Stone masonry buildings: Analysis of structural acoustic and energy performance within the seismic safety criteria

Stone Masonry Buildings: Analysis Of Structural Acoustic And Energy Performance Within The Seismic Safety Criteria

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Highlights

•Development, technological innovations and building physics of natural stone masonry.

•Sustainable renovation of stone buildings, preservation of original local landscape.

•Surveys on the recent legislative/technical framework of Italian building technology.

•Analysis of structure-borne and air-borne sound insulation of building elements.

•Evaluation of energy performance, reduction of energy consumption, thermal comfort.

ABSTRACT

Natural stone masonry is a building technology largely used all over the world, since the dawn of humankind. At present day stone masonry buildings, beyond being naturally characterized by intrinsic building physics performances, allow to reconsider the use of natural stone masonry (together with new technological supports, components and materials), as a promising "new trend" for both newly developed buildings and renovation of existing buildings, in particular where it is a priority to retrieve the historical identity of the urban landscape.

In this paper, energy performance and structural-acoustic properties of stone masonry buildings, in compliance with seismic safety criteria, are investigated and discussed on the basis of current technical standards and scientific literature. Related performances are evaluated by means of accurate calculation models. The results show that stone masonry buildings can offer often higher performance than those normally attributed to it.

1. INTRODUCTION

The use of natural stone material for buildings is coeval with the development of the human societies. As it is commonly known, the evidences of this building technology, from the Neolithic era up to the present day, are widespread all over the world. Furthermore, many stone buildings and historical centers of great historical, cultural and architectural relevance are listed among the UNESCO World Heritage sites [1]. As a consequence, restoration, renovation and safety technologies (in particular in seismic risk areas) of monumental and historical masonry stone buildings are fundamental requirements for the preservation of cultural heritages.

Many methodologies and technical procedures have been studied and applied for the preservation of stone masonry buildings [2 - 5]. Recent proposals of recovery or reconstruction, also supported by laws and regulations, aim to preserve both the historical buildings and its local landscape, by using (or re-using) the same building materials [6].

On the basis of this cultural perspective, with reference to Italy, in which historical and monumental stone masonry buildings are widespread on high seismic risk areas, MiBAC (Ministry of Cultural Heritage) recognizes the value of ordinary historical buildings as monumental buildings, by considering ancient villages and even minor historical towns, as cultural heritages as a whole. Natural stone masonry is thus a priority resource for buildings reconstruction or renovation in areas recently devastated by seismic events, in order to recover the historical-typological identity of Central Italy urban landscape. Indeed, in recent regulations (The Directive on Cultural Heritage [7]), according to new Technical Standards for Buildings (NTC 2018, *Decreto Ministeriale* 17/01/2018 [8]), methods of preservation and rebuilding provided for monumental buildings are implemented to the ordinary ones. For public buildings a specific regulation (*Decreto Ministeriale* 11/10/2017 [9]) prescribes the recovery of existing buildings for the limitation of land consumption, the reduction of the impact on the environment and the conservation of landscape characteristics.

In this paper, the building physics properties of ordinary residential stone masonry buildings, typical of Mediterranean area, as well as typical of Alps and Apennine mountain areas, are investigated in terms of structural acoustic behavior and energy performance, in accordance with seismic safety criteria. As it will be shown in very general terms, the basic principles of a proper design in seismic areas depend on the structural simplicity and regularity, particularly taking into account the elastic-plastic behavior of the structure. On the other hand, residential buildings must also guarantee the adequate *comfort* for inhabitants, based on well-defined technical performances. From an acoustic point of view the reduction of sound transmissions through stone masonry walls basically depends on the mass, but also on the inhomogeneity of the structures, which reduce the transmission of vibrations. From the energy point of view, the thermal behavior is mainly related to high inertia performance of the natural stone involved: by decreasing the peaks of thermal loads, the temperatures of the heated (or cooled) environment are more stable throughout the day and the seasons, allowing to use smaller plants and powered by renewable sources, and to reduce the phenomenon of the urban heat island.

Moreover, stone masonry buildings can be considered of interest, even from the environmental and societal impact point of view, since a sustainable renovation of buildings aims at re-using collapsed and good quality stone material, otherwise destined for landfills as solid urban waste; besides, the possibility to re-build “how they were and where they were” ordinary buildings close to monumental buildings, as well as small villages, with traditional building techniques and materials, can relaunch the craft activities and local economies.

In such context, within the frame of current regulations and standards of structural and seismic safety requirements, the building engineering physics performances of stone masonry buildings are investigated, for both newly developed buildings and renovation of existing buildings. In particular for residential buildings, the energy performance and the acoustical properties are well defined law requirements; in many country worldwide, thermal classifications, as well as acoustic classifications, are also proposed and applied [10, 11]. However, for stone masonry buildings, few studies regarding these performances are available in scientific/technical literature [12 - 15], and, as a consequence, building physics properties and behaviors are less known. The aim of this work, on the basis of empirical models, is to investigate the building physics properties of stone masonry buildings, in terms of acoustic and energy performance.

2. METHODOLOGY

The building physic performance of natural stone masonries, in terms of structural acoustic and thermal behavior in the frame of seismic safety, are investigated, on the basis of analytical calculation models and advanced simulations. The study involves the analysis 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 [8], 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.

The technical content of the paper is subdivided in three main thematic Sections, in which proper methods and models are applied and the results of the investigated performances are derived and discussed, namely:

- The basic structural and technical requirements of stone masonry buildings (Section 3);
- The acoustical and structural acoustic properties (Section 4);
- The energy performance and thermal comfort (Section 5).

In Section 3, according to recent regulations, a brief survey of the structural (Section 3.1), technical (Section 3.2) and seismic basic requirements (Section 3.3), in order to contextualize the field of investigation, are summarized; moreover a mention regarding management and recycling of construction and demolition waste is reported (Section 3.4).

In Section 4 the analysis and discussion on the acoustical performance, in terms of air-borne transmission loss (Section 4.1), impact sound insulation and façade insulation (Section 4.2), is carried out. A short consideration about induced-vibrations in buildings is also proposed (Section 4.3). Air-borne transmission loss is evaluated by means of the most recent analytical model, allowing to estimate the resonant and forced sound transmission through the examined partitions. Although this model returns accurate estimations of the acoustical behavior, results here obtained are presumably underestimated, due to the non-homogeneity of the stone walls; a discussion on the role of non-homogeneity in transmission loss, is then proposed.

In Section 5 the energy performance and thermal comfort of this kind of building, are investigated by a non-invasive graphic method: a typology generator, free and open source 3D creation suite Blender, with add-on “Cell Fracture”, for the realization of masonry patterns is used (Section 5.1). Analysis of thermal properties of stone masonry buildings, on the basis of proper advanced FEM simulations, is presented (Section 5.2). The description of the simulation and obtained results are shown and commented in detail (Section 5.3).

3. BASIC REQUIREMENTS OF STONE MASONRY BUILDINGS

In this Section only the fundamental structural stone masonry buildings requirements, as well as the seismic safety building technologies, are summarized, since these argumentations are outside the main purposes of the paper. In scientific literature and in current technical standards many methodologies and improved building technologies, based on the theoretical and applied structural engineering knowledge, are proposed. Nevertheless a brief survey is needed, in order to analyze the building physics performances, in compliance with current standards, regulation requirements and applied technologies.

