TECHNISCHE UNIVERSITÄT DRESDEN

IMS International Masonry Society

8th International Masonry Conference 2010 in Dresden

Mechanical properties of tuff and calcarenite stone masonry panels under compression

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ABSTRACT:

A significant number of historic and monumental buildings located in Mediterranean areas, and in particular in South-central Italy, are characterized by soft stone masonry, i.e. tuff or calcarenite. Many are exposed to seismic risk, so that a reference data base in terms of mechanical properties is of paramount importance in seismic assessment of this type of masonry structures. Over the past decades, relevant experimental research has been carried out on masonry panels that represent traditional arrangements. Investigations on their in-plane response under compression, shear and combined shear-compression loading are available. In the present work, a systematic interpretation of available data is carried out with reference to compressive behaviour of tuff and calcarenite stone masonry. The aim is to widen our knowledge about large single and multiple-leaf panel response. Results can be used to validate the estimation of mechanical properties in view of nonlinear analyses of historic masonry structures.

Keywords: *historical masonry, existing structures, soft stone, tuff, calcarenite, compressive behaviour.*

1 INTRODUCTION

Historic heritage diffused over the Mediterranean area mostly consists of masonry constructions built using local natural stones. In central and south Italy, in particular, the use for building works of lithotypes derived from pyroclastic deposits found in the volcanic Phlegrean Field area and in volcanic areas surrounding the city of Rome, sometimes many kilometres away from the sites of eruption exsits Neapolitan yellow tuff is the most common building material in the Campania Region. It is a highly inhomogeneous material with a vesicular feature containing unevenly distributed cavities, pumices obsidian fragments, crystals and lithis embedded in an ashy matrix. In Latium, though, one of the most used stone consists of tuff named “Tufo Rosso a scorie Nere” (red tuff with black inclusions) [1].

Other natural masonry stones that can be found in South-Central Italy incluce a broad variety of calcarenite stones produced by a sedimentary process, amongst which “tufo bianco pugliese” (‘white tuff’) and “pietra leccese” (‘leccese stone’) ([2]). Tuffs and calcarenite stones are usually called ‘soft stones’. Such materials display, on average, low to medium mechanical properties and large variability in the physical and mechanical features depending on the quarry location and depth of extraction ([3]). Tuff stones, in addition, are highly sensitive to the degree of saturation. The high seismic hazard of historical and heritage structures located in some southern Italy areas calls for a rational approach to safety assessment, well supported by experimental research.

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Most of the experimental work carried out in recent decades has been focussed on uniaxial compressive behaviour of single or multiple leaf masonry panels built with Neapolitan yellow tuff stones, in the direction normal to bed joints (e.g. [4], [5], [6], [7]). In such cases, medium to large-size wall panels with different material properties, dimensions and textures were tested. Moreover, research on masonry under eccentric loading is available for both yellow tuff masonry and calcarenite masonry.

The tensile and biaxial behaviour of panels are issues not yet considered in the literature, while environmental data is limited ([8]). Such a lack of knowledge is clearly critical when vulnerability assessment is concerned, because numerical analysis would lead to inaccurate prediction of seismic capacity and failure mechanisms of structures.

Within this context, the paper deals with historical masonry in regions located in South-Central Italy. It presents, in particular, the state-of-the-art of the literature on representative tuff and calcarenite masonry panels subjected to compression, with particular emphasis on recent published results. The aim is to expand knowledge about medium-large panels, sharing the effort made within the Research Project DPC-Reluis 2005-2008 (Db Murature Unina-Dist, 2009 [9]). Single and multiple-leaf panels have been accounted for, characterized by different specimen sizes and block arrangements. Since masonry mechanical parameters plays a key role in any vulnerability assessment and rehabilitation design process, attention is also focused on reference values in compression for soft stone masonry, provided by the recent Italian Design Guidelines (2009) [10]. Comparisons with available test data are used as a preliminary assessment of the reliability of the proposed range of values, with respect to 'soft stone' masonries. Special attention is paid to the softening response of panels. In particular, stress-strain curves from available experimental works are plotted and compared for single and multiple-leaf panels. The whole set of data here reported represents a valid support into advanced seismic analysis and the assessment of historical structures when no direct experimental testing on masonry walls is available.

