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27th International Congress on Sound and Vibration
The annual congress of the International Institute of Acoustics and Vibration (IIAV)
11-16 July, 2021
ICSV27
Annual Congress of the International Institute of Acoustics and Vibration (IIAV)

STONE MASONRY WALLS: INSIGHTS IN PREDICTION OF STRUCTURAL TRANSMISSION LOSS IN NON-HOMOGENEOUS AND ANISOTROPIC PARTITIONS

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To preserve the historical stone masonry buildings and the local landscape, for both newly developed buildings and renovation of existing buildings, natural stone masonry is a priority resource for reconstruction or renovation, in particular in areas recently devastated by seismic events. Since residential buildings must guarantee adequate comfort for inhabitants, based on well-defined technical performances, the transmission loss of vertical partitions in stone masonry building, typical of the Mediterranean area, as well as typical of the Alps and Apennine mountain areas, is evaluated, according to seismic safety criteria. From an acoustic point of view, the reduction of sound transmissions through stone masonry walls mainly depends on the mass, but also on the inhomogeneity of the structures, which reduce the transmission of vibrations.

Keywords: Stone masonry building, transmission loss

1. Introduction

Natural stone masonry is the oldest known building material, being coeval with the development of human societies. As known, evidence of this building technology is widespread all over the world. Methodologies and procedures for restoration and renovation, in compliance with safety technologies (in particular in seismic risk areas) of monumental, historical, and residential masonry stone buildings are fundamental requirements for the preservation of cultural heritage and local landscape [1]. Regarding Italy, in which historical and monumental stone masonry buildings are widespread in high seismic risk areas, MiBAC (Ministry of Cultural Heritage) promotes the importance of existing historical stone masonry buildings, as well as renovation and new building technologies, based on natural stone masonry. From this perspective, the new Technical Standards for Buildings (NTC 2018, *Decreto Ministeriale* 17/01/2018 [2]), according to recent regulation (The Directive on Cultural Heritage [3]), define in details the principles for the design, execution, and testing of constructions, concerning the performance required, in terms of essential requirements of mechanical strength, stability and of durability.

In this work, the structural-acoustic behavior, in terms of transmission loss, of vertical partitions in residential stone masonry buildings, typical of the Mediterranean area, is investigated based on empirical models. Residential buildings must guarantee adequate *comfort* for inhabitants, based on well-defined technical performance. The building engineering physics performances of stone masonry buildings are addressed for both newly developed buildings and renovation of existing buildings [4]. In particular, for residential buildings, the acoustical properties are well-defined law requirements, such as thermal performance. From an acoustic point of view, the reduction of sound transmissions through stone masonry walls depends on the mass, but also on the inhomogeneity of the structures, which reduce the transmission of vibrations.

The structural acoustical performance of natural stone masonry vertical partitions are investigated: the analytical calculation model is carried out on different typologies of stone masonry walls (taken as explicative examples, and exploitable as a function of different materials, shape of blocks, and dimensions), in compliance with NTC 2018 requirements [2], namely both soft stone (such as Etruscan tuff, shale) and hard stone blocks (such as limestone, granite), in the form of squared blocks or assembled in ordinary brickwork with huddled/mixed stones blocks.

2. The natural stone masonry walls

The Italian Technical Standards for Buildings (NTC 2018 [2]) define the masonry building techniques based on the organized and effective assembly of natural elements obtained from non-friable or flaking stone material and mortar. Many different kinds of natural stone are used in buildings, such as limestone, sandstone, tuff, travertine, marble, granite, and basalt, depending on the availability of the building area. The building technology requires a careful selection of the stone blocks distribution, which is achieved by optimizing the approaches of the junctions; afterward, the use of cement mortars, with suitable properties of adhesiveness and compressive strength (not less than 2,5 N/mm^2), allows a further strengthening of the structure, by increasing the adhesion of the blocks and occluding the empty spaces.

In stone masonry buildings, the vertical structures must be suitable for supporting vertical and horizontal forces, and well-defined values of mechanical properties of mortars [5, 6] and stone masonries are provided, such as compressive and shear mechanical strength, elastic and shear modulus. Vertical supporting structures are connected by timber floors and roof, and they are also connected to the foundation. Buildings must have both vertical and horizontal regularity, and timber horizontal partitions (i.e., floors and roofs) must not be pushing on vertical partitions [7, 8].

Limitations in height of stone masonry structural walls, as a function of thickness and typology of bearing stone masonries, are defined based on the building area seismic risk level. In figure 1 some typical examples of structural stone masonry walls are shown.

