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FLAT-JACK TESTS ON OLD MASONRY BUILDINGS

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ABSTRACT

In this work an experimental campaign with flat-jacks on old masonry buildings is presented and discussed. The tests were carried out on load bearing masonry walls of an 18th century building of Lisbon downtown. They aimed the evaluation of the rubble stone masonry deformability properties in compression and compressive strength (double flat-jack test) and the shear strength parameters (shear flat-jack test). This study was developed within the scope of the Portuguese research project SEVERES (www.severes.org).

Keywords: masonry, in situ tests, experimental results

INTRODUCTION

It is estimated that half of the existing building stock in Lisbon County is composed by old masonry buildings (Ravara *et al*., 2001). The survey 'Censos 2001' (INE, 2002) estimated that approximately 67% of these buildings are in need of structural intervention works and that 10% are in an advanced stage of degradation. The functions that old buildings still have nowadays, justify the concern about their structural safety and seismic vulnerability.

This study describes an experimental campaign developed to assess the physical and mechanical properties of the old masonry buildings in the historical centre of Lisbon; essential data to validate the numerical models that assess the seismic behaviour of the buildings.

The exterior masonry walls of Lisbon old masonry buildings are generally made of rubble limestone masonry with grit (red aggregate) or fragments of ceramic bricks, bounded by air lime mortar. Due to the irregularity of the material and workmanship, the mechanical characterization should be carried out on undisturbed and large dimension masonry specimens. However, due to the historical value of the building most of the times the survey has to be conducted with less destructive testing techniques.

The flat-jack test provides a relatively non-destructive way of determining the in situ mechanical properties of masonry. This testing technique has been successfully used in regular brick and stone masonry structures but its practice on rubble stone masonry structures is not so common. In these cases the experimental procedures have to be adapted and calibrated.

The experimental campaign with flat-jacks herein described was conducted on rubble stone masonry bearing walls of an 18th century building in Lisbon. The mechanical properties analysed were: (i) deformability properties in compression and compressive strength (double flat-jack test); and (ii) shear strength parameters (shear flat-jack test). In this article, the experimental results obtained with the in situ flat-jack testing are presented and discussed.

EXPERIMENTAL CAMPAIGN

The tests were carried out on an 18th century building located in the historical downtown area rebuilt after the 1755 earthquake. This typology of buildings (so called Pombalino's buildings) is characterized by a three-dimensional timber structure (named 'gaiola pombalina') enclosed on the interior walls of the building and above the first storey.
Vaults and arches support the first storey floor, while the upper floors are composed by timber beams usually placed perpendicular to the rubble stone masonry façade walls (Cardoso *et al*., 2005). The roof with ceramic roof tiles is supported by timber trusses. The exterior walls are made of rubble stone masonry with decreasing thickness with the height of the building.
The experimental tests were performed on the wall of the back façade at the ground floor level (Fig. 1). At this location the wall has no openings and is thick enough to support the cuts perpendicular to its surface without endangering the structure.

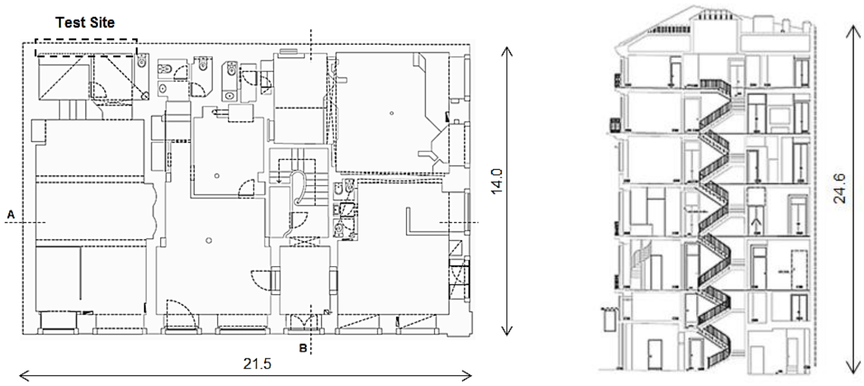


Fig. 1 Test site: back façade wall on the ground floor level and vertical cut B (dimensions in meters).

The flat-jacks used were manufactured according with the specifications of ASTM C 1196-04 (2004) and RILEM MDT.D.4 (2004). The flat-jack steel sheets are 0.12 centimetres (cm) thick and have a semi-circular shape in plane (34.5 cm x 25.5 cm - Fig. 2), as recommended for irregular stone masonry structures (Rossi, nd).

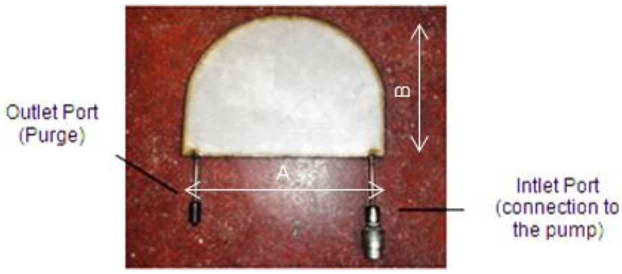


Fig. 2 Semi-circular flat-jack with (A) 34.5 cm and (B) 25.5 cm.

