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Comparison between in situ experimental data and Italian code standard values

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ABSTRACT: The determination of masonry mechanical features is one of the major problems to face when the safety level of existing constructions is evaluated, with the purpose to improve their structural performance. The seismic Italian code prescribes that the masonry mechanical characterisation must be defined on the basis of available data analysis, visual investigation and *in-situ* experimental tests. With reference to the most common masonry typologies, the code also provides ranges of both strength and elastic properties; these values are widely used in engineering practice, so it is essential to assess if experimental data match well with them. This paper provides a contribute for the critical comparison between standard values and field analysis data, achieved from tests performed within a widespread research activity on the Abruzzo architectural heritage, since the 2009 L'Aquila earthquake. Specific diagnostic procedures, consisting in the application of standardised testing sets, have been developed, with the purpose of optimising the number of measures to reach the knowledge levels required by the Italian code. Data are discussed for some masonry typologies, comparing strength values obtained from quick survey forms, *in situ* experimental campaigns, and codified references. The work can represent a step towards the realisation of a database for the collection of experimental data related to the Abruzzo masonry patterns, aiming at a wider comparison between *in situ* test and standard values, also considering performance improvements subsequent to the reconstruction activity.

1 INTRODUCTION

The seismic Italian Technical Codes for Construction (NTC 2008) requires the assessment of the safety levels before/after any intervention on existing constructions, taking into account the seismic improvement or the local strengthening of the building. The selection of the appropriate methodology for the seismic vulnerability evaluation is dictated by the building type. This is a very complex matter when the historical and architectural heritage is concerned, due to the peculiarities of the structural elements, the geometric proportions and, not least, the need for conservation of the building and the precious artistic value assets housed inside (Mazzolani et al. 2008). According to NTC 2008, it is necessary to acquire information about the geological and geotechnical characteristics of the subsoil (not object of this paper) and the mechanical properties of the structures, in order to evaluate the safety levels. The information should be collected by means of appropriate diagnostic campaigns, through specific testing sets, generally carried out as a preliminary. The evaluation of the mechanical properties of a masonry panel can be obtained combining different methodologies, including non-destructive and semi-destructive tests (Binda et al. 2007; Valluzzi et al. 2009; Indirli et al. 2006a); for both typologies, although to varying degrees, the critical aspect consists in the relationship between testing results and strength/elastic modulus values. In fact, the results may not be indicative of the mechanical properties of the structure, since the values obtained within a single structural element may have high variability due to the masonry anisotropy. Extensive diagnostic campaigns are then needed, in order to achieve reliable results; however, a large number of tests, either non-destructive or semi-destructive, is not often realisable for economic reasons or architectural/heritage restrictions (Guadagnuolo et al. 2015). In these cases, the resort to reference values of the masonry mechanical parameters becomes the minimum knowledge level required by the Code. The recognition of the masonry typology and material quality, estimated after a visual inspection, is then used to associate it with the mechanical parameters reported in a reference table, compiled on the basis of the experimental data available on the most common masonry typologies (Magenes & Penna 2009). In this paper, the results of some experimental campaigns on historic masonry buildings are analysed to assess their correspondence with NTC 2008, and find possible correlations between different testing methods (Bracchi et al. 2015, Fanale & Galeota 2015). The experimental values of the masonry mechanical properties are then compared with the reference ranges proposed in the Code, with the aim to contribute at the identification of a probabilistic meaning of the proposed ranges and, if appropriate, to improve of the definition of the intervals themselves. The authors took advantage of their direct investigations after seismic events (Alterio et al. 2010; Borg et al. 2010; De Gregorio et al. 2010; Florio et al. 2010; Formisano et al. 2010a, 2010b, 2011, 2012 & 2015; Forni et al. 1998; Indirli et al. 2004a, 2006a, 2006b, 2012, 2013; Cami et al. 2007; Maio et al. 2015; Marghella et al. 2013; Marzo et al. 2013) and participation to post-earthquake reconstruction plans (Bertocchi 2002, Formisano et al. 2013; Indirli et al. 2004b, 2007, 2014).

2 ON SITE EXPERIMENTAL CAMPAIGN

2.1 *Data sample and masonry features*

The experimental data amount analysed in this paper comes from several *in situ* diagnostic campaigns carried out on historic masonry buildings affected by the earthquake that struck the city of L'Aquila and some neighbouring towns on April 6, 2009. The investigations mainly regarded ecclesiastical complexes (churches and aggregated buildings) dating back to the city's reconstruction after the upsetting 1703seismic event. Both non-destructive and semi-destructive tests (such as plaster removal, extraction of core samples, borescope inspections, sonic/ultrasonic testing, simple/double flat jack tests) took place on masonry patterns, having different structural purposes.

