X International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2023
M. Papadrakakis, B. Schrefler and E. Oñate (Eds)

SOUND INSULATION OPTIMIZATION OF A ROLLER SHUTTER BOX

S. BAKHOUCHE[*], W. LARBI[*], J-F. DEÜ[*] AND P. MACQUART[†]

[*] Conservatoire national des arts et métiers (Cnam)
Laboratoire de Mécanique des Structures et des Systèmes Couplés (LMSSC)
2 rue Conté, 75003 Paris,France
web page: http://www.lmssc.cnam.fr

[†] Union des Fabricants de Menuiseries (UFME)
39 rue Louis Blanc, 92038 Courbevoie
web page: https://www.ufme.fr

Key words: Roller Shutter Box, Experimental Test, Numerical Simulation, Porous Material

Abstract. This research aims to develop an advanced numerical model to accurately predict and optimize the acoustic insulation performance of roller shutter boxes, which are important for thermal and acoustic insulation in building facades. Traditional laboratory tests for evaluating sound transmission can be expensive and lack repeatability, particularly at low frequencies. To overcome these limitations, the proposed numerical approach utilizes the finite element method to model solid and fluid domains within the roller shutter box structure. Poroelastic layers are accounted for using a mixed displacement-pressure formulation of the Biot poroelasticity equations. Excitation and sound radiation are simulated using a diffuse field of plane waves with random phases and directions, employing the infinite elements method. The numerical model is validated by comparing its results with laboratory tests, which are described in detail. The practical application of this numerical method includes investigating factors such as assembly conditions, positioning of poroelastic layers, and the inclusion of heavy masses on the acoustic behavior of roller shutter boxes.

1 INTRODUCTION

The effective acoustic performance of building facades plays a crucial role in minimizing disturbances within buildings. To achieve satisfactory sound insulation, it is essential to understand the individual acoustic performance of various components such as windows, air inlets, and roller shutter boxes, as they often represent the weakest links in terms of acoustic insulation. Traditional experimental tests based on established standards evaluate the sound insulation of building elements through sound transmission loss (TL) measurements. However, these tests assume ideal conditions that may not hold true at extremely low frequencies, leading to discrepancies in observed transmission loss. Additionally, variations in test conditions and different test laboratories can yield inconsistent results. To overcome these limitations, numerical approaches such as the Finite Element Method (FEM) [1,2], Statistical Energy Analysis (SEA)[3], or Matrix Transfer Method (TMM) [4] can be employed to provide more representative measurement conditions and accurate analysis of complex systems depending on the frequency range of interest.

This study focuses specifically on the sound transmission loss of roller shutter boxes, which are crucial components of building facades. Previous studies [5,6] have highlighted challenges in replicating precise acoustic data in laboratory tests and the significant impact of the position of the curtain (extended or retracted) on transmission loss. The choice of sound insulation material also plays a vital role, with the combination of melamine foam and heavy masses offering optimal insulation. To address these concerns and provide a reliable technique for predicting the acoustic behavior of roller shutter boxes, this study combines numerical analysis and experimental data. Limited research has been conducted on the acoustic evaluation of roller shutter boxes, with only a few accessible references available. The present study is unique in its use of numerical techniques for the acoustic characterization of roller shutter boxes, contributing to the existing knowledge. Furthermore, the authors have previously utilized numerical prediction and experimental calibration methodologies to analyze the sound transmission properties of windows and double glazing, enhancing the expertise utilized in this study on roller shutter boxes [7].

The objective of this work is to investigate the sound transmission characteristics of roller shutter boxes with the curtain retracted and propose design improvements for better acoustic performance in the frequency range between 100 Hz and 1000 Hz. The paper is structured as follows. Section 2 provides a detailed description of the roller shutter box design, examining its construction and constituent components that significantly influence sound transmission. Section 3 focuses on experimental measurements conducted according to ISO 14010:2010 standards [8] to assess the sound transmission loss of roller shutter boxes. Laboratory measurements and advanced acoustic techniques are employed to evaluate the effectiveness of these boxes in reducing sound transmission. Section 4 concentrates specifically on sound transmission through the roller shutter box. It utilizes the numerical model to simulate and analyze the acoustic behavior, establishing a correlation between numerical results and experimental findings for reliable simulations. In Section 5, a rigorous parametric analysis investigates various factors influencing sound transmission in the roller shutter box. Critical parameters such as the presence of end caps, boundary conditions, positioning of sound insulation material, and optimal placement of heavy masses are thoroughly examined.