The deformation on the masonry surface were taken with a removal mechanical meter which measures the relative distance between reference points (metal discs) disposed on the masonry. The mechanical meter in use has a gauge length of 20.0 cm. Three measurement repetitions are required at each row of points, the final value being the average of the measurements.
The cuts on the masonry were made by a circular saw. Steel sheets (shims) with the same plane shape of the flat-jack were used to pack the flat-jack inside the cut and to protect the equipment from the rough surface of the masonry or local swelling. Between the flat-jack and

the shims, a sheet of painting paper wrapped in white paper is placed to print the effective contact surface between the flat-jack and the cut (paper stamp).

DOUBLE FLAT-JACK TEST

The double flat-jack test supports the assessment of the masonry deformability properties in compression. The test procedure is described in ASTM C 1197-04 (2004) and in RILEM MDT.D.5 (2004). In this test two horizontal cuts, 40.0 cm spaced, were made in the wall delimiting a masonry specimen to be tested under uniaxial compression.

Vertical and horizontal distances on selected points were recorded to provide the masonry Young's modulus and the Poisson ratio. The maximum pressure of the test may be used to estimate the compressive strength of the masonry.

According to ASTM C 1197-04 (2004) and RILEM MDT.D.5 (2004), the flat-jacks have an inherent stiffness which resists expansion when pressurized and therefore, the internal pressure of the flat-jack is greater than the state of stress on the masonry. The flat-jacks have to be calibrated to determine this conversion factor according with the procedure described on ASTM C 1197-04 (2004) and in RILEM MDT.D.5 (2004). As a result, the state of compression stress in the masonry (f_m) is approximately equal to the flat-jack pressure (p) multiplied by the calibration factor of the flat-jack (K_e) and the ratio (K_c) between the bearing area of the flat-jack in contact with the masonry (A_{je}) and the bearing area of the cut (A_{cut}), according to equation (1):

$$f_m = p \times K_e \times (A_{je} / A_{cut}) = p \times K_e \times K_c \quad (1)$$

In what concerns the deformability properties, the tangent Young's modulus (E_t) is given by equation (2), where δf_m is the increment of stress and $\delta\varepsilon_m$ is the corresponding increment of strain:

$$E_t = \delta f_m / \delta\varepsilon_m \quad (2)$$

The secant Young's modulus (E_s) is given by equation (3), where f_m is the cumulative stress and ε_m is the cumulative strain increment from zero:

$$E_t = f_m / \varepsilon_m \quad (3)$$

The Poisson ratio (ν) is given by equation (4), where ε_h is the horizontal strain and ε_v the vertical strain:

$$\nu = \varepsilon_h / \varepsilon_v \quad (4)$$

In order to seat the flat-jacks and the shims to the cut, the Standards recommend an initial pressure of half the estimated maximum compressive strength of the masonry. Results from other experimental tests with flat-jacks conducted on existing walls are summarized in Table 1, showing a wide range of values for this type of masonry. The values proposed by the Italian standard OPCM 3274 (2003) for rubble stone masonry were also included.

The maximum compressive pressure was estimated based on the flat-jack test results from Pagaimo (2004). In this case, the average maximum compressive stress applied on the masonry is equal to 0.99 MPa. Taking equation (1), the factor K_e was based on the calibration factors of the used flat-jacks (K_e=0.76) and K_c was taken as the average values defined by Pagaimo (K_c=0.67). As a result, the maximum pressure on the flat-jack is 1.94 MPa; hence an initial pressure of 0.97 MPa shall be applied to adjust the flat-jacks and the shims to the cut.

Table 1 Masonry Compressive Mechanical Properties (literature results).

Type of Test		**Maximum Compressive Stress (MPa)** (*)	**Young's Modulus E (MPa)**	
Vicente (2008)	Double Flat-Jack Test on limestone rubble masonry and air lime mortar (in situ)	0.76	144 – 2670	Secant between 30% and 60% of the maximum stress
Pagaimo (2004)	Double Flat-Jack Tests on limestone rubble masonry and clay air lime mortar (in-situ)	0.93 – 1.05	210 – 380	Secant between 30% and 60% of the maximum stress
Roque (2002)	Double Flat-Jack Tests on 'xisto' rubble masonry and clay mortar (in-situ)	0.60 – 0.80	800 – 1200	Secant between 30% and 60% of the maximum stress
OPCM 3274 (2003)	Table 11.D.1 – Irregular stone masonry (pebbles, erratic and irregular stone)	0.60 – 0.90	690 – 1050	
	Table 11.D.1 – Uncut stone masonry with facing walls of limited thickness and infill core	1.10 – 1.55	1020 – 1440	

(*) For double flat jacks tests the 'Maximum Compressive Stress' values correspond to the maximum stresses applied during the test, which may not be the masonry compressive strength. The values from OPCM 33274 are indicative values for the masonry compressive strength.

DOUBLE FLAT-JACK TEST RESULTS

The double flat-jack test setup is displayed in Fig. 3. The points 1-1' to 4-4' refer to vertical measurement rows and the points 5-5' refer to the horizontal row.