Aiming at the comparison between the experimental output and the reference values, the investigated data have been classified, according to NTC 2008, into two main classes (Figure 1) among several typologies (Figures 2–5): *T1*, irregular stone masonry (pebbles, erratic, irregular stones), Figure 2; *T2*, roughly-hewn stone masonry with facing walls of limited thickness and infill core, Figure 3. These two typologies, very common in the historic buildings of the central area of Italy, can be found in the city of L'Aquila with the following constructive main features. *T1* is characterised by irregular courses and very poor care for the horizontal set up of the stonework layers; the calcareous stone

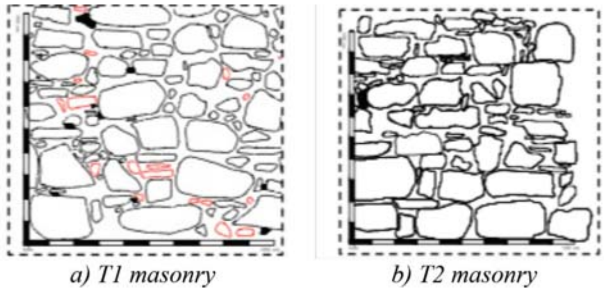

Figure 1. Investigated masonry typologies.

Figure 2. Santa Maria del Suffragio church (T1 masonry).

elements are undressed, of irregular or slightly rounded shape and of different sizes (8÷30 cm). *T2* shows more regular courses (with a certain attention in order to arrange horizontal layers) and roughly-hewn stone elements. In both types, the spaces between the larger stones are filled with smaller elements and fragments of brick, in order to reduce mortar layers and improve the normal strain of panels. The binding material is usually quicklime mortar but, according to historical sources, sometimes *pozzolana* was added, especially in the outer part of the wall, to provide the mortar with hydraulic property (Zordan 1992).

Regarding the inner masonry texture, it is not easy to assess the quality of transverse interlocking. The presence and size of a rubble infill has been investigated by the core samples extracted during the diagnostic campaign, but the data analysis has not always provided conclusive evidence about it. However, in the absence of open transverse wall sections, a general ascription to the "*sack*" type should be avoided.

Figure 3. Archiepiscopal-Cathedral compound (T2 masonry).

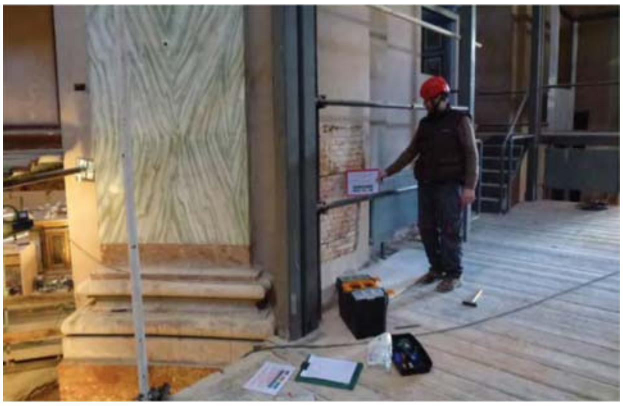

Figure 4. Sant'Agostino church (B masonry).

As pointed out in previous researches, many masonry textures in the L'Aquila region show a constructive rule which may provide effective transverse connection; in this respect, they differ significantly from the "*sack*" type (Carocci & Tocci 2012). In a detailed study on L'Aquila building techniques (Zordan 1992), "*sack*" masonry types are not mentioned; the typical so-called *"apparecchio aquilano"* is described as formed by two facing walls plus an inner one forming a homogenous structure. In addition to the above described kind of masonry works, a small number of tests was carried out on other different masonry typologies, such as dressed rectangular (ashlar) stone masonry (*DS*) and solid brick masonry with lime mortar (*B*). Simple/double flat jack tests (Figure 6) and sonic/ultrasonic tests (Figure 7) have been performed for each building. The collected experimental data

Figure 5. Sant'Eusanio church (DS masonry).

have been compared in terms of the sonic wave propagation velocity, compressive strength and elastic modulus of the examined masonry sets. The data sample can be considered enough significant from the statistical point of view, as it consists in a number of data relative mainly to the *T1* specific masonry typology, which has been realised with similar constructive techniques and materials, dating back to the same epoch. Table 1 summarises the tests carried out (building name/age, masonry type, testing localisation).

