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Calibration of a visual method for the analysis of the mechanical properties of historic masonry

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Abstract

The conservation and preservation of historic buildings affords many challenges to those who aim to retain our building heritage. In this area, the knowledge of the mechanical characteristics of the masonry material is fundamental. However, mechanical destructive testing is always expensive and time-consuming, especially when applied to masonry historic structures. In order to overcome such kind of problems, the authors of this article, proposed in 2014 a visual method for the estimation of some critical mechanical parameters of the masonry material. Based on the fact that the mechanical behavior of masonry material depends on many factors, such as compressive or shear strength of components (mortar and masonry units), unit shape, volumetric ratio between components and stone arrangement, that is the result of applying a series of construction solutions which form the ‘‘rule of art’’. Taking into account the complexity of the problem due to the great number of variables, and being on-site testing a not-always viable solution, a visual estimate of the mechanical parameters of the walls can be made on the basis of a qualitative criteria evaluation. A revision of this visual method is proposed in this paper. The draft version of new Italian Building Code have been used to re-calibrate this visual method and more tests results have been also considered for a better estimation of the mechanical properties of masonry.

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Keywords: Mechanical properties of masonry, visual analysys, earthquake engineering.

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1. Introduction

Stone work masonry is very common in Europe and Middle East. This was the main construction material for centuries. Its craft continued to develop in the medieval period, when ever-more ambitious structures, mainly religious buildings, were constructed from stone (Giuffrè, 1999; Binda et al., 2000; Valluzzi et al., 2004; D'Ayala and Paganoni, 2011). In this period, the use of stone for residences, agricultural outbuildings, public and religious buildings and bridges became more common. Especially in areas where stone was abundant, this material became the material of choice for all types of constructions (Lagomarsino and Podestà, 2004; Lourenço et al., 2011). However, even if the constituent material was the same, for humbler buildings rubble or irregular stone was used, sometimes with only minimal dressing and often rendered (Chiostrini and Vignoli, 1993). For more important buildings (i.e. religious and public buildings) the stone was perfectly or roughly squared up and constructed in courses. In many situations, the masonry of these important buildings was fair-faced (Mastrodicasa, 1978; Augenti, 2008).

The Central Italy seismic events of 2016 clearly confirmed the critical importance of the masonry quality to access the capacity of a building to resist to a dynamic horizontal action. It has been noted that several random and rubble/irregular stone masonry buildings experienced serious damage or complete collapse during the quakes. On opposite, perfectly squared or roughly-cut stone masonry buildings resisted to the seismic events with limited damage. Based on this, a statistical analysis of the level of damage of the masonry buildings of the centre of Norcia, Italy was performed. It is demonstrated that the level of knowledge of the effects of a quake on a building highly varied in the past from area to area and this had a critical effect of the behavior of the buildings when struck by a quake. The use of a high-quality masonry (perfectly or roughly squared stone masonry) was often the consequence of this "seismic knowledge". This was highly influenced by past destructive seismic events, forcing people and authorities to a critical analysis of the causes of collapses and encouraging them to find effective construction solutions. Norcia, the capital city of the Nera's valley in Umbria, was only few kilometers away from the Oct. 30 quake epicenter (magnitude 6.5 ML). The modern ordinary masonry constructions of Norcia are made of engineering tile blocks (Fig. 2). This was the typical construction material of Norcia introduced after the 1979 and 1987 quakes. Most historic buildings of Norcia had been also retrofitted with well-known techniques. In general, ordinary buildings of the centre of Norcia did not experience a heavy damage and collapses were very rare.

Unreinforced masonry (URM) buildings located outside the center of Norcia were heavily damaged by the quakes. Collapses' were very common, especially for irregular stonework masonry constructions. In particular, the earthquakes completely destroyed several medieval churches, made of URM rubble stone masonry. The most part of these religious buildings were under the protection of statutory conservation bodies. These bodies did not easily authorize retrofitting interventions, following the concept of "minimum intervention". However recent catastrophic collapses should suggest a different strategy to follow. In a recent study (Borri et al., 2018), it was also concluded that conservation bodies, when approving or delaying restoration works of structures in their portfolio and located in areas of high seismic risk, should apply the concept of "minimum intervention" with more consideration to structural problems and the long-run safety of the structures under their supervision and protection.