2 DESIGN DESCRIPTION OF ROLLER SHUTTER BOX

A roller shutter box, depicted in Figure 1, is an enclosure typically installed above windows to house a roller shutter system. It serves as a secure and compact storage space for the roller shutter when not in use, protecting and concealing the mechanism. The specific components within a roller shutter box may vary, but the common ones are described below.

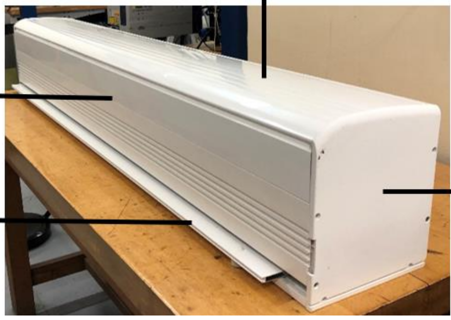

Figure 1: Retracted roller shutter box

Figure 1 shows a retracted roller shutter box. The main structure is the box casing, made of aluminum or PVC and available in different sizes to accommodate various shutter dimensions. The box casing consists of double-leaf panels with stiffeners, reducing weight while maintaining strength. The stiffeners evenly distribute the load, enhancing resistance against bending or deformation. They also contribute to thermal insulation by trapping air within the panel cells, reducing heat transfer between the inside and outside environments.

Figure 2 displays an extended roller shutter box. In addition to the box casing, it includes a trapdoor providing access for maintenance, repairs, or adjustments. End caps are fitted on both ends of the box casing to seal and secure the roller shutter, preserving the box's integrity and preventing the entry of dust, debris, or insects.

Figure 2: Extended roller shutter box

The movable part of the roller shutter is called the shutter curtain, shown in Figure 2. It consists of interconnected slats or panels made of aluminum or PVC. These slats offer security, insulation, and protection against noise, sunlight, and weather conditions. Two types of slats exist: full and hollow. Hollow slats can be filled with insulation materials like polyurethane foam. The end slat, located at the bottom, serves as the closing element, ensuring a secure seal when the roller shutter is fully closed.

The curtain axis includes a roller tube, a hollow metal tube within the roller shutter box.When retracted, the shutter curtain or slats coil around the roller tube. To facilitate opening and closing, a spring or motorized system rolls and unrolls the shutter. Manual equipment, which may have a strap or crank handle, may be less insulated than motorized systems due to potential gaps that allow air passage.

Apart from being an area with poor thermal and acoustic performance, the roller shutter box casing is also susceptible to dust, humidity, and pest accumulation. Effective insulation is essential to address these issues and minimize external disturbances. Insulation materials such as rock wool, glass wool, expanded polystyrene, melamine foam, and heavy masses can be used. For optimal sound insulation against airborne noise, dense and thick insulation is required. Even small uninsulated areas can create sound bridges that compromise the box's performance.

3 EXPERIMENTAL SOUND TRANSMISSION LOSS MEASUREMENTS

3.1 Measurements in a laboratory

ISO 14010 [8] is the standard utilized for assessing the sound insulation of building components. The testing laboratory consists of two connected rooms, with a recommended minimum difference of 10% in their volumes. The room dimensions are selected to ensure evenly spaced natural frequencies in the low-frequency range. The room volume should not be less than 50 m^3, and the reverberation time should not exceed 2 seconds. Maintaining the room temperature between 17°C and 23°C and ensuring a relative humidity of at least 30% are necessary.

To conduct tests on samples like windows, air inlets, or roller shutter boxes, an opening is present between the two rooms. During sound loss index measurements in laboratories, the sound transmitted through any indirect path must be negligible compared to the sound transmitted through the sample.