2 MASONRY BEHAVIOUR UNDER COMPRESSION

Analysis of experimental data on medium-large size panels under compression allows for the evaluation of strength and deformation behaviour. The investigated panels were built with Neapolitan yellow tuff, tufo romano a scorie nere (here referred to as 'Roman tuff'), leccese and calcarenite stones.

Detailed results on Neapolitan yellow tuff masonry panels can be found in [4], [6], [7], [8], [11], [12], [13], [14], [15], [16], [17]. Data for Roman tuff panels can be found in [1], for leccese stone panels in [18], [19] and for calcarenite panels in [20], [21], [22], [23], [24], [25]. All the tested panels were built with full scale bricks. Mortar joints were between 10 mm and 20 mm in thickness; in [26] joints were 5 mm. The panel height-to-width ratio (*H/B*) ranged from 0.68 to 1.5 for tuff panels, and from 0.85 to 1.44 for calcarenite panels. Different masonry textures, dimensional ratios and cross sections (i.e. single or multiple-leaf) were built in order to investigate the most representative masonry walls within the Neapolitan area. A sketch of these panels may be found in [27]. The panels made of leccese or calcarenite stones were single leaf except in [21], and were characterized by a regular block arrangement.

Multiple-leaf panels were generally composed of two outer-leaves poorly connected, with an inner core of rubble materials. In [21] the multiple-leaf panels had keyed or straight collar joints with no transverse connection, representing possible configurations of the pillars of the historic Noto Cathedral in Sicily, Italy.

The majority of the tests were performed under monotonic loading and controlled displacement to capture the softening response. However, no harmonized test methods have been found.

Cyclic tests on yellow tuff masonry were carried out up to failure in [12]. In [6] force controlled tests were performed to evaluate the elastic modulus of yellow tuff panels, followed by a monotonic displacement control test up to failure. In [1] cyclic tests on Roman tuff panels were conducted under force control. As far as calcarenite masonry under cyclic loading is concerned, references can be found in [23] and [28]. Uniaxial tests under force control were presented in [25]. In [24] cyclic tests were carried out under displacement or force control.

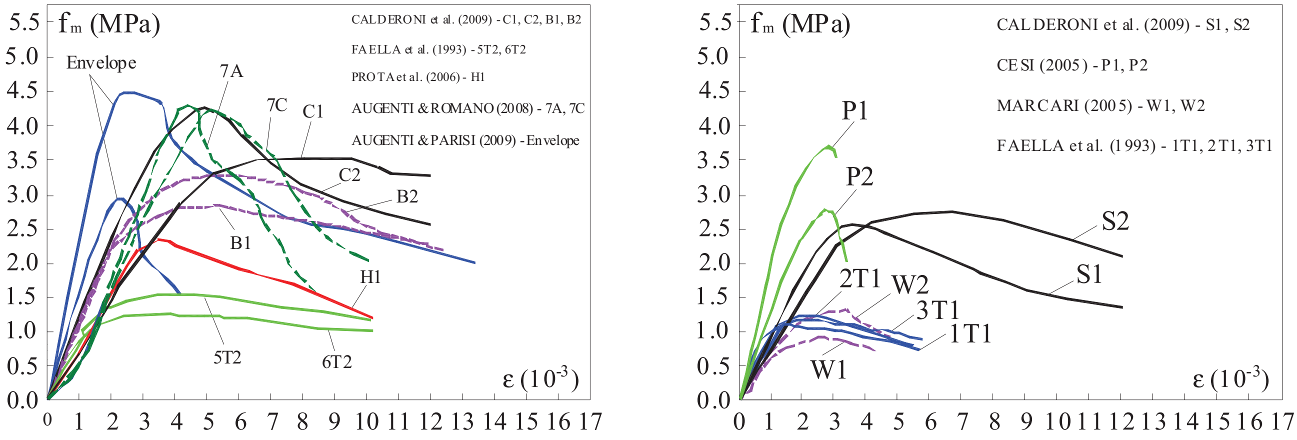
The stress-strain curves σ - ε for single and multiple-leaf panels made with Neapolitan yellow tuff are plotted in Figure 1 (a) and Figure 1 (b) respectively. The curves have been identified according to the reference.

Figure 1(c) shows a comparison between different single leaf calcarenite panels. In particular, four of the six curves are shown for the tests carried out by [22] that are compared against the mean response of the panels tested by [24], namely Type A (i.e. built with hydrated lime mortar) and Type B (i.e. with hydraulic lime-based mortar).

