APPLICATION OF NONDESTRUCTIVE EVALUATION TEST METHOD FOR ITALIAN MASONRY: MASONRY QUALITY INDEX (MQI) METHOD

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ABSTRACT

On the 6th of April 2009 a catastrophic earthquake struck the city of L'Aquila. This seismic event caused serious damage to several masonry buildings, putting at imminent risk a valuable historical and architectural heritage. Partial collapse or severe damage affected many buildings in the city centre, which consists primarily of masonry buildings. This paper investigates the regional peculiarity of the masonry, especially its material, mortar and technique, and compares the results to in-situ experimental tests and nondestructive MQI analysis. Since in-situ tests being semi-destructive and are not always viable, a numerical estimate of the mechanical parameters of the walls can be based on some qualitative criteria, a new method proposed by Borri A. and De Maria A. [1,2,3,4] (2009, Schede di valutazione dell'IQM RELUIS), which is currently under evaluation to be introduced in the Italian code. Our aim is to contribute to the preservation of our historical heritage, to propose a new catalogue for the masonry manufacturing types of L'Aquila and to provide a correlation curve which makes it possible to estimate the compressive strength only on the basis of observational tests, by calculating the MQI value.

KEYWORDS: *ancient masonry, MQI method, in-situ test*

INTRODUCTION

The present paper is the result of direct experience of the structural damage observed after the earthquake of L'Aquila, 6TH April 2009. A catastrophic event that caused serious damage in particular to the masonry buildings in the centre of L'Aquila and several surrounding villages. As apparent from the level of destruction, it is clear that there is a need for further studies in the field of seismic engineering of masonry buildings. As evidence of this we can consider that the current Italian code [5,6] (Instructions to the current Italian Technical Code DM 14.01.2008, Annex C8A.2.1, February 2009), identifies only 11 types of masonry valid for the whole of Italy,

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although masonry, being a product strongly characterized by the period of construction and place of origin, has a large number of subtypes with their own particular characteristics.

A good structural design of historical buildings rests on a sound understanding of the materials and structure behaviour. In fact, the appropriateness and effectiveness of the retrofitting technique strictly depend on the accuracy of the analysis and in-situ tests, due to the variability in materials and construction of this kind of buildings. In order to contribute to the research and, above all, to promote further discussion of L'Aquila's reconstruction, the present work proposes a new classification of local masonry types, based on a preliminary analysis of a large number of in-situ experimental tests and their comparison with the observations of some qualitative characteristics of the panels.