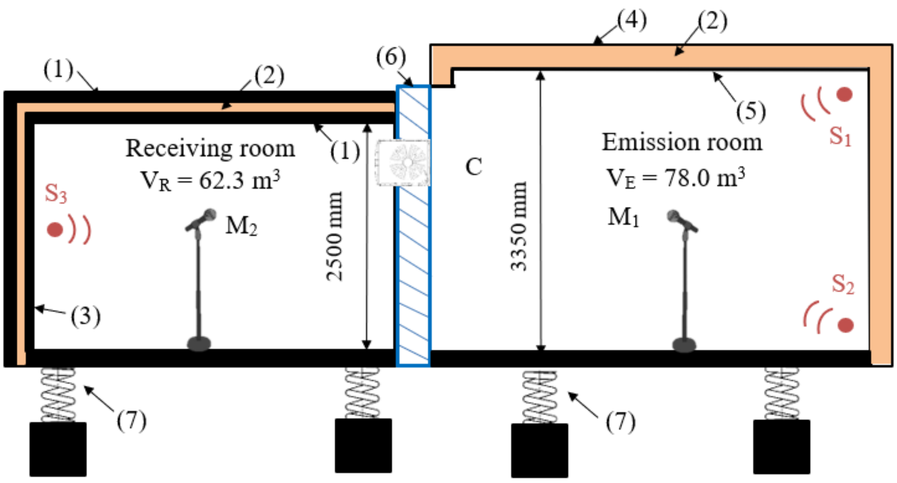

Figure 3: Experimental set-up of acoustic experimental test

For this study, the experimental setup is based on the configuration of emitting and receiving rooms depicted in Figure 3. The emission chamber has a volume of 78 m^3, while the receiving chamber has a volume of 62.3 m^3. The receiving room walls are made of 200 mm thick concrete and are separated by a layer of mineral wool for insulation. The wall labeled 3 is constructed using a 100 mm thick concrete block. Both rooms are placed on spring boxes denoted as 7. In the emission chamber, there are two steel sheets with thicknesses of 2 mm and 6 mm, respectively, separated by mineral wool. The separating wall is labeled as 6, and the tested box is labeled as C.

In the emission chamber, two monopole sources (S_1 and S_2) are positioned in the corners to generate multiple acoustic wave reflections on the walls, creating a sufficiently diffuse field. The power incident on the sample is deduced from the sound pressure. A rotating microphone (M_1) and a sound amplifier are employed in the emitting chamber. In the receiving room, a rotating microphone (M_2) and a source (S_3) are present to measure the room's reverberation time. The microphone in the receiving room also measures the sound pressure level transmitted by the tested element. Finally, there is a control room equipped with a real-time spectrum analyzer that provides results in third octave bands, a calibrator, and a computer for post-processing the results.

3.2 Acoustic indicators

Transmission loss (TL) refers to the reduction in energy intensity of a waveform as it propagates away from its source or through a specific medium or structure. This decrease in intensity can be quantified in decibels (dB) using the following formula [7,9] :

$$TL = 10 \log \left| \frac{W_i}{W_t} \right| \tag{1}$$

Here, W_i represents the power of the incident wave, and W_t represents the power of the transmitted wave.

The sound insulation between rooms is determined by the difference in sound pressure level between the emission room and the reception room. There are two types of indicators used to assess sound insulation between rooms: (i) The sound level difference between rooms D in dB, defined as:

$$D = L_1 - L_2 \tag{2}$$

where L_1 and L_2 are the average sound pressure levels in the emission and reception rooms, respectively. (ii) The normalized sound insulation index between rooms D_n in dB, defined as:

$$D_n = L_1 - L_2 - 10 \log \left(\frac{A}{A_0} \right) \tag{3}$$

Here, A_0 represents a reference equivalent absorption area of 10 m², and A is the equivalent absorption area of the reception room in m², considering different surface materials S_i with their corresponding absorption coefficients α_i:

$$A = \sum_i \alpha_i . S_i \tag{4}$$

For a room with a volume V, the equivalent absorption area A is related to the reverberation time T_R using Sabine's formula [10]:

$$T_R = \frac{0.16V}{A} \tag{5}$$

The sound level difference provides a straightforward measure of the overall sound reduction achieved by a building element. On the other hand, the normalized sound insulation index considers the room size being tested and offers a more accurate assessment of the building element's sound insulation performance. The corrective term in equation (3) accounts for the level difference in the reception room when the equivalent absorption area varies from A to A_0. This normalized index is commonly used for laboratory measurements.