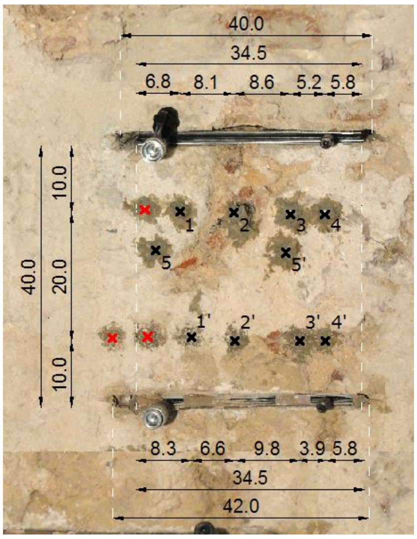


Fig. 3 Double flat-jack test setup (dimensions in cm).

An initial pressure of 0.80 MPa was applied to the flat-jacks to pack them into the cuts (slightly less than the initial estimative of 0.97 MPa). The pressure was after removed, though it was not possible to completely nullify, retaining an internal pressure of 0.10 MPa.

Then, two cycles of loading and unloading were completed. On the first cycle, the flat-jacks were pressurized up to 1.00 MPa and depressurized after, reaching an internal pressure of 0.10 MPa. In the second cycle, the flat-jacks were pressurized up to 2.09 MPa. Above this level the upper part of the wall was not offering enough reaction and it was not possible to increase the flat-jacks pressure. The relation between the stresses in the masonry (K_e=0.76

and K_c=0.57) and the vertical strain for the first and second loading cycle is plotted in Fig. 4. The strain value was calculated dividing the distance recorded at each load increment by the initial length.

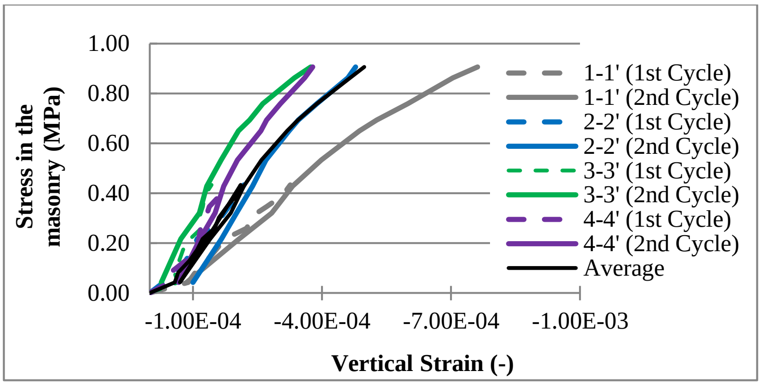


Fig. 4 Relation between stress in the masonry and vertical strain.

The slope of the curves "stress in the masonry – vertical strain" (Fig. 4) of the first and second cycles of pressure is much similar. However, comparing the measured relative distances of the four pairs of points it is evident an asymmetric deformation of the wall. For instance, row 1-1', on the left hand side of the flat-jacks, has a higher deformation than the rows 3-3' and 4-4', on the right hand side.

The maximum pressure level of the second cycle was conditioned by the insufficient reaction of the upper part of the wall and the corresponding stress in the masonry (0.91 MPa) must be regarded as a lower limit of the masonry compressive strength. It is worth mention that this value is close to the maximum stress applied on similar flat-jack tests performed by Pagaimo (2004) and Vicente (2008) on rubble limestone masonry (Table 1). Nevertheless, more tests have to be performed in the same conditions to confront and support the present results.

In what concerns the deformability properties in compression, Fig. 5 displays the relation between the stress in the masonry and the vertical and horizontal strains for both cycles of pressure.

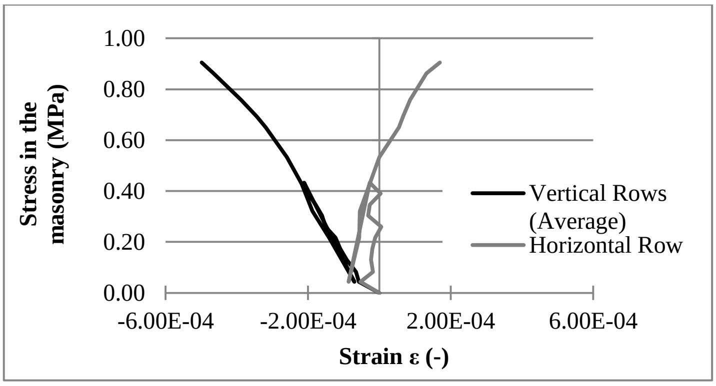


Fig. 5 Relation between stress in the masonry and vertical and horizontal strains.