2. The Quality of Masonry

Historic masonry is a generic term. It cannot also be considered as an artificial material, using the modern definition of artificial materials ("artificial materials do not occur naturally and are created by human beings, using science or technology"). Historic masonry is not the result of an industrial and controlled process, it is more an artisan product, depending on a large number of factors (availability of the constituent materials, period of construction, importance of the building, skills of the masons, etc.). The assemblage of the two constituent materials (mortar and masonry units), either in courses or not, leads to the creation of a composite material, with elevated non-linear stress-strain characteristics, very low tensile strength, non-homogenous and non-isotropous. Structural engineers are aware of the difficulties in modeling historic buildings using FEM (Finite Element Method) methods.

The seismic behavior of a historic masonry building can be classified as it follows: 1. if the quality of the masonry material is very low, the only possible collapse mechanism of the building is due to the disgregation/crumbling of the masonry material (i.e. during the quake, wall macro-elements cannot develop). We define this behavior as “Puntual”; 2. On opposite, if the quality of the masonry material is not very low, and this is able to resist to the seismic forces without crumbling, cracking causes the formation of macro-elements of masonry joined together or arranged in a manner that permits them to move relative to one another, similarly to a kinematic chain. Collapse occurs when the kinematic chain becomes a mechanism. Examples of mechanisms of masonry macro-elements are the overturning of the facades. We define this behavior as “Local”. 3. A further possible response of a building under the seismic action is defined as “Global”. Again this can occur when the quality of the masonry material is not low and the connections between walls at intersections (wall-to-wall junctions) are effective. In this situation the so-called “box behaviour” of the building can be activated. When failure occurs in a structural member of a building, the wall-to-wall connections are able to re-distribute the seismic load previously absorbed by the cracked member, preventing and blocking local collapse mechanisms. The overall response of the building depends on the stiffness of all its members, including the horizontal plate structures (floors, roof). On that basis, it is possible to conclude that a hierarchical analysis is a viable method for the definition of the best retrofitting intervention. Table 1 shows the three possible structural responses of a building (punctual, local and global), essentially depending on the quality of the masonry material and effectiveness of wall-to-wall connections. For each response, the best type of analysis and retrofitting intervention were listed. Interventions are prioritized with the aim at shifting the overall structural behaviour to next one (by increasing the quality of the masonry material from punctual to local response, by improving the level of wall-to-wall connections from local to global, etc.)

Table 1. Types of analysis and proposed retrofitting interventions.

		Seismic Behavior	Type of Analysis	Priority Intervention
Low-quality masonry material		Masonry crumbling (punctual response)	Analysis of the quality of the masonry	Improve the quality of the masonry
Medium-to-high quality masonry, without wall-to-wall effective connections		Local behavior, Macro-elements, with local collapse mechanisms	Analysis of local mechanisms. Calculation of the vertical loads acting on each single element	Insertion of ties, transversal connections, reinforcement of horizontal structures (floors, roof)
Medium-to-high quality masonry, effective wall-to-wall connections	Deformable floors	Global behavior, loads acting within their areas of influence, no twisting effects on the building	Non-linear analysis, 3-dimensional models, walls in-line analysis [*Analisi non lineare per allineamenti*]	Improvement of the load- and deformation capacities of the structural members
	Rigid floors	Global behavior, distribution of the seismic load depending of the stiffness of each structural elements, existence of twisting effects	Non-linear analysis, 3-dimensional models	Improvement of the load- and deformation capacities of the structural members

3. The Quality Masonry Index (MQI)

This study is aimed at improving the accuracy of calibration of the Quality Masonry Index (MQI) proposed by the authors in the past (Regione Umbria, 2003; Borri and De Maria, 2009; Rovero and Fratini, 2013; Corradi et al., 2014; Borri et al., 2015). This is a visual method for the estimation of the mechanical properties of historic masonry and it can be considered an interesting alternative to on-site destructive testing (ASTM E519, Corradi et al., 2003; Borri et al., 2011). The new Italian Building code (draft version, 2018), to be used for the reconstruction of heavily-damaged buildings after the 2016 Central Italy quakes, introduced some relevant modifications to the previous normative, dated 2009 (IMIT, 2009). In detail, the mechanical parameters of the different typologies of historic masonry and the corrective multiplication factors, both tabulated in the code, were amended and integrated.