CLASSIFICATION OF LOCAL MASONRY

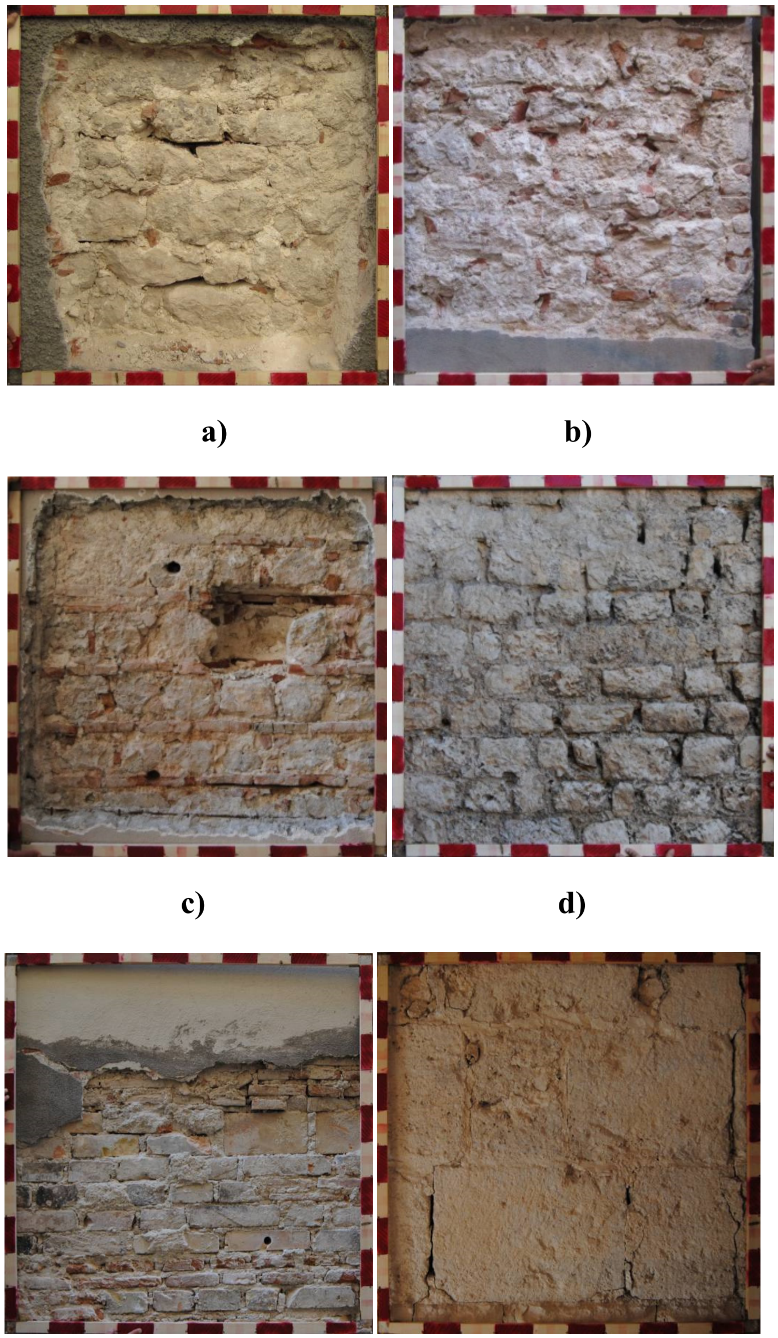
The classification procedure adopted in the present paper consists in the assignment of an MQI value (Masonry Quality Index), calculated in accordance with the "score method" recently developed by the Italian researchers of ReLUIS, [7] (Borri A. et al DEI 2011). The MQI value has been correlated to the normal strain arising from in situ double flat-jack tests. Masonry Quality Index (MQI) method is based on the identification of masonry buildings typical features evaluated with respect to the "rules of art" [1,2,3,4] (2009, Schede di valutazione dell'IQM ReLUIS), as reported in ancient and modern handbooks; from the visual inspection of masonry texture in façade and in cross section, a numerical evaluation is given to different parameters and the quality index can be obtained.

Masonry types

The masonry types suggested for L'Aquila are: 1) irregular stone, Fig. 1a; 2) irregular stone with brick pieces, Fig. 1b, 3) irregular stone with brick lines, Fig. 1c; 4) a.m.a. ("apparecchio murario aquilano"), Fig. 1d; 5) bricks, Fig. 1e; 6) regular stone, Fig. 1f.

The first type is of low quality, is commonly found in the monumental buildings in the centre of L'Aquila and is widespread also in the rest of Italy. For this reason it represents the first class in the Italian code ranking of historical masonry. It can be found in L'Aquila as irregular calcareous stone systems (8÷30cm) made with quicklime mortar. The second type is the likely result of the reconstruction work carried out after the seismic disaster of 1703 that destroyed the centre of L'Aquila (much as the last catastrophic event did in 2009). Pieces of brick were inserted to reduce the amount of mortar and to improve the normal strain of the panels. The third type consists of irregular calcareous stones and brick lines introduced to make more regular panels, thus improving the shear and normal strain of the masonry. The fourth type (a.m.a) is commonly found in religious buildings dating from the XIII-XIV century. It is made with regular square or rectangular stones, whose size varies between 10 and 20 cm.