3.1 Structural requirements

The Italian Technical Standards for Buildings (NTC 2018 [8]) and the contents of the *Decreto Ministeriale* 11/10/2017 [9], led to a cultural revision on 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 building, such as limestone, sandstone, tuff, travertine, marble, granite and basalt. Although stone materials are extremely varied, depending on the availability of the building area, the building technology basically involves two techniques: dry laying and mortar laying. Both techniques require a careful selection of the stone blocks distribution, which is achieved by optimizing the approaches of the junctions; afterwards, 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 the case of newly developed stone masonry buildings, NTC 2018 states three different typologies of bearing stone masonries, as shown in Fig. 1, with defined limitations in height and thickness:

- Mixed stone masonry with insertion of horizontal brick strips
- Non-squared stone blocks masonry, with almost regular joints.
- Squared stone blocks masonry regular joints.

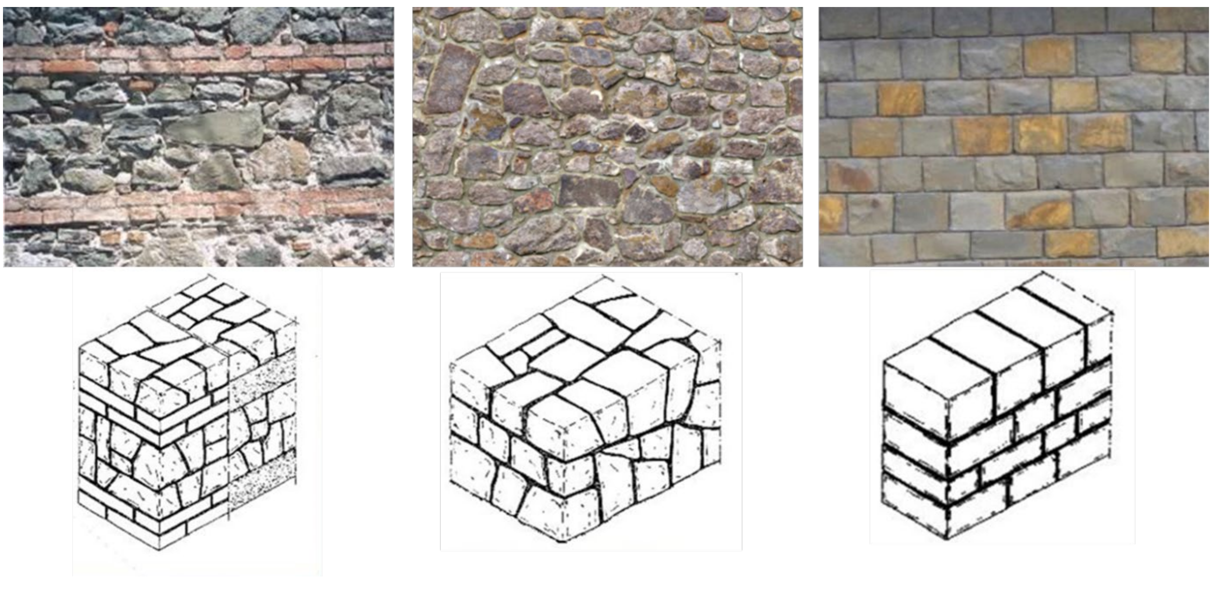


Fig. 1. Typologies of bearing stone masonries (NTC 2018 [8]): mixed stone masonry with insertion of horizontal brick strips (left); ordinary brickwork with huddled stones (center); Regular brickwork with squared stone blocks (right).

According to NTC 2018 [8], 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 [16, 17] and stone masonries are provided, such as compressive and shear mechanical strength, elastic and shear modulus. Vertical supporting structures are connected to each other by timber floors and roof, and they are also connected to the foundation.
Buildings must have both vertical and horizontal regularity, and horizontal partitions (i.e., floors and roofs) must not be pushing on vertical partitions. The timber beams, well connected to the walls, must perform a distribution of horizontal forces between the structural walls, acting as a proper functioning diaphragm, with maximum height between two floors less than 5 m. The building plans must be as compact and symmetrical as possible, by improving the connections, without altering the mass/stiffness ratio, by means of cords, curbs and chaining, in order to give a "*box-like behavior*", to the whole building [18-21].
Limitations in height of stone masonry structural walls, as a function of thickness and typology of bearing stone masonries, are defined on the basis of the building area seismic risk level.

3.2 Strengthening components and technological supports

As previously described, the vertical supporting structures are connected to each other by horizontal timber joists, acting as floors. The mechanical properties of materials and components involved, allow to improve the elasto-plastic behavior of the structure as a whole. Fig. 2 shows a typical timber floor, where the stiff behavior is ensured by the lightened concrete hood clamped to lateral structural walls by pins or continuous perimeter stringcourse. Alternatively, it is possible to stiffen the floor by laying double or triple crossed timber planks (connected to the structural walls) or, to contain the weights, by applying crossed FRP (Fiber Reinforced Polymer) strips [22]. The different strengthening techniques of the timber floors, illustrated in Fig. 2, have been tested in various university laboratories [23-25] validating their effectiveness and their application on many historic buildings. The dry applications, in particular, besides being reversible, allow a considerable stiffening without increasing the masses on the existing structure, to the benefit of reducing the seismic loads on the masonry stone building.

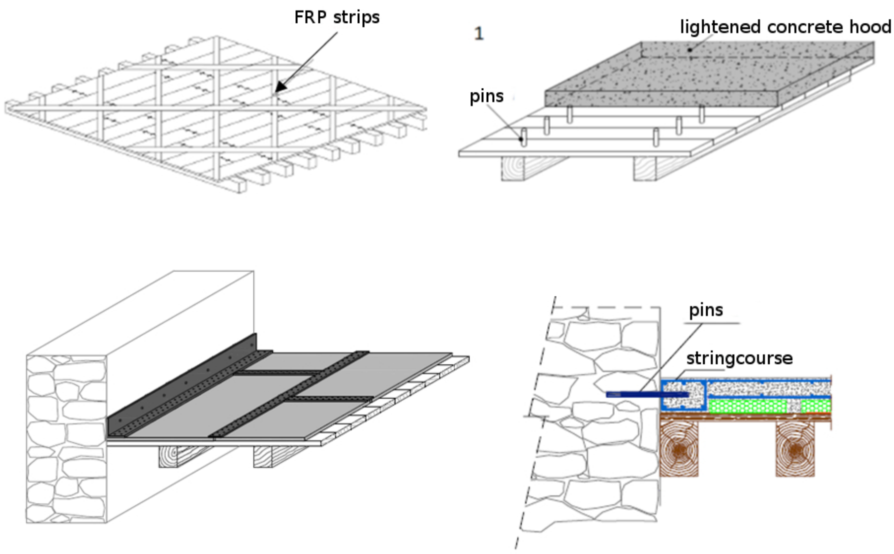


Fig. 2. Examples of reinforcement solutions for timber floors with diaphragm function. Timber floor with diaphragm function: connection to the walls; reinforcement with lateral steel beam riveted to the panel and to the wall.

