Characterization of Old Masonry Walls: Flat-Jack Method

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SUMMARY:

This paper describes an experimental campaign developed to assess the physical and mechanical properties of the rubble stone masonry walls present in the Lisbon old masonry buildings. That data is essential to define appropriate and realistic numerical models to be used on the structural assessment and retrofitting of existing buildings. The tests were carried out on load bearing masonry walls of an 18th century building located in the historical centre of Lisbon taking advantage of the flat-jack method. These in situ tests aimed the evaluation of the rubble stone masonry deformability properties in compression (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 Buildings, Experimental Tests, In Situ Tests

1. INTRODUCTION

The exterior masonry walls of Lisbon old masonry buildings are commonly made of rubble limestone masonry with grit (red aggregate) or fragments of ceramic bricks, bounded by air lime mortar. Regarding the heterogeneity of the material and workmanship, the mechanical survey of masonry structures should be carried out on undisturbed and large dimension specimens. On the other hand, when dealing with old buildings, sampling is often impossible and difficult to perform.
The flat-jack method is a relatively non-destructive testing technique to assess the in situ mechanical properties of masonry. Extensively used in regular brick and stone masonry structures, its practice on irregular stone masonry structures is not so common. This paper describes an experimental campaign with flat-jacks conducted on rubble stone masonry walls from an 18th century building. 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).

2. EXPERIMENTAL CAMPAIGN

The flat-jack tests were carried out on an 18th century building located in Lisbon. The exterior bearing walls are made of rubble stone masonry with decreasing thickness with the height of the building. The tests were performed on the back façade wall at the ground floor level. At this location the wall is thick enough to support the cuts perpendicular to its surface without endangering the structure.
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 - Figure 1).
During the tests, the deformation of the masonry specimen was assessed with a removal mechanical meter with 20.0 cm gauge length. Three measurement repetitions are required at each pair of reference

points (metal discs) disposed on the masonry, being the final value 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.

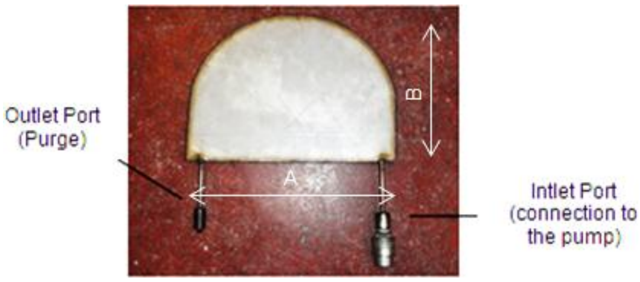


Figure 1. Semi-circular flat-jack with (A) 34.5 cm and (B) 25.5 cm.

3. DOUBLE FLAT-JACK TEST

The double flat-jack test described in ASTM C 1197-04 (2004) and in RILEM MDT.D.5 (2004) support the assessment of the masonry deformability properties in compression. The procedure comprehends the test of a masonry specimen under uniaxial compression. Two horizontal cuts are performed on the wall delimiting a specimen with 40.0 cm height. During the test, vertical and horizontal distances on selected points are 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.
The flat-jacks have to be first calibrated to determine a conversion factor between the internal pressure of the flat-jack and the pressure effectively applied to the masonry. 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 Eqn. 3.1:

$$f_m = p \text{ x } K_e \text{ x } (A_{je} / A_{cut}) = p \text{ x } K_e \text{ x } K_c \tag{3.1}$$

In what concerns the deformability properties, the tangent Young's modulus (E_t) is given by Eqn. 3.2, where δf_m is the increment of stress and $\delta\varepsilon_m$ is the corresponding increment of strain:

$$E_t = \delta f_m / \delta\varepsilon_m \tag{3.2}$$

The secant Young's modulus (E_s) is defined by Eqn. 3.3, where f_m is the cumulative stress and ε_m is the cumulative strain increment from zero.

$$E_t = f_m / \varepsilon_m \tag{3.3}$$

The Poisson ratio (ν) is given by Eqn. 3.4, where ε_h is the horizontal strain and ε_v the vertical strain:

$$\nu = \varepsilon_h / \varepsilon_v \tag{3.4}$$

3.1. Double Flat-Jack Test Results

The double flat-jack test setup is displayed in Figure 2. Points 1-1' to 4-4' refer to vertical measurement rows and points 5-5' to horizontal measurement row. An initial pressure was applied to the flat-jacks to pack them into the cuts, followed by two cycles of loading and unloading. With the first cycle, the flat-jacks were pressurized up to 1.00 MPa, while in the second cycle maximum pressure was of 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 Figure 3. The strain value was calculated dividing the distance recorded at each load increment by the initial length.