The method for the calculation of the MQI, as proposed and described in Borri and De Maria (2009) is not affected by the modifications introduced in the Italian Building Code (2018) and the authors confirms its validity for the analysis of masonry quality. However, a brief summary of MQI is reported below, to introduce the reader to the method and justify the subsequent comments. The visual analysis of a historic wall is based on 8 parameters (identified by the acronyms *r*, *SM, SD, SS, WC, HJ, VJ* and *MM*). The analysis of each parameter leads to a numerical value (for a total of 8 numerical results) based on its fulfilment category. The combination, according to eq. (1), respectively, of the 8 numerical values gives the value of MQI.

$$MQI = r \times SM \times \left(SD + SS + WC + HJ + VJ + MM\right) \tag{1}$$

As it can be noted from eq. (1), the r and SM parameters are factored by the summation of the values assigned to the remaining six parameters to produce the value of the final index representing the quality of the masonry, MQI. The factor *r* was introduced in the original formulation of the MQI in order to take into account that for brickwork masonry the quality of the mortar is more important compared to a stone work masonry *(r=1* for stone work masonry*)*.

Because a single wall panel could be subjected to varying loading conditions which directly affect the masonry quality, the values assigned to the 8 parameters depend on the loading condition acting on the wall under consideration. Three loading conditions were considered: V (vertical static loads), O (out-of-plane static and dynamic loads) and I (in-plane dynamic loads). Consequently, eq. (1) can lead to three different values (MQI_V, MQI_O, MQI_I), one for each loading condition, The approach is to attribute different weights to the above parameters (between 0 and 3) based on the evidence that they affect the quality of the masonry with different degree depending on the loading condition. In case of fulfilment of all parameters of quality eq. (1) gives a numerical value of 10 irrespective of the loading condition.

Finally, the MQI value can then be used to obtain, through a correlation procedure, an estimation of the mechanical parameters (compressive strength f_m, shear strength τ_0 and moduli of elasticity E and G) of existing masonry. Low outcomes in one of the 8 parameters may lead to different variations of the masonry strengths depending on the loading conditions.

4. The parameters to consider for the assessment

On consideration a given masonry structure, the integrity of the wall can be assessed by considering several quality factors and constructive solutions. In detail, the integrity of a wall is defined in construction manuals, dating back from Roman to pre-modern times and it is based on well documented construction techniques and observation of damage suffered by buildings during severe loading conditions (both static and dynamic actions). As a consequence of this, a set of rules were introduced since ancient times and even now these are unanimously considered by the scientific community as a base for a correct assemblage of a wall. These rules were used here to define the seven parameters needed to calculate the MQI value. The estimation requires an in-depth knowledge of historical construction methods due to the demands placed upon the engineer to categorize each parameter under three possible outcomes: Fulfilled—F, Partially Fulfilled—PF, Not Fulfilled—NF. Table 2 illustrates the criteria for application of these categories relative to the seven parameters.

4.1. Mechanical characteristics and quality of masonry units (SM parameter)

This parameter takes into account the conservation state and the mechanical properties of the bricks or stones. For unfired and mud bricks, whose compressive strength is very low (0.5–5 MPa), the outcome is generally NF while for masonry made of softstone like tuff and sandstone the assumed outcome is PF (compressive strength 5–20 MPa). The outcome is also NF for hollow-core bricks (less than 30 % solid) or highly degraded stones. Pollution, water, light, inappropriate humidity and temperature may reduce material mechanical properties and cause material erosion. Parameter SM consider these problems including the common phenomenon of erosion of porous stones.

4.2. Dimensions of the masonry units (SD parameter)

The dimensions of the masonry units, i.e. ratio between the longest dimension of the block and the wall thickness, is another important factor to consider to assess the quality of a masonry wall. Similarly to the effect of headers, a wall made of large masonry units has a better seismic and static responses. Large-stone walls are typically more monolithic (disgregation or crumbling of these walls is more difficult to occur during earthquakes). Furthermore, the high weight of large stones causes a mutual confinement effect between adjacent stones in a wall. These walls also facilitate the distribution of both static (vertical) and dynamic (horizontal) actions along a larger portion of masonry.

4.3. Shape of the masonry units (SS parameter)

Typically, a stone work historic wall can be made of pebbles, roughly-cut or perfectly-cut masonry units. When perfectly-cut units are used for walling, the existence of the two horizontal contact surfaces between the block itself and the mortar facilitates the activation of a frictional reaction. This reaction is critical for the capacity of a wall to resist to horizontal in-plane actions. However, the frictional reaction, which is generated by the static compressive loads acting on the wall, is maximum when the contact surface is horizontal and perpendicular to the direction of the vertical loads (i.e. horizontal contact surfaces).