4 ANALYSIS OF SOUND TRANSMISSION THROUGH ROLLER SHUTTER BOXES

4.1 Description of the numerical model

The roller shutter box being studied (Fig.4.a) is constructed using PVC (PolyVinyl Chloride) with the following mechanical properties: E_b = 2.8 GPa, ν_b = 0.35, ρ_b = 1460 kg/m^3 and η_b = 0.04. Its dimensions are 210 mm x 250 mm x 1450 mm. The end caps of the box, with a thickness of 10 mm, are made of ABS (Acrylonitrile Butadiene Styrene), an industrial thermoplastic polymer, with the following mechanical properties: Young's modulus : E_c = 2.9 GPa, ν_c = 0.42 ρ_c = 1100 kg/m^3 and damping coefficient η_c = 0.01.

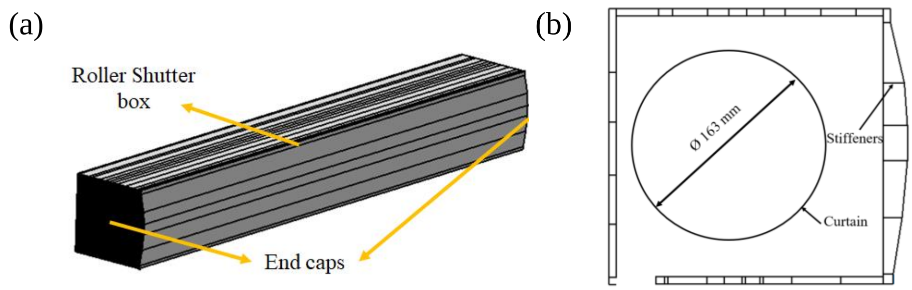

Figure 4: The CAD model of (a) the complete roller shutter

The box structure consists of double-leaf panels with stiffeners, where each wall and stiffener have a thickness of 1.5 mm (Fig.4.b). In the laboratory tests, the box is screwed onto surface 2 and sealed airtight with a sealant joint on surfaces 1, 1', and 3 (Fig. 5.a). The roller shutter box is filled with air (speed of sound, c = 340 m/s, density, ρ = 1.225 kg/m3, and damping coefficient, η = 0.01). In the retracted configuration, the rolled curtain has a diameter of 163 mm.

To improve sound transmission reduction through the roller shutter box, a combination of porous material (melamine foam) and heavy viscoelastic masses is introduced (Fig.5.b). The melamine foam used in the study has the following parameters: Young's modulus E_f = 120 kPa, ν_f = 0.1, ρ_f = 750 kg/m^3, η_f = 0.15, σ = 10000 N.m^{-4}.s, ϕ = 0.98, α = 1, Λ = 0.0001 m and Λ' = 0.0003 m. The melamine foam is modeled using Biot theory [4]. The heavy mass, with a thickness of 4 mm, has the following properties: E_h = 120 MPa, ν_h = 0.43, ρ_h= 1600 kg/m^3 and η_h = 0.65. In the numerical model, the panels and stiffeners of the roller shutter box were meshed using linear quadrilateral elements with a size of 10 mm. The emission room is replaced by a diffuse field, and the proposed Cholesky method is applied to handle the diffuse field with a maximal normal angle of 90 degrees and 30 realizations [11].