These horizontal partitions can support technical systems improving the acoustic and energy performance of the building and the inhabitants comfort, such as typical impact floor insulation systems, such as resilient floor coverings [27] or floating floors [28] with radiant floor or thermal insulation systems [29, 30] between separate dwellings; in the case of a steel stringcourse an elastomeric damping material can be inserted, allowing to reduce both thermal bridge effects [31] and flanking sound transmissions [32]. In Fig. 3 are depicted two examples of thermal and acoustic technical solution for timber floors: a radiant water underfloor heating system, located between joists [33], and a floating floor for impact sound insulation [34].

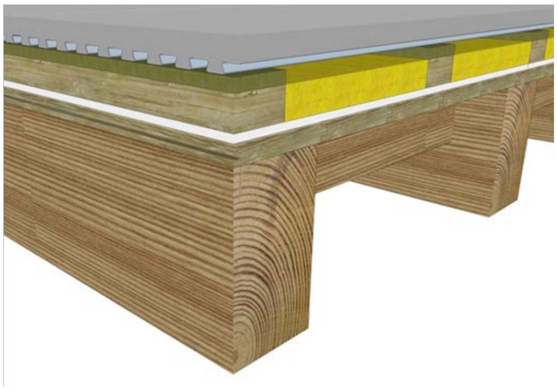



Fig. 3: Examples of technical systems improving the energy and acoustic performance of the horizontal timber partitions in stone masonry buildings.

3.3 Seismic safety

The evaluation of seismic action and safety requirements for stone masonry buildings is addressed in detail in the NTC 2018 [8], for both new buildings and restoration technologies. The issue of seismic behavior of masonry stone buildings and seismic safety technologies is well known and agreed among the research community and technical experts [4]: the theoretical knowledge, basically founded on the study of static, kinematic and dynamic behavior of multi-body systems and from the involved material properties, is in agreement with experimental evidences, from laboratory controlled measurements of mechanical behavior of fullscale or in-scale building systems subjected to static and dynamic effects, and also from *in-situ* measurements and seismic effects observation on buildings and structures [35-46].

The recent Central Italy earthquake has highlighted many structural vulnerabilities of historic stone masonry buildings [47]. However, there are many seismic improvement techniques whose application, by intervening on the individual structural elements, improve their mutual connections and the box-like behavior. It is worth noting some evidences in traditional and historical building techniques, in several European countries, already oriented towards the seismic safety of buildings [48-50]. From a research carried out in regions affected by earthquakes, it emerged that buildings realized with framed masonry showed an effective seismic behavior; in southern Italy, a peculiar framed building technology (the so-called "*opera Beneventana*"), established after the Capitanata earthquake in 1627, required that walls were divided into small fields, separated by timber boards well connected to the main pillars, within which it is allowed to create fractures. It is possible that, sometimes, some parts of the wall collapse, but the collapsing area is limited and circumscribed within the timber diagonal parts. Starting from 1700 the stone masonry with timber boards technique, known as "*Borbone*" system, was further improved [51-53].

Based on this experience, at the CNR-IVALSA laboratories a wall model was built according to this technique: once subjected to high mechanical stresses, this structure showed an excellent seismic behavior [54]. In Fig. 4 the wall and the testing system are shown.

Fig. 4. Reconstruction of the "*Borbone*" seismic safety masonry building technology at the CNR-IVALSA laboratories.

Among the most recent technologies, based on the analogous mechanical principle for the consolidation of stone masonry structures and for the seismic safety, the use of steel mesh or lattice fiber, is very interesting. The reinforcement technique, called "*Reticulatus*" [55], consists in the insertion of a continuous mesh made of stainless steel ropes or composite cords in the joints of mortar. This technique allows to strength stone masonry structures, preserving the original aesthetic aspects. The new retrofit techniques have been validated by laboratory tests [56] and applied in many seismic retrofitting work after Italian earthquakes. In Fig. 5, some examples of the consolidation system are shown.

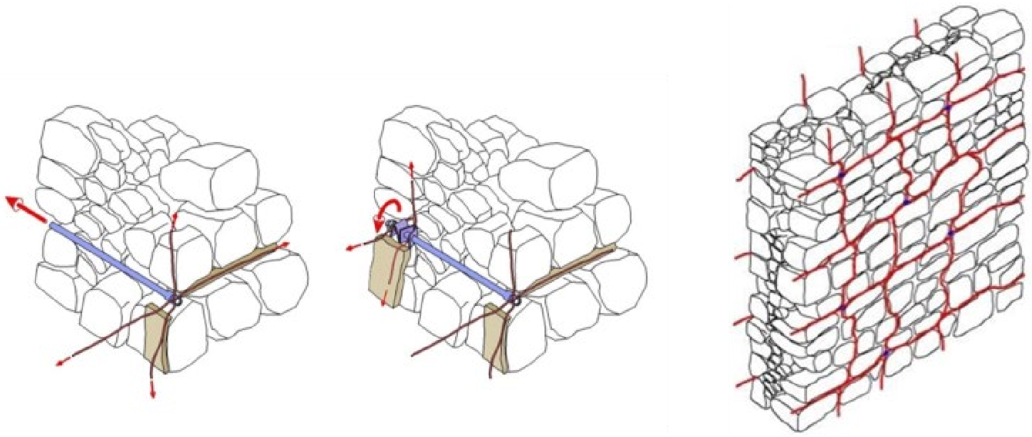


Fig. 5. The "*Reticulatus*" method for shear strengthening of fair-faced masonry [55].

3.4 Management and recycling of construction and demolition waste

The European Directive 2008/98/EC [57] concerning waste (implemented in Italy by Legislative Decree no. 205/2010 [58]), provides new targets for recycling to be achieved by 2020, with recycling rates of 70% for construction and demolition waste. Construction and demolition waste accounts for a significant proportion of total waste production in all EU countries, accounting for around 25% by weight of all waste generated in Europe. Indeed, from studies carried out at the beginning of the new century, around 180 Mt per year of waste deriving from construction and demolition of buildings are produced in the European Union [59]. This category of waste also includes rubble of collapsed stone buildings due to earthquakes and natural disasters. All these waste products are classified according to the European Waste Catalog, starting from 2015 according to Decision 2014/955/EU [60]. Construction and demolition waste are special waste, for which a separation from the other kind of waste must be guaranteed. Given the huge amount of natural resources characterizing the building industry, in order to reduce the environmental impact it is of importance to evaluate alternative solutions with respect to simple disposal of waste in authorized centers. The rubble and waste from the building process can become important resources, thanks to recycling, recovery and reuse; moreover, a careful selection of collapsed stone material, of good quality and integrity, can be easily reused in case of reconstruction and renovation, significantly reducing the production of special waste and therefore storage and disposal costs.

4. ACOUSTIC AND STRUCTURAL ACOUSTIC PROPERTIES

An intrinsic technological aspect of stone masonry buildings is the ability to attenuate the transmission of sounds and vibrations. In first analysis, two factors mainly contribute to this performance: the high mass per unit area of the stone materials and the structural discontinuity between the elements. As a matter of fact, 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. It can be assumed that by using mortars with appropriate elastic and damping properties, but at the same time able to guarantee the adequate structural stability of the building, it is possible to further increase the acoustic attenuation in stone masonry. Three typologies of stone masonry walls, in compliance with NTC 2018 requirements [8], 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. 6. The proposed acoustic calculation model and procedure can be easily applied to other typologies of natural stone masonry partitions.