As regards the Roman tuff panels, the monotonic envelope curve of the cyclic tests carried out by [1] has been illustrated in Figure 1 (d).

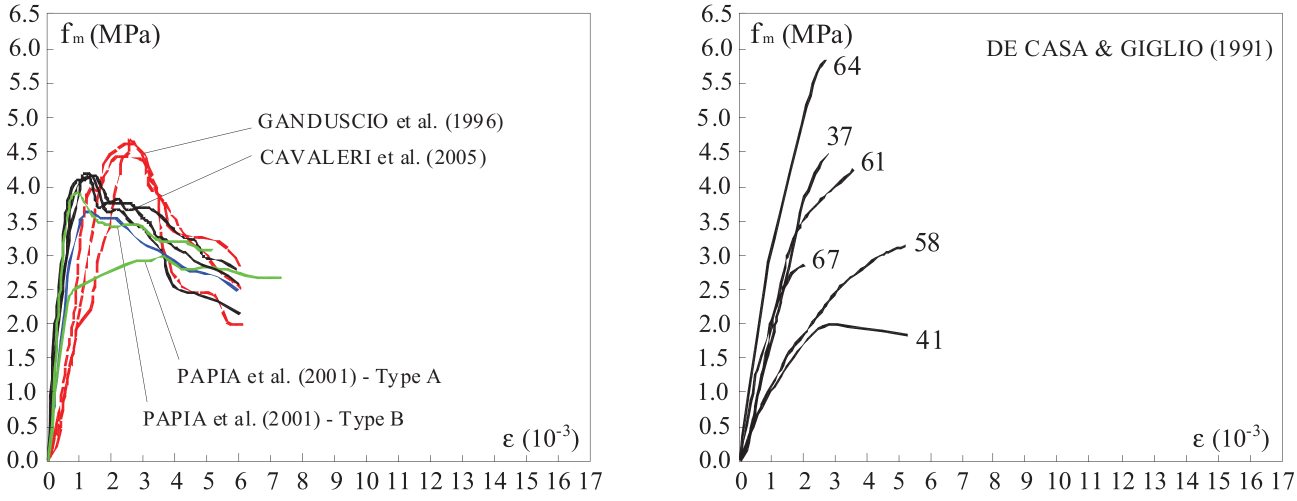
It is worth noting that the experimental behaviour of calcarenite panels in [23] is given in terms of σ/σ_0 - $\varepsilon/\varepsilon_0$ curves, where σ_0 and ε_0 are the maximum stress and the corresponding strain, respectively. In order to make possible comparisons in terms of σ - ε relationships, the values σ_0 = 4.76 MPa and ε_0 = 0.25 % were used, in compliance with the experimental outcomes.

Figure 1 shows that maximum and ultimate strength, as well as the global deformation behaviour, are affected by large variability. However, observation of the curves shows that calcarenite panels tend to show high elastic stiffness and a more rapid strength decrease in the post-peak branch, compared to Neapolitan yellow tuff panels.



a) SINGLE LEAF PANELS - Neapolitan yellow tuff

b) MULTIPLE LEAF PANELS - Neapolitan yellow tuff



c) SINGLE LEAF PANELS - Calcarenite stones

d) SINGLE LEAF PANELS - Roman tuff stone

Figure 1. Stress-strain relationships of tuff and calcarenite masonry panels

Attempts to develop analytical stress-strain relationships for yellow tuff masonry under monotonic or cyclic loading were made by [4], [5] and [22]. However, these constitutive laws were calibrated with reference to panels that differ in respect of geometry, type of materials and materials mechanical properties. Regarding calcarenite panels, an analytical stress-strain relationship for panels under uniaxial cyclic compression can be found in [28], while in [22] analytical relations were formulated for panels under vertical or eccentric vertical loads.

2.1 Mechanical properties of masonry stones

In this section, data on calcarenite stones are investigated. Detailed analysis of mechanical properties about yellow tuff stones and pozzolanic-based mortars used to build the panels here investigated can be found in [27].