The fifth type, the classical bricks and lime mortar, is probably the most recent of the historical masonry types. The use of bricks spread during the XIX and XX century for public, religious and private buildings. The dimensions of the bricks are usually 12.5x5.5cm and their thickness is about 2÷3cm. The sixth and last masonry type is made of very large regular stones measuring 30÷60cm. It is used in columns and at the corners of historical palaces, most notably in the civic tower of L'Aquila.



a) b)

c) d)

e) f)

Figure 1: L'Aquila's local masonry: a) irregular stone; b) irregular stone with brick pieces; c) irregular stones with brick lines; d) apparecchio murario aquilano; e) bricks; f) regular stones.

Investigation of mechanical parameters

In the present work 48 masonry panel specimens are analysed, all classifiable according to the first four types proposed above (types a, b, c, d). In Tab.1 we list the masonry compressive strengths, deduced by in situ double flat-jack tests (3rd column). These ranges of values are compared with the Italian code Annex C8A.2.1 (4th column). The results show that the minimum experimental value of the first, third and fourth type is lower than the values given in the code. For the second type the minimum value is quite similar to that in the code.

Table 1: Masonry compressive strength

Masonries	N° of test	σ_u in situ test (min-max) [N/mm^2]	f_m NTC08 italian code (min-max) [N/mm^2]
a) irregular stones	26	0.63÷1.62	1.0÷1.8
b) irregular stone with brick pieces	14	0.97÷2.10	1.0÷1.8
c) irregular stone with brick lines	4	0.81÷2.05	1.0÷1.8
d) a.m.a	4	1.13÷2.60	2.0÷3.0

Correlation curve MQI-σ_u

The attribution of the MQI value (1) is based on simplified methods of analysis of seven properties of the panels: quality of mortar (MA); presence of “diatoni” (PD); element shape (F.EL); element dimension (D.EL); vertical joint (SG); presence of horizontal rows (OR); element resistance (RE.EL). Points are assigned to each property on the basis if it is respected (RE), partially respected (PR) and not respected (NR). The MQI method does not require in-situ destructive tests but only the observation of the surface of the masonry. The conditions of respect, partial respect and not respect of each property are qualitative defined below.

(MA): Is ‘’NR’’ in presence of poor and degraded mortar or powdery. The mortar is completely devoid of cohesion. The joint are overly thick in comparison to the elements of the wall. Is ’’PR’’ when the quality of the mortar is rated intermediate level. Mortar joints are not excessively eroded. Is ‘’R’’ when mortar is in good condition and well maintained, the joint size is not excessive in relation to the stones or bricks.

(PD): Is ‘’NR’’ when the stones are smaller in dimension compared to the thickness of masonry wall and with the absence of ‘'diatoni’’. Is ’’PR’’ when the front facing surface of the masonry wall is well organized on one side. Some ‘’diatoni’’ are present, the thickness of the wall is not to excessive in relation to the size of the elements. Is ‘’R’’ if the masonry wall is well organized on both sides, the thickness of the wall is comparable in relation to the size of the elements and there is a systematic presence of ‘’diatoni’’.

(F.EL): Is ‘’NR’’ with the only presence of elements with irregular shape or pebbles. Is ’’PR’’ with the copresence of elements with irregular shape, regular shape, pebbles and bricks. Is ‘’R’’ with regular and squared stones or bricks.

(D.EL): Is ‘’NR’’ when inside the masonry wall there is a general prevalence of elements whose largest dimension is below 20 cm. Is ’’PR’’ with a prevalence of elements whose size is greater than 20 cm and smaller than 40 cm. Is ‘’R’’ if the prevalent size of the masonry elements is greater than 40 cm.

(SG): Is ‘’NR’’ if there is also an apparent lack of meshing of one more the vertical lines of the wall. Is ’’PR’’ when the vertical joints is in intermediate position between the central zone and the edge of the bottom element. Is ‘’R’’ when the vertical joints generally correspond to the central zone of the lower masonry element.