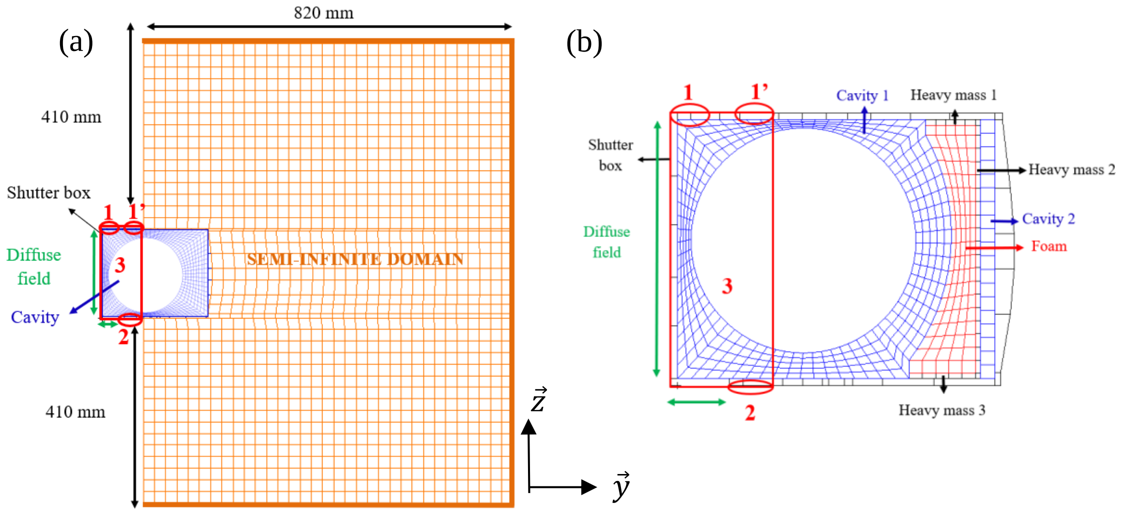

Figure 5: Numerical model used for acoustic simulation without (a) and with (b) insulation

The receiving chamber is represented by a parallelepiped-shaped domain with dimensions of 820 mm x 1030 mm x 1850 mm. This domain is meshed using hexahedral elements with a size of 25 mm and filled with air. The properties of the air in the receiving chamber are as follows: speed of sound c_{IE} = 340 m/s, density ρ_{IE} = 1.225 kg/m3, and damping coefficient η_{IE} = 0.02. To prevent acoustic wave reflections, 2D quadrilateral infinite elements [12] with a size of 25 mm are applied at the border of the receiving chamber domain (Fig.5.a). The melamine foam and heavy masses are also meshed using hexahedral elements with sizes of 9 mm and 4 mm, respectively. The cavities labeled as 1 and 2 in the roller shutter box are meshed using hexahedral elements with a size of 10 mm. Only the position of the retracted curtain will be studied.

4.2 Correlation between numerical and experimental results

In this section, we examine and analyze the correlation between numerical predictions and laboratory results regarding sound transmission through a roller shutter box. The study will also investigate the impact of introducing melamine foam and heavy mass acoustic treatment, as depicted in Fig.5.b.To evaluate the effectiveness of the soundproofing treatments, illustrates a comparison of the sound transmission loss (measured in dB) obtained from laboratory experiments and calculated numerically in third octave bands. In Fig.6.a, we present the results obtained without soundproofing's treatment and in Fig.6.b with treatment.

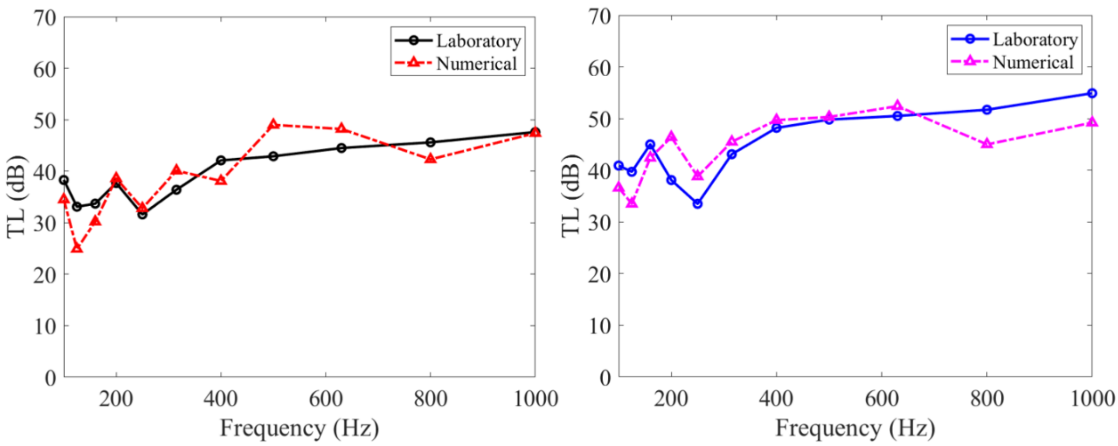

Figure 6: Correlation between test and numerical calculation without (a) and with (b) sound insulation

For all the cases studied, the average relative difference between the experimental results and the numerical calculations remains below 10%. This indicates the validation of our numerical model for predicting the sound transmission of roller shutter boxes when the curtain is retracted. This model will be utilized in the subsequent part of this section to optimize the structure and conduct further investigations. The numerical results indicate an average gain of 5.4 dB with insulation materials. These findings suggest that the combination of a retracted curtain and insulation materials offers the most effective acoustic performance.