From destructive testing, a wide range of compressive strengths were found, varying from 1.98 MPa to 17.6 MPa, with an average of 7.36 MPa and a c.o.v. greater than 50 %. The significant difference between maximum and minimum values, as well as the high scatter in results were also found in literature about calcareniti sampled in Puglia Region, south-eastern Italy. High compressive strength values were found in comparison to those of Neapolitan yellow tuffs. From in-situ investigation carried out on historic constructions in South Italy, for example, by [29] and [30], it was found that the compressive strength varied between 5.0 MPa and 18 MPa. Tensile strength approached values between 1.0 MPa and 3.5 MPa with a mean of 1.64 MPa (c.o.v. = 0.55). Lower values of 0.7 MPa to 0.9 MPa were found in [30]. Moreover, the average ratio between compression and indirect tensile strength, f_c/f_t was 5.1 (c.o.v. = 64 %). It should be observed that even larger f_c/f_t values were found in the literature ranging, from 6.4 to 8.18 [29]. The latter value, in particular, resulted from tests on the pillars of an historic church placed in Sicily, South Italy.

The elastic modulus of calcarenite stones varied from about 4300 MPa to 12000 MPa, with an average of 7083 MPa and c.o.v. = 40 %. Data obtained from in-situ tests displayed values in the range 9300 MPa to 13400 MPa [30].

2.2 Compressive strength of masonry panels

A large scatter characterizes strength, stiffness and post peak-behaviour, due to differences in terms of material properties, specimen texture and dimensions. However, some general remarks can be stated for structural analysis or safety assessment purposes.

The compressive strength of multi-leaf panels was generally based on the gross area of the walls, neglecting the presence of multiple leaves, or possible differences in strength between the inner core and the surrounding masonry. Even though significant literature on load-transfer mechanisms in multi-leaf masonry are currently available ([21]), a simple approach seems to be the only feasible one when addressing existing masonry, due to the difficulty of recognizing geometrical and mechanical properties of the leaves (Design Guidelines to the NTC 08, 2009 [26]).

Results from tests on single leaf tuff masonry panels showed a mean compressive strength ($f_{m,exp}$) equal to 2.78 MPa, associated to a standard deviation = 1.20 MPa and c.o.v. = 43 %. As for multiple-leaf panels, an average compressive strength equal to 1.83 MPa was obtained, with a standard deviation = 0.77 MPa and c.o.v. = 42.0 %. Good agreement in terms of global behaviour is found between masonry panels built with comparable materials strength and masonry layout (see [6] and [7]).

For calcarenite panels values ranged from 1.02 MPa to 4.76 MPa (average = 2.93 MPa, stand. dev.= 1.35 MPa and c.o.v. = 0.46). From in-situ tests carried out by [29] on historical masonry, a compressive strength of 2.85 MPa was found. Available results on multi-leaf panels can be found in [21], and showed an average compressive strength equal to 6.1 MPa.

It is worth noting that masonry compressive strength results were lower than the compressive strength of the constituents. This evidence comes from tests on yellow tuff multi-leaf panels ([7], [14]) as well as from the tests on calcarenite panels.

The data gathered about Neapolitan tuff panels allowed one to compare the masonry characteristic compressive strength f_k estimated according to the NTC 08 (2009) [10], and EC6 (2005) [31]. NTC 08 provides a specific table to estimate the characteristic strength, f_k, of masonry whenever a comprehensive number of tests is not available. It is based on components characteristics: mortars are classified according to their mean compressive strength, while stones are characterized according to their characteristic compressive strength given by f_{bk} = 0.75 f_b, where f_b is the stone mean compressive strength. EC6 defines an empirical relation for the characteristic strength of masonry built with general-purpose mortar, with adjustment for unit proportions and wall characteristics. It is worth noting that NTC 08 gives on average values lower than those predicted by EC6 of about 20 %. A comparison study between characteristic strengths and EC6 predicted values for Neapolitan yellow tuff panels can be found in [6].

2.3 Masonry Young's Modulus

The experimental Young's modulus ($E_{m,exp}$) of Neapolitan yellow tuff masonry varied between 630 MPa and 2943 MPa in the case of single-leaf, and from 635 MPa to 1800 MPa for multiple-leaf panels. The single-leaf specimens, in particular, showed an average $E_{m,exp}$ = 1607 MPa (stand. dev.= 642 MPa; c.o.v = 40 %). The multiple-leaf panels approached a lower average value $E_{m,exp}$ = 1280 MPa (stand. dev. = 420 MPa; c.o.v = 32 %).

