Sound insulation of heavyweight walls with linings and additional layers: numerical investigation

Andrea Santoni
Department of Engineering, University of Ferrara, Ferrara, Italy.

Paolo Bonfiglio
Department of Engineering, University of Ferrara, Ferrara, Italy.

Patrizio Fausti
Department of Engineering, University of Ferrara, Ferrara, Italy.

Nicolò Zuccherini Martello
Department of Engineering, University of Ferrara, Ferrara, Italy.

Summary

This paper investigates the transfer matrix method to compute the sound transmission loss of heavyweight building structures with linings or coupled with additional layers to improve acoustic performances. The simulation of this kind of partitions does not only allow the estimation of the sound insulation given by the element, but it also represents a useful tool to design and optimize wall linings to increase sound insulation. The transfer matrix method is a powerful instrument to examine the sound transmission in multi-layered structures. Thanks to the recent developments presented by different authors, which allow to consider the finite size of the elements and to compute the sound transmission through the structural connections, it is possible to predict results with great accuracy. This method is used in building acoustics mainly to simulate lightweight structures, like double-leaf gypsum board walls. In these cases it is possible to simplify calculations by assuming that the leaves behave as thin plates, and by describing them using a simplified matrix. With heavyweight walls this is not always possible, therefore it is necessary to implement the complete matrix for solid elements. Furthermore, most of these partitions are not homogeneous elements, because they are made in masonry, with concrete or clay bricks and blocks with mortar joints. Hence, it is necessary to determine equivalent mechanical parameters to characterize them. The simulated results are compared to the sound transmission loss values of different walls measured in laboratory in order to validate the model.

PACS no. 43.55.Rg

1. Introduction

Double panel structures have been extensively studied in the last years, since they can be used in many fields for several applications. In buildings, for instance, double-leaf walls are widely used. Some years ago Hongisto [1] presented a comparison between the results of different models to predict sound insulation of double walls and the results of experimental measurements. Among these models, the transfer matrix method (TMM) represents one of the most efficient and most used tools to predict sound transmission in multi-layered structures. Thanks to the spatial windowing technique presented by Villot et al. [2], and provided in a simplified version by Vigran [3], it is possible to consider in the TMM framework the finite size of the elements, and to obtain predicted results, which are much closer to the experimental measurements. Recently, various authors have presented models to take into account the connections between the two panels, using different approaches [4, 5]. The TMM is especially applied to lightweight double leaf structures, in which plates can be described using thin plate theory and considering homogeneous materials with well-defined mechanical and acoustic parameters. The basic idea of this research is to use the TMM to investigate the sound transmission loss of masonry

Table I. Characteristics of the masonry wall used as input data in the TMM model

	Plaster	*Brick Wall*	*Plaster*
t $[mm]$	15	280	15
ρ $[kg/m^3]$	1900	840	1900
E $[Pa]$	Variable to determine		
η $[-]$	Variable to determine		
ν $[-]$	0.33 from literature		

walls made of hollows bricks with linings or additional lightweight walls applied in order to increase the soud insulation. Due to the inhomogeneous structure of this kind of massive partition, the prediction of the sound transmission presents some difficulties. The TMM requires the mechanical properties of each layer as input data but the definition of parameters such as the elastic modulus, E, and the loss factor, η, of a brick wall is not straightforward, neither with a theoretical, nor with an experimental approach. It this paper a method to estimate E and η of a heavyweight inhomogeneous element, knowing the transmission loss (TL), is presented. Initially only the heavyweight wall is considered in order to evaluate E and η, then these parameters are used to simulate the massive wall coupled with a lining layer in a TMM scheme. The results are compared with measured TL.