4.4. Level of connection between adjacent wall leaves / headers (WC parameter)

Connection between adjacent wall leaves have considerable effect on the global behaviour of a multi-leaf wall. This varies from cases where there is no connection between the wall leaves to ones with well-constructed connection between the leaves. Headers (*diatoni* in Italian, i. e. masonry units or bricks placed transversally to the wall's surface) are typically used to connect each other multi-leaf walls. Length of the headers can be equal to the wall thickness (through-headers) or not (partially-through headers). For multi-leaf stone work walls, single- or double-course of bricks placed at fixed intervals are used to connect the wall leaves.

For the analysis of wall leaf connections (WC) both the compressive and the out of-plane behaviors are significantly affected by the presence of headers between masonry leaves. The existence of headers facilitates the distribution of the vertical static loads along the full cross section of a multi-leaf wall.

The qualitative analysis is used when the wall section is not visible: the outcome NF is assumed if no headers or less than $2/m^2$ are present. For double-leaf stone walls the outcome PF is assumed when the wall thickness is larger than the stone larger dimension and when are present a limited number of headers ($2–5/m^2$). The outcome is F when there is a systematic presence of headers ($>4–5/m^2$) and when the wall thickness is similar to the stone/brick larger dimension. For the assessment of the level of connection of wall leaves, the authors also proposed a quantitative analysis (Borri et al., 2015).

4.5. Horizontality of mortar bed joints (HJ parameter)

Horizontal layers of mortar, on which masonry units are laid, are typically used for walling. Depending on the type of masonry and construction technique, horizontal layers of mortars are sometimes non-continuous. This may highly affect the lateral and compressive strength of a masonry wall panel. Horizontal and continuous bed joints facilitates an uniform distribution of the vertical loads on the horizontal cross section of the wall. During earthquakes, the continuity and horizontality of bed joints allow the formation of cylindrical hinges, reducing damage from crumbling. A similar effect can be induced by courses of bricks placed at fixed interval in stone work walls. Finally, the horizontality of the bed joints maximizes the frictional reaction (at the contact surface between the block and the mortar), generated by vertical static loads.

4.6. Staggering of vertical mortar joints (VJ parameter)

The vertical joint of a masonry wall could be well staggered, partially staggered or not staggered at all. This characteristic of the vertical mortar joint has several positive effects: when vertical joints are properly staggered, the failure surface along the mortar joints (mortar typically is weaker compared to the material of the masonry units, and failure occurs within the mortar) is larger, increasing the frictional reaction during horizontal loading and thus providing the masonry material with limited tensile strength. Mechanical interlocking along a crack is another positive effect of properly joint-staggered walls.

4.7. Quality of the mortar / contact between masonry units / pinnings (MM parameter)

In order to transfer the stresses between the masonry units (made of stone, brick, etc.) and ultimately to the foundations of the building without concentration of stresses it is required that the units to be flat and smooth or to use a mortar interposed between them. The use of pinnings may be of help for this and it is encouraged in many manuals, especially when barely cut stones are used. The quality of the mortar is also important, as this can also confine the stones and facilitate the distribution of the acting loads. Mortar used in historical buildings is usually based on lime (aerial or hydraulic). However, the variation in the volumetric ratio of binder: aggregate, the quality of the lime and the type of lime does have considerable effect on the mechanical properties of the mortar.

Table 2. Criteria for the analysis of the seven parameters.