The tangent Young's modulus (E_t – equation (2)) in the beginning of the first cycle is 2661.1 MPa, decreasing to 2440.6 MPa in the beginning of the second cycle. The secant Young's modulus (E_s – equation (3)) and the Poisson ratio (ν – equation (4)) may be determined for two cumulative range of results: (i) the ultimate stress level of the cycle, and (ii) 1/3 of the ultimate stress level of the test according to EN 1052-1 (2002) recommendations. The

obtained values for the secant Young's modulus and the Poisson ratio vary, respectively, between (i) 1817.4 MPa and 0.34, (ii) 1684.4 MPa and 0.31.
The values for the secant Young's modulus are slightly higher than the medium values proposed by OPCM 2374 (2003) for the same masonry typology (Table 1). However, the values proposed on the Italian standard cannot be directly used for the calibration of tests performed on traditional Portuguese masonries. Additional experimental in situ tests have to be conducted to confront the obtained values.

SHEAR FLAT-JACK TEST

The shear tests were based on the procedure suggested by Caliò (Caliò, 2009) for the test of brick masonry specimens loaded by the building self-weight. However, in the present work a vertical stress was applied to the rubble stone masonry specimen by a set of horizontal flat-jacks. To define the masonry specimen to be tested under shear load, two vertical cuts with a distance of 35.0 cm were made on the wall. A flat-jack was placed in one of the vertical cuts while the other remained free. After imposing a vertical compressive stress on both horizontal flat-jacks, the pressure on the vertical flat-jack is gradually increased. During the test horizontal and diagonal distances are recorded. The horizontal load applied by the vertical flat-jack to the masonry (F_h) is obtained from the flat-jack pressure (p), according to (6):

$$F_h = p \times K_e \times K_c \times A_{je} \tag{6}$$

Assuming a Mohr-Coulomb Law for the masonry shear strength and considering that the vertical stress on the posterior surface of the specimen (A_p) is zero (Caliò, 2009), the maximum horizontal load ($F_{h,max}$) applied by the vertical flat-jack to the masonry is given by (7):

$$F_{h,max} = A_s \times (\tau_o + \mu \times \sigma_n) + A_p \times \tau_o \tag{7}$$

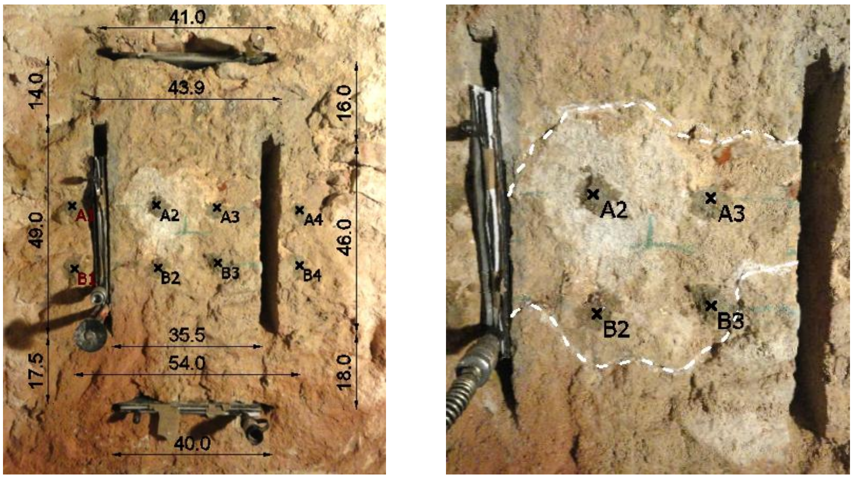
where A_s is the area of the horizontal sliding surfaces, τ_o is the masonry cohesion, μ the coefficient of friction and σ_n is the vertical stress applied to the specimen.
Knowing the magnitude of the vertical stress (σ_n) and the correspondent horizontal maximum pressure (p) from at least two shear tests, the masonry cohesion (τ_o) and the coefficient of friction (μ) can be calculated by equation (7).

SHEAR FLAT-JACK TEST RESULTS

Three shear flat-jack tests were carried out to evaluate the shear strength of the masonry. In addition to the horizontal force applied, on the first two tests a set of horizontal flat-jacks impose a vertical compressive stress to the masonry specimen. The third test aimed the evaluation of the shear strength of the posterior surface of the masonry specimen. In this case, in addition to the vertical cuts, two horizontal were made on the specimen to release the state of vertical stress.

SHEAR TEST 1

The test 1 setup is shown in Fig. 6.a. Points A1-A2, A3-A4, B1-B2, B3-B4 are related with measurements on of the horizontal relative distances and A2-B3, B2-A3 with the diagonal relative distances. First, the pressure on the horizontal flat-jacks was increased and kept with a constant value of 0.40 MPa. The pressure on the vertical flat-jack was then gradually increased until the maximum resistance of the specimen was obtained. The frontal cracks on the masonry specimen at the end of the test are shown in Fig. 6.b.



a) b)

Fig. 6 Shear Test 1: a) test setup with a vertical pressure of 0.40 MPa (dimensions in cm); b) frontal cracks on the masonry at the end of the test.

The ratio between the flat-jack pressure and the horizontal and diagonal relative distances of the masonry specimen is plotted in Fig. 7. The final pressure on the vertical flat-jack was of 3.10 MPa to a maximum horizontal deformation between 2.62 mm (rows A1-A2 and B1-B2) and 2.13 mm (rows A3-A4 and B3-B4).