2.2 *Methodology*

The most widespread semi-destructive test is realised with the use of the simple/double flat jacks (ASTM C1196/91, ASTM C1197/91 & ASTM D4729, Figure 6); the main advantage is the assessment of the masonry *in situ* stress level (single) and deformability properties in compression (double); this technique allows an approximate estimate of the compressive strength of the portion of masonry under investigation; on the other hand, it is quite expensive, and not applicable when the historic building walls have mural paintings or decorations, because the removal of plaster is needed.

Quick and cheaper non-destructive sonic/ultrasonic testing provides a qualitative evaluation of the masonry homogeneity, through the investigation of the wall section morphology, detection of discontinuities, voids and crack/damage patterns (EN 583, EN 12668, ASTM C1383 & ASTM E494, Figure 7).

Both the above cited methods are largely employed, often coupled with borescope inspection (coring), and tomography.

It is important to note that the real crucial point is to obtain a reliable and direct correlation between masonry sonic wave velocity and mechanical parameters (*in primis* elastic modulus), possible when the examined structure is homogeneous

Table 1. Semi-destructive/non-destructive tests on buildings.

Building	Age (century)	Masonry type	Test zone
Sant'Agostino church	XIII-XIV	brick (B)	Pillar
Archiepiscopal-Cathedral compound	XVIII	T2	lateral wall (right side)
Archiepiscopal-Cathedral compound	XVIII	T1	lateral wall (left side)
Archiepiscopal-Curia compound	XVIII	T1	perimeter wall (courtyard)
Archiepiscopal-Palace compound	XVIII	T2	façade of the Palace
Archiepiscopal-Sacristy compound and Museum	XVIII	T1	perimeter wall (Roio street)
Palace ex Bank of Naples	XIX	brick (B)	underground floor
Santa Maria delle Anime del Suffragio church	XVII-XVIII	T1	perimeter wall (Ramieri street)
Santa Maria delle Anime del Suffragio church	XVII-XVIII	T1	ground floor facade (Simeonibus street)
Archiepiscopal-University compound	XIII	T1	intermediate wall between hall and staircase
Sant'Agostino church	XIII-XIV	brick (B)	4th column on the left of the dome
Archiepiscopal-Seminary compound	XVIII	T1	wall (Seminario street)
Sant'Eusanio church	XII-XX	dressed stone (DS)	lateral wall (left side)
San Benedetto church	XII	dressed stone (DS)	first column (right side)
San Benedetto church	XII	T1	lateral wall (left side)

and isotropic (Da Porto et al. 2013). To extend this approach to real cases, a good compromise between a limited number of targeted flat jacks tests (more onerous) and a spread series of ultrasonic tests (less expensive, extensively applicable, but less accurate) is necessary, in order to optimise the results of the diagnostic campaign and contain its costs. In fact, the exclusive use of non-destructive tests may provide unreliable results, due to indirect measurement that can be affected by uncertainties. Therefore, the direct evaluation supplied by the flat jacks tests becomes fundamental for the calibration of the sonic/ultrasonic testing results.

Figure 6. Example of double flat jack test.

Figure 7. Example of sonic/ultrasonic test.

Consequently, the methodology followed by the teams during the diagnostic campaigns (carried out in L'Aquila and surroundings after the 2009 earthquake) led to identify some key points of the structure under examination, in which to perform complete investigations (single/double flat jacks, ultrasonic, extraction of core samples for the direct observation of the internal pattern of the masonry or borescope inspection). A second phase regarded a wide implementation of non-destructive testing in other selected points, being now reliable correlations between direct and indirect results.

3 DATA ANALYSIS

A great amount of data has been achieved during non-destructive/semi-destructive campaigns; among them, flat jack and sonic/ultrasonic tests have been performed in the same place for a limited number of points of the selected buildings listed in

Table 2. Mean values of flat jack and ultrasonic test results.