Figure 1: Structural natural stone masonry vertical partititons; Etruscan tuff/claystone masonry wall, limestone masonry wall and huddled/mixed stones wall.

3. Structural acoustic behavior: analysis and considerations

In stone masonry vertical partitions, two factors are expected to mainly contribute to the attenuation of sound transmission and vibrations: the high mass per unit area of the stone materials and the structural discontinuity between the elements. The set of stones and the mortar among them constitutes a considerable obstacle to the free propagation of vibrations, reducing the field of bending waves, which mainly contributes to the sound radiation of a partition. While the «mass-law» behavior can be easily evaluated, the effects due to the discontinuities in a non-homogeneous and randomly assembled partition on the vibrational field, are practically unpredictable, from an analytical point of view.

In the first analysis, it is possible to consider the partition as a *continuum medium*, in terms of inertial and elastic properties, characterized by high dissipative effects, behaving like a «locally reacting» plate. By considering the overall transmission loss of a homogenous partition, as a combination of resonant and forced transmission, it is expected a predominance of forced transmission in non-homogeneous and anisotropic partitions, due to «damped» amplitudes of resonant behavior, as well other frequency-dependent effects, as the coincidence.

As a first step, the transmission loss R of this kind of partitions is estimated from the advanced analytical Rindle's model [9], by assuming the masonry wall as a finite *continuum medium* [10]. However, this simplification is expected to underestimate the actual transmission loss, since in a homogeneous and isotropic partition, the field of the bending waves propagates freely according to the elastic and inertial properties of the partition itself; on the contrary, the presence of structural discontinuities, as well as the variations in impedance between stones and mortar, counteract the free propagation of elastic waves by reducing the sound transmission and the propagation of vibrations. The proposed acoustic calculation model and procedure can be applied to other typologies of natural stone masonry partitions, once proper mechanical and physical properties are known.

3.1 Materials involved in non-homogeneous and anisotropic partitions

Three typologies of stone masonry walls, in compliance with NTC 2018 requirements [2], are considered for acoustical performance investigation: masonry with squared soft stone (*Etruscan tuff*), masonry with squared hard stone blocks (*limestone*), and ordinary brickwork with *huddled/mixed stones*, typical of the Mediterranean building tradition, as shown in Fig. 1. Mechanical properties of actual stone materials can largely vary, as well as the elastic response of the wall as a whole. For this reason, in this schematic analysis, only average indicative values are taken into account (with margins even higher than 20%). In Table 1 the basic average properties of these masonries, needed for the implementation of the calculation model, are shown. Thickness t is the minimum admissible thickness, according to the NTC 2018 [2], values of density ρ, Poisson ratio ν and η_{int} internal loss factor, are common average values for natural stones, available in the technical database of materials, e.g., [11]. Young's modulus E^* is the average elastic response of the whole stone masonry wall, built with high-performance mortars, according to [12], while η^*_{int} is the average damping behavior of the whole wall, expressed as internal loss factor.

Table 1: Mechanical properties of investigated stone masonry walls

Materials of the partition	Thickness t /m	Density ρ /kg·m^{-3}	Young's modulus E^* /MPa	Poisson ratio ν /-	Stone loss factor η_{int} /-	Wall loss factor η^*_{int} /-
Squared limestone stone blocks	0.24	2780	2260	0.2 - 0.3	0.01 -0.02	~0.1
Squared tuff stone blocks	0.24	2445	1620	0.2 - 0.3	0.01 -0.02	~0.1
Huddled/mixed stone blocks	0.50	2690	3360	0.2 - 0.3	0.01 -0.02	~0.1

It is important to underline that the values of Young's modulus E^* of the whole stone masonry wall are experimentally determined from the measurement of stress-strain in compression, e.g., [13], and differs from the values of involved stone blocks Young's modulus. As shown in Table 1, values of Young's modulus of the stone masonry walls (as a whole) range between 1.6 GPa and 3 GPa, while Young's modulus of the involved stone ranges at least from 5-10 GPa (soft-medium strong stones, conglomerate) up to 50-100 GPa (strong stones, limestone) [14]. As a first consequence, since from the theory of elasticity damping increases with decreasing stiffness, the loss factor of the whole stone masonry walls is expected to be greater than in the stone alone. As an example, it has been shown that the dynamic dissipative behavior of stones and mortar system, in terms of internal loss factor, is ~10^{-1}, while in stone blocks are ~10^{-2}, as shown in Table 1. The values of η^*_{int}, are estimated from the experimental evaluation of dissipative effects, from the dynamic measurement of out-of-plane vibrations and damping analysis [6]. As it will be shown, these values are very important for the implementation of the calculation model.

