EVALUATION OF SHEAR STRENGTH OF MASONRY PANELS THROUGH DIFFERENT EXPERIMENTAL ANALYSES

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ABSTRACT
The paper addresses the problem of evaluation of strength of masonry walls, within the context of seismic assessment of existing buildings. In-plane behaviour of full scale stone and brick masonry panels has been studied under monotonic diagonal-compression and shear-compression loading in quasi-static test facility. The experimental research was carried out in Abruzzi and Umbria since the 1990s, and it represents an important database for mechanical characterization of some widely used masonry walls in these seismic regions. The monotonic shear-compression and diagonal compression tests were performed under load control and experimental data have provided information about in-plane behaviour of un-reinforced masonry (URM) walls. Failure modes, shear strength, displacement capacity and post-peak performance are discussed. A presentation is also given of the results of a F.E. investigation for shear strength evaluation of masonry walls. F.E. modeling non-linear procedure (available in code Lusas) was used for the representation of masonry panels. The numerical simulations are compared with experimental results and the reliability of the different finite element models is discussed. These models are used for the simulation of diagonal compression and shear-compression tests on masonry panels.

INTRODUCTION
Historic masonry buildings in urban centres have not been conceived to resist seismic loads. They have been built in materials and systems that resist the compression caused by the gravity loads but not the tensile and shear resulting from earthquake ground motion. These disadvantages associated with many historic masonry walls have recently led researchers to the development of testing methods in order to calculate the shear strength of masonry panels.

The reconstruction work is now underway in the area struck by the 2009 earthquake in Abruzzi, but many difficulties could be eliminated if better technical information regarding the mechanical characteristics of masonry structures typical of this part of Italy are available. In their calculations structural engineers and technicians have often referred to not well-identified parameters for different kinds of masonry walls found in scarce bibliography studies. Double-leaf stone masonry walls are commonly encountered in Italy and Mediterranean countries in historic buildings dating back to ancient times and up to the beginning of 20^{th} century.

Developing reliable mathematical models to predict and analyze the behaviour of this type of masonry under horizontal forces is known to be a difficult task. The classification and the analysis of historical masonry typologies were conducted in the past with different purposes in mind. However these contributions have rarely included an experimental part regarding the mechanical characteristics of masonry due to the uncertainty in the determination of mechanical characteristic from in-situ test. Masonry walls have been classified with regard to the constituting materials, section dimensions, texture and mortar types, but very rarely with regard to their shear strength and shear elastic modulus.

Since the mechanical data of masonry relevant for the assessment of seismic behavior of historic masonry buildings was lacking, a substantial amount of experimental and analytical research has been carried out in the last decade to investigate their seismic behavior.

When studying literature with respect to shear tests on masonry, different types of test are found. In this paper two types of test will be distinguished, that are characterized by the way in which the load is applied.

The first type is the shear compression test. A masonry wall panel with bed joints in horizontal direction is supported at the lower and at the upper sides. It is loaded in–plane by a horizontal force placed at mid-span. It was first performed in-site by Turnsek and Sheppard (1980) in Slovenia. Several shear-compression tests were carried out on panels from buildings in the city of Lubiana. The compression stress was equal to that effectively hanging over the panels, but not completely well-defined. In the recent past in Italy many historical constructions have been tested: Vignoli et al. (1999) applied the shear compression test on some historical buildings in Toscany fixing the compression stress using oil jacks positioned over the panels. Other experimental campaigns were carried out by Chiostrini et al. (2000), Corradi et al. (2003, 2008), Valluzzi et al. (2004).

The second type is the diagonal compression test. The loading is applied by means of a compression force only and the bed joints are at an angle with the loading direction. The diagonal compression test is clearly defined by ASTM and RILEM Specifications, to which this experimental work refers. Several experimental campaigns were carried out in the past, but most results refer to new masonries made of hollow bricks or concrete masonry units. With regard to historic masonries, during the last decades diagonal tests were carried out on masonry panels by Vestroni et al. (1995), Valluzzi et al. (2002), Gabor et al. (2006) and recently by Brignola et al. (2009).

Beside variations in wall panel dimensions, masonry textures, mortar quality, this study aim to validate the two test methods and to discuss and compare the results in terms of shear strength for similar wall panels tested with the two test methods. The authors have performed a series of both analytical and experimental studies on the mechanical characterization of historic masonry walls, and most of the results have either been published or are currently under consideration for publication.

TEST SETUP AND PROCEDURE

(1) Diagonal compression test

The diagonal compression test, as well as the shear compression test, was designed in order to evaluate the shear strength, the shear elastic modulus of the masonry. The masonry panels employed for the diagonal compression tests were built according to the ASTM and RILEM recommendations.

The diagonal test was carried out on panels 120 x120 cm. The panel remained anchored to the rest of masonry wall through a part of the 70 cm of the lower horizontal edge. The remaining three edges and a part of the fourth were cut and isolated from the rest of the masonry wall.