5 PARAMETRIC ANALYSIS

5.1 Presence of end caps

The end caps of a roller shutter box serve multiple important functions and play a vital role in its overall performance. We conducted an investigation to explore the impact of end caps on the sound transmission characteristics of the roller shutter box without insulation. Specifically, we examined two scenarios: one with end caps and another without end caps, where the side surfaces of the box were treated as rigid end caps. We evaluated the sound transmission loss for the retracted curtain (Fig.7) in third band octave.

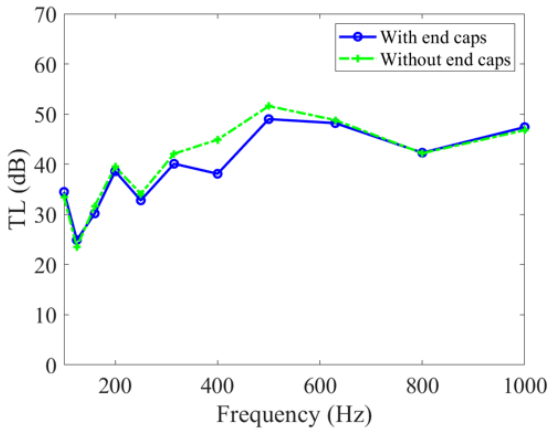

Figure 7: Analysis of the effect of the end caps

Interestingly, our findings indicate that the effect of end caps does not significantly affect the sound transmission loss when the curtain is retracted. In other words, the end caps do not appear to have a noticeable influence on the reduction of sound transmission. It is important to highlight that significant enhancements are evident when incorporating rigid end caps specifically at a frequency of 400 Hz. Our observations reveal a remarkable increase of 6.8 dB in acoustic performance when the curtain is retracted.This suggests that the rigid end caps may contribute to an enhancement in sound transmission loss at this specific frequency.

5.2 Effect of the boundary conditions of the box

Boundary conditions refer to the constraints and characteristics imposed on the system's boundaries or interfaces. Four configurations are considered (Fig.8). The first configuration represents the boundary conditions of the box during the laboratory tests. The box is screwed in surface 2 and on surfaces 1 and 1' a silicone sealant is applied to ensure airtightness (Fig.6.b). The three translations along x, y and z were blocked for the screwed part and only the translation along x for the part with the seal. In configuration 2, we have blocked the translation along x and along z for the part with the sealant leaving the screwed part unchanged. In configuration 3, we have blocked the three translations for the screwed part and for the part with the seal. Finally, the box is clamped (blocking of the 3 translations and 3 rotations) for configuration 4.

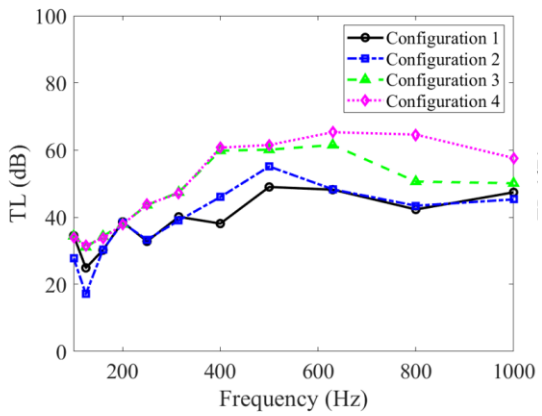

Figure 8: Analysis of the influence of the boundary conditions of the box

It is evident that the boundary conditions plays a crucial role in enhancing the stiffness and overall performance of the structure. the impact of boundary conditions becomes apparent, although there is relatively little variation between configuration 1 and configuration 2. However, when examining configuration 3 and 4, significant improvements in sound transmission loss can be observed. Among the various configurations, configuration 4 stands out as particularly promising in terms of acoustic performance

5.3 Effect of the position of the sound insulation material

Sound insulation materials are specifically engineered to minimize the transmission of sound by effectively absorbing sound waves. To illustrate this point, two configurations are compared. The first configuration, as depicted in Fig.5.b, involves the foam and heavy mass being unbonded and not attached to the trapdoor. The second configuration, shown in Fig.10.a, involves bonding the foam and heavy mass directly onto the trapdoor. By examining these two setups, the impact of the insulation materials' placement can be assessed in terms of sound transmission loss.