Fig. 6. Examples of Etruscan tuff masonry wall, limestone masonry wall and huddled/mixed stones wall.

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. The mass per unit area of the partitions is calculated according to the minimum admissible thickness, according to the NTC 2018 [8], and the Young's modulus is the average elastic response of the whole stone masonry wall, built with high performance mortars, according to [61]. Values of density and Poisson ratio are common average values for natural stones, available in technical database of materials [e.g., 62, 63], the average experimental internal loss factor, for building material is available in [64].

Table 1: Mechanical and physical properties of 3 stone masonry typologies

Materials	Thickness t /m	Density ρ /kg·m^{-3}	Mass u.a. m /kg·m^{-2}	Young's modulus E /MPa	Poisson ratio ν /-	Internal Loss factor η_{int} /-
Wall with squared limestone stone blocks	0.24	2780	667	2260	0.2-0.3	0.01-0.02
Wall with squared tuff stone blocks	0.24	2445	587	1620	0.2-0.3	0.01-0.02
Wall with huddled/mixed stones blocks	0.50	2690	1345	3360	0.2-0.3	0.01-0.02

4.1 Transmission loss of stone masonry walls

In general terms, it is possible to preliminary estimate the acoustic performances, in terms of transmission loss R, of these kind of partitions. Here the recent and most advanced analytical model [65] is applied, by assuming for simplicity the masonry wall as a monolithic and homogeneous partition. However, this simplification is expected to underestimate the actual transmission loss, since in a homogeneous and isotropic partition, the field of elastic waves (and in particular of the bending waves) propagates freely according to the elastic and inertial properties of the partition itself [66]; 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. Unfortunately, at present, an acoustic model that takes into account structural discontinuities is unavailable in literature.

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, on the basis of 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:

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

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

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

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 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:

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

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 [65], 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, the coincidence frequency f_c, calculated according Eq. (5) and the fundamental frequency f_{11}, taking into account a surface area of 10 m^2, calculated according to the above-mentioned Rindel's model [65]. 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 [67].

Table 2: Calculated acoustical and structural parameters of 3 stone masonry typologies analyzed.

Materials	Phase velocity of shear waves c_s /ms^{-1}	Coincidence frequency f_c /Hz	Fundamental frequency f_{11} /Hz	Weighted sound reduction index R_w /dB
Wall with squared limestone stone blocks	570.2	290.2	20.7	53.3
Wall with squared tuff stone blocks	514.8	321.5	18.7	51.2
Wall with huddled/mixed stones blocks	706.8	112.4	53.6	63.7

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 Fig. 7 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 very high performances in terms of noise reduction, in particular at low frequency, although the presence of sound transmission loss dips around the coincidence frequencies listed in Table 2. The acoustic performances of the stone masonry walls in terms of the weighted sound reduction index, are R_w=53.3 dB, for 24 cm thick limestone wall, R_w=51.2 dB for 24 cm thick limestone wall and R_w=63.7 dB for 50 cm thick hubbled/mixed stone wall.

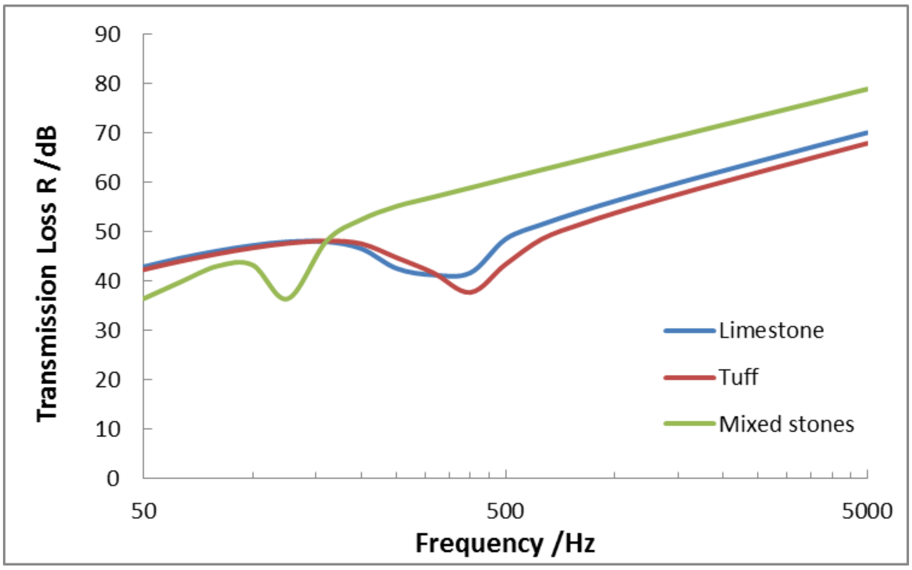


Fig. 7. Empirical evaluations of the transmission loss of 3 stone masonry partitions.

However, the transmission losses of the three partitions, are presumably underestimated, since the impedance variations between stone blocks and mortar and the structural discontinuities, as depicted in Fig. 8 (a), increase the dissipative effects, as damping, in the whole wall system; in particular, the internal damping of a heterogeneous system, as a masonry stone wall, is expected to be more effective than in a homogeneous system. As a consequence the loss of insulation due to the coincidence frequency dips is supposed to be reduced by the attenuation of the flexural waves field in the partitions [68]. The graph of Fig. 8 (b) qualitatively shows how such attenuation increases as a function of discontinuities characterized by different geometrical dimensions. Although graph of Fig. 8 (b) is related to the transmission loss across discontinuity in a plate cross-section, as a function of different plate thickness ratio, a similar behavior can be supposed across discontinuity between blocks of different dimensions, separated by mortar.

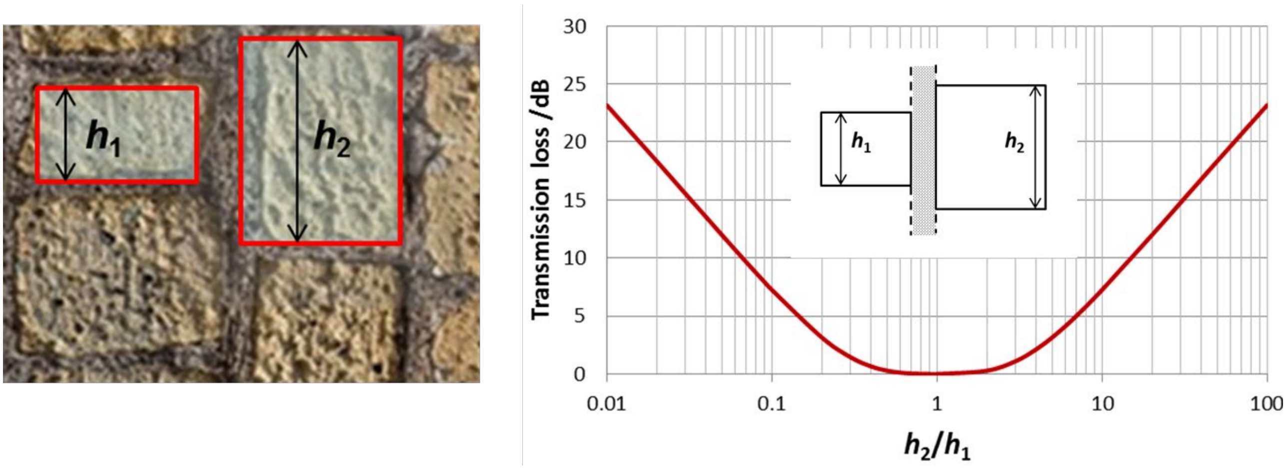


Fig. 8. Two adjacent block stones of different geometries (a); qualitative attenuation of sound transmission through a structural discontinuity between two different stone blocks, depending on the ratio of different geometric dimensions (b) [65].