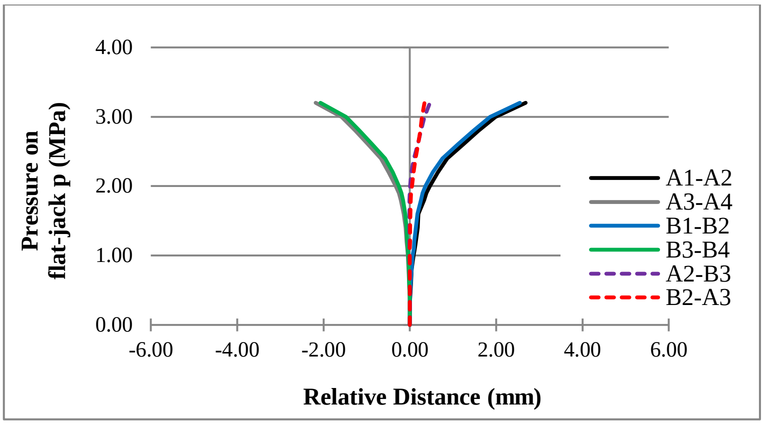


Fig. 7 Loading cycle with a vertical pressure of 0.40 MPa.

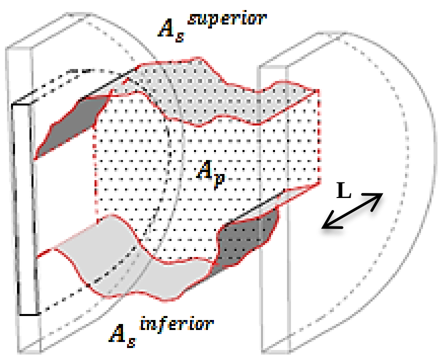
Converting the pressure on the flat-jacks to stresses in the masonry, the maximum horizontal stress was 1.03 MPa (K_e=0.71 and K_c=0.47), for a vertical stress of 0.16 MPa (K_e=0.70 and K_c=0.58). The corresponding maximum horizontal force (equation (6)) is 47.5 kN.
For shear flat-jack tests of brick masonry it is reasonable to assume that the shear failure of specimen occurs along two horizontal surfaces, coincident with the mortar bed joints, and on the posterior surface of the masonry specimen (Bosiljkov *et al*., 2010). However, in rubble stone masonry specimens, the definition of the sliding surfaces (horizontal and posterior) is more ambiguous.
At the end of the test, two semi-horizontal cracks were clearly visible on the frontal surface of the specimen (Fig. 8.a) and on the lateral sides (inside the vertical cuts). On the lateral sides, 3 to 4 cm long cracks were detected on the bottom of the specimen, while on the top a 20 cm

long crack was visible on the left side (Fig. 8.b) and a 9 cm long crack on the right side (Fig. 8.c). However, its propagation inside the masonry specimen is undetermined.

a) b) c)

Fig. 8 Shear failure: a) frontal cracks and details from the top crack inside the vertical cuts; b) left lateral crack and; c) right lateral crack (dimensions in cm).

In order to define the area of the sliding surfaces, the horizontal surfaces may consider the frontal cracks visible on the masonry (Fig. 8.a) and accept that these cracks propagate inside the specimen according with two different options. The first option assumes a propagation length of 11 cm corresponding to the length of the rectangular part of the semi-circular flat-jacks (Fig. 2), in which the masonry specimen is presumed to be under uniform stress state (vertical and horizontal). The second considers a propagation length of 21 cm considering the area of the flat-jack (A_j=75200 mm^2) divided by the distance between the vertical cuts (equal to 35 cm). The imprecision is significant, but the first option is expected to be less conservative as the underestimation of the area of the failure surface leads to the overestimation of the shear strength parameters.
The posterior vertical sliding surface is assumed to be the plane surface that connects both horizontal sliding surfaces. The sliding surface failure is depicted in Fig. 9 along with the area of the surfaces for both options.



Surface Area	Option 1 L = 11 cm	Option 2 L = 21 cm
$\mathbf{A_s^{superior}}$	48785 mm^2	93135 mm^2
$\mathbf{A_s^{inferior}}$	52437 mm^2	100107 mm^2
$\mathbf{A_p}$	91651 mm^2	91651 mm^2

Fig. 9 Test 1 failure surfaces.

SHEAR TEST 2

On the second shear test, a pressure of 0.60 MPa was applied to the horizontal flat-jacks. The test 2 setup is shown in Fig. 10.a. Like before, points A1-A2, A3-A4, B1-B2, B3-B4 are related with horizontal relative distances and A2-B3, B2-A3 with diagonal relative distances. Fig. 10.b shows the frontal cracks on the masonry specimen at the end of the test. The masonry that offers reaction to the vertical flat-jack also suffered a local crush, which conditioned the pressurization of the flat-jack and, probably induced the premature conclusion of the test (with a final pressure on the flat-jack of 2.92 MPa). This premature failure may explain the fact that the maximum horizontal pressure applied on the flat-jack is lower than the maximum horizontal pressure applied on test 1, where a lower vertical stress was imposed to the specimen.