(OR): Is ‘’NR’’ if the horizontal rows are continually interrupted or do not have clear offsets throughout the entire masonry wall. Is ’’PR’’ in intermediate situation between ‘’NR’’ and ‘’R’’. Is ‘’R’’ if masonry horizontal rows are lined up without interrupting the continuity of the rows and they are present on the both face of the wall.

(RE.EL): Is ‘’NR’’ if elements degraded are > 50% of the total. The masonry walls are composed with hollow bricks with perforations up to 70%, mud or unbaked clay bricks. Is ’’PR’’ if elements degraded are between 10% and 50 % of the total. The masonry walls are composed with hollow bricks with perforations between 70% and 45%. Is ‘’R’’ when the masonry is not degraded. The masonry walls are composed with hollow bricks with perforations < 45%, hard tufa or concrete elements (hollow and not).

The MQI values are related to the values attributed to the above properties (see Tab. 2) by the following formula:

$$MQI = RE.EL \times (OR + PD + F.EL + SG + D.EL + MA) \quad (1)$$

Points are assigned for vertical (AV), horizontal (AP) and out of plane forces (AFP) at work in typical collapse mechanisms, with the best qualities corresponding to higher scores.

Table 2: Parameters assigned for each property

	AV			AFP			AP		
	NR	PR	R	NR	PR	R	NR	PR	R
OR.	0	1	2	0	1	2	0	0.5	1
P.D.	0	1	1	0	1.5	3	0	1	2
F.EL	0	1.5	3	0	1	2	0	1	2
S.G	0	0.5	1	0	0.5	1	0	1	2
D.EL	0	0.5	1	0	0.5	1	0	0.5	1
MA.	0	0.5	2	0	0.5	1	0	1	2
RE.EL	0	0.7	1	0.5	0.7	1	0.3	0.7	1
M.Q.I	MQI=RE.EL X (OR.+P.D.+F.EL.+S.G.+D.EL.+MA.)								

To correlate the MQI value with the compressive strength we used an exponential law and calculated the coefficient of determination R^2 (2) which is defined as follows:

$$R^2 = 1 - \frac{SSE}{SST}$$
$$SSE = \sum \left(Y_j - Y_{Pj}\right)^2$$
$$SST = \sum \left(Y_j\right)^2 - \frac{\sum Y_j^{\,2}}{n} \qquad (2)$$

Where Y_j is the exact value of the mechanical parameter, Y_{Pj} is the interpolated value, and n is the number of points to interpolate. A correlation between the MQI, calculated for the vertical force (AV), and the compressive strength, obtained from in-situ double flat-jack tests, is proposed below. For each MQI class we considered the σ_u(max), σ_u(min) and calculated the corresponding σ_u medium. The coefficients of determination so obtained show a good MQI-σ_u correlation for each individual masonry type.

Table 3: Irregular stone type (26 tests)

MQI value	σ max(med) MPa	σ max(min) MPa	σ max(max) MPa
0.5	0.88	0.63	0.97
0.7	0.95	0.94	0.96
1	1.18	0.94	1.45
2	1.54	1.45	1.62