The diagonal compression load is applied on the corners of the panels via a hydraulic actuator. The experimental setup for the diagonal compression is presented in Fig. 1. The load is gradually applied by a 1000 kN hydraulic jack. The displacements of compressed and stretched diagonals on both sides of masonry panels are measured by LVDT transducers. The total number of the channels of acquisition was six (displacements of the four inductive transducers, pressure at the jack, time). The tests were performed with many cycles of loading and unloading, increasing the jack action gradually until the failure of the panel to identify the diagonal shear strength and the degradation of the shear stiffness.

According to ASTM standard, this test was introduced to simulate a pure shear stress state. In these conditions the Mohr circle of the stress state is centered in the origins of $\sigma-\tau$ axes and the value of the average shear stress S_s , equal to the principal tensile stress σ_I, is given by:

$$S_s = \sigma_I = \frac{0.707P}{A_n} \qquad (1)$$

in which P is the diagonal compression load and A_n the cross-horizontal section of the panel, calculated as follows:

$$A_n = \left(\frac{W+h}{2}\right)tn \qquad (2)$$

where:
W = width of specimen, *h* = height of specimen, *t* = total thickness of specimen
n= 1 percent of the gross area of the unit that is solid

Fig. 1 Typical layout of a diagonal compression test.

From the diagonal compression test it is possible to determine the shear modulus G. In the experimental analysis the angular strain γ was evaluated:

$$\gamma = \left(\frac{\Delta V + \Delta H}{g}\right) \qquad (3)$$

where:
ΔV = diagonal shortening, *ΔH*= diagonal extension, *g*= gage length
The compressive and tensile strain values have been calculated from the relative displacement between two control points in each diagonal (gage length). With the aim of determining, from the global response of the panel (uniform shear), the shear modulus G of masonry according to the ASTM standard is given:

$$G = \frac{S_S}{\gamma}$$

RILEM assumes as reference state of stress the maximum principal (tensile) stress in the centre of the panel:

$$\sigma_x = \sigma_y = -0.56\frac{P}{A_n} \qquad \sigma_{xy} = 1.05\frac{P}{A_n} \qquad (4)$$

According to this interpretation, it is possible to evaluate the tensile strength f_t of masonry by:

$$f_t = 0.5\frac{P}{A_n} \qquad (5)$$

and using the Turnsek and Cacovic formulation, the shear strength τ_{0D} from a diagonal-compression test is given by:

$$\tau_{0D} = \frac{f_t}{1.5} \qquad (6)$$

(2) Shear-compression tests

Shear resistance of a wall can be calculated in more different ways. The shear strength is evaluated here with the shear-compression test as the average shear stress in a panel subjected to a vertical compression and to an horizontal load in its plane. The specimen length and height were nominally 900 and 1800 mm respectively. The panel thickness varied between 240 and 600 mm.

Fig. 2 shows the test set-up., the specimens were placed in the test set-up and firstly subjected to the desired level of pre-compression which was kept constant during the test. The level of compression applied, corresponding to aprox 10-20% of the estimated masonry compressive strength, was 0.30 MPa (typical for a three-storey building). The axial load was applied by means of two hydraulic jacks placed between the support frame and the upper spreader beam.

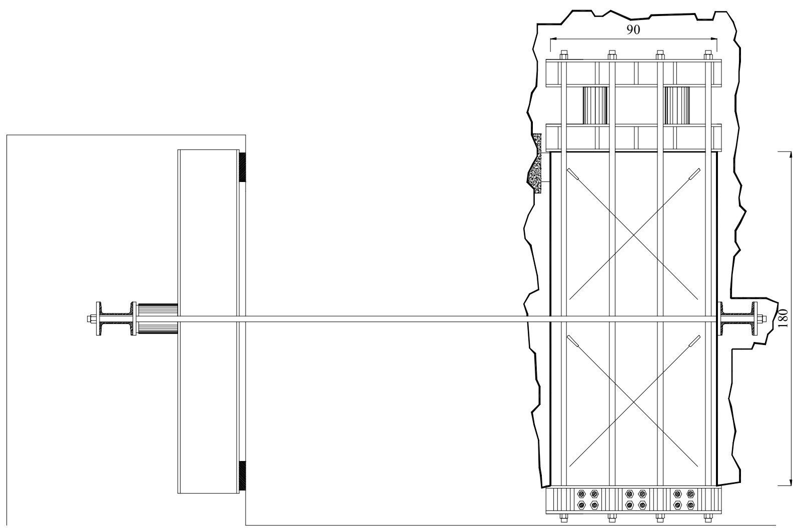


Fig. 2 Position of the inductive transducers during the shear-compression tests on both sides of the masonry panels

The shear load was applied by two steel rods which acted on a special metal element made of two C shapes, coupled with plates welded to the webs, positioned at the center line of the panels. All the tests were performed under force control (monotonic up to the point of failure), using a 100 tons hydraulic jacks, at a load increment rate approximately equal to 0.25 kN/s. The two steel rods were connected, on the one hand, to the metal element and, on the other hand, to an analogous element. An hydraulic jack was interposed between these two elements. During the loading the jack acts on the second metal element and then on the two connected steel ties, thus resulting in traction.A load cell, placed horizontally at the top of the panel, allowed measurement of the horizontal reaction. Applied loads and corresponding displacements were recorded with a frequency of 2 Hz.

