and measuring the response at the excitation positions. For system IS+OS5 this means one excitation point on the IS and one excitation point on the OS5.

The modal analysis of the measured transfer functions was carried out using the Me'ScopeVES software. The modes up to a frequency of 150 Hz, of the IS and the IS+OS5 walls, are show in Figure 2, whereby the later was excited on both shells.

Looking at the bending wave mode shapes of the IS in the first column, shines light on the actual boundary conditions (BC), which are not the ideal simply supported BCs. There is movement at the edges of the wall at low frequencies, which implies that the connecting structures are also in motion. Comparing the first two modal resonance frequencies of the IS and the IS+OS5 excited on the IS, shows that the resonance frequency of the IS is quite a bit lower (Mode 1,1: IS: $f_{1,1}$=43 Hz – IS+OS5: $f_{1,1}$=32 Hz; Mode 2,1: IS: $f_{2,1}$=65 Hz – IS+OS5: $f_{2,1}$=48 Hz). As both shells are moving in phase, because they are coupled by the stiff air cavity and tie-bars, the overall stiffness of the IS+OS5 increases, thereby increasing the bending wavelength, which leads to a lower modal resonance frequency.

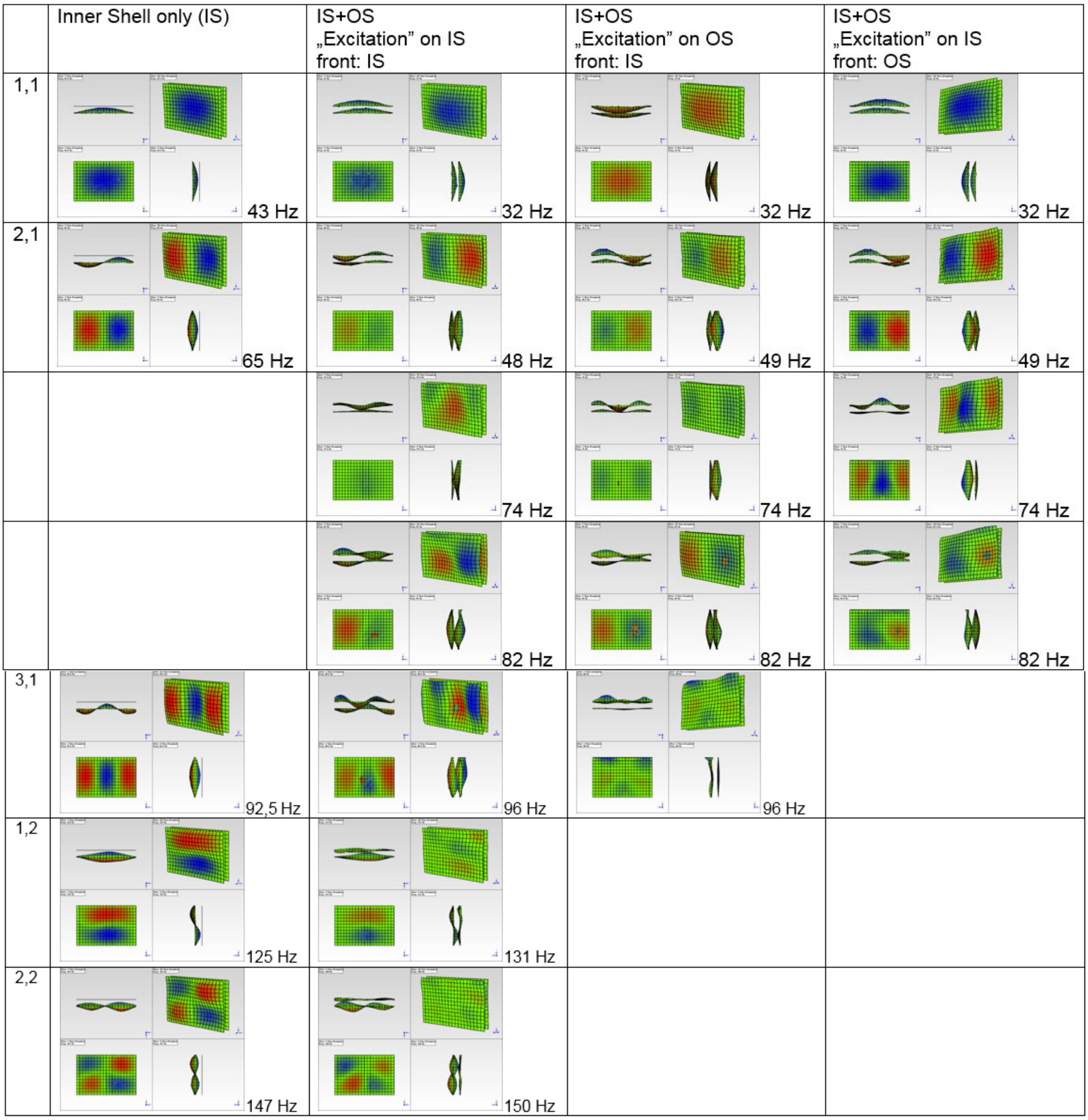

Figure 2: Mode shapes and corresponding resonance frequencies of the walls IS and IS+OS5