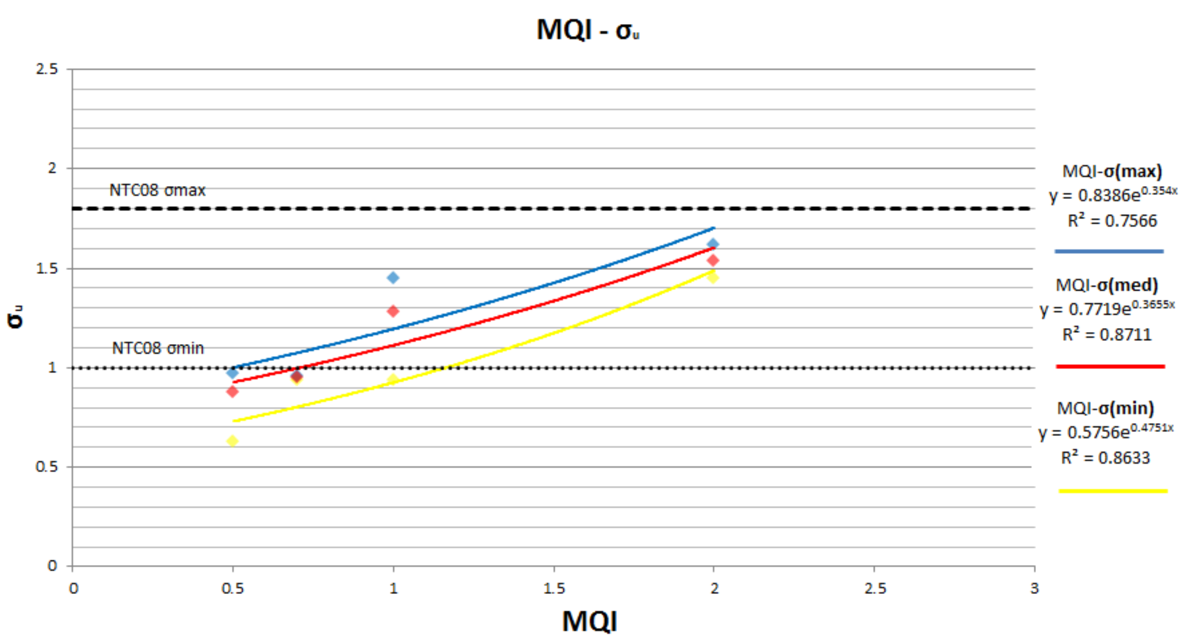


Figure 2: Irregular stone correlation curve

The Fig.2, refers to irregular stones masonry type Fig.1a, show how some σu values are lower than the minimum suggested by Italian code and the correlation curves MQI- σ(max), MQI- σ(med) and MQI- σ(min) have a good correspondence with the range code.

Table 4: Irregular stone with brick pieces type (14 tests)

MQI value	σ max(med) MPa	σ max(min) MPa	σ max(max) MPa
0.5	1.05	0.97	1.13
1	1.53	1.29	1.62
2	1.78	1.62	2.13