As for single leaf calcarenite panels, values ranged between 1768 MPa and 9000 MPa, with a mean value equalsto 4419 MPa (stand. dev. = 2484 MPa and c.o.v. = 0.56 MPa). Data on multiple leaf panels are very limited. However, an average elastic stiffness of about 2000 MPa has been found in [21]). Thus, calcarenite panels showed, on average, a greater elastic stiffness than yellow tuff panels, especially for single leaf panels.

Several attempts to develop accurate methods of prediction of Young's modulus are available in the literature. This parameter is, however, rather variable even for nominally identical specimens, and a prediction of its value is not simple. In this section attention is also focussed on the ratio of the modulus of elasticity to mean compressive strength that has been widely investigated in literature for brick masonry, and actually implemented in relevant masonry building guidelines.

Single-leaf panels made of Neapolitan tuff showed a mean value $E_{m,exp}/f_{m,exp}$ = 600, with a standard deviation = 288 and c.o.v. = 47 %, while multi-leaf approached the average $E_{m,exp}/f_{m,exp}$ = 715 (stand. dev. = 238 ; c.o.v. = 33 %). Consequently, the empirical relationship proposed by [6] and given by $E_{m,exp}/f_{m,exp}$ = 800, provides values higher than the experimental results in the case of single-leaf panels, while it seems reliable for multiple-leaf masonry.

For single calcarenite panels, the average $E_{m,exp}/f_{m,exp}$ was higher than that noticed for Neapolitan yellow tuff, and equal to about 1450 (c.o.v. = 34%). A lower value =330 was found in [21] for multi-leaf panels.

Results allowed one to estimate the ratio $E_{m,max}/E_{m,exp}$ for Neapolitan yellow tuff panels, with $E_{m,max}$ the secant modulus of masonry at maximum stress. This is certainly of interest when analytical stress-strain relations available in the literature are used to predict the masonry response under compression. This ratio varies between 0.33 and 0.91 with a mean value of 0.73 for single-leaf, and between 0.48 and 0.9 with an average of 0.59 for multi-leaf panels. Therefore, the suggested value for the ratio $E_{m,max}/E_{m,exp}$ is 0.6 for single and multi-leaf walls.

2.4 Masonry Poisson's coefficient

The Poisson's coefficient υ for yellow tuff panels was obtained in [4], [6], [7], [13] and [16]. This coefficient was generally calculated as the horizontal strain ε_h to vertical strain ε_v ratio within the range 0 – 30 % of the peak strength. On average, the single and multiple-leaf panels showed υ = 0.13, associated to a standard deviation equal to 0.07 (c.o.v. = 52 %) and 0.04 (c.o.v. = 33 %), respectively. Few data have been found about calcarenite panels. Single leaf panels showed values between 0.10 and 0.18 in [25], and between 0.06 and 0.09 in [29]. For multiple-leaf, υ = 0.15 was found in [21].

2.5 Maximum and ultimate strains, ductility

The maximum and ultimate strain, as well as the ductility ratio μ, have been investigated. Maximum strain $\varepsilon_{m,max}$ exhibits a large scatter. With reference to the single-leaf panels, values varied in the range 0.24 % to 0.88 %, with a mean value of 0.39 % (stand. dev. = 0.16 %, c.o.v. = 41 %). About 67 % of data are in the range (0.2 – 0.4) % with a mean value of 0.31 %, and 33 % are higher than 0.4 %, with a mean value of 0.57 %. Data about multiple-leaf panels vary from 0.15 % to 0.61 %, with a mean value of 0.30 % (stand. dev. = 0.12 %; c.o.v. = 40.3 %). About 90 % of values are within the range (0.2 – 0.4) % with a mean value of 0.27 %, and 10 % are higher than 0.4 %.

The ultimate strain ε_u has been calculated as the strain corresponding to the ultimate stress. Due to the uncertainty on the residual strength values, the ultimate strength is here assumed to be 85 % of the masonry compressive strength in accordance with technical literature. The single-leaf panels exhibited higher ultimate strains than the multi-leaf ones. For the single leaf the variation was in the range 0.34 % - 1.4 %, with an average of 0.83 % (stand. dev. = 0.3 %, c.o.v. = 37.8 %), while for multiple leaf the range was 0.25 % - 1.2 % with average equals to 0.49 % (stand. dev. = 0.30 %, c.o.v. = 61 %).