4.2 Impact sound insulation and façade sound insulation

The impact sound insulation, as well the façade sound insulation, depends on the performances of the involved structures and components and does not directly depend on the mechanical properties of the masonry stones. As a matter of fact, either timber floors, as described in section 3.2, and façade elements, such as windows or doors, are light/weak components, with respect to the masonry stone partitions. As a consequence, the expected acoustical performance, is determined mainly from the insulation properties of these elements, measured in standard laboratories or estimated from computational models.

The impact sound transmission mainly depends on the radiation of the timber slab. If resilient covering or floating floors are used, in order to improve impact sound insulation [69, 70], it is possible to evaluate the occurring reduction of impact sound by directly applying standardized calculation models [71]. Moreover, several studies are recently proposed in order to evaluate impact sound insulation for timber structures and components [72]. Performance of impact sound insulation can be also considered independent from the flanking transmissions, since the horizontal partitions are much lighter than lateral walls, thus a significant reduction of vibrations transmission is easily achieved [73].

Similarly, the façade sound insulation depends on the insulation properties of the windows and/or doors installed on it. Since stone masonry walls are supposed to have high effective sound insulation properties, with respect to windows and/or doors, the sound from outdoor can only be reduced from the performance of the façade element and its components, such as frames, glass, shutters and technical profiles [74]. Sound insulations of façade can be improved by installing new-concept windows and/or doors, with effective sound insulating properties; moreover, these elements are in agreement also with energy and breathability criteria.

4.3 Vibration and shock control

Vibration and shock control in historical stone masonry buildings is a fundamental requirement for safety and preservation, since several sources of vibration, such as heavy car/tramway traffic, are nowadays increasing in historical centers [75, 76]. Criteria for the evaluation of vibrations and the

assessment of their effects on buildings are collected in several Standards [77, 78], regarding both structural/architectural damages and comfort for inhabitants.
A stone masonry wall is a complex mechanical system with many degrees of freedom [79], composed of a set of rigid bodies (stones) interconnected by mortar. The action of a force on this system accelerates rigid bodies and propagates, in the form of vibration, through the whole system. However, the set of system discontinuities is a first obstacle to the free propagation of vibrations, as described in Sec. 4.1. The series of "jump" of impedance between a stone and the adjacent stone, reduce the amplitude of the transmitted vibration and, moreover, the mortar acts as a further element of discontinuity. In this system the mortar can be assumed as a set of interconnected springs and dampers, as depicted in Fig. 9.

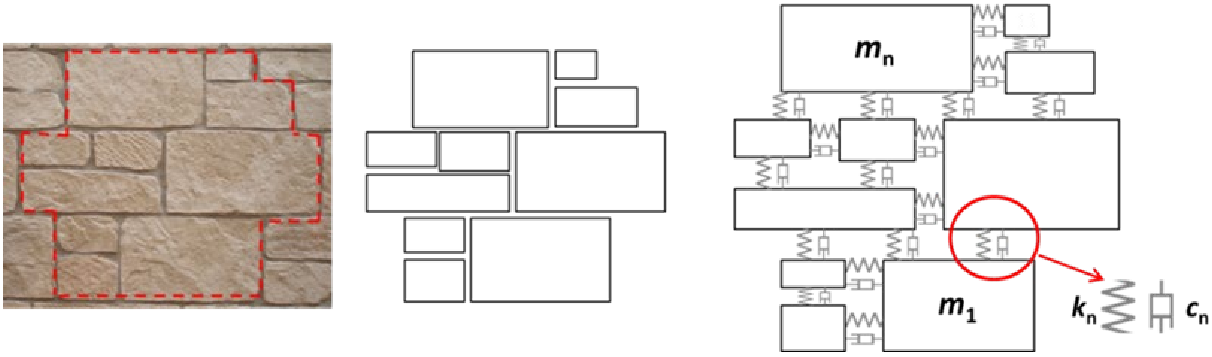


Fig. 9. Stone masonry represented as a multi-degree of freedom mechanical system.

A continuous or impulsive force, acting on the mass m_1 is transmitted to the adjacent masses through the mortar, represented as an interconnected system of springs k_n and dampers c_n. The elastic and damping properties of the mortar dissipate part of kinetic energy into heat and, consequently, the vibratory motion which reaches the mass m_n is actually reduced. Moreover, the set of stones of different sizes (hence different masses) acts as a "frequency filter" of the oscillatory motion of the vibration, since the frequencies of all the various mass-spring-damper subsets are different one from each other.
The elastic and damping properties of the mortar are therefore particularly significant, in terms of attenuation of vibrations and shocks. Using structural mortars characterized by appropriate mechanical properties, such as high internal damping coefficients, a further attenuation of the transmitted kinetic energy is expected. In addition, the use of mortars with suitable elasto-plastic properties, together with systems for consolidating stone masonry structures, such as steel mesh or lattice fiber [55], as depicted in Fig. 5, is supposed to further improve also the performance of the seismic safety action.

5. METHODS FOR INVESTIGATING ENERGY PERFORMANCE AND THERMAL COMFORT

The thermal performance of a stone masonry envelope depends fundamentally on its thermal inertia. The performances required by standards regarding thermal inertia are easily to be ensured in both cases by the masonry mass, while the very high transmittance values of the stone walls can be reduce by applying insulation system of adequate thickness. For the separation walls between dwellings, partitions with sound insulating materials, even on one side of the walls, can actually also ensure compliance with energy criteria.

Furthermore, adequate conditions of thermal comfort in indoor environments can be obtained through the masonry mass which allows a high periodic internal thermal capacity. In the summer period the albedo of the stones contribute to reduce the demand for cooling due to transmission of the solar radiation to inner and the heat island in the inhabited areas [80], according to [9].

The thermal behavior of the stone masonry building envelope is primarily affected by solar radiation and related temperature external variation, by the properties of the components, such as reflectance/emittance coefficients of the exterior surface or *SRI* (Solar Reflection Index), thermal conductivity λ [W/mK] of stone and mortar, density ρ [kg/m^3], specific heat capacity c_p [J/kg K] and periodic thermal transmittance Y_{IE} [W/m^{2}K], and finally by the frame typology created by the stone elements and the mortar joints.

The laboratory spectrophotometer measurement of solar reflectance for the types of examined stones (limestone and tuff) showed a thermal emittance varying in the range 0.88 – 0.93 for the stones samples, while solar reflectance measurement showed values greater than about 0.4, thus masonry stone can be considered *cool surfaces* [81-84].