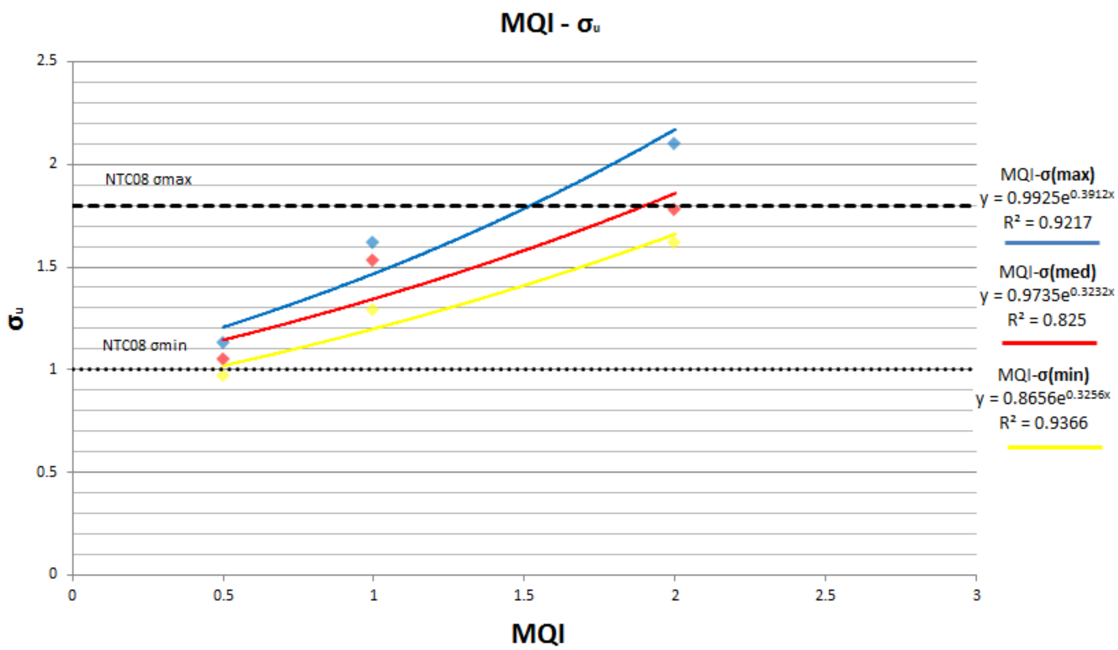


Figure 3: Irregular stone with brick pieces correlation curve

The Fig.3 shows how the upper bound is exceeded by the σ(max) values for the irregular stones with brick pieces masonry type, Fig.1b. Also for this masonry type a correlation curves have a good correspondence with the range suggested by Italian code.

Table 5: Irregular stone with brick lines type (4 tests)

MQI value	σ max(med) MPa	σ max(min) MPa	σ max(max) MPa
1.4	1.05	0.81	1.29
2.45	1.29	1.29	1.29
4.2	2.05	2.05	2.05

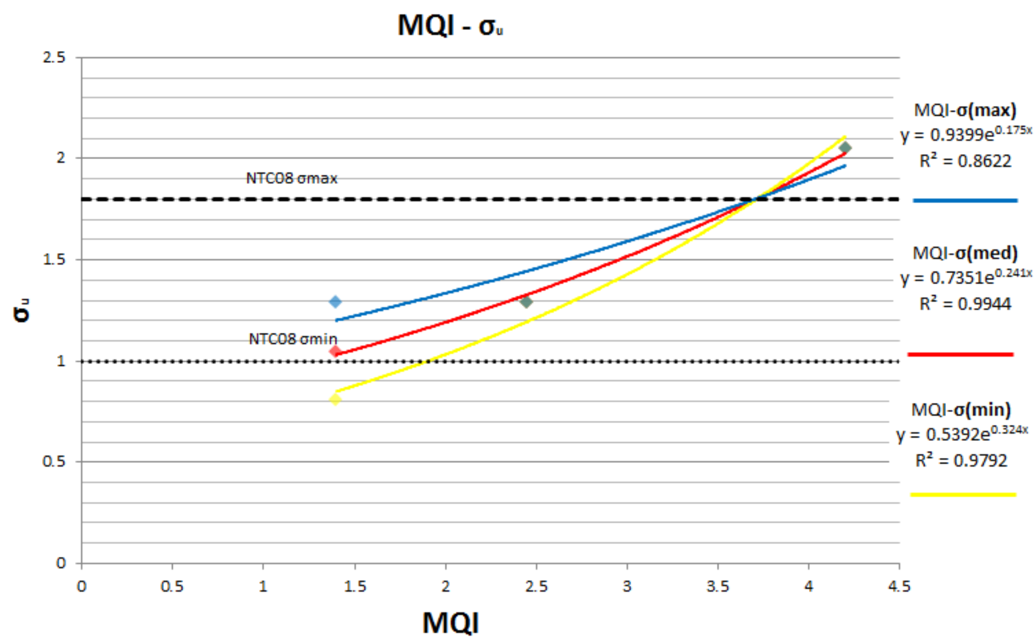


Figure 4: Irregular stone with brick lines correlation curve

In the Fig.4, refers to irregular stones with brick lines masonry type Fig.1c, is possible to see how the correlation curves MQI-σ(max), MQI-σ(med) and MQI-σ(min) have a good correspondence with the range suggested by Italian code with only few values that exceeded the upper and lower bound.