The presence of the apparatus overhanging the panel was not enough to constitute a perfect constraint (Fig. 3). The upper half of the panel was able to translate and rotate while the lower half, connected to the rest of the masonry, could be considered as a perfect constraint. This caused a lack of symmetry in shear distribution between the upper and lower halves of the panel, which was taken into account during the elaboration of the data. As consequence of this lack of symmetry, the lower half of the panel resulted always more stressed and the failure always occurred here. Sixteen displacement transducers were adopted: eight W50 (50 mm of maximum deformation) were applied on the main façades of the wall to record the diagonal displacements (4 shortenings and 4 extensions), respectively, whereas 6 other transducers W50 were placed along each side of one vertical edge (at the base, the center point, the top of the panel) and two more transducers were placed on one side to measure vertical movements on the edge of one side of the panel and eventual rotations at the top of the panel.

Fig. 3 Typical layout of a shear-compression test.

In order to evaluate the shear strength of the masonry, the well-known Turnsek and Cacovic formulation is assumed:

$$T = f_t \frac{Dt}{b} \sqrt{1 + \frac{\sigma_0}{f_t}} \tag{7}$$

where:

$$f_t \cong 1.5 \tau_{0T} \tag{8}$$

and f_t represents the tensile strength of masonry and b is a parameter which was assumed to be dependent on the panel aspect ratio H/D (H=height of the panel, D=width of the panel) and accounts for the distribution of shear stress. σ_0 is the vertical compression stress equal to 0.3 MPa and T is the maximum shear load in the lower half of the panel. τ_{0T} is the shear strength for a shear-compression test according to the Turnsek and Cacovic formulation. The parameter b takes into account the variability and distribution of the shear stresses at the center of the wall. This parameter with aspect ratio greater than 1.5 is assumed by the Italian Standards and the well-known POR method equal to 1.5.

EXPERIMENTAL WORK

(1) Test matrix

The tests presented in this paper should be considered as pilot tests. The evaluation of the shear strength of non-reinforced masonry panels was the main thrust of this study. The total number of specimens is twenty-six, fifteen of which were manufactured in laboratory, and eleven were cut from existing buildings. Two types of shear test were used: the diagonal compression test and the shear compression test. The in-site tests were carried out on historic constructions located in the Italian region of Umbria while the laboratory tests were conducted at the Lastru laboratory of the University of Perugia located in Terni.

The test matrix of shear-compression and diagonal compression tests was based on the following panels:

1. In-site tests:
    a. five full-scale tests carried out at the Farnetta building (2 diagonal compression tests and 3 shear compression tests);
    b. three full-scale tests carried out at the Belfiore building (2 diagonal compression tests and 1 shear compression test);

   c. one full-scale test carried out at the Vescia building (shear compression test);
   d. two full-scale tests carried out at the Ponte Postignano building (1 diagonal compression test and 1 shear compression test);
2. Laboratory tests:
   a. 10 full scale tests (3 diagonal compression tests and 7 shear compression tests);
   b. 7 reduced scale tests (5 diagonal compression tests and 2 shear compression tests);

Considering the importance of the type of masonry and its texture a brief description of the buildings where the panels were cut is reported in the following sections. The mortars of all buildings are rather weak and all lime-based in consideration to the absence of portlandite and of silicates of calcium and aluminum. The chemical analysis shows that the main differences are in relation to the period of construction of the buildings: the Ponte di Postignano mortar has a high weight ratio cement/aggregates. The other buildings, constructed before Ponte di Postignano one, have a smaller value of this ratio and the mortars have small quartz traces removed by the erosive action of water. The walls of the four buildings are made of barely cut calcareous stones. The dimensions of the stones vary for the different buildings from which the panels were cut. Larger stones were present in Belfiore and Vescia and (average dimension of the longest edge equal to 30 cm) while smaller stones constituted the panels at Farnetta and Ponte di Postignano (average dimension of the longest edge equal to 20-25 cm).

The characteristics of the two types of stone were obtained on cylindrical specimens 70mm in diameter and 150mm in height, cored from irregular cut stones. The compressive strength was 57.5 MPa for pink color calcareous stone and 36.0 for white-color calcareous stones. The weight density of these stones is sufficiently constant and average values equal to 23.30 kN/m^3 for the pink color one and 24.85 kN/m^3 for the white color one were measured.

The results show a significant scattering in the data of the compression tests carried out on the sponge travertine of the building of Ponte di Postignano. This depends on the high inhomogeneity of the stone due to the presence of large and frequent voids. The average values of the weight density and of the compression strength are respectively equal to 13.35 kN/m^3 e 2.66 MPa.

The panels are identified by a four index code, in which the first indicates the type of test (CD=diagonal compression, TC=shear-compression); the second identification number of the panel; the third location of the structure from which the panels were obtained (B=Belfiore, V=Vescia, F=Farnetta, P=Ponte di Postignano, L=Laboratory), while the fourth index indicates the type of intervention carried out (in this case the fourth index is always OR because this paper reports only the results on un-strengthened panels, with the exception of tests identified by codes V-T-07-IN in which the strengthening technique using preventive injections resulted as not effective).