Parameter	**Possible Outcome**		
	NF	**PF**	**F**
MM Mortar properties	– Very weak mortar, dusty mortar with no cohesion. – No mortar (dry rubble or pebble stonework). – Large bed joints made of weak mortar (thickness comparable to stone/brick thickness). – Porous stones/bricks with weak bonding to mortar.	– Medium quality mortar, with bed joints not largely notched. – Masonry made of irregular (rubble) stones and weak mortar, but with presence of pinning stones.	– Good quality and non-degraded mortar, regular bed joint thickness or large bed joint thickness made of very good quality mortar. – Masonry made of large perfectly cut stones with no mortar or very thin bed joint thickness.
WC Wall leaf connections	– Small stones compare to wall thickness. – No headers.	– For double-leaf walls: • Presence of some headers; • Wall thickness larger than stone large dimension.	– Wall thickness similar to stone large dimension.
SS Stone/brick shape	– Rubble, rounded or pebble stonework (predominant) on both masonry leaves.	– Co-presence of rubble, rounded or pebble stonework and barely/perfectly cut stone and bricks on both masonry leaves. – One masonry leaf made of perfectly cut stones or bricks. – Masonry made of irregular (rubble, rounded, pebble) stones, but with presence of pinning stones.	– Barely cut stones or perfectly cut stones on both masonry leaves (predominant). – Brickwork.
SD Stone/brick dimensions	– Presence of more than 50% of elements with large dimension < 20 cm. – Brick bond pattern made of only head joints.	– Presence of more than 50% of elements with large dimension 20-40 cm. – Co-presence of elements of different dimensions.	– Presence of more than 50% of elements with large dimension > 40 cm.
VJ Stagger properties of vertical joints	– Aligned vertical joints. – Aligned vertical joints for at least 2 large stones. – Solid brick wall made of only headers.	– Partially staggered vertical joints (vertical joint between 2 brick is not placed in the middle of adjacent upper and lower brick).	– Properly staggered vertical joints (vertical joint between 2 stones is placed in the middle of adjacent upper and lower stone).
HJ Horizontality of bed joints	– Bed joints not continuous.	– Intermediate situation between NF and F. – For double-leaf wall: only one leaf with continuous bed joints.	– Bed joints continuous. – Stone masonry wall with bricks courses (distance between courses < 60 cm).
SM Stone/brick mechanical properties and conservation state	– Degraded/damaged elements (>50% of total number of elements). – Hollow-core bricks (solid < 30%). – Mud bricks. – Unfired bricks.	– Presence of degraded/damaged elements (≥10%, ≤50%). – Hollow-core bricks (55% ≥ solid ≥ 30%). – Sandstone or tuff elements.	– Un-damaged elements of degraded/damaged elements < 10%. – Solid fired bricks. – Hollow-core bricks (55% < solid). – Concrete units. – Hardstone.

Results of past experimental campaigns have demonstrated that shear and compressive strengths of brickwork masonry is highly governed by the quality of the used mortar. This could be explained by considering the following: 1. Because of the typical brick arrangement of the brickwork masonry, mechanical interlocking is not often possible for preventing failure mechanisms; 2. For brickwork masonry, the mechanical properties of the mortar are typically highly smaller compared to the ones of the bricks. Furthermore, the bonding characteristics of the mortar to the bricks are often weak. For these reasons cracks typically open at the mortar joints, due to mortar rupture or detachment from the bricks. These failure mechanism are usually different for perfectly-cut stone work masonry. For this masonry typology, the mortar has the only role of facilitating the stress transfer by making flat and smooth the surface between adjacent stones. In this situation, the thickness of the mortar joints is typically very small and phenomena of mechanical interlocking may easily occur during loading. These considerations have been used to introduce the multiplication factor *r* in eq. (1).

Table 3. Numerical values for the assessment of the MQI.

	Vertical loading (V)			Horizontal in-plane loading (I)			Horizontal out-of-plane loading (O)		
	NF	PF	F	NF	PF	F	NF	PF	F
SM	0.3	0.7	1	0.3	0.7	1	0.5	0.7	1
SD	0	0.5	1	0	0.5	1	0	0.5	1
SS	0	1.5	3	0	1	2	0	1	2
WC	0	1	1	0	1	2	0	1.5	3
HJ	0	1	2	0	0.5	1	0	1	2
VJ	0	0.5	1	0	1	2	0	0.5	1
MM	0	0.5	2	0	1	2	0	0.5	1
r	0.2	0.6	1	0.1	0.7	1	1	1	1

Table 4. Italian Building Code: mechanical properties of masonry and multiplication factors.