In the frequency range of 50 Hz to 150 Hz the shells still seem to be interacting, however they no longer move in-phase but out-of-phase. Towards higher frequencies the shells become more and more decoupled and the vibrational amplitude of the shell that was not "excited" drops.

The spatially averaged transfer function, between excitation force on the one shell and acceleration response on the other, is presented in Figure 3. It being the reciprocal value of the dynamic mass, having a unit of 1/kg, exhibits how easily the reception shell can be excited. The peaks, indicating a high excitability, depict the resonances of the system and coincide with those listed in Figure 2. The transfer function of the of the IS (TR: IS, red curve) shows modal resonance frequencies at 43 Hz, 65 Hz, 92 Hz, and 125 Hz. By adding the exterior wall, IS+OS5, again one can see that the first two modal resonances (32 Hz and 48 Hz) shift to lower frequencies (black and green curves).

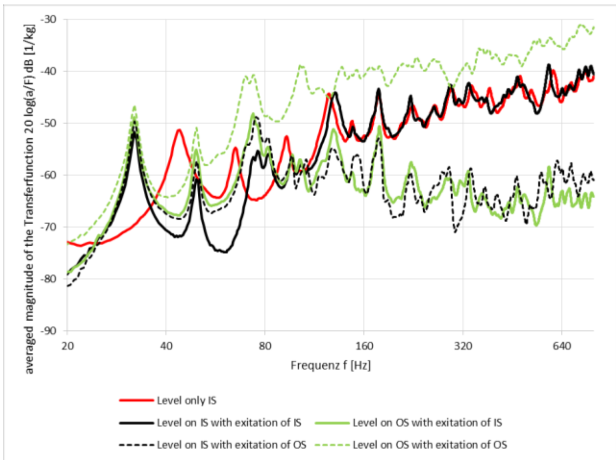

Figure 3: Spatiall averaged transfer function for the investigated walls systems. Solid line denotes excitation on IS, dashed line denote excitation on OS5, red line IS system and levels on IS, black line IS+OS5 system and levels on IS, green line IS+OS5 system and levels on OS5.

Also depicted in Figure 3 are the four transfer functions of the IS+OS5 system for which both shells were separately excited and the response of both shells was measured. Written out that means the IS was excited and the response of IS was measured (TF:IS-IS, solid black line), the IS was excited and the response of OS5 was measured (TR:IS-OS5, solid green line), the OS5 was excited and the response of IS was measured (TR:OS5-IS, dashed black line), and the OS5 was excited and the response of OS5 was measured (TR:OS5-OS5, dashed green line).

At the low frequency range, around the first two modal resonance frequencies, the four transfer functions overlap, due to the fact that the two shells are fully coupled by the stiff air cavity and tie-bars.

High above the "mass-spring-mass" resonance of the two shells at approx. $f_r = 65$ Hz, where the shells become decoupled, the transfer functions start to diverge. However, with exception of the TR:OS5-OS5, two of the transfer function converge with each other. The TR:IS-IS converges with TR:IS (solid red and black lines) because when the IS is decoupled from the OS5 it vibrates as if it were standing on its own. TR:IS-OS5 converges with TR:OS5-IS, because of the reciprocity explained previously, the excitation points and receiver points can be exchanged, and if a measurement would have been made on OS5 standing alone, then TR:OS5-OS5 would converge to the transfer function of OS5, because it also becomes decoupled from the IS at high frequencies. The high levels of TR:OS5-OS5 show that the OS5 is most easily excitable due to OS5 having the lowest mass per area. Far above the resonance frequency the transfer functions to the other shell become lower. It can also be seen that the acceleration levels on the receiving shell sinks due to the decoupling. This has a positive effect on the sound insulation of the wall.

4. Sound Insulation

The weighted sound reduction index of the IS normalized to the standardized in-situ loss factor is $R_{w,situ,ref} = 55.4$ dB. This value is only 0.7 dB lower than the value calculated from the mass per area of the wall, according to DIN 4109-32:2016-07. The weighted sound reduction index of IS+OS5 and IS+OS9 are $R_w = 70$ dB and $R_w = 65$ dB, respectively. The value calculated according to the same German standard, $R_w = 70$ dB, matches that of the IS+OS5 case, but over predicts the performance of the IS+OS9 case by 5 dB. This over prediction is because the calculated value only depends on the mass per area of the two shells and not on the type of fastening. As can be seen in Figure 4, the extra tie-bars lower the sound reduction index between 80 Hz and 500 Hz and above 2k Hz. The low frequency reduction causes the drop of 5 dB in the single number rating.