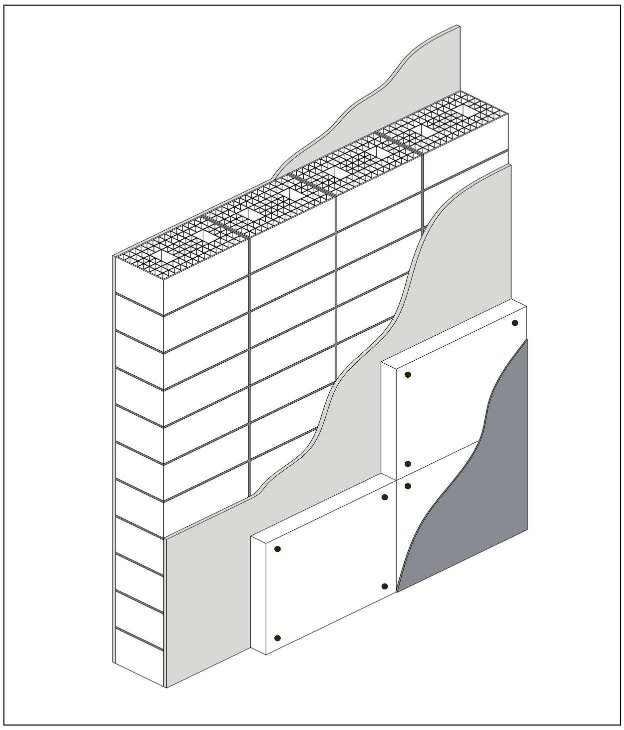

Figure 1. Studied structure: 280 mm thick hollow brick wall, plastered on both sides and lined with 80 mm of mineral wool and a plaster finishing.

2. Methods of investigation

2.1. The studied structure

For this research five different masonry walls, with attached layers of fibrous or porous linings connected with adhesive mortar and screws have been investigated. The first step was to determine the mechanical parameters of the massive wall. The results presented in this paper refer to a wall made of 250 mm thick hollow bricks, with vertical and horizontal mortar joints with nominal thickness of 10 mm and plastered on both sides. The lining consists of 80 mm tick mineral wool, fixed with six screws per square meter and with adhesive mortar along the border, and 5 mm cement plaster finishing. In Table I, an overview of the masonry wall characteristics is provided and in Table II the literature parameters used for the lining are listed. The wall is 3 meters high and 3.6 meters wide to fit the test window of the laboratory, therefore in the calculation a correction to consider this dimension of the element is applied.

2.2. Masonry wall characterization

As already mentioned the prediction of the mechanical parameters of masonry walls presents several difficulties. Previous works tried to deal with this problem using different approaches. Maysenholder and Haberkern in [6] calculated the sound transmission through a periodically inhomogeneous infinite plate under general conditions, but this method is not easily applicable because of the required computation capacities. Another homogenization method described in [8] calculates the equivalent material parameters from the measurements of the thickness resonance frequency. Jacqus et al. [8] presented a homogenized vibratory model to predict the acoustic properties of hollow brick walls starting from the elastic tensor of the brick material measured using an ultrasonic technique. The presented method does not consider the single brick, but deals with the entire wall, because the presence of mortar joints and plaster highly influences the wall behaviour. The basic idea is to consider the massive wall, constituted by bricks jointed with mortar, and the possible layers of plaster as a single equivalent homogeneous layer, and to determine the equivalent mechanical parameters of this layer using a minimization based procedure. In this process the equivalent layer is modeled with the TMM, in which the geometric parameters together with the measured TL of the wall and the Poisson ratio are the input data, whereas E and η represent the variables. A nonlinear unconstrained optimization algorithm, which minimizes the sum square of the errors between the experimental TL and the results of the TMM model, varing E and η, is used to estimate these parameters. The result of this process represents just one of the mathematical solutions, and does not have a strong

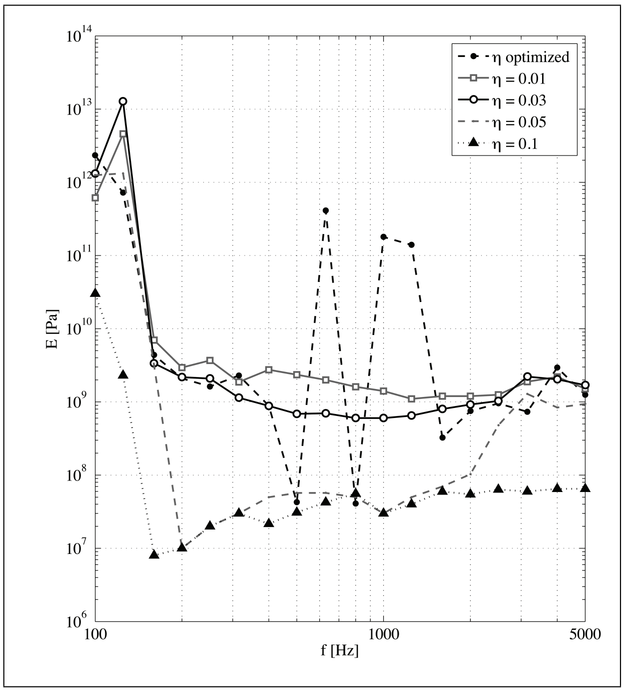

Figure 2. Estimated values of E associated to different values of η of the equivalent homogeneous layer.