	Compressive Strength f_m (MPa)		Shear Strength τ_0 (MPa)		Young's modulus E (MPa)		Shear Modulus G (MPa)		Good quality mortar	Brick courses	Transversal connection
	Min	Max	Min	Max	Min	Max	Min	Max			
Irregular stone masonry (pebbles, erratic, irregular stones)	1.0	2.0	.018	.032	690	1050	230	350	1.5	1.3	1.5
Roughly cut stone masonry	2.0	3.0	.035	.051	1020	1440	340	480	1.4	1.2	1.5
Barely cut stone masonry, properly dressed	2.6	3.8	.056	.074	1500	1980	500	660	1.3	1.1	1.3
Irregular softstone masonry	1.4	2.2	.028	.042	900	1260	300	420	1.5	1.2	1.3
Squared softstone masonry	2.0	3.2	.040	.080	1200	1620	400	500	1.6		1.2
Squared hardstone masonry	5.8	8.2	.090	.120	2400	3300	800	1100	1.2		1.2
Brickwork (lime-based mortar)	2.6	4.3	.050	.130	1200	1800	400	600	1.27		1.3
Hollow bricks masonry (cement mortar)	5.0	8.0	.080	.170	2500	5600	875	1400	1.2		

5. Judgment criteria of the quality parameters

On consideration a given masonry structure, the initial assumption of the integrity of the structure is based on the fulfillment (F outcome) of the seven quality parameters discussed in the previous sections (Tab. 2). The analysis and interpretation of the seven parameters is a difficult task, not only for the high variability of masonry typologies, but also because several parameters are difficult to address as are not visually accessible. In these situations, works are needed to facilitate this (for example the inspection of the cross section of a wall). Furthermore, the removal of the plaster is often needed for the analysis of the arrangement of the masonry units. These essential preliminary works have an economic cost. However, these works and analyses may induce significant savings in on-site destructive testing, unnecessary retrofitting interventions and, in general, in repair and restoration works.

In general, it is easy to define the two possible extreme outcomes: Fulfilled (F) and Not Fulfilled (NF). More complicated is to define the intermediate outcome: Partially Fulfilled (PF), where the expertise of the person in charge for the visual assessment is critical.

Table 3 reports the numerical values for each possible parameter's outcome (NF, PF and F). These values depend on the loading condition acting on the wall under consideration. Using eq. (1), the MQI can be easily calculated and the mechanical properties of the masonry estimated.

6. Calibration of the MQI with the new Italian Building Code

The draft version of new Italian Building Code (to be used for the reconstruction of heavy-damaged buildings struck by the 2016 Central Italy seismic events) introduced new values for the mechanical properties of historic and modern masonry, compared to the previous Code (2009). These values, given for eight different masonry typologies, are listed in Table 4. This table also shows the multiplication factors to be used when particular situations occur (for example a masonry assembled with a good quality mortar, the existence of courses of bricks in stone work masonry, or the existence of headers or connectors).

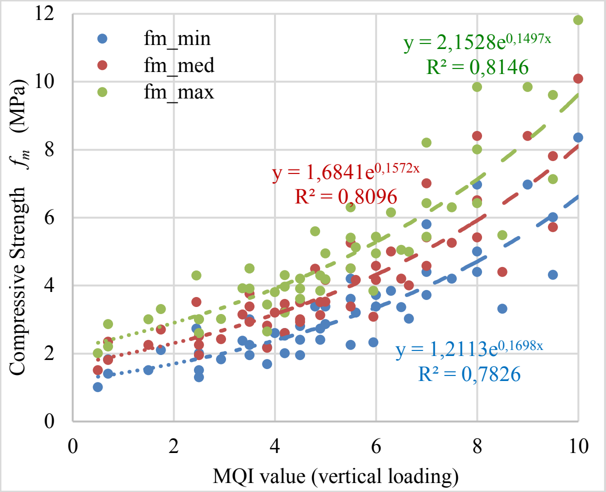

Fig. 1. MQI (vertical loading) vs. Compressive Strength f_m.

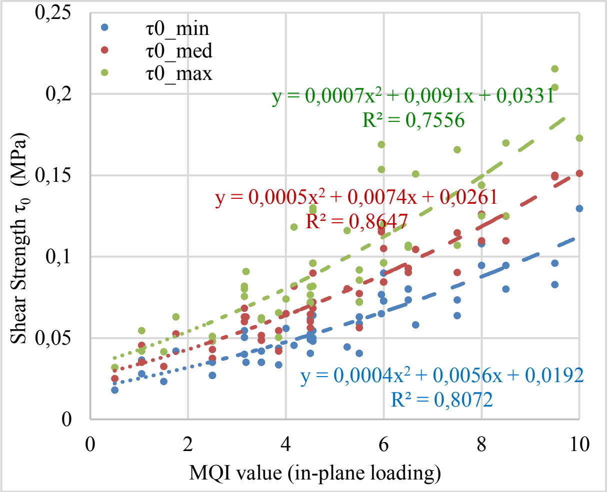

Fig. 2. MQI (in-plane loading) vs. Shear Strength τ_0.