(2) <u>Description of the buildings</u>

The Farnetta building

The first building located in the countryside of the village of Farnetta was constructed at the beginning of the 20th century as a rural house (farm). The plan is rectangular with the longest side of 15 m. The building is two floors high with the ground floor used as goods storage subdivided in three rooms; the walls are made with a two leaf masonry of irregular stones (barely cut) with weak connections and a thickness of 480 mm. The mortar is based on putty lime and silty sand. The panels used for testing were situated at the ground floor; five panels were tested, two under diagonal compression, three under shear-compression.

The buildings of Belfiore and Vescia

Four panels were cut off at these buildings, located in Belfiore and Vescia (two hamlets in the Foligno Commune). These stone-masonry buildings are two stories high. The masonry texture of the buildings is very similar and made, for the first floor, of stone double-leaf walls with double solid brick courses interposed at intervals of 120 cm. Both buildings were built at the beginning of 20th century to host the elementary school of the villages. The two external leaves, approximately 18-24 cm thick each, consisted of rough-shaped calcareous limestone white- and pink-colored blocks (their highest dimension is about 30 cm), bonded in sub-horizontal courses, with mortar joints from 10 to 40 mm thick. The double-leaf walls, weakly connected, had a thickness of 48 cm. The mortar is lime-based and connecting stones are not present.

The Ponte di Postignano building
The building was constructed just before 1950 to serve as a residence and it was never restored. From the 1997 onwards, after the Umbria earthquake, it remained unexploited and neglected. The building was constructed using the traditional construction techniques for historic masonry; the damages after the Umbrian earthquake of 1997 were so heavy that it was decided to demolish it. White and pink limestone, and travertine (sponga) are present in 25-35% of the surface of the walls. The building is three floors high with stables at the ground floor. The masonry texture is made with irregularly cut stones with a maximum thickness of 480 mm and the wall is a double leaf masonry with weak connections between the leave. Compared to the other examined structures, there is also a notable percentage of sponge travertine (20-30% of the panel surface). The mortar, based on putty lime, has a good consistency. The panels used for the tests were situated at the ground floor. Connecting stones are not present.

(3) <u>Description of the panels built in laboratory</u>
Full scale panels
The investigation was carried out on two types of full-scale, solid clay brick- or stone-panels (nominal dimensions 120x120 cm and 180x90 cm) (Fig. 4). All specimens were constructed in laboratory by experienced masons. Clay solid bricks (dimensions: 240x120x55 mm, bulk density: 970 kg/m^3) were supplied by a local Manufacturer (Fornaci briziarelli Marsciano S.p.A). In all walls, the first row of bricks was laid on a 10 mm thick horizontal layer of mortar. In all specimens the joints (bed and head) consisted of a general purpose masonry lime-based mortar and were made approximately 10 mm thick.

The mean compressive strength of the clay-brick masonry units was derived from thirty compressive tests; the average value obtained was 20.99 MPa. Flexural tests on ten specimens provided an average value equal to 7.39 MPa.

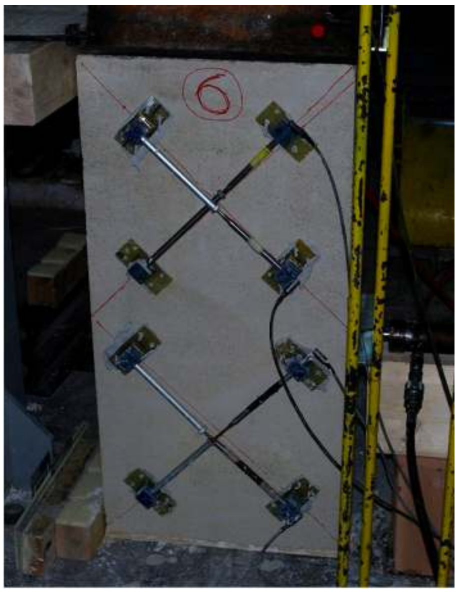
Fig. 4 Diagonal compression and shear-compression tests carried out on mortar small-scale panels.

Mortar used for the masonry panels had the following mix composition in volume: 33% lime-based mortar; 66% of sand. The flexural and compressive standard tests on six specimens (40x40x160 mm) after a period of 28 days of curing revealed an average strength equal to 0.59 N/mm^2 and 1.06 N/mm^2, respectively.

Small-scale panels

Small-scale modelling was conducted at a linear scale of about 1:2 as shown in Figs. 5 and 6. Determination of masonry shear resistance to in-plane lateral load was achieved by testing square wallettes in compression along one diagonal following the American Standard (diagonal compression test) and rectangular ones in shear-compression.

The panels were only made of weak mortar (without stones or bricks) in order to study influence of the type of shear test (diagonal compression or shear compression test). The mortar used for the small-scale masonry panels had the following mix composition: sand/ inorganic binder weight ratio =3.0 and water/binder weight ratio = 0.85. The binder is produced by Colacem S.p.A. and its commercial name is "Calce Idrata Colacem". The flexural and compressive standard tests on twenty-one specimens (40x40x160 mm^3, after a period of 90 days of curing) revealed an average strength respectively equal to 0.281 and 0.549 MPa (standard deviation: 0.015 and 0.074 MPa).