The energy performance of stone masonry building is strictly influenced by the above mentioned parameters, which are of particular interest in the new regulatory framework which pays particular attention to the energy performance of buildings in summer, to the protection of the urban microclimate and to thermal comfort.

In order to reduce the impact on the urban microclimate known as Urban Heat Island (UHI) effect, the Italian decree [9] requires that external surfaces exposed to solar irradiation with a slope greater than 15% have SRI ≥ 29 and adequate conditions of thermal comfort in internal environments, through a design that provides a surface heat capacity $\kappa \geq 40$ kJ/m²K, referred to each individual opaque structure of the outer envelope [85].

Moreover, the influence of stone masonry on the urban microclimate and external thermal comfort is very low because the surface temperature of the stone is close to the temperature of the outdoor air during the day while it falls below the outside air temperature during the night.

The above-mentioned energy performances of stone masonry are determined by the thermal properties of the two main components, stone and mortar, but are also related to the shape of the stone blocks and of the mortar joints. The calculation of the thermal performance of existing buildings should therefore be based on the realization of samples in many points of the masonry to define the shape and the size of the stone blocks and the type of mortar used or, alternatively, on non-invasive methods, such as visual inspection and infrared thermography or ultrasonic measurements. In laboratory it is possible to define experimental procedure with hot box method for the thermal performance evaluation of stone walls. A detailed description of these methods is available in [86, 87].

5.1 A graphic method to determine the typologies of stone masonry

Although the influence of the mass components and thermal conductivity is well investigated [88-92], the role of the shape of stone blocks on masonry properties is less known, due to the great variability of the masonry typologies and involved materials. Indeed, thermal properties of stone and mortar are different and their volume ratio affects the thermal performances. Therefore, it is

very important to define a non-invasive method to easily calculate the performances of every typology of stone masonry.
At this purpose, in analogy to other researches [93-95], the typology generator, free and open source 3D creation suite Blender®, with add-on “Cell Fracture” [96], for the realization of masonry specimens with different mortar/stone volume ratio, is applied.
Unlike the above mentioned works, in which a 2D representation of masonry to study the compressive strength of the generated samples is used, the calculation of thermal performance of stone masonry is derived from a 3D model, that allows to analyze, as a complex system, the set of stones and mortar joints differently assembled, as shown in Fig. 10.
The 3D model, with add-on “Cell Fracture”, performs a semi-random creation of different elements, based on the assigned parametric values. After the creation, it is possible to “smooth” the elements (by using the command line “meshsmooth” with Autocad 3D software®), in order to obtain an approximated model of a real random rubble (irregular joints) and coursed rubble (regular joints) masonry walls. Clearly, by smoothing a 3D solid stone, its volume decreases and increases the ratio between the volumes of mortar and of stones. Therefore, it is possible to model the base sample of masonry in order to obtain the desired range of ratio *r* (%) between the volumes of the joint mortar and of the stone. In this study, the range limits were set between 5% and 30% (namely, from 5.5% up to 30.4%), in agreement with typical literature values, ranging between 10% and 20 %, as reported in [88] and in [94].
On the base of the value of “noise” N assigned to the add-on “Cell Fracture” and on the base of the application of “smooth” S to the element, 10 different assemblies of stone components and mortar joints were modelled, as shown in Table 3.

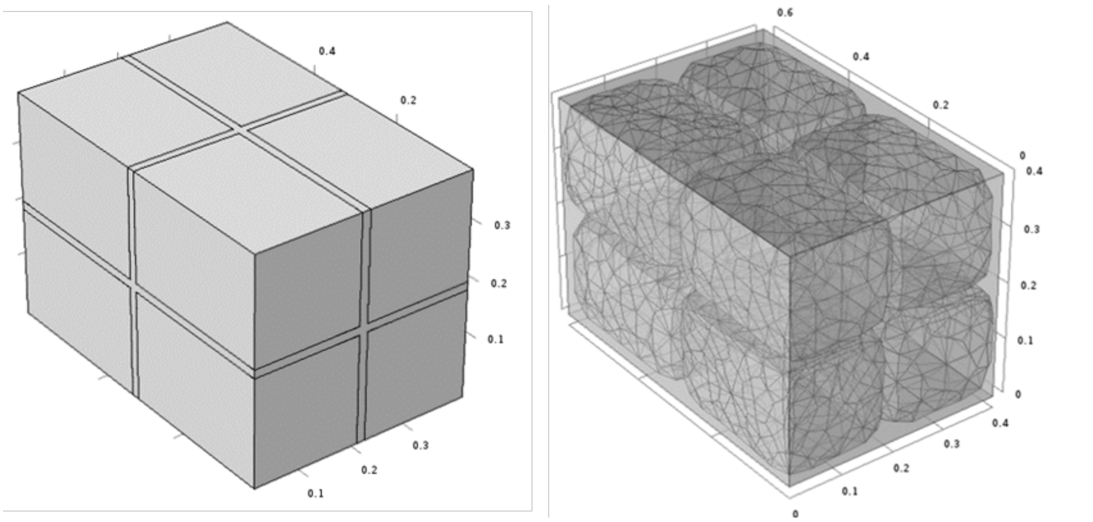
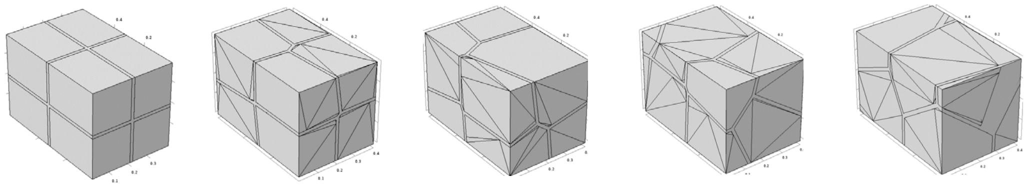
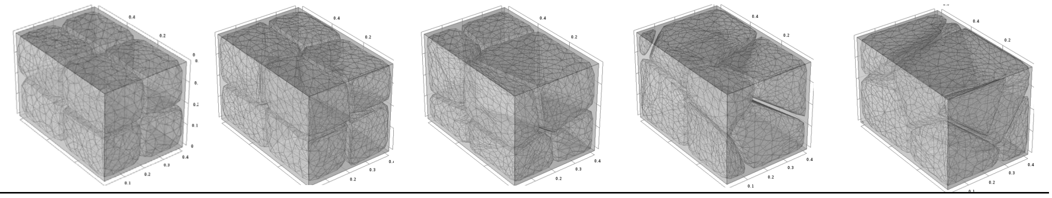


Fig. 10. Left - the basic specimen with dimensions 60 cm of width, and 40 cm of height and thickness; right - the same specimen with smooth and noise 0.0.

Table 3: Representation of 10 specimens with different assemblies of stone and mortar joints (mortar/stone volume ratio *r*)

Noise	N=0.0	N=0.2	N=0.4	N=0.6	N=0.8
No smooth (S-0)					
Smooth (S-1)					
	r (mortar/stone volume ratio %)				
No smooth (S-0)	11	10	10	10	9
Smooth (S-1)	21	17	17	17	14

The “noise” N represents the different ways to assembly stone and mortar joints, expressed by the mortar/stone volume ratio *r* (%): there is a perfect subdivision in the middle of the specimen for N=0 and a maximum chaotic subdivision for N=1. The different values obtained with this methodology vary between a minimum of 9% ratio (S=0; N=0.8) up to 21% ratio (S=1; N=0). The no smooth procedure has a small influence on the ratio *r*, constantly about 10%.