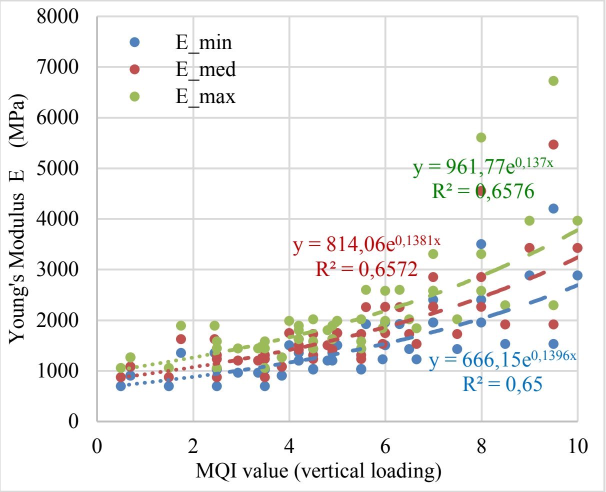

Fig. 3. MQI (vertical loading) vs. Young's modulus E.

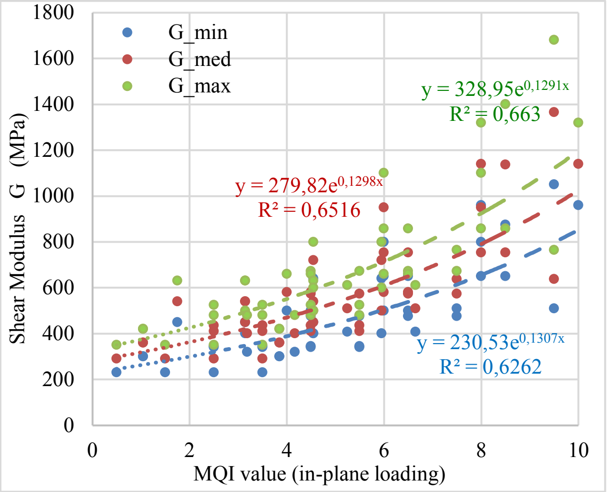

Fig. 4. MQI (in-plane loading) vs. shear modulus G.

By combining the eight typologies in Table 4 with the multiplication factors it was possible to artificially define 50 different masonry types (herein defined "virtual masonry"). For these 50 types, all the mechanical properties were derived (Compressive strength f_m, Shear strength τ_0, Young's modulus E, Shear modulus G). Results of the analyses were plotted and trend lines calculated. In detail, the following curves were plotted: 1. MQI_V vs. f_m, 2. MQI_I vs. τ_0, 3. MQI_V vs. E, 4. MQI_I vs. G (Figs 1-4). For each correlated mechanical property, three curves were plotted (for the minimum, medium and maximum value of the mechanical property as defined by the Italian Code).

The twelve trend curves are reported in Figures 1-4 together with the values of the coefficients of determination R^2. The equations of the trend curves are the following:

1. For the estimation of the masonry shear strength τ_0:
   τ_0 min = $0.0004\,(MQI_I)^2 + 0.0056\,(MQI_I) + 0.0192$ Coefficient of determination $R^2 = 0.8072$
   τ_0 med = $0.0005\,(MQI_I)^2 + 0.0074\,(MQI_I) + 0.0261$ $R^2 = 0.8647$
   τ_0 max = $0.0007\,(MQI_I)^2 + 0.0091\,(MQI_I) + 0.0331$ $R^2 = 0.7556$
2. For the estimation of the masonry Young's modulus E:
   E min = $666.15\, e^{0.1396\,(MQI_V)}$ Coefficient of determination $R^2 = 0.65$
   E med = $814.06\, e^{0.1381\,(MQI_V)}$ $R^2 = 0.6572$
   E max = $961.77\, e^{0.137\,(MQI_V)}$ $R^2 = 0.6576$
3. For the estimation of the masonry compressive strength f_m:
   f_m min = $1.2113\, e^{0.1698\,(MQI_V)}$ Coefficient of determination $R^2 = 0.7826$
   f_m med = $1.6841\, e^{0.1572\,(MQI_V)}$ $R^2 = 0.8096$
   f_m max = $2.1528\, e^{0.1497\,(MQI_V)}$ $R^2 = 0.8146$
4. For the estimation of the masonry shear modulus G:
   G min = $230.53\, e^{0.1307\,(MQI_I)}$ Coefficient of determination $R^2 = 0.6262$
   G med = $279.82\, e^{0.1298\,(MQI_I)}$ $R^2 = 0.6516$
   G max = $328.95\, e^{0.1291\,(MQI_I)}$ $R^2 = 0.663$