3.2 Prediction model insights

The solution of the general problem of sound transmission through inhomogeneous plates has been investigated only for periodical structures [15], but cannot be (easily) applied for anisotropic and randomly-assembled structures, although considered as a three-dimensional linearized elastic-dynamics system since boundary conditions are different, i.e., no iterative periodical sub-sets are identifiable.

The Cremer's wave-like approach [16], for homogenous (infinite) plate, affirms that the behavior of bending waves across a (single) discontinuity is known if (and only if) the transverse velocities, the shear forces, the angular velocities, and the moments are continuous across the discontinuity. In the cases described above, these conditions are not satisfied, due to the different material (i.e., the mortar) in the discontinuity, between the stone blocks. In any case according to Cremer [16], discontinuity in cross-section plate, increases the transmission loss of flexural waves, as a function of plate thickness ratio.

In non-homogeneous and anisotropic partitions, it could be admissible to consider a relevant influence of dissipative effects in the finite *continuum medium*, in terms of a three-dimensional linearized damped-dynamic system. The values of total loss factor (of the whole masonry wall, in analogy to the average elastic response E^*) need to be reconsidered, as well as the losses related to the resonant radiation efficiency; moreover, resonant mode of the flexural waves field in the partition, due to the coincidence effect, have to be considered "dampened".

3.3 Implementation of the analytical model

The overall transmission loss R of a vertical partition of surface area S, is determined as a composition of sound reduction for resonant transmission R_r and forced transmission R_f, based on the following frequency-dependent relation:

$$R = 10\log(10^{-0.1R_r} + 10^{-0.1R_f}) \quad \text{dB} \tag{1}$$

Where the sound reduction for resonant transmission R_r is calculated as:

$$R_r = R_0 - 10\log\frac{c_0^2\sigma_{res}^2}{2\eta_{tot}^* Sf}\cdot\frac{\Delta N}{\Delta f} \quad \text{dB} \tag{2}$$

And the sound reduction for forced transmission R_f is calculated according to the relation:

$$R_f = R_0 + 10\log\left[\left(1-\frac{f_{11}^2}{f^2}\right)^2 \cdot \left(1-\left(\frac{c_0^2}{c_s^2}+\frac{f_c^2}{f^2}\right)^{-1}\right)^2 + (\eta_{tot}^*)^2\right] - 10log\left(2\sigma_{for}\right)\ \text{dB} \tag{3}$$

The sound reduction R_0 is the mass-law for normal incidence:

$$R_0 = 10\log\left[1+\left(\frac{2\pi f m}{2\rho_0 c_0}\right)^2\right]\ \text{dB} \tag{4}$$

where m [kg·m^{-2}] is the mass per unit area of the vertical partition, $\rho_0 c_0$ [kg·s^{-1}·m^{-2}] is the characteristic air impedance (≈415 kg·s^{-1}·m^{-2}).

In equations (2) and (3), η^*_{tot} [-] is the wall total loss factor and f_c [Hz] is the coincidence frequency. In particular, the total loss factor is a composition of all possible losses, $\eta_{tot} = \eta_{int} + \eta_{border} + \eta_{rad}$, i.e., internal loss, boundary losses and losses related to the resonant radiation efficiency and the coincidence frequency is a resonant mode of the flexural waves field in the partition, calculated from the following relation:

$$f_c = \frac{c_0^2}{2\pi} \cdot \sqrt{\frac{12\,(1-\nu^2)m}{E^* \cdot t^3}}\ \ \text{Hz} \tag{5}$$

where c_0 [ms^{-1}] is the sound speed in air, ν is the Poisson ratio, m [kg·m^{-2}] is the surface area of the partition, E^* [MPa] is the average Young modulus and t [m] is the thickness of the partition.

According to the Rindel's model [9], it is possible to calculate the frequency-dependent radiation efficiency of forced σ_{for} [-] and resonant σ_{res} [-] vibrations at random incidence, as well as the fundamental frequency f_{11} [Hz] and the modal density of the partition $\Delta N/\Delta f$ [Hz^{-1}]. Phase velocity of shear waves c_s [ms^{-1}] is determined from Young's modulus E^* [Pa], density ρ [kg· m^{-3}] and Poisson ratio ν [-], from the following relation: $c_s=[E^*/2\rho(1+\nu)]^{1/2}$.

Table 2 shows the values of the phase velocity of shear waves c_s, the coincidence frequency f_c, calculated according to Eq. (5) and the fundamental frequency f_{11}, taking into account a surface area S=10 m^2, calculated according to the above-mentioned Rindel's model [9]. The weighted sound reduction index R_w is determined from the frequency-dependent transmission loss, calculated according to equation (1), by applying the ISO Standard 717-1 procedure [17].