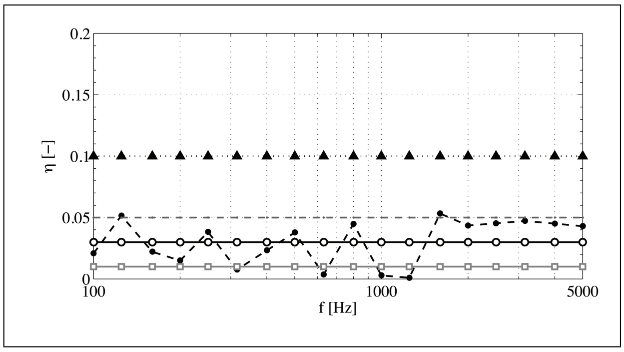

Figure 3. Different values of η of the equivalent homogeneous layer

physical meaning in itself. Moreover the optimization algorithm is not independent from the initial guess value. Hence both E and η are highly fluctuating in frequency, Figure 2 and 3. In order to preserve the physical meaning for both the elastic modulus and the loss factor it is very important to choose the range of values in which the algorithm searches for the optimized parameters. Since η does not vary much in frequency, its mean value has been kept constant all over the frequency range. In this way, for all the partitions simulated, the resulting curve of E is less fluctuating and tends to level off to a value as the frequency increases (Figure 2). The maximum value of the cost function was set at 3 dB.

2.3. Lining and structural connections

The sketch in Figure 5 outlines the model used to simulate the transmission through the wall with the

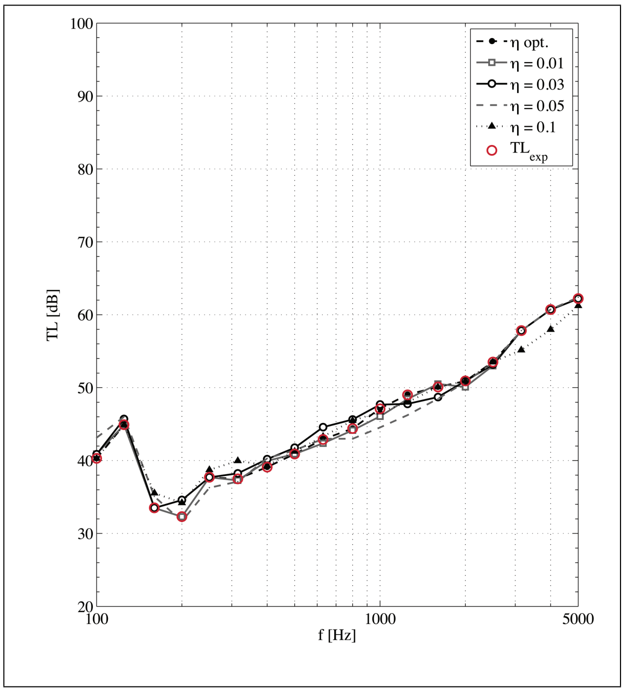

Figure 4. Transmission Loss of the masonry wall plastered on both sides. Measured and predicted results. The differences between the experimental values and the numerical results represent the cost fuction related to a specific pair of E and η