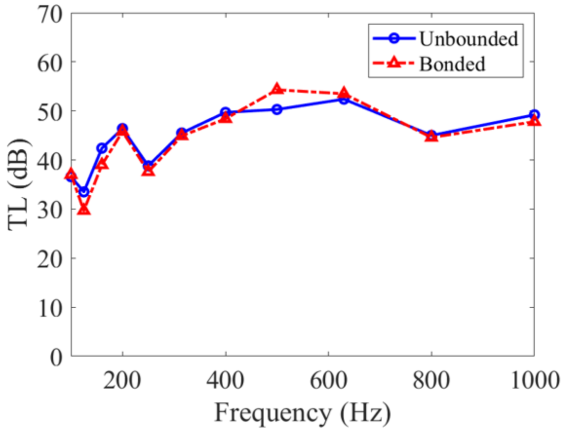

Figure 9: Effect of the position of the sound insulation material

The position of the insulation material does not show significant differences between the unbonded and bonded cases (Fig. 9). The retracted curtain acts as a barrier that prevents the easy passage of vibrations and noises contributing to the overall sound insulation performance. Its presence alone plays a vital role in reducing sound transmission, regardless of the position of the insulation material.

Within the frequency range of 100 Hz to 200 Hz., when the insulation materials are bonded to the trapdoor, a slight deterioration in sound transmission performance is observed. This phenomenon can be attributed to the absence of an air cavity between the insulation material and the trapdoor. The air cavity typically serves as an additional layer of sound insulation by providing an acoustic insulator. Without it, there is a minor influence on sound transmission within this specific frequency range, resulting in a slightly decreased sound transmission loss.

5.4 Optimization of the placement of heavy masses

Adding heavy masses strategically can enhance soundproofing by effectively blocking sound waves and reducing sound transmission. The number of heavy masses should be optimized based on factors such as design, dimensions, materials, and desired sound insulation level for the roller shutter box. Increasing the number of heavy masses can potentially improve soundproofing, but there may be diminishing returns beyond a certain point. Our focus is on optimizing the placement of heavy masses within the box to maximize sound insulation. We examine three configurations: Configuration 1 (insulation materials bonded to the trapdoor (reference (Fig 10.a))), Configuration 2 (addition of a heavy mass on the inner underside of the box (Fig 10.b)), Configuration 3 (replication of configuration 2 with an additional heavy mass on the upper inner side of the box (Fig 10.c)). The added heavy thicknesses are 4 mm.

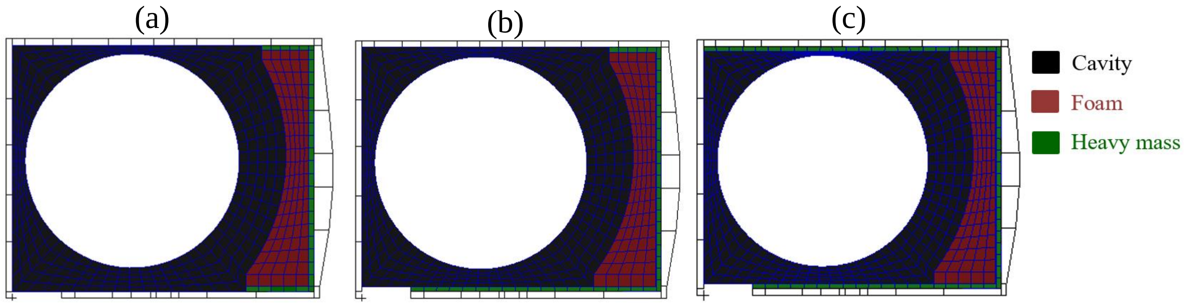

Figure 10: (a) Configuration 1, (b) Configuration 2 and (c) Configuration 3

Configuration 2 shows a slight improvement in sound insulation compared to Configuration 1 with an average gain of 2.3 dB. This indicates that the inclusion of a heavy mass on the inner underside of the box contributes to a modest enhancement in reducing sound transmission, (Fig.11).