Figs. 5-6 Diagonal compression and shear-compression tests carried out on mortar small-scale panels.

(4) <u>Test results</u>
The results of in-site tests show significantly different values depending on the type of test carried out on the masonry panels. Fifteen (9 in laboratory, 6 in site) un-reinforced masonry panels were tested under shear-compression test setup. All these panels (except for TC-36-L-OR) failed due a shear-friction crack along the diagonal of the lowest half panel. Considering only the double-leaf walls in the building of Belfiore shear strengths S_S and τ_{0T} was 0.130 MPa and 0.072 MPa respectively for the shear-compression test and the diagonal compression test (Table 1).

Similar results were obtained for the panels tested in Ponte di Postigliano building: a shear strength τ_{0T} of 0.136 MPa was measured for panel number 15, submitted to a shear-compression test, and a shear strength S_S of 0.059 MPa for panel number 13 (diagonal compression test). For both Belfiore and Ponte di Postigliano buildings the results of shear-compression tests are about 100% higher than the results of diagonal compression tests (respectively 81% and +132% higher).

With regard of shear-compression tests carried out on masonry stone panels in laboratory, the maximum shear strength τ_{0T} of the walls varied between 0.071 and 0.180 MPa, but evident cracks pattern already started at a stress level varying from 0.55 to 0.140 MPa. The average value of shear strength τ_{0T} of these panels was 0.131 MPa (Table 2).

Table 1 Results from the diagonal compression and the shear-compression tests (masonry panels tested in site)

Test No.	Panel dimensions (cm)	Masonry texture	Failure Load (kN)	Compression stress σ_0 (MPa)	Shear Strength τ_{0D} (MPa)	Shear Strength (MPa)
CD-03-F-OR	120x119x48	1	37.0	-	0.0215	0.046**
CD-04-F-OR	120x120x48	1	37.9	-	0.0219	0.047**
CD-01-B-OR	120x122x48	1A	58.8	-	0.0337	0.072**
CD-13-P-OR	123x122x48	1	47.7	-	0.0270	0.059**
TC-01-F-OR	86x48x182	1	34.3*	0.147	-	0.048*
TC-02-F-OR	86.3x48x180	1	37.0*	0.184	-	0.047*
TC-05-F-OR	90x48x180	1	62.5*	0.183	-	0.096*
TC-04-B-OR	88x48x183	1A	88.3*	0.308	-	0.130*
TC-07-V-IN	93x48x183	1A	100.5*	0.287	-	0.149*
TC-15-P-OR	88x48x182	1	74.4*	0.122	-	0.136*

Masonry textures: 1: double-leaf stone panel, 1A: double-leaf stone masonry with two solid brick courses at intervals of 80-120 cm; * according to (5), lowest-half panel; ** according to ASTM specifications

Table 2 Results of laboratory tests carried out on masonry panels.

Test No.	Panel dimensions (cm)	Masonry texture	Failure Load (kN)	Compression stress σ_0 (MPa)	Shear Strength τ_{0D} (MPa)	Shear Strength (MPa)
CD-08-L-OR	120x120x48	1	34.8	-	0.0201	0.044**
TC-35-L-OR	90x51x180.5	1	109.3	0.208	-	0.180*
TC-36-L-OR	90x49x181	1	52.0	0.208	-	0.071^X
TC-37-L-OR	90x51x180.5	1	80.7	0.188	-	0.126*
TC-39-L-OR	90x48.6x190	1	87.6	0.209	-	0.146*
CD-20-L-OR	119x120x24.5	2	38.1	-	0.043	0.090**
CD-21-L-OR	119x120x24.5	2	46.5	-	0.053	0.117**
TC-22-L-OR	89x181x24.5	2	84.1	0.482	-	0.257*
TC-42-L-OR	90x179x25	2	61.3	0.397	-	0.173*
TC-44-L-OR	92.5x180x25	2	70.8	0.386	-	0.198*

Masonry textures: 1: double-leaf stone panel, 2: solid bricks
* according to (5), lowest-half panel; ** according to ASTM specifications; ^{X} according to (5), highest-half panel.

Table 3 Comparison of the results from the diagonal compression and the shear-compression tests (masonry panels tested in laboratory)

Test No.	Test type	Texture	$r=\tau_{0T}/S_S$
CD-08-L-OR	Diagonal compression	Double-leaf roughly cut stone masonry	2.98
TC-35-L-OR	Shear-compression		
TC-36-L-OR	Shear-compression		
TC-37-L-OR	Shear-compression		
TC-39-L-OR	Shear-compression		
CD-20-L-OR	Diagonal compression	Solid bricks	2.02
CD-21-L-OR	Diagonal compression		
TC-22-L-OR	Shear-compression		
TC-42-L-OR	Shear-compression		
TC-44-L-OR	Shear-compression		

Only one panel with this texture (Double-leaf roughly cut stone masonry) was tested in laboratory in diagonal compression (CD-08-L-OR) and a shear strength S_S of 0.044 MPa was measured. The cracks had a diagonal pattern, located on both panel surfaces and in the transverse sections. The ratio r between shear strengths τ_{0T} /S_S of these tests is 2.98. Higher values of shear strength S_S were detected for the two solid brick panels (shear strength 0.090 and 0.115 MPa), whereas shear strengths τ_{0T} of brick panels tested in shear-compression were much higher, varying from 0.170 to 0.227 MPa.