Table 2: Acoustical and structural parameters of investigated stone masonry walls

Materials of the partition	Phase velocity of shear waves c_s /m·s^{-1}	Coincidence frequency f_c /Hz	Fundamental frequency f_{11} /Hz	Weighted sound reduction index R_w /dB
Squared limestone stone blocks	570.2	290.2	20.7	57.2
Squared tuff stone blocks	514.8	321.5	18.7	55.2
Huddled/mixed stone blocks	706.8	112.4	53.6	67.6

The transmission loss of the 3 partitions is determined from the Rindel's analytical model, defined in the Eqs. (1-4), by using the values shown in Table 1 and Table 2. In the graph of figure 2 the estimated transmission losses are shown, as a function of frequency: limestone wall (blue line), tuff wall (red line) and hubbled/mixed stone wall (green line). The calculated transmission losses show good performances in terms of noise reduction, in particular at low frequency, although the presence of sound transmission loss dips around the coincidence and fundamental frequencies, listed in Table 2. However, the "shape" of resonant and coincidence dips, strongly depends on the dissipative effects. As a consequence, it is important to have a very accurate estimation of all possible losses.

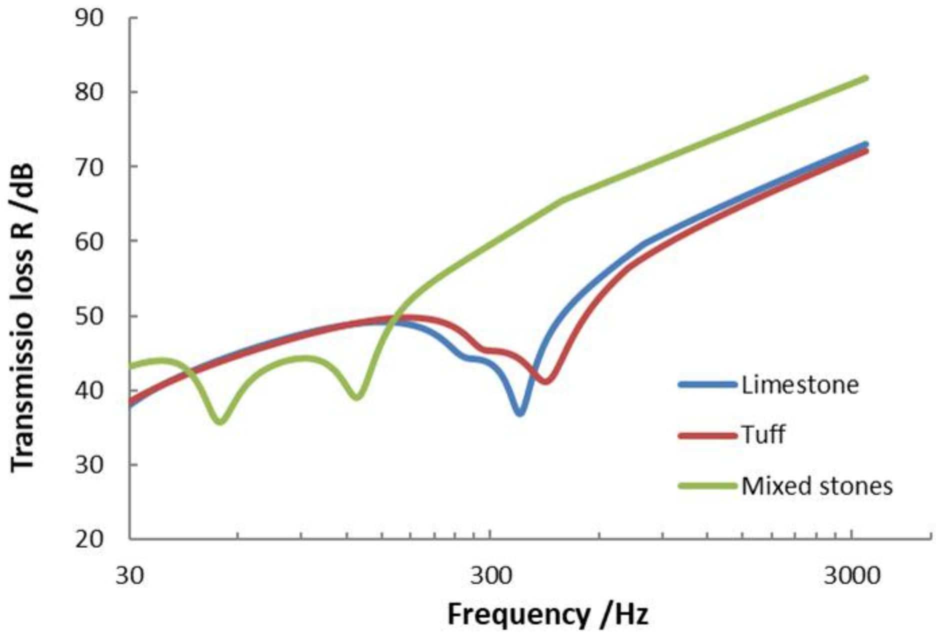

Figure 2: Empirical evaluations of the transmission loss of the 3 stone masonry partitions, with the proposed average values of the whole masonry wall high internal damping (η^*_{int} ~10^{-1}).

As an explicative example, in order to evaluate the sensitivity of the calculation model, with respect to the Young's modulus and the loss factor, a comparison of transmission losses variations of the mixed stones wall, is carried out. In the graph of figure 3a, the transmission losses are calculated for three different values of Young's modulus E^* within 20% of uncertainty, namely between 3000 MPa and 3700 MPa, at constant loss factor η_{int}=0.05; in the graph of figure 3b, the transmission losses are evaluated for three values of internal loss factor, namely η_{int}=0.1 (whole wall loss factor), η_{int}=0.05 and η_{int}=0.01 (stone loss factor), at constant Young's modulus E^*=3360 MPa. To emphasize differences, the graphs of figure 3 are plotted in a limited frequency range between 40 Hz and 500 Hz.