In this preliminary phase, with the aim to simulate stone masonry walls in compliance with current seismic standards [8], the dimensions of the base specimen is 40 cm thickness, 60 cm width and 40 cm height, as shown in Fig. 10: this allowed to reduce the calculation time and to test the limits of the dimensional simplification implemented.

5.2 Thermal performance of the specimens with different joints and shapes of stone and mortar

The new Italian requirements concerning the reduction of energy consumption in buildings [97] give minimum values for the thermal transmittance U (W/m^{2}K) taken from EN ISO 6946 [98], also for the renovation of existing buildings. In order to reduce the impact on the urban microclimate in summer, it is required that the surface mass of the masonry exposed to solar radiation is higher than 230 kg/m^2 (without plaster); alternatively, the periodic thermal transmittance, Y_{IE}, must be lower than 0.10 W/m^{2}K. Besides, other important dynamic thermal performances are given by EN ISO 13786 [99]:

- time shift, Δt: time interval between the maximum amplitude of sinusoidal variations of the external and internal temperature on the faces of masonry (*h*);
- decrement factor *f*: ratio between the periodic thermal transmittance Y_{IE} and the steady-state thermal transmittance U (-).

The 3D simulated specimens, shown in Table 3, with the stone and the mortar joints differently arranged, were imported on COMSOL®, a multiphysics software for finite element method analysis (FEM). The model is discretized by creating a grid (mesh) composed of codified elements (finite elements) [100].
Two distinct calculation conditions (called “Thermal Insulation” on COMSOL®) are implemented for each model: a steady-state and a dynamic calculation. For both steady-state and time dependent analyses, the equation implemented by the software calculation model, is:

$$\rho C_p \left(\frac{\partial T}{\partial t} + u_{rans} \cdot \nabla T\right) + \nabla \cdot (q + q_r) = -\alpha T \frac{dS}{dT} + Q \tag{6}$$

where ρ is the density [kg/m^3], C_p is the specific heat capacity at constant stress [J/(kg K)], T is the absolute temperature [K], u_{trans} is the velocity vector of translational motion [m/s], q is the heat flux by conduction [W/m^2], q_r is the heat flux by radiation [W/m^2], α is the coefficient of thermal expansion [1/K], S is the second Piola-Kirchoff stress tensor [Pa], Q contains additional heat sources [W/m^3].

In the present model, the equation (6) is simplified as follows:

$$\rho C_p \left(\frac{\partial T}{\partial t}\right) + \nabla \cdot (q) = Q \tag{7}$$

where $q = -k\nabla T$, and k is thermal conductivity [W/(m K)].

For a steady-state problem, the temperature does not change with time and the terms with time derivate disappears. In this case, the condition of "Thermal Insulation" has been applied on the side walls of the specimen, with a convective and conductive heat flow calculated assigning both the external and internal surface resistance and the internal and external air temperature [101].
In the dynamic calculation, the condition of "Thermal Insulation" are equal to the first case, while a sinusoidal temperature variation has been applied to the external surface, as a function of time. The calculation was performed in steps of $0.1h$ [102].
The boundary conditions, imposed for the calculation model, are the followings:

- Side walls: *“Thermal Insulation”*, $n \cdot q=0$;
- External and internal surface: *“Heat Flux”*, $n \cdot q = q_0$, where $q_0 = h \cdot (T_i - T)$, $h = 1/R_s$ and n is the normal vector toward exterior;
- Steady-state calculation: *T*_air_external 0°C, *T*_air_internal 40°C, *T*_starting_temp. 20°C;
- Dynamic calculation: *T* air_external (50sin[(2π/24)·(t)]+15)°C, *T*_air_internal 20°C, *T*_starting_temp. 10°C;
- Surface resistance (EN ISO 6946 [98]): External R_{se}=0,04 m^{2}K/W, Internal R_{si}=0,13 m^{2}K/W.

The thermal properties assumed for the masonry, according to the average values of UNI TR 11552 Standard [103] and EN 1745 Standard [104], are shown in Table 4. In particular, since standards show different typologies of natural stones, the simulations are developed for the following stone walls, with thermal parameters similar to the values shown in Table 4:

- Shale, slates, granites (ρ=2000÷2800 kg/m^3, λ=2.2÷2.8 W/mK);
- very hard limestone (ρ=2200÷2590 kg/m^3, λ=2.3 W/mK);
- Siliceous, quartz sandstone (ρ=2200÷2800 kg/m^3, λ=2.3÷2.6 W/mK).

Table 4: Average value of the physical properties of selected masonry, according to [103] and [104].

Parameters /unit	Stone	Mortar
Thermal conductivity /W·m^{-1}K^{-1}	2.4	0.9
Specific heat capacity /J·kg^{-1} K^{-1}	1000	1000
Density /kg·m^{-3}	2500	1800
Mass per unit area of masonry /kg·m^{-2}	~950	~950

Regarding the summer period, a good delay factor varies between 10 and 12 hours, excellent if it is higher than 12 hours, while the decrement factor *f* is considered good when varying between 0.3 and 0.15 and excellent if lower than 0.15. [105].

In Table 5 the calculation results are summarized, while in Figs. 11 and 12 the correlations between *r* (%) and thermal and periodic thermal transmittance are shown.

Table 5: Results of the calculation of thermal performances of stone masonry specimens.

Noise	0.0	0.2	0.4	0.6	0.8
	No smoothed specimens				
U /W·m^{-2}K^{-1}	2.83	2.86	2.87	2.85	2.90
Y_{IE} /W·m^{-2}K^{-1}	0.61	0.61	0.61	0.62	0.63
r /%	11	10	10	10	9
Δt /h	9.3	9.2	9.0	9.1	9.3
f /-	0.21	0.21	0.21	0.22	0.20
	Smoothed specimens				
U /W·m^{-2}K^{-1}	2.71	2.76	2.76	2.76	2.81
Y_{IE} /W·m^{-2}K^{-1}	0.54	0.57	0.55	0.51	0.58
r /%	21	17	17	17	14
Δt /h	8.5	9.3	8.2	8.7	9.2
f /-	0,20	0,20	0,20	0.19	0.21

The calculation results show an excellent correlation between the ratio *r* (%) between the volumes of the joint mortar and of the stone and the thermal transmittance *U* (R^2 = 0.95), and an acceptable correlation with periodic thermal transmittance Y_{IE} (R^2 = 0.78).

Despite the simplifications introduced by restricting the analysis to a single basic model and the limited number of specimens examined, it can be noted that the ratio between volumes of mortar and stone largely affects the thermal performances.

With this assumption, from 9 to 21% of the ratio *r*, the transmittance is reduced by 7.5%, and the periodic transmittance by more than 14%.
On the other hand, a clear correlation between the ratio *r* and the other examined parameters, is not achieved: time shift Δt and decrement factor *f* are both essentially nearly-stationary and in agreement with good values, as shown in the guidelines [105], also considering that masonry is analyzed without plaster.
Finally, the mass of the masonry is very high and the surface heat capacity κ is much greater than 40 kJ/m²K [106], that is the minimum value considered for thermal comfort.