In the Italian Building Codes (IMIT and 2018), particular emphasis is devoted to the solid brickwork masonry. For this masonry typology the compressive strength and stiffness is highly dependent on the mechanical properties of the mortar. This influence has been also introduced for the calculation of MQI value: when the masonry compressive strength f_m is higher than 2 MPa, the strength value, calculated using MQI method, should be factored by $f_m^{0.35}/1.27$ [results in (MPa)].

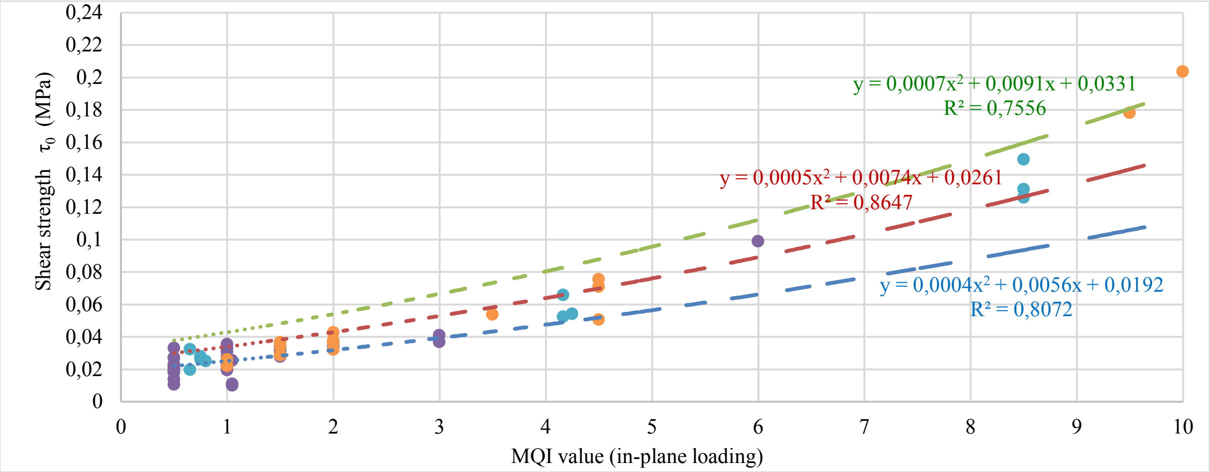

Fig. 5. MQI (in-plane loading) vs. shear strength τ_0, Italian Building Code (2018).

7. Experimental Validation

For the calibration of the proposed visual method, available experimental evidence has been used. In detail, particular emphasis was devoted to the relationship between the MQI_I (in-plane value) and the available test results in terms of masonry shear strength. Sixty experimental results of diagonal tension tests have been used for calibration purposes. These tests (55 conducted on-site and 5 in the laboratory) have been carried out on full-scale wall panels (1.2 x 1.2 m). On-site testing was performed in buildings located in Italy (Umbria, Abruzzi, Emilia Romagna and Tuscany regions). In Figure 5 shear strengths are compared with MQI_I values. It can be noted that several masonry typologies with a very low MQI_I value (smaller than 1) exhibited a shear strength smaller compared to the one suggested by the MQI method. For this reason it is suggested to apply a multiplication factor of 0.7 for low-quality masonry ($MQI_I \leq 1$) for the strength values obtained using the MQI method.

8. Conclusions

This paper has presented a revision of a visual method for the analysis of the quality of historic masonry suitable for design and repair calculation. The analysis is a powerful tool for investigating the strength of masonry and its behavior under the seismic action, as the mechanical characteristic can be derived without testing the walls. A number of critical quality parameters have been explored and their influence discussed. The proposed visual method has been calibrated using available experimental evidence and it is proposed as effective way of calculating mechanical properties of historic masonry. It was also important to assess the sensitivity of the proposed visual method to the different typologies of historic masonry, as categorized and reported by draft version of the new Italian Building Code (2018), such as irregular stone masonry, which can significantly reduce the masonry compressive and shear strengths.

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