Table 4 Comparison of the results from the diagonal compression and the shear-compression tests

(masonry panels tested in site)

Test No.	Test type	Texture	$r=\tau_{0T}/S_S$
CD-01-B-OR	Diagonal compression	Double-leaf roughly cut stone masonry with two solid brick courses at intervals of 80-120 cm	1.81
TC-04-B-OR	Shear-compression		
CD-01-B-OR	Diagonal compression	Double-leaf roughly cut stone masonry with two solid brick courses at intervals of 80-120 cm	2.07
TC-07-V-IN	Shear-compression		
CD-13-P-OR	Diagonal compression	Double-leaf roughly cut stone masonry	2.32
TC-15-P-OR	Shear-compression		
CD-03-F-OR	Diagonal compression	Double-leaf roughly cut stone masonry	1.37
CD-04-F-OR	Diagonal compression		
TC-01-F-OR	Shear-compression		
TC-02-F-OR	Shear-compression		
TC-05-F-OR	Shear-compression		

Solid brick panels, although stepped shear friction cracks were observed, failed due to shear slide, observed on both sides of the panels, at the bed and vertical joints, with a shear strength τ_{0T} of 0.103 MPa (for diagonal compression tests) and 0.209 MPa (for shear compression tests). The test results are reported in Table 2. Table 3 shows the comparison between the results of diagonal- and shear-compression tests: the ratio $r=\tau_{0T}/S_S$ is always higher than 1. For solid bricks panels it was 2.02.

Shear tests performed on mortar small-scale panels, having nominal dimensions of 50x50x12 cm (diagonal compression tests) and 100x50x12 cm (shear compression tests), revealed an average shear strength respectively of 0.0274 MPa and 0.0221 MPa. These tests (panels made only of weak mortar) were performed in order to remove the influence of masonry texture from results. Even if the number of performed tests was limited, the results in terms of shear strength are very similar for both the types of shear strength. From these tests it appears evident that the results are not connected to the type of test used for testing the panels. As a matter of fact the diagonal compression tests and the shear compression tests lead to similar values of strength (first results of diagonal compression tests: S_S= 0.0274 MPa, shear compression tests τ_{0T}=0.0221 MPa).

It is therefore possible, using both tests in the very same building, to evaluate the ratio between the results of shear strength. Working with three couples of results related to the three above-mentioned buildings of Belfiore and Vescia, the average ratio obtained are equal to and 1.81 and 2.07 (Table 4). A similar value of the ratio ($r = 2.32$) has been found at the building of Ponte di Postignano. Surely, due to the very few number of tests carried out, the above quoted correlation must be investigated by a bigger number of tests. However, the emerging line seems quite correct and hence they allow the following considerations.

Table 5 Comparison of the results from the diagonal compression and the shear-compression tests (small panels made of mortar)

Test No.	Panel dimensions (cm)	Failure Load (kN)	Compression stress σ_0 (MPa)	Shear Strength τ_{0D} (MPa)	Shear Strength (MPa)
CD-50-L-OR	50x51x12	2.44	-	0.0136	0.0288**
CD-51-L-OR	50x50x12	2.24	-	0.0124	0.0264**
CD-52-L-OR	50x50.5x12	2.28	-	0.0127	0.0269**
CD-53-L-OR	50x50x12	2.25	-	0.0125	0.0265**
CD-54-L-OR	50.5x50x12	2.41	-	0.0134	0.0284**
TC-60-L-OR	100x51x12	2.09	0.040	-	0.0240*
TC-61-L-OR	101x50x12	1.84	0.040	-	0.0202*

* according to (5), lowest-half panel; ** according to ASTM specifications

On the contrary the tests carried out on small mortar panels demonstrated that the type of shear tests do not affect the results of shear strength. Identical mortar panels (for dimensions 50x50x12 cm and mix design) have been tested and similar results have been found. However the effect of type of shear test needs more extensive experimental examination. The shear tests carried out in site on historic masonry wall panels have demonstrated that the results of shear strength are different when the diagonal compression test and the shear-compression test are applied (Table 5). Tables 2 and 4 show the comparison between the results of diagonal- and shear-compression tests: the ratio $r=\tau_{0T} / S_S$ is always higher than 1 and varied between 1.37 and 2.98.

Once it is assumed that a ratio exists between the results of the two shear tests, we face the problem of choosing the one more representative of the real behavior of masonry walls stressed by horizontal loads typical of seismic actions. Diagonal compression tests allow the panel a free deformation, since its four sides are free from any kind of constraints, with the exception of the small portion of masonry that permits the connection between the panel and the rest of the masonry wall. Numerical calculations demonstrated its un-influence and the panel can be considered completely un-constrained. On the contrary, during the shear-compression test, the two square halves resulting from the division of the panels in two parts have therefore a common edge. This causes an effect of confinement from one half to the other. These are also constrained by the presence, on the upper part of the panel, of the apparatus overhanging the panel (steel plates, jacks, rods) and, by the bottom one, of the remaining masonry constituting the wall.