Table 6: A.M.A type (4 tests)

MQI value	σ max(med) MPa	σ max(min) MPa	σ max(max) MPa
3	1.13	1.13	1.13
3.5	2.08	2.08	2.08
5.5	2.51	2.42	2.60

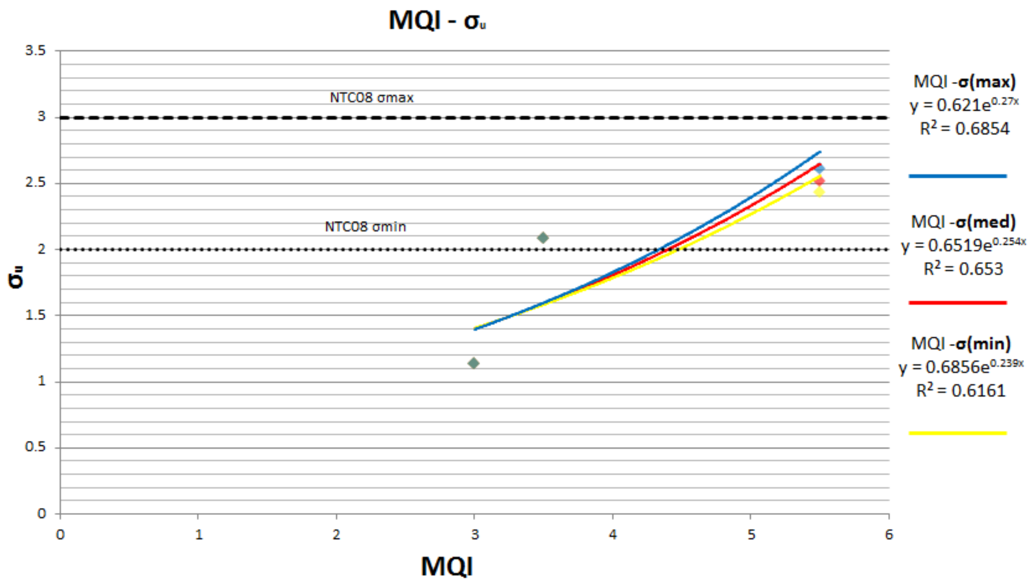


Figure 5: A.M.A correlation curve

The Fig.5, refers to a.m.a masonry type Fig.1d, show how some values have a lower σ_u values compared to those suggested by the code. Is very important to emphasize the fact that this type of masonry is typical of religious buildings present in L'Aquila and is very difficult to compare with the types of masonry proposed by the Italian code.

We also studied the correlation between the MQI value and the compressive strength for all pairs of values Tab.7, not divided into types, in order to find a generic correlation curve defined for all σ_u(med) values, Fig.6. The general correlation curve show how all medium values are in the range suggested by Italian code. The coefficient of determination so obtained show a good MQI-σ(med) correlation.

Table 7: Masonry parameters

MQI value	σ_u (med) MPa
0.5	1.00
0.7	1.05
1	1.43
1.4	1.05
1.5	1.13
2	1.78
2.45	1.29
3.5	2.08
4.2	2.05
5.5	2.51