Building	σ_t [MPa]	E [N/mm^2]	v [m/s]	s [m/s]
Sant'Agostino church (B)	3,00	1948,18	1603,60	69,00
Archiepiscopal-Cathedral compound (T1)	1,20	993,38	643,90	175,60
Archiepiscopal-Cathedral compound (T2)	1,60	1142,86	993,40	147,60
Archiepiscopal-Curia compound (T1)	3,00	4464,29	1672,50	226,60
Archiepiscopal-Palace compound (T2)	3,00	3521,13	895,80	177,30
Archiepiscopal-Sacristy compound and Museum (T1)	1,20	2483,44	822,20	141,20
Palace ex Bank of Naples (B)	3,00	6521,74	2243,30	175,90
Santa Maria delle Anime del Suffragio church (T1)	1,60	847,46	1712,50	137,30
Santa Maria delle Anime del Suffragio church (T1)	3,00	5309,73	1315,50	275,00
Archiepiscopal-University compound (T1)	2,40	3550,30	2085,40	80,00
Sant'Agostino church (B)	3,00	3260,52	2047,40	83,80
Archiepiscopal-Seminary compound (T1)	2,40	2742.86	1740,10	268,90
Sant'Eusanio church (DS)	2,40	1466,28	1631,60	271,90
San Benedetto church (DS)	2,40	1566,58	1971,50	127,00
San Benedetto church (T1)	2,40	863,62	1723,60	189,10

Table 1. The results are illustrated in Table 2, where the average values detected for Young modulus (E), compression strength (σ_t), ultrasonic velocity (v) and its standard deviation (s) are reported. The analysis of data, obtained from experimental investigations on different types of masonry patterns, provided the mean velocities and standard deviations shown in Table 3.

The probability distribution of sonic/ultrasonic velocities on the inspected masonry patterns is depicted in Figure 8; it appears that minimum/maximum standard deviations are accomplished respectively with *B* and *DS* masonry types. Finally, the diagrams Young modulus E vs. sonic/ultrasonic velocity v and compression stress σ_t vs. sonic/ultrasonic velocity v for all the investigated masonry patterns are respectively plotted in Figures 9 and 10.

Table 3. Mean velocity and standard deviation of investigated masonry patterns.

Masonry type	Mean velocity (m/s)	Mean standard deviation (m/s)
T1	1464,46	186,71
T2	944,60	162,45
B	1964,77	109,57
DS	1801,55	199,45

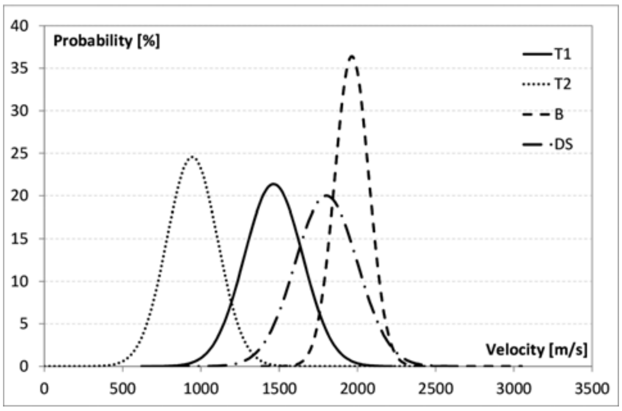

Figure 8. Gaussian distribution of the ultrasonic velocity for the investigated masonry types.

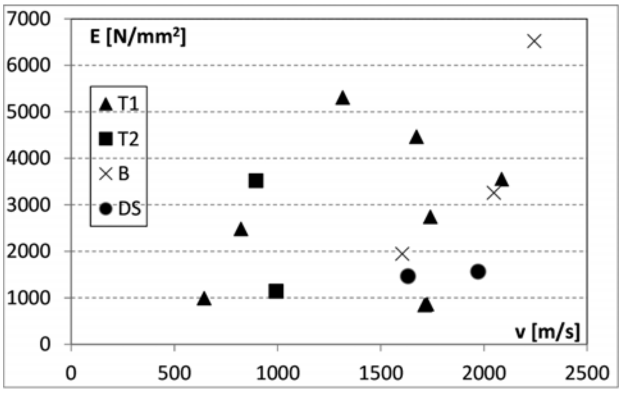

Figure 9. E vs. v relationship for investigated masonry types.

4 COMPARISON BETWEEN EXPERIMENTAL DATA AND CODE STANDARD VALUES

From Table 1 it is noticed that the most of the experimental values have been obtained for *T1*

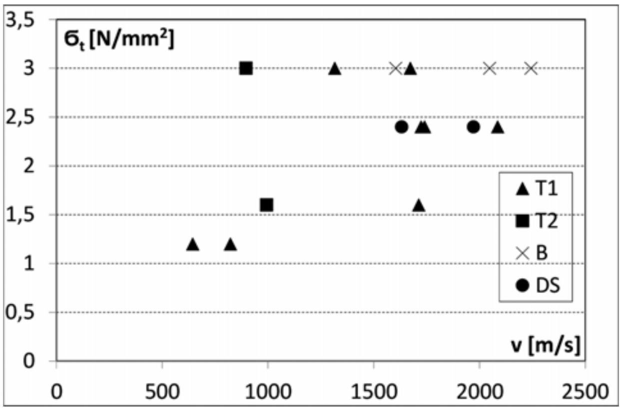

Figure 10. σ_t vs. v relationship for investigated masonry types.