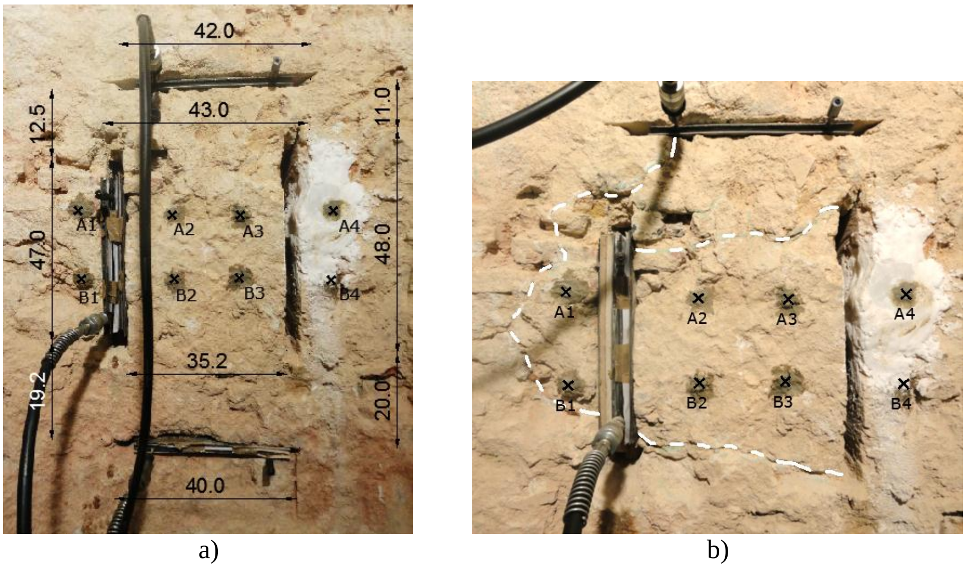


Fig. 10 Shear Test 2: a) test setup with a vertical pressure of 0.60 MPa (dimensions in cm); b) frontal cracks on the masonry at the end of the test.

The ratio between the flat-jack pressure and the horizontal and diagonal relative distances of the masonry specimen is described in Fig. 11. In this test the masonry specimen experienced a great horizontal deformation, which ended up exceeding, on rows A1-A2 and B1-B2, the range of the mechanical gauge in use. The final horizontal deformation was between 4.96 mm (rows A1-A2 and B1-B2) and 2.80 mm (rows A3-A4 and B3-B4).

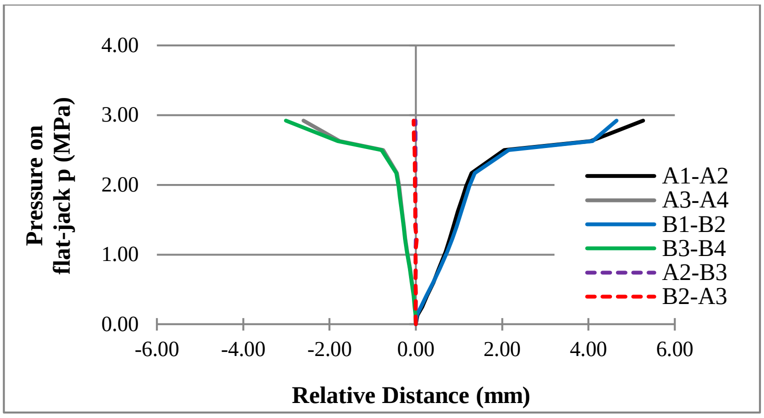
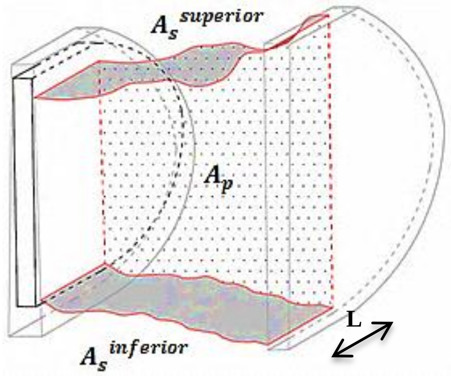


Fig. 11 Loading cycle with a vertical pressure of 0.60 MPa.

The results from test 2 were also influenced by the accumulated deformation of the masonry specimen due to a previous loading. The second test was previously performed, but uncompleted in consequence of the flat-jack's weld throat rupture. In addition, and as mentioned before, during the test the masonry against which the vertical flat-jack reacted suffered a local crush (Fig. 10.b), which conditioned the pressurization of the vertical flat-jack. The shear failure occurred for a horizontal stress on masonry of 1.07 MPa (K_e=0.73 and

K_c=0.50), when the specimen was under a vertical stress of 0.24 MPa (K_e=0.70 and K_c=0.57). The corresponding maximum horizontal force (equation (6)) was 52.6 kN. Though, it is important to refer that the results from the shear test 2 are not completely reliable in consequence of the incomplete test previously performed.
At the end of the test, cracks were visible on the frontal surface (Fig. 10.b) and on the lateral side of the masonry specimen (inside the vertical cuts). On lateral surfaces, approximately 2 to 3 cm long cracks were visible on the bottom of the specimen and 6 cm long cracks on the top. Once more, the test was stopped before the effective sliding of the masonry specimen and the definition of the cracked surface is ambiguous. The sliding surfaces were defined assuming the same hypothesis referred for test 1, as presented in Fig. 12.