The installation of the four threaded rods to simulate the console bracket (IS+OSC) causes a dip in the sound reduction index around 400 Hz and lowers it above 1k Hz as well. However, the single number rating stays the same at $R_w = 65$ dB. Although the threaded rods have the same overall cross-sectional area as the added tie-bars, they have a different effect on the sound reduction index, probably due to their higher stiffness and less spatially spread location.

A console bracket constructed in the field is usually fastened to the floor slab and not to the base wall as done in this lab study due to restrictions. Therefore, the sound reduction index in the field is expected to be higher for the in-situ console than for the one tested here. All three outer shell wall variants (IS+OS5, IS+OS9, and IS) degrade the sound reduction index at and below 50 Hz, yet show a steep improvement at and above 63 Hz (see Figure 4). Part of the improvement, especially at the lower frequency range is due to the mass added by the external wall, which rises from 340 kg/m^2 to 540 kg/m^2.

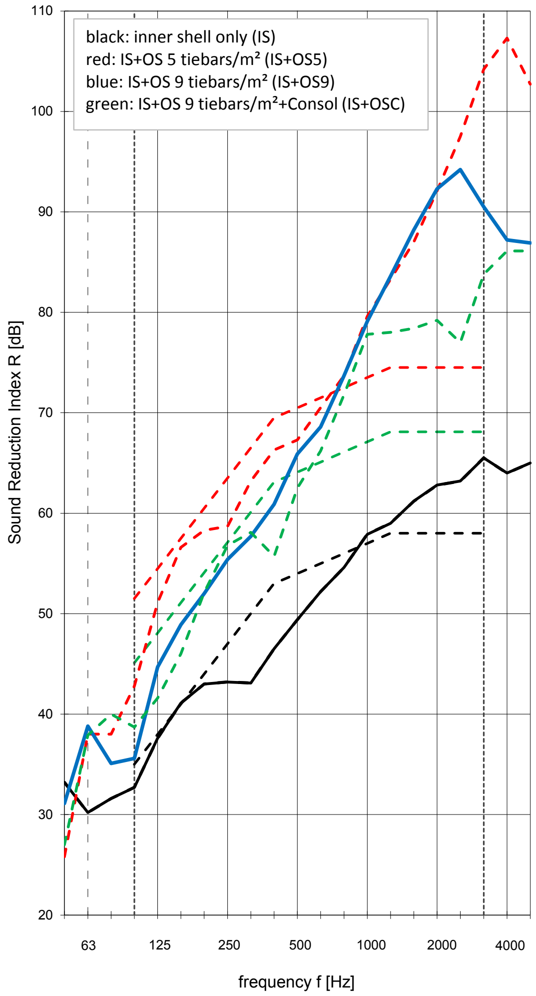

Figure 4: Sound reduction index of the wall systems: IS (black); IS+OS5 (red); IS+OS9 (blue); IS+OSC (green).

5. Summary

The wall system constructed of two shells of calcium-silicate blocks masonry behave typically for a double wall.
The weighted sound reduction index of the double wall is $R_w = 70$ dB, which is comprised of that of the inner shell wall, $R_w = 55$ dB, and an improvement of $\Delta R_w = 16$ dB due to the outer shell. Adding additional fastenings between the two shells, either with tie-bars or threaded rods, reduces the sound insulation of the total system, but most significantly in the high frequency range.

The acoustical coupling of the shells at low frequencies is caused by the tie-bars and cavity insulation, but it is mainly the tie-bars that define the frequency f_r of the mass-spring-mass resonance (between 60 Hz and 80 Hz). How well the shells are coupled below this frequency can be seen in the two modes (33 Hz and 48 Hz) that lie below f_r. Both shells are in phase and have the same vibrational shape (coupled). The decoupling above f_r can also be seen in the mode shapes. The mode around f_r are in anti-phase (mass-spring-mass resonance) and the difference in vibrational magnitude becomes larger and larger towards higher frequencies (decoupled).

The calculation of the weighted sound reduction index of a massive double wall system should be carried out according to EN ISO 12354-1 [4] by calculating the weighted sound reduction index of the base wall and adding the improvement caused by the massive lining. However, currently no method exists to calculate the improvement of the sound reduction index by massive outer shells. Further studies are planned to ensure the development of such a calculation method that incorporates the mass per area of the shells and their fastening.

Acknowledgements

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