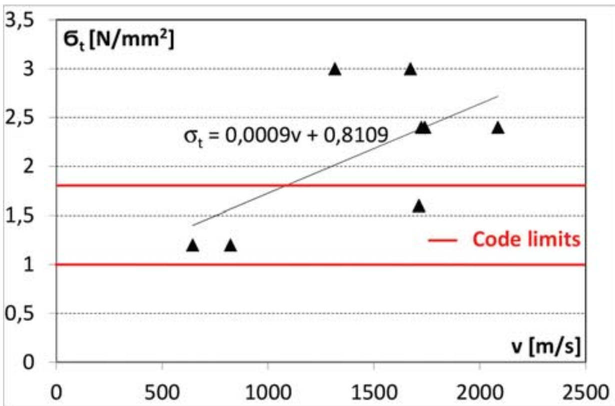

Figure 12. σ_t vs. v relationship for *T1* masonry and comparison with standard values.

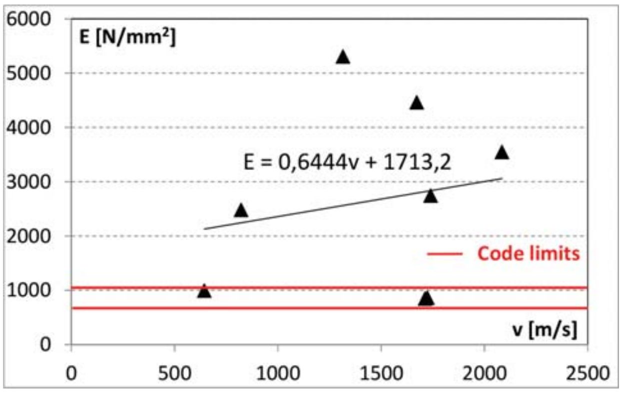

Figure 11. E vs. v relationship for *T1* masonry and comparison with standard values.

masonry (8 sites). Therefore, sufficiently reliable Young modulus E vs. sonic/ultrasonic velocity v (Figure 11) and compression stress σ_t vs. sonic/ultrasonic velocity v (Figure 12) correlation laws have been derived for that typology.

The achieved results have been used to implement simple linear relationships (E-v; σ_t-v) aiming at understanding, in the case of execution of sonic/ultrasonic tests without the support of more expensive flat jack tests, if the experimental mechanical properties of *T1* masonry fall within the codes requirements.

From the analysis of a wide - but not exhaustive - set of investigated data, it is clear that NTC 2008standards cover the scattered range of experimental values only for the lower limit, both for E and σ_t (E-v: E_{min} = 690 N/mm^2; σ_t-v: σ_{tmin} = 1.0 N/mm^2); on the contrary, the upper limit is too conservative (E-v: E_{max} = 1050 N/mm^2; σ_t-v: σ_{tmax} = 1.8 N/mm^2).

Finally, further analyses of *in situ* testing outputs should be implemented, leading to reliable relationships in order to optimise the choice/calibration of testing typologies, and check/refine the standard provisions, firstly for *T1*-*T2* masonry, but also for other texture typologies.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

In the present step of the study, the comparison between the results of *in situ* experimental campaigns on L'Aquila masonry patterns and NTC 2008 provisions has been carried out. Four masonry types (irregular stone *T1*, roughly-hewn stone *T2*, brick *B*, dressed stone *DS*) from cultural heritage buildings have been investigated through semi-destructive and non-destructive testing.

In particular, minimum/maximum standard deviations of the sonic/ultrasonic velocity probability distribution of the inspected masonry patterns are accomplished respectively with *B* and *DS* masonry types. On the other hand, from the analysis of a wide, but not exhaustive, set of *T1* masonry test data, it is evident that the construction of reliable relationships (E-v; σ_t-v) are useful to optimise the choice/calibration of testing typologies, and check/refine the standard provisions.

Widespread strengthening interventions, foreseen by the L'Aquila post-earthquake reconstruction plan, are providing a huge amount of experimental data; the information, if uniformly collected, catalogued and critically studied, can represent a real and unique treasure for our technical-scientific research. For this reason, the work done for this paper could be robustly implemented (number of samples, selection of case studies, typology of texture) if the organisation of a wide database regarding masonry mechanical properties will be quickly implemented.

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