Surface Area	Option 1 L = 11 cm	Option 2 L = 21 cm
$A_s^{superior}$	38954 mm^2	74367 mm^2
$A_s^{inferior}$	38005 mm^2	72555 mm^2
A_p	116708 mm^2	116708 mm^2

Fig. 12 Test 2 failure surfaces.

SHEAR TEST 3

The last shear test was performed on a specimen already tested by double flat-jack vertical loading; hence the specimen size differs from the test setup 1 and 2. Two vertical cuts were made adjacent to the already existing horizontal cuts, defining a specimen approximately 40 cm high with a 40 cm width, connected to the masonry wall only on the posterior surface. The test setup is shown in Fig. 13, as well as the gage point's position. The rows A1-A2, A3-A4, B1-B2, B3-B4 are related with horizontal relative distances and A2-B5, A5-B2 with diagonal relative distances. A flat-jack was placed on the left vertical cut, while the right vertical cut remained free for the specimen horizontal deformation (Fig. 13).

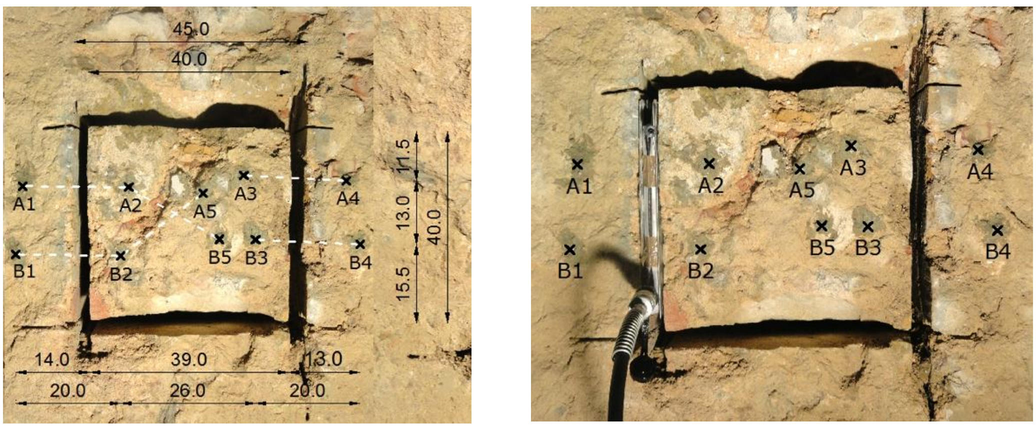


Fig. 13 Shear flat-jack test setup and gage point's position (dimensions in cm).

The relation between the flat-jack pressure and the horizontal and diagonal relative distances on the masonry specimen is described in Fig. 14. Due to the boundary conditions, it was impossible to observe the cracked surface of the wall (frontal and lateral). The test was stopped with a final pressure on the flat-jack of 2.18 MPa, as the support was not offering enough reaction to proceed with the test.

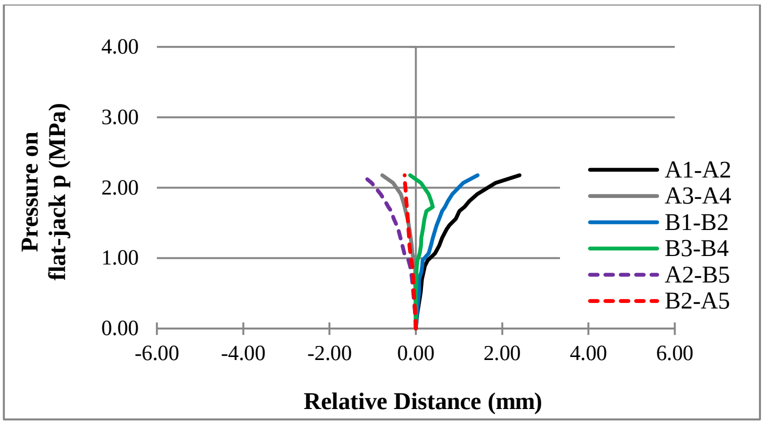


Fig. 14 Loading cycle without vertical pressure.

The final deformation was between 1.92 mm (rows A1-A2 and B1-B2) and 0.46 mm (rows A3-A4 and B3-B4), a variation that cannot be ignored. In fact, considering both the distances measured on the horizontal row B3-B4 and on the diagonal row A2-B5, it seems that the masonry specimen was under in plane rotation (clockwise direction). Nevertheless, it will be assumed that the shear failure occurred on the connection between the posterior part of the specimen and the wall (A_p = 1600 mm^2). The maximum pressure applied by the flat-jack was 2.18 MPa, which corresponds to a horizontal stress on the masonry of 0.74 MPa (K_e=0.64 and K_c=0.53) and maximum horizontal force of 33.8 kN. Considering the assumed shear failure, the shear strength of the posterior surface is 0.21 MPa.