A significant scatter in maximum and ultimate strains was found for calcarenite panels. Amongst the available reference tests, those carried out under displacement control have been used to evaluate both $\varepsilon_{m,max}$ and ε_u ([22], [23], [24]).

The average $\varepsilon_{m,max}$ of single leaf specimens was found to be 0.16 % (stand. dev. = 0.081 % and c.o.v. = 49 %). As for the ultimate strain, the average was equal to 0.44 % (stand. dev. = 0.19 % and c.o.v. = 43 %). The computed values show that calcarenite panels tend to have shorter vertical deformation at maximum and ultimate load than yellow tuff panels.

The inelastic deformation capacity is stressed by the ductility ratio μ that was calculated as $\varepsilon_u/\varepsilon_{m,max}$. Ductility values for single-leaf panels ranged between 1.23 to about 2.40, with an average μ = 1.80 (stand. dev. = 0.44; c.o.v. = 24.2 %). The multiple-leaf ranged between about 1.1 to 2.15, with an average μ = 1.50 (stand. dev. = 0.38; c.o.v. = 25.3 %). The ductility of calcarenite single leaf panels was found to be about 1.15 in [22] and [23], resulting lower than that calculated for yellow tuff panels. However a higher value equals to 3.0 was detected in [24]. Such high value may be due to the fact that a mortar of low strength was used compared to the one used in [22] or in [23], that lead to a more diffused crack pattern. It was also observed that cyclic tests performed on calcarenite panels allowed masonry to show higher ductility than that detected in monotonic tests ([23]).

It is also interesting to compare the ductility provided by EC6 (μ_{EC6} = 1.75) and the experimental results. Although the EC6 ductility holds for new masonry, it seems to be reliable for single-leaf masonry, but tends to overestimate the deformation capacity of multiple-leaf of about 20 %. Average experimental properties of a selection of yellow tuff and calcarenite panels are given in Table 1.

Table 1. Experimental masonry mechanical properties

Masonry properties	$f_{m,exp}$ (MPa)	$E_{m,exp}$ (MPa)	$\varepsilon_{m,max}$	μ
Calderoni et al. (2009) - C1 + C2, (S.L.– Y.T)	3,97	965	0,68%	1,50
CESI (2005), (M.L.-Y.T.)	3,25	1655	0,27%	1,12
Stella (1993) - Cava 1 (S.L. - C.)	1,62	1768	0,1%	1,02
Ganduscio et al. (1996) (S.L. – C.)	4,76	3010	0,25%	1,28

Note: C1+C2=masonry speciments type "a cantieri C1 and "a cantieri C2"; Cava 1=quarry #1; S.L.=single leaf; M.L.=multiple leaf; Y.T.=yellow tuff; C.=calcarenite

3 EXPERIMENTAL VS. DESIGN GUIDELINE VALUES: A COMPARATIVE ANALYSIS

The current section presents a comparative analysis aimed at a preliminary investigation of the reliability of the range of mechanical properties given by the Design Guidelines to the NTC 08 (2009) [26]. The test masonry panels considered herein are "soft stone" masonry defined by the code. The corresponding average strength f_m and elastic modulus E_m values (maxima and minima) are summarized in Table 2.

The range is given for masonry characterized by poor mortar quality, by the absence of regular courses, by wall leaves merely placed together and badly connected, or with an inner core thinner than the outer leaf, and by loose stones. This means that multiple-leaf panels, with poor mortar and large/weak inner core are considered as reference.

For masonry panels with good mortar and/or suitable transverse connections, the strength values shown in Table 2 are corrected using appropriate correction factors as follows (Design Guidelines 2009 [26]): good mortar = 1.5; transverse connection = 1.5.

Regarding the multiple-leaf panels with weak or large inner cores, the corrective factor is 0.9 that should be used to adjust for both strength and Young's Modulus, in accordance to the Design Guidelines. It is worth noting that no masonry properties are given for single-leaf panels. Moreover, the code does not account for the presence of any stone courses or ashlar borders.

In this work, single leaf panels with poor mortar are assumed to be the reference panels (i.e. poor mortar, wall leaves merely placed together or badly connected) with effective transverse connections. As a result, the new set of reference values for single leaf panels with poor mortar is defined and given in Table 2 (columns c and d). Finally, the correction factor related to transverse connections was not used to adjust the elastic modulus, in compliance with the Design Guidelines.