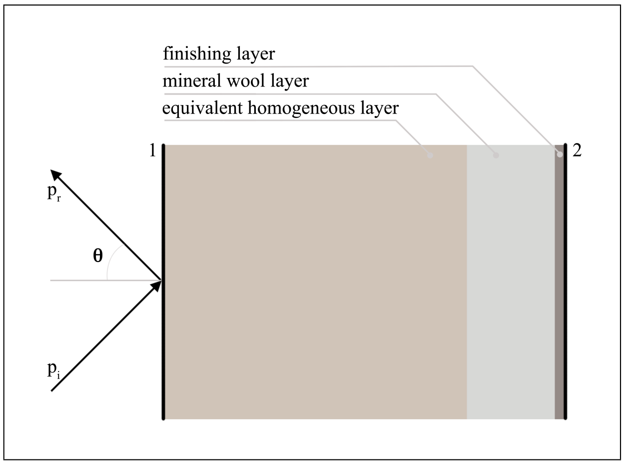

Figure 5. TMM model scheme

lining. The first layer represents the equivalent homogeneous layer that replaces the masonry wall and the plaster on both sides and it is modeled with the solid matrix using Young's modulus and the loss factor estimated through the procedure described in the previous section. The second layer represents the mineral wool. Some tests proved that describing it by using the fluid matrix overestimates the TL. This kind of mineral wool is a high-density fibrous material and the solid phase gives a contribution to the sound transmission, which is neglected using the fluid matrix formalism. Therefore this layer has been modeled by the

Table II. Characteristics of the lining used as input data in the TMM model

	Mineral Wall	*Cement Plaster*
t [mm]	80	5
ρ [kg/m^3]	90	1580
E [Pa]	7E05	4E09
η [$-$]	0.05	0.05
ν [$-$]	0.01	0.3
σ [Pas/m^2]	59100	–
ϕ [$-$]	0.9	–
α [$-$]	1	–
Λ [μm]	18	–
Λ' [μm]	0.01	–

porous matrix using the values in Table II. The same table also summarizes the input data for the last layer, the finishing, modeled with the solid matrix. In this phase we also investigated if and how the arbitrary choice of different pairs of E and η, estimated for the equivalent homogeneous layer, influenced the transmission in the global model, which also considers the lining. Five simulations were carried out: the first one used, for both E and η, the optimized values, which gave the smallest cost function. The others mantained constant the loss factor value all over the frequency range: $\eta = 0.01$ - 0.03 - 0.05 - 0.1, optimizing the elastic modulus for each value of η, (Figures 2 and 3). In all these cases the cost function value is always kept lower than 3 dB. As will be discussed in greater detail in the next paragraph, the results do not highlight significant differences in the resulting TL. Despite the pair of E and η used for the equivalent layer, the resulting transmission losses were overestimated in the high frequency range. This is due both to the adhesive mortar and to the screws used to connect the lining to the masonry wall. Considering the transmission through the adhesive connections negligible, the attention is focused on the structural connections.

The calculation necesary to consider point-like structural connections, described in [5], has been implemented. Vigran derived from [9] a simple model to consider both line and point bridges, in which the TL is corrected using the ratio between the power radiated due the bridge action on the plate, W_B, over the power radiated by the plate without any bridges, W_P, as reported in Equations 1 and 2. However this model considers only [$2x2$] matrix with solid layers modeled as thin plates and air cavities or porous materials modeled as fluids.

$$TL_c = TL - 10\log\left(1 - \frac{W_B}{W_P}\right), \tag{1}$$

$$\frac{W_B}{W_P} = n\sigma_B \left|\frac{v_B}{v_1}\right|^2 \left\langle \left|\frac{v_1}{v_2}\right|^2 \right\rangle, \tag{2}$$

Modeling the masonry heavy walls as homogenous thin plates leads to an overestimated TL, therefore the complete [$4x4$] matrix for solid elements is required. The term σ_B in Equation 2 is the radiation factor of plate 2 driven by one of the n structural connections. The ratio v_B over v_1 represents the input impedance of the plates from the connection point of view. Both of these terms are calculated using Vigran's formulation, although the ratio of the velocities on the surface of the plates needs to be adequate to a generic matrix, which describes the sound transmission through a multilayered structure. The last term of Equation 2 is derivated from the transfer matrix scheme formulation given by Allard and Atalla in [10].