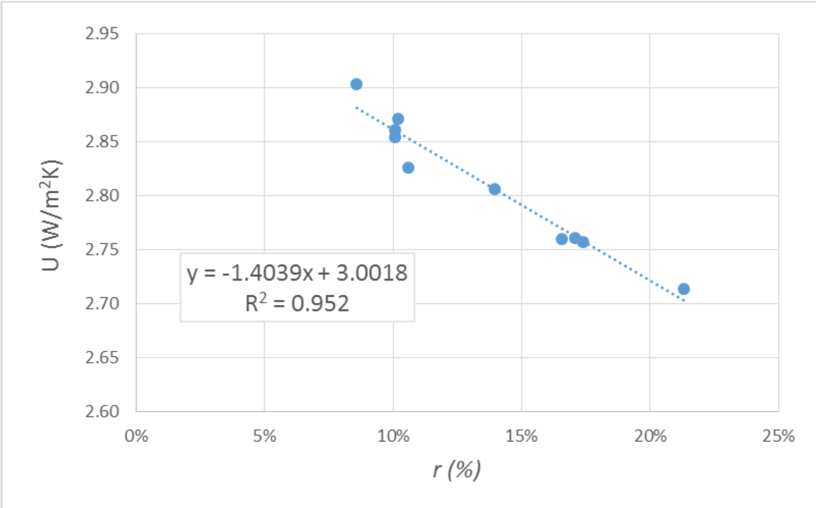


Fig. 11. Relationship between thermal transmittance U and ratio *r*.

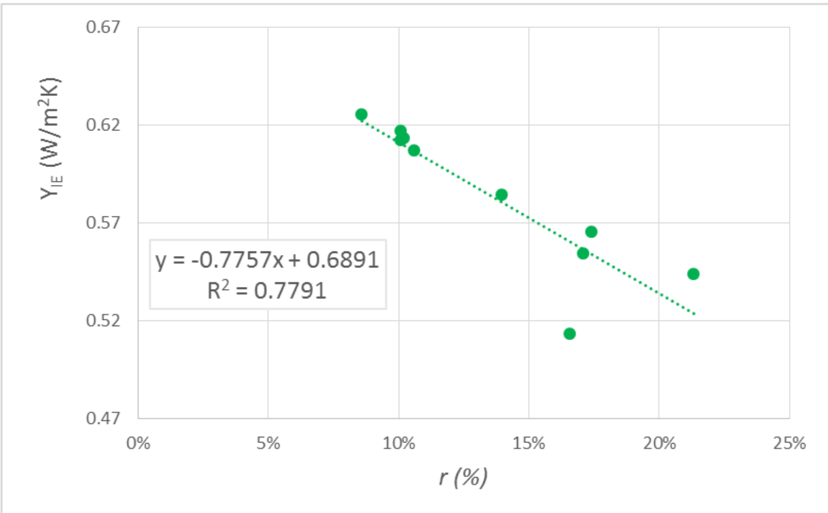


Fig. 12. Relationship between periodic thermal transmittance Y_{IE} and ratio *r*.

5.3 Comparison with calculated *U*-values in literature

It is possible to compare *U*-values of different kind of stone masonry walls by means of the calculation procedure described in EN ISO 6946 Standard [98]. This parameter can be calculated or measured *in-situ*, as shown in literature [88, 90, 107, 108]. Results of these researches show a remarkable difference between calculated and measured values, since the analytic calculation generally overestimates the *U*-value of existing building walls: this demonstrates the wide variability of the thermal properties of stone masonry walls realized with heterogeneous materials, often chaotically assembled and with different proportion of materials (stone and mortar) and unknown moisture content of the masonry at the time of the measurement.

By limiting the comparison to the calculated values, from cited literature, values of the transmittance *U* for masonry, are comparable with values derived in present study, included between 2.5 and 3.3 W/m^{2}K, with an average value of 2.8 W/m^{2}K.

The values of thermal transmittance given by the Italian standard UNI TR 11552 [103], without considering the thermal resistance of the plaster, for a width of 40 cm, are about 2.98 W/m^{2}K, higher than values calculated with the software COMSOL®, by taking into account also the presence of the mortar joint.

Lucchi [88] reported, for a width of 40 cm and average values of thermal parameters within values collected in standards UNI 10351[109] and EN 1745 [104], the thermal transmittance of about 2.65 W/m^{2}K; taking into account the influence of the percentage of stones and mortar, the author calculated the values of thermal transmittance between 2.2 and 2.4 W/m^{2}K respectively for a ratio *r* of 10% and 20%, with a difference of 0.2, whereas in the present study, a difference of 0.14 is obtained.

In summary, the simplified methodology provides prudential values of thermal transmittance, but consistent with values calculated by other researchers; more detailed comparisons can be made by calculating the influence of the type of mortar and stone, by varying the thickness of the masonry and expanding the number of samples, from different basic models and with different values of smooth and noise.

6. CONCLUDING REMARKS AND COMMENT

Stone masonry is nowadays a promising building technology for both newly developed buildings and renovation of existing buildings, in order to retrieve the historical identity of peculiar urban landscapes and to preserve cultural heritages, ancient villages, minor historical towns and even ordinary residential buildings. Besides, the possibility to re-build stone masonry buildings by recycling collapsed and good quality stone material, in particular in areas devastated by seismic events, is a sustainable renovation process, in compliance with European Directive concerning the reduction of construction and demolition waste. On the other hand, the reconstruction of stone masonry buildings, even improved with suitable (but not invasive) new technological supports, components and materials, can be considered an interesting resource from the economical and societal point of view, since it relaunches the craft activities and local economies.

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 and energy performance, are barely investigated.

In this paper, the main building physics properties of natural stone masonries, in the frame of structural and seismic safety criteria, are described and discussed on the basis of literature review, current standards and regulations, empirical models and computer simulations.

In particular it is shown the intrinsic ability of stone masonry to attenuate the transmission of sounds and vibrations, due the high mass per unit area of the stone materials and the structural discontinuity between the elements. Prediction of acoustical performances is analyzed in terms of airborne transmission loss, impact sound and façade insulation, taking into account the performances of the main structures and the involved components and materials.

The thermal performance of stone masonry wall is very interesting as a consequence of the high mass, typical of this construction typology, and for the effective attitude to reduce the thermal isle effect and inlet solar energy by a good solar reflection index SRI.

In particular, the areal heat capacity κ is very good and it is possible to have thermal comfort conditions with reduced energy consumption in summer and winter conditions.

The excellent thermal inertia reduces the energy peaks and, as a consequence, it is possible to use smaller mechanical plants with lower environmental impact.

A graphic methodology has been implemented to define ten specimens with different configurations of stone and mortar joints, representative of different typological situations, expressed by the ratio r, between volume of mortar and stone: the method allows to override the calculation difficulties caused by the high variability of masonry typologies by the use of a computational FEM software. The results of calculation on these specimens have shown a strong relationship between the ratio r and the U value and a good relationship with the periodic thermal transmittance Y_{IE}, in accordance with the results of other researchers, and encourage deepening the research on a larger number of samples and constructive typologies.

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