Table 2. Average values of masonry mechanical parameters

	Reference values (Design Guidelines 2009)		**Single leaf with poor mortar (calculated)**	
Masonry properties	f_m (MPa) -a-	E_m (MPa) -b-	f_m (MPa) -c-	E_m (MPa) -d-
Min value	1.4	900	2.1	900
Max value	2.4	1260	3.6	1260

For what concerns the quality of mortar, it has been assumed that a compressive strength not larger than 2.5 MPa corresponds to a mortar of poor characteristics. The value of 2.5 MPa is, infact, the lower bound of the mortar compressive strength prescribed by the NTC 08 for the design of new masonry structures. It is worth mentioning that no data are available for calcarenite single and multiple leaf panels with weak mortars.

Comparative analyses are illustrated in Figure 2. For panels tested by [12], the following codes have been used: GM = good mortar, PM = poor mortar, GT= good texture, BT bad texture. In [25], the panels were build with stones extracted from three different quarries, namely Cava1, Cava 2 and Cava 3.

Examining the values suggested by the Design Guidelines and comparing them with the experimental data, it is pointed out that the average compressive strength of single leaf tuff panels (i.e. Neapolitan + Roman tuffs) with Good or Poor Mortar, is very close to the minimum limit code value as can be observed in Figure 2. (a) Figure 2. (b), respectively.

The compressive strength of multiple-leaf tuff panels + Good Mortar + Poor and/or Wide core was found to be lower than the proposed range, but close to the lower bound. In particular, those with transverse connections showed an average of 2.17 MPa ([6] and [13]) and and against the minimum code value of 2.83 MPa. Those with no transverse connections showed an average of 1.75 MPa ([11]) below the minimum code value of 1.89 MPa.

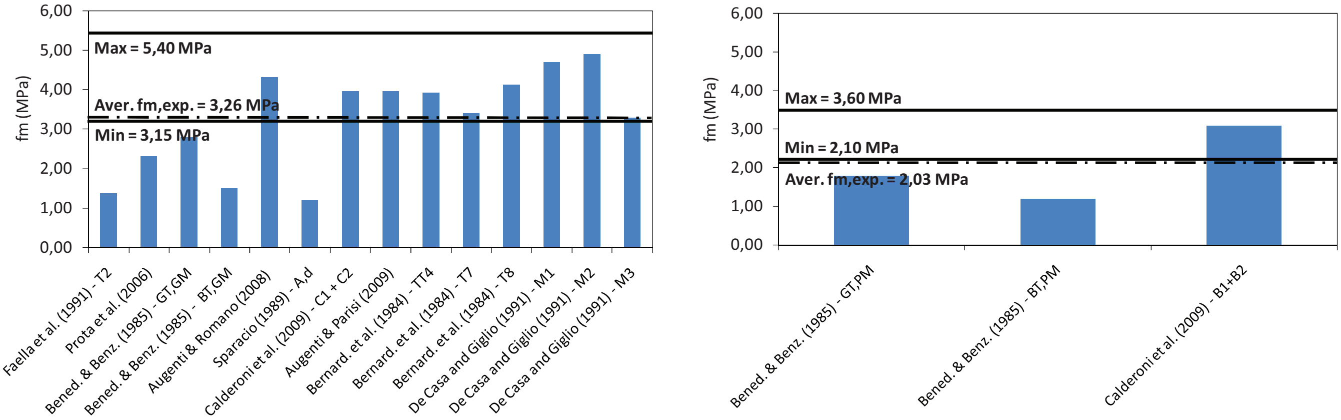
Instead, the average strength of multiple leaf tuff panels with Poor mortar, poor and/or wide cores and no connection between leaves was equal to 1.78 MPa ([5], [11]), that is within the code range 1.26 MPa – 2.16 MPa.

In terms of elastic modulus, average $E_{m,exp}$ values within the code range were found in the following cases: a) single leaf tuff panels with good mortar ([1], [6], [8], [11], [12], [16], [17]), that showed an average 1855 MPa while the code range is 1350 MPa - 1890 MPa; b) multiple leaf tuff panels with good mortar, poor and/or wide core ([11], [13], [30]), with an average = 1371 MPa against the code range = 1215 MPa - 1371 MPa; c) multiple leaf tuff panels with poor mortar + poor and/or wide cores ([5], [7] and [11]), with an average of 1057 MPa against a code range 810 MPa - 1134 MPa.