Assuming a diffuse field, the surface 1 and the surface 2 impedances are defined as:

$$Z_1(\theta) = \frac{p_1(\theta)}{v_1(\theta)}, \tag{3}$$

$$Z_2(\theta) = \frac{p_2(\theta)}{v_2(\theta)} = \frac{\rho_0 c_0}{\cos\theta}, \tag{4}$$

The ratio of the pressures at the interfaces between fluid and plate surface on both sides can be expressed as a function of the transmission and the reflection coefficients, T and R:

$$\frac{p_1(\theta)}{p_2(\theta)} = \frac{1 + R(\theta)}{T(\theta)}, \tag{5}$$

Finally the last term of Equation 2 is calculated from the ratio of surface impedances Z_1 and Z_2:

$$\left|\frac{v_1(\theta)}{v_2(\theta)}\right|^2 = \left|\frac{Z_0(1 + R(\theta))}{Z_S(\theta)\,T(\theta)\cos\theta}\right|^2, \tag{6}$$

The square absolute value of the ratio of the velocities v_1 and v_2 is integrated over the angle θ since a diffuse field is considered.

3. Results

The elastic modulus associated to different values of loss factor, calculated for the equivalent homogeneous layer to represent the massive wall, is reported in one-third octave bands in Figure 2. The resulting TL from the simulation of this layer with the TMM is reported in Figure 4 and compared to the measured data; like all the others graphs in this paper, it is expressed in one-third octave bands. The difference between the experimental and the calculated values

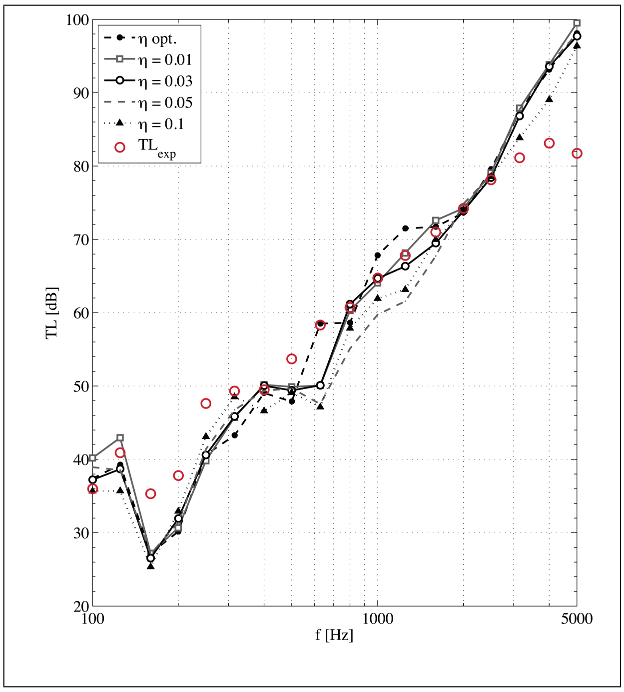

Figure 6. Transmission Loss of the masonsry wall with the lining. Measured and predicted results without structural connections.

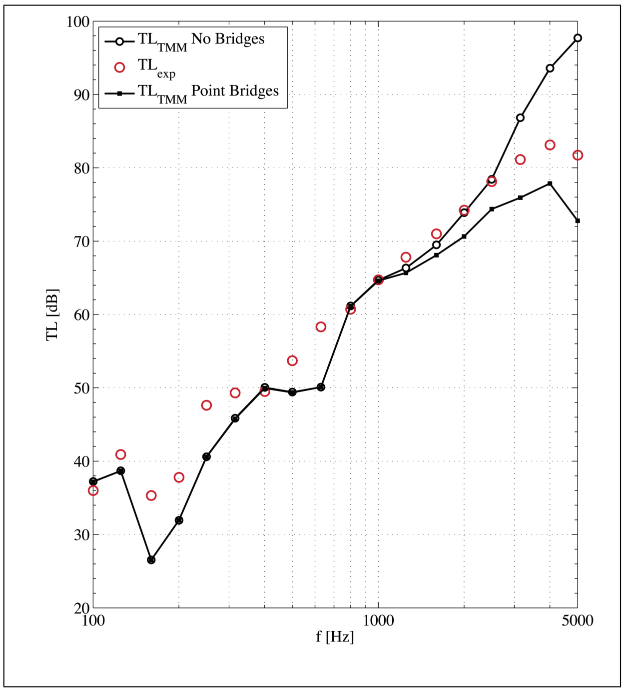

Figure 7. Transmission Loss of the masonsry wall with the lining. Comparision with experimental data and numerical result with and without structural bridges