In the comparison between Configuration 1 and Configuration 3, there are no significant improvements observed in terms of sound insulation (Fig.11). During our investigation, we have identified an average gain of 1.3 dB within the frequency range of 100 Hz to 315 Hz. However, beyond 315 Hz, the acoustic performance of the box begins to decline. This suggests that the addition of an extra heavy mass on the upper inner side of the box, as implemented in Configuration 3, does not significantly enhance soundproofing when the curtain is retracted.

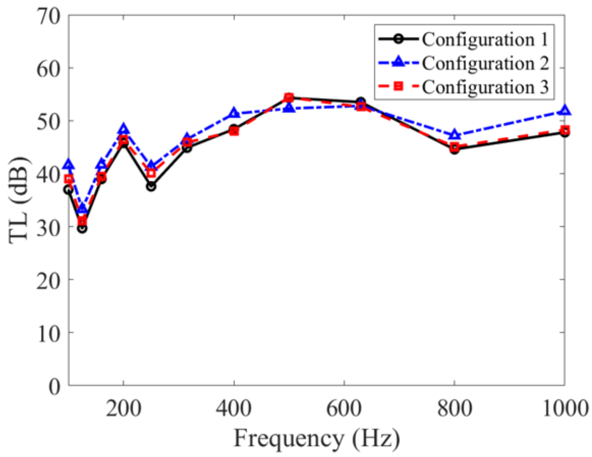

Figure 11: Numerical comparisons for different positions and number of heavy masses

6 CONCLUSION

We developed a numerical model to analyze roller shutter box acoustics, considering insulation, end caps, and boundary conditions. Validation experiments and simulations confirmed our model's accuracy. In our study, end caps had minimal impact on sound transmission loss except at 400 Hz. For the effect of the boundary configurations, configurations 3 and 4 showed significant improvements. Properly positioning sound insulation materials was crucial in 500 Hz when the insulation materials where bonded to the trapdoor. Strategic placement of heavy masses slightly enhanced sound insulation. Future work involves making the numerical model for the extended curtain and optimizing acoustic insulation by identifying key parameters and conducting a cost-effective sensitivity analysis using a metamodel.

ACKNOWLEDGMENTS

The authors would like to express gratitude to CODIFAB (Comité professionnel de Développement des Industries Française de l'Ameublement et du Bois) and UFME (Union des Fabricants de Menuiseries) for their cooperation and financial support.

REFERENCES

[1] Soussi C, Aucejo M, Larbi W, Deü JF. Numerical analyses of the sound transmission at

low frequencies of a calibrated domestic wooden window. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2021;235(14):2637-2650.

[2] Larbi W, Deü JF, Ohayon R. Vibroacoustic analysis of double-wall sandwich panels with viscoelastic core. Computers & Structures.2016;174: 92-103.

[3] Hwang HD, Maxit L, Ege K, Gerges Y, Guyader JL. SmEdA vibro-acoustic modelling in the mid-frequency range including the effect of dissipative treatments. Journal of Sound and Vibration.2017;393(14):187-215.

[4] Allard JF, Atalla N. Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials. 2nd Edition. John Wiley & Sons. 2009.

[5] Asdrubali F, Buratti C. Sound intensity investigation of the acoustics performances of high insulation ventilating windows integrated with rolling shutter boxes. Appl. Acoust. 2005;66(9): 1088-1101.

[6] Díaz C, Pedrero A. An experimental study on the effect of rolling shutters and shutter boxes on the airborne sound insulation of windows. Appl. Acoust.2009;70(2): 369-377.

[7] Soussi C, Aucejo M, Larbi W, Deü JF. Sound transmission through double-glazed window: Numerical and experimental analyses. In Proceedings of ICA 2019, Aachen, Germany.

[8] ISO 14010: Acoustics - Measuring the sound insulation of buildings and building components.

[9] Guyader JL, Lesueur C. Acoustic transmission through orthotropic multilayered plates, part II: Transmission loss. Journal of Sound and Vibration.1978;58(1): 69–86.

[10] Vigran TE. Building acoustics. Taylor & Francis. 2008.

[11] Nélisse H, Nicolas J. Characterization of a diffuse field in a reverberant room. J Acoust Soc Am. 1997;101(6):3517–24.

[12] Lloret MG. Prediction of the airborne sound transmission through a car front end model including poroelastic acousitc treatments. PhD Dissertation, Magdeburg University.2018.