The most common seismic verifications for buildings, constituted of 2-3 floors with walls characterized by a low slenderness ratio, assume the vertical masonry elements between adjacent openings as infinitely stiff. In analogy with the shear-compression tests, the failure of these elements occurs when the shear strength is not able to absorb the seismic loads. The strains along the vertical edges of masonry elements are free, while an effect of confinement is produced by the remaining overhanging part of the masonry wall.

A behavior such as this is easy to verify from the analysis of damages to constructions struck by the earthquake, in which the failure condition occurs when the tensile strength in the center of the masonry panel is achieved.

NUMERICAL ANALISYS

In this paragraph first results of a numerical simulation of some real panels, tested during the experimental campaign of 1998-2006 in Umbria are presented. FE software was used to model the shear tests on the masonry panels. In particular we considered the panels characterized by double-leaf stone masonry, with horizontal brick courses extended throughout the panel thickness cut from the buildings of Belfiore and Vescia. The numerical simulation was carried out using LUSAS code ver. 13.2; the panel was modeled using isoparametric elements (QPM8) with the hypothesis of plane stress (Fig. 7). A three dimensional model was developed: panel for diagonal compression and shear-compression tests are characterized by the dimensions respectively of 120x120x25 cm and 180x90x25 cm. A compression stress σ_0 of 0.30 MPa was applied over the panels tested in shear-compression.

The average elastic Young E_S modulus, fracture energy G_f and tensile strength f_{wt} of masonry values used in the FE analyses were: E_S = 1000 and 2000 MPa, G_f = 0.005 and 0.05 N/mm, f_{wt}=0.015, 0.02, 0.03, 0.04, 0.05 and 0.06 MPa. These values were derived from experimental tests on panels and bibliography values and are somewhat higher than the values found from diagonal compression tests (Corradi, 2003). It is evident from Figs. 8 and 9 that the ratio $r=\tau_{0T} / S_S$ is often higher than 1. In the case of E_S=1000 MPa, the ratio value varied between 0.78 and 1.6, but with the exception of 2 results all the values were higher than 1.

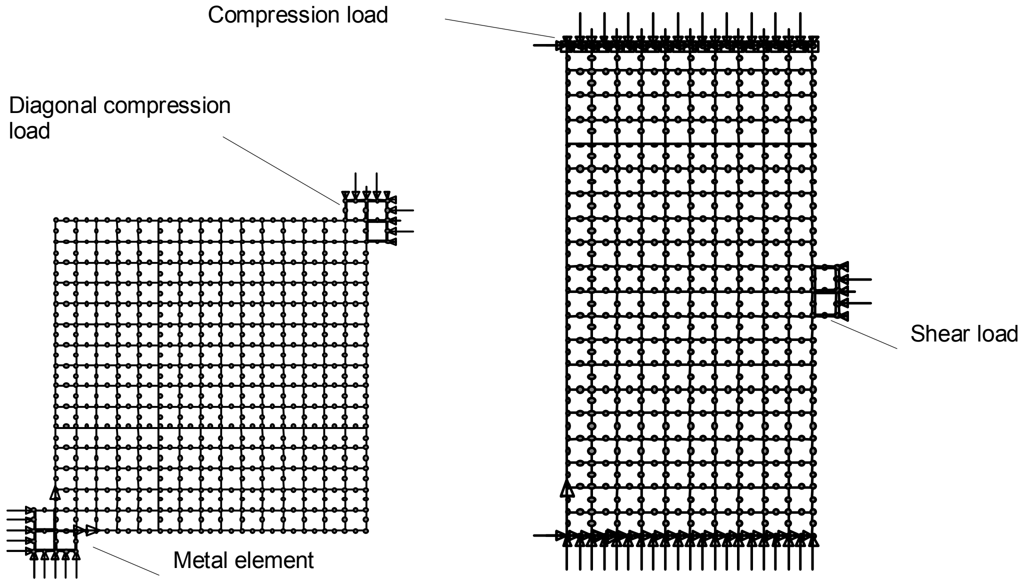
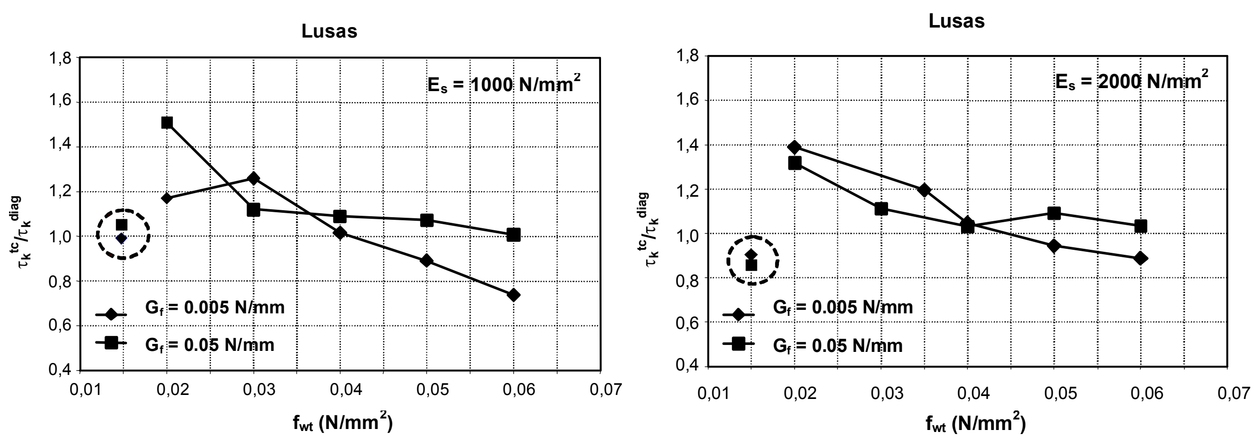