represents the cost function. These pairs of elastic modulus and loss factor are the input data used to estimate the sound transmission through the different layers, described in the previous section and explained by the scheme in Figure 5, using the TMM. The predicted TL referred to the multilayered structure, considering both the massive wall and the lining, is shown in Figure 6 plotted together with the experimental results. The agreement between predicted and measured data is satisfactory, regardless of the chosen pair of E and η. At low-frequency the dip corresponding to the mass-spring-mass resonance in the 160 Hz band is emphasised by the TMM results, probably because the litterature parameters used for the mineral wool and the finishing represent just an approximation of the real values. At high frequency the TL is overestimated because the transmission through the structural bridges was neglected. In Figure 7 the experimental data are compared with two TMM results: one is obtained without considering structural connections and the other one assuming six point-like bridges per square meter. In this case the TMM simulations underestimate the TL, because, as explained in [5], this model allows to consider structural bridges that are mass-less and infinitely stiff; the agreement could be improved by considering finite stiffness connections as described in [11].

4. CONCLUSIONS

In this paper we described a method to estimate mechanical parameters of a inhomogeneous thick wall from the known transmission loss. The masonry wall and the mortar joints, together with the plaster layers, are considered as a single equivalent homogeneous layer and its elastic modulus and loss factor are estimated minimizing the cost function, defined as the difference between the measured TL and the result of a TMM model. Various pairs of E and η, which represent equivalent mathematical solutions in terms of cost functions, have been considered in order to understand the influence of these parameters in a multilayered structure. The calculated TL, of the massive wall lined with a mineral wool layer finished with cement mortar, was in satisfactory agreement with the measured data despite the chosen pair of E and η for the equivalent homogeneous layer, as long as they remain in a realistic range of values. Finally to obtain results closer to the experimental data, a correction term to consider infinite stiffness structural connections has been applied. The correction has been calculated as described by Vigran in [5] adapting the formulas for a general matrix. The finite stiffness of the connections leads to an underestimation of the TL, therefore to improve the results the real values of stiffness should be considered. Moreover the measured value of the mechanical and acoustic properties of the mineral wool, or any other fibrous and porous material that can be used in the cavity, are more reliable than literature data. Further developments of this reasearch will involve other heavyweight partitions and different materials for the lining. The charcteristics parameters of the lining material will be measured, instead of using the literature values as input data.

References

[1] V. Hongisto: Sound insulation of double panels – Comparison of existing prediction models. Acta Acustica united with Acustica Vol. 92 (2006) 61-78.

[2] M. Villot, C. Guigou, L. Gagliardini: Predicting the acoustical radiation of finite size multi-layered structures by applying spatial windowing on infinite structures. Journal of Sound and Vibration 245(3) (2001), 433-455.

[3] T. E. Vigran: Predicting the sound reduction index of finite size specimen by a simplified spatial windowing technique. Journal of Sound and Vibration 325 (2009), 507-512.

[4] J. Legault, N. Atalla: Numerical and experimental investigation of the effect if structural links n the sound transmission of a lightweight double panel structure. Journal of Sound and Vibration 324 (2009), 712-732.

[5] T. E. Vigran: Sound transmission in multi-layered structures – Introducing finite structural connections in the transfer matrix method. Applied Acoustic 71 (2010), 39-44.

[6] W. Maysenholder, R. Haberkern: Sound transmission through periodically inhomogeneous plates: solution of the general problem by a variational formulation. Acta Acustica united with Acustica 89 (2003), 323-332.

[7] A. Dijckmans: Wave based calculation methods for sound-structure interaction: application to sound insulation and sound radiation of composite walls and floors. PhD thesis, K.U. Leuven (2011).

[8] G. Jacqus, S. Berger, V. Gibiat, P. Jean, M. Villot, S. Ciukaj: A homogenised vibratory model for prediction the acoustic properties of hollow brick wall. Journal of Sound and Vibration 330 (2011), 3400-3409.

[9] D. Innes, D. G. Crighton: Power radiated by an infinite plate subject to a fluid floading and line drive. Journal of Sound and Vibration 123 (1988), 437-450.

[10] J. F. Allard, N. Atalla: Propagation in porous media. John Wiley and Sons Ltd., UK, 2009.

[11] T. E. Vigran: Sound insulation of double-leaf walls – Allowing for studs of finite stiffness in a transfer matrix scheme. Applied Acoustic 71 (2010), 616-621.