In terms of elastic modulus, the results presented in Figure 2. (c) indicate that the mean elastic modulus of single leaf tuff with Poor mortar was beyond the upper limit of the range.

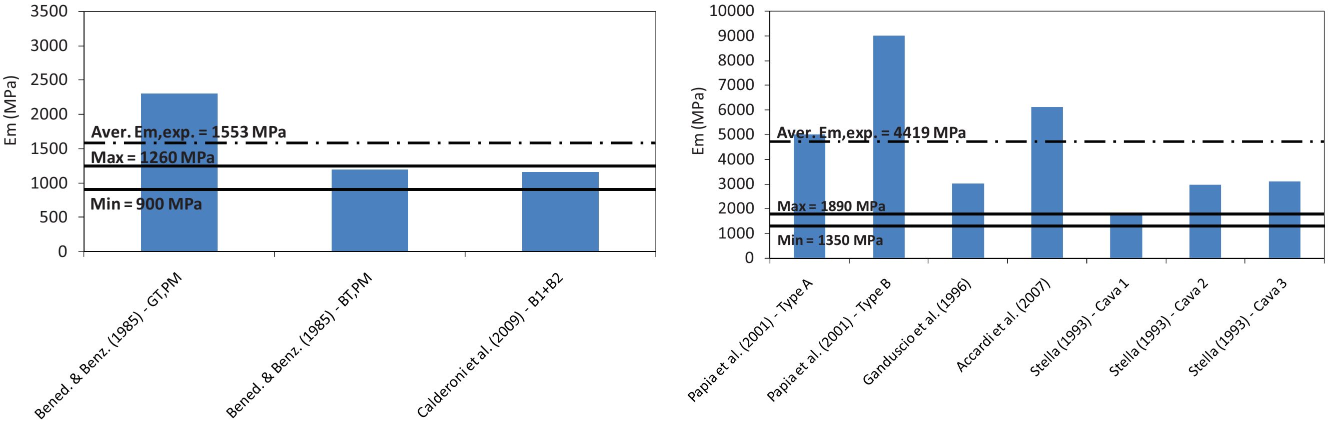
As regards calcarenite panels, good agreement between experimental strength values and code limits is found for single leaf + Good mortar specimens ([19], [20], [23], [24], [25]). In particular the average strength = 3.72 MPa was within the code range 3.15 MPa - 5.40 MPa. Conversely, the experimental strength of multiple leaf panels equals to 6.1 MPa ([21]) was significantly beyond the code range 1.89 MPa - 3.24 MPa, but more data are needed.

In terms of elastic modulus, the average value of single leaf calcarenite panels + Good mortar was significantly higher the maximum code limit of 1890 MPa, as can be seen in Figure 2. (d). The elastic modulus values provided by [21] for multiple leaf calcarenite panels + Good mortar + poor and/or wide cavities were, on average, higher than the maximum code limit (i.e. $E_{m,exp}$ = 1927 MPa and maximum code value = 1701 MPa). However, the limited sample size requires more experimental outcomes to provide assessment of this trend.



(a) Single leaf + Tuff stones + Good Mortar (Compressive strength)

(b) Single leaf + Tuff stones + Poor Mortar (Compressive strength)



(c) Single leaf + Tuff stones+ Poor Mortar (Elastic Modulus)

(d) Single leaf + Calcarenite + Good Mortar (Elastic Modulus)

Figure 2. Comparisons between the experimental values and the code range

4 CONCLUSIONS

An extended review of the state-of the art on experimental research on tuff and calcarenite stone masonry under compression has been carried out. The collected data provided a library of mechanical properties about materials and wall panels representative of historical masonry located in South-central Italy, that could be used as reference in advanced numerical analysis. Obtained data may be also used is seismic assessment of historical structures when only a limited knowledge of masonry behaviour can be attained, for instance when direct experimental measurement of masonry mechanical parameters is not feasible or completely unreliable.

Although an accurate statistical analysis of available results is required, some remarks have been drawn from comparisons of the experimental results against the mechanical parameters provided by the Italian Design Guidelines. The ranges of the compressive strength and elastic modulus given for 'soft stones', as well as the corrective factors, have been shown to be fairly appropriate for tuff masonry. Results on single leaf calcarenite panels, instead, showed that the Young' s Modulus values provided by the guidelines may be not appropriate when single leaf + good mortar are considered. However, more experimental study is required in this area.

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