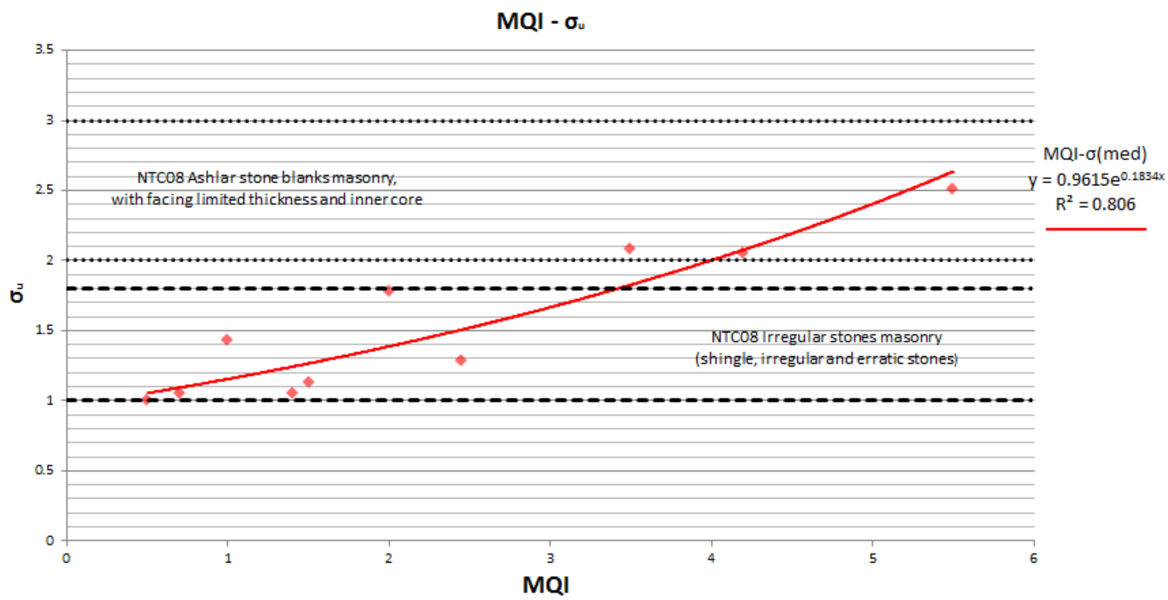


Figure 6: All masonry types correlation curve

Remarks

Observing the σ values for the irregular stone and a.m.a types it appears that some of them are below the straight lines corresponding to the minimum values suggested by the Italian code. This means that in some cases the code may overestimate the mechanical values of these particular types. In these specific case and generally for the historical building where is not allowed to make destructive tests it might be useful to refer to specific correlation laws like the proposed below, Tab.8, to have a good evaluation of compressive strength without invasive procedures.

Table 8: Summary Experience Table

Masonries	MQI- σu(minimum)	MQI- σu(medium)	MQI- σu(maximum value)
a) irregular stones (Fig.2)	$y = 0.5756e^{0.4751x}$ $R^2 = 0.8633$	$y = 0.7719e^{0.3655x}$ $R^2 = 0.8711$	$y = 0.8386e^{0.354x}$ $R^2 = 0.7566$
b) irregular stone with brick pieces (Fig.3)	$y = 0.8656e^{0.3256x}$ $R^2 = 0.9366$	$y = 0.9735e^{0.3232x}$ $R^2 = 0.825$	$y = 0.9925e^{0.3912x}$ $R^2 = 0.9217$
c) irregular stone with brick lines (Fig.4)	$y = 0.5392e^{0.3248x}$ $R^2 = 0.9792$	$y = 0.7351e^{0.2416x}$ $R^2 = 0.9944$	$y = 0.9399e^{0.1756x}$ $R^2 = 0.8622$
d) a.m.a (Fig.5)	$y = 0.6856e^{0.2392x}$ $R^2 = 0.6161$	$y = 0.6519e^{0.2549x}$ $R^2 = 0.653$	$y = 0.621e^{0.27x}$ $R^2 = 0.6854$

CONCLUSION

The present paper gives a contribution to seismic engineering of historical buildings. Our research was motivated by L'Aquila's seismic event that in 2009 destroyed its historical urban centre and several of the surrounding villages. It became immediately apparent that there was a need to improve our current knowledge of masonry types and materials, paying greater attention to local features, and to find innovative solutions for retrofitting the buildings. For these reasons many in-situ tests were performed to identify the masonry properties and to create a new classification, specific to the area. We presented several MQI- σ_u correlation curves (see Table 8). They can be used to estimate the vertical strength of local masonry walls without destructive in-situ tests like double flat-jack. In the future more data could be collected to optimize the curves.

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