DISCUSSION OF THE SHEAR TESTS RESULTS

Several tests were carried out in the laboratory to assess the shear strength parameters of traditional rubble stone masonry (Milošević *et al.*, 2011) (Milošević *et al.*, 2012). The masonry panels were built with the same materials (limestone and lime mortars) and techniques used in traditional construction and subjected to diagonal compression tests and triplet tests (Table 2).

Table 2 Masonry Shear Strength Parameters (literature results).

Type of Test		Cohesion τ_0 (MPa)	Coefficient of friction μ
Milošević *et al.* (2011)	Triplet Tests on limestone rubble masonry and air lime mortar specimens	0.0815	0.558
	Diagonal Compression Tests on limestone rubble masonry and air lime mortar specimens	0.024	--
OPCM 3274 (2003)	Table 11.D.1 – Irregular stone masonry (pebbles, erratic and irregular stone)	0.020 – 0.032	0.40 (Characteristic value)
	Table 11.D.1 – Uncut stone masonry with facing walls of limited thickness and infill core	0.035 – 0.051	

From the diagonal compression tests on masonry and air lime mortar specimens it was obtained for the cohesion a value of 0.024 MPa. From the triplet tests on masonry and air lime

mortar specimens it was obtained for the cohesion a value of 0.0815 MPa and a coefficient of friction of 0.558.
Despite the fact that Portuguese masonries do not exactly fit the Italian masonry typologies and a regional influence on the technics and materials may have an important influence, the values proposed by the OPCM 3274 (2003) can be used as indicative values (Table 2). For masonry typologies that may be related with the present masonry the standard OPCM 3274 (2003) indicates cohesion values between 0.020 MPa and 0.051 MPa and a (characteristic) value of 0.40 for the coefficient of friction.
Considering the shear surfaces based on the options depicted in Fig. 9 and Fig. 12, respectively for test 1 and 2, values for the shear parameters (cohesion and coefficient of friction) obtained with equation (7) are significantly different from the expected, particularly the coefficient of friction which resulted greater than 1.0 (Table 3).

Table 3 Shear strength parameters (test 1 and 2).

Surface Area	Option 1 L = 11 cm	Option 2 L = 21 cm
Cohesion τ_0 (MPa)	0.060	0.026
Coefficient of friction μ	2.22	1.30

The shear test 3 aimed the determination of the shear strength of the posterior surface of the specimen, which is possibly related to the masonry cohesion. In this test, the obtained shear strength was 0.21 MPa, which is much higher than the referred values for the masonry cohesion (Table 2).
In fact, if the results from test 1 and 2 (considering the conservative option of the 21 cm uniform propagation) are affected by 0.21 MPa stress on the posterior failure surface, the shear strength on the horizontal failure surfaces is lower than the shear strength of the posterior surface. Assuming a Mohr-Coulomb Law for the masonry shear strength and considering that the vertical stress on the posterior surface of the specimen (A_p) is zero (Caliò, 2009), this result cannot be correct (the coefficient of friction is a positive value).
If in one hand, the results from test 2 are not completely reliable, as well as the definition of the shear failure surfaces (horizontal and posterior), on the other hand, test 3 indicated that the posterior surface of the specimen has an influence on the shear strength that may be higher than in reality.
These results may derive from the uncertainties in the definition of the failure surface and of the heterogeneity of the materials, which may lead to an above normal resistance in a surface across a major stone or to a change in the failure surface. Therefore more data is necessary for comparison, to allow the identification of those types of situations and to purge unreliable/unrepresentative results. It can thus be concluded that the experimental campaign herein presented shows the need of performing more shear tests in rubble stone masonry walls with the similar boundary conditions in order to calibrate the test procedure and to get satisfactory correlating factors.

CONCLUSION

The flat-jack tests provide a relatively non-destructive technique to assess the in situ mechanical properties of masonry walls. This testing technique has been successfully used in regular brick and stone masonry structures, but its practice on rubble stone masonry structures is not so common.

From the compressive flat-jack tests experimental acceptable values were obtained for the secant Young's modulus (between 1684.4 MPa and 1817.4 MPa) and for the Poisson ratio (between 0.31 and 0.34). The maximum compressive stress applied to the masonry specimen (0.91 MPa) is also compatible with the maximum compressive stresses referred on the literature regarding flat-jack tests.
As to the shear strength parameters, considerable deviations from the reference values were obtained in this experimental campaign. As mentioned, the boundary conditions of the specimen and the high heterogeneity of the material had a great influence on the results.
The existent standards concerning shear tests with flat-jacks (ASTM C 1531-03 (2003) and RILEM MS-D.6 (1996)) were developed for regular block masonry where the cuts cross the entire thickness of the wall, completely isolating the specimens from the remaining masonry.
The great thickness of the traditional masonry walls implies on boundary conditions which have a major influence on the test results. Further studies have to be conducted to define the necessary calibration parameters.

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