Fig. 7 Modeling of diagonal- and shear-compression tests using the code Lusas.



Figs. 8-9 FE Analysis predictions: ratio $r=\tau_{0T}/S_S$ vs. tensile strength of masonry f_{wt} for two values of Young modulus E_s of 1000 MPa and 2000 MPa.

CONCLUSIONS

An experimental research on the shear behavior of masonry panels tested in diagonal- and shear-compression has been presented. Based on the results obtained from the experimental program, the following conclusions can be stated:

1. The experimental work allowed an evaluation of the values of shear strength for some typical historic masonry walls in central Italy. In particular the masonry made of double-leaf roughly cut stone walls was analyzed. The high number of tests carried out on panels made of this texture, produced a large number of data from which the mechanical characteristics of this type of masonry were deduced.
2. The diagonal compression test and the shear-compression test were carried out on the same buildings made of the same masonry textures. This allowed to identify a significant differentiation in site between the results obtained from the two test types. It was noted that the ratio between the results of shear strength for the two tests is always higher than 1, highlighting the problem of choosing the test which best simulates to the real behaviour of the masonry when stressed by a seismic actions.

3. On the contrary the first experimental results of laboratory tests carried out on small panels made only of weak lime-based mortar demonstrate that the type of shear test don not influence the shear strength of the mortar panels.
4. FE analysis of the shear tests has shown that the ratio $r=\tau_{0T}/S_S$ is generally bigger than 1 for low tensile strength masonries. However the value of this ratio never exceeded 1.6 for all FE analyses carried out.
5. Further developments of this study are focused on the influence of the type and influence of masonry texture of the panels and of the geometrical characteristics on the formulation for the prediction of the strength.

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REFERENCES

- ASTM E 519-81 (1981), *Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages*, American Society for Testing Materials.
- Brignola, A., Frumento, S. , Lagomarsino, S. and Podestà, S. (2009), "Identification of Shear Parameters of Masonry Panels Through the In-Situ Diagonal Compression Test", *International Journal of Architectural Heritage*, Vol. 3: 1, 52 -73.
- Chiostrini, S., Galano, L. and Vignoli, A. (2000), "On the determination of stregth of ancient masonry walls via experimental tests". *Proc. 12th World Conference on Earthquake Engineering*, cd-rom, Aukland, New Zealand, January 30–February 4, 2000, paper No. 2564.
- Corradi M., Borri A., and Vignoli A. (200), "Experimental study on the determination of strength of masonry walls". *Journal of Construction and Building Material*, Vol. 17: 325–37.
- Corradi M., Tedeschi C., Binda L., and Borri A. (2008), "Experimental evaluation of shear and compression strength of masonry wall before and after reinforcement: Deep repointing". *Journal of Construction and Building Material,* Vol. 22: 463–472.
- Gabor, A., Bennani, A., Jacquelin, E. and Lebon, F. (2006), "Modelling approaches of the in-plane shear behavior of unreinforced and FRP strengthened masonry panels", *Composite Structures*, Vol. 74: 277–288.
- RILEM TC. (1994), 76-LUM. Diagonal tensile strength tests of small wall specimens, 1991. In RILEM, Recommendations for the Testing and Use of Constructions Materials. London: E& FN SPON, 488–489.
- Tunseck, V. and Sheppard, P.F. (1980), "The shear and flexural resistance of masonry walls", Proc. Research Conference on Earthquake Eng., Skopje, Macedonia, September 8–13, 517–573
- Valluzzi, M. R., Tinazzi, D., and Modena, C. (2002), "Shear behavior of masonry panels strengthened by FRP laminates". *Journal of Construction and Building Materials*, Vol. 16:409–416.
- Valluzzi, M. R., Da Porto, F. and Modena, C. (2004), "Behavior and modeling of strengthened three-leaf stone masonry walls". *Materials and Structures / Matériaux et Constructions*, Vol. 37, April 2004, 184-192.
- Vestroni, F., Beolchini, G., Grillo, F., Martinelli, A., Ricciardulli, G.L. and Buffarini, G. (1995), "Il progetto di un'indagine sperimentale su una vecchia casa in muratura", *Proc. VII Convegno Nazionale Ingegneria Sismica,* September 25-28, Vol 1:331-340.