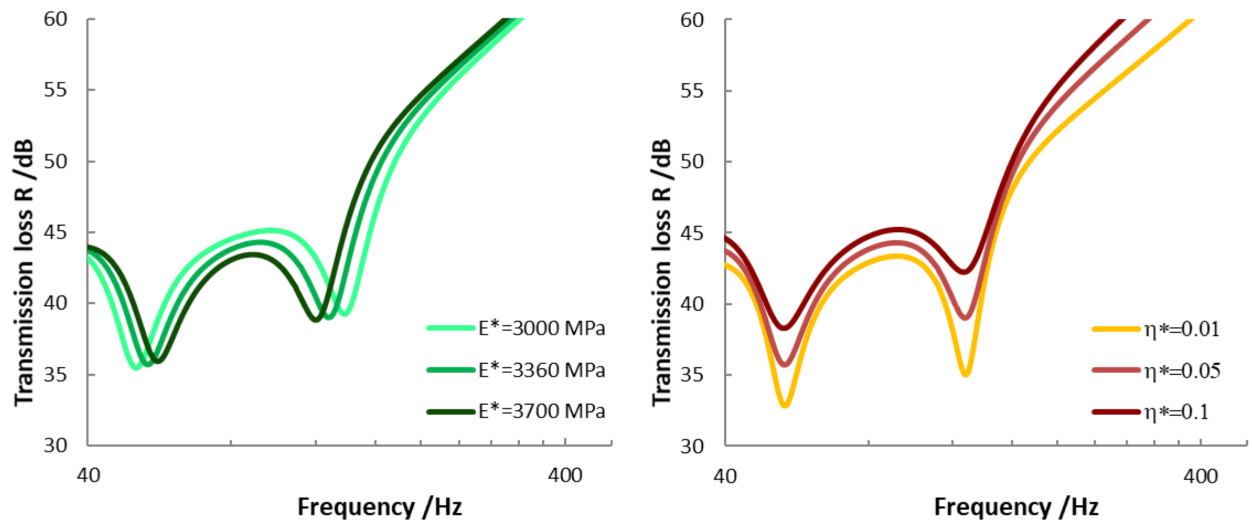

Figure 3: Empirical evaluations of the transmission loss of the mixed stones wall, as a function of different elastic and damping properties: a) effects of Young's modulus variation; b) effects of loss factor variations.

As shown in the graphs of figure 3a, the transmission losses of the partition under investigation show small differences by varying the Young's modulus; only a small shift in fundamental and coincidence frequencies occurs: f_{11} ranges between 50 Hz and 56 Hz and f_c range between 118 Hz and 107 Hz. It means that the elastic constant introduces only a relatively small error in the evaluation of transmission loss and the resulting weighted sound reduction index does not show significant variations.

On the contrary, by varying the loss factor, the radiation efficiency, and in turn the transmission loss, greatly varies, as a function of frequency, as shown in figure 3b. For values of loss factor η^*_{int} ~0.01 (typical of only stone), the resulting weighted sound reduction index is $R_w \approx 63$ dB, while for values of loss factor η^*_{int} ~0.1 (of the non-homogeneous and anisotropic partition as a whole), the resulting weighted sound reduction index is $R_w \approx 67$ dB.

Observed differences of about 4 dB shown that dissipative properties play a fundamental role in the prediction of acoustical behavior, as a consequence it is necessary to have accurate values of this parameter for suitable evaluations. It is possible to find in literature, devoted in particular to earthquake safety engineering, some interesting experimental works, in which damping properties of non-homogeneous and anisotropic stone masonry partitions, have been evaluated [18, 20]. As well as the average elastic response of the stone masonry wall as a whole, in terms of Young's modulus E^*, a suitable knowledge of dissipative properties is needed for an accurate evaluation of structural-acoustic behavior of this building technology.

4. Conclusions

Stone masonry is nowadays a promising building technology for both newly developed buildings and renovation of existing buildings, to retrieve the historical identity of peculiar urban landscapes and to preserve cultural heritage, ancient villages, minor historical towns, and even ordinary residential buildings. Requirements of stone masonry building technology are defined in specific technical standards. Although structural properties and seismic safety of this building technology are well known and agreed among experts, the building physics properties, in terms of acoustic performance, are barely investigated. In this work, it is shown the intrinsic ability of stone masonry to attenuate the transmission of sounds and vibrations, due to the high mass per unit area of the stone materials and the structural discontinuity between the elements as a function of loss factor and Young's modulus. Prediction of acoustical performances is analyzed in terms of airborne transmission loss, through an advanced analytical model. It has been shown that, by assuming in first analysis the non-homogeneous, anisotropic, and randomly-assembled partition as a *continuum medium*, with suitable mechanical features, in terms of elastic and dissipative properties, it is possible to evaluate the acoustical behavior, within a reasonable range of uncertainties due to the possible inaccuracy of input data.

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