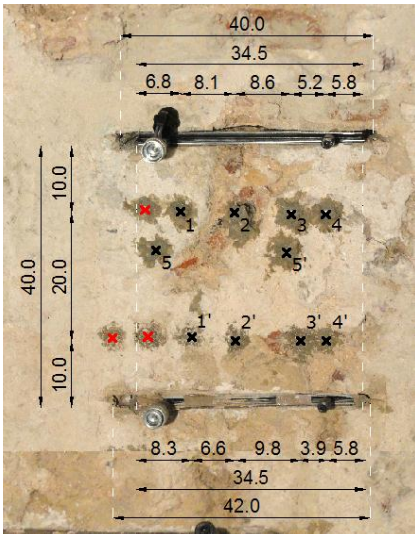


Figure 2. Double flat-jack test setup (dimensions in cm).

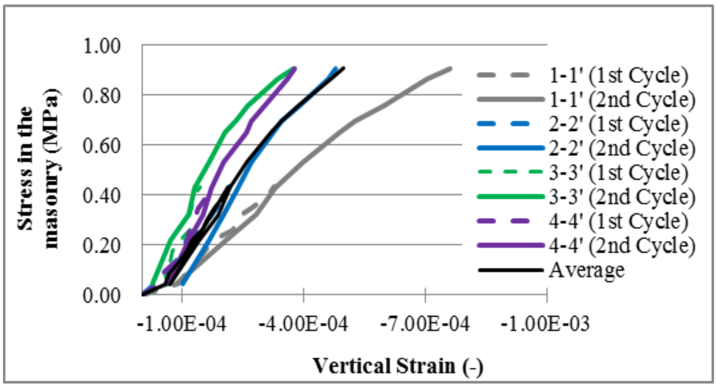


Figure 3. Relation between stress in the masonry and vertical strain.

Although the slope of the curves "stress in the masonry – vertical strain" of both cycles of pressure is similar (Figure 3), 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 ultimate pressure of the second cycle (2.09 MPa) corresponds to a stress in the masonry of 0.91 MPa. Though, this stress value must be regarded as a lower limit of the masonry compressive strength as the test was stopped by the insufficient reaction of the upper part of the wall.

Figure 4 displays the relation between the stress in the masonry and the vertical and horizontal strains for both cycles of pressure. In what concerns the deformability properties in compression, the tangent Young's modulus (E_t – Eqn. 3.2) 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 – Eqn. 3.3) and the Poisson ratio (ν – Eqn. 3.4) 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 3431 (2005) for the same masonry typology, placed between 690 MPa and 1440 MPa. 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 performed in the same conditions to confront and support the present results.

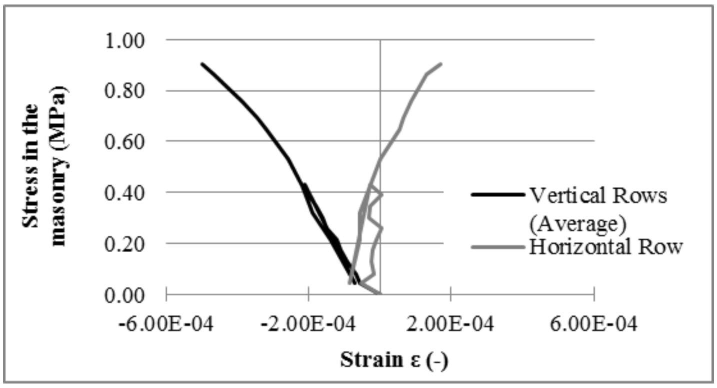


Figure 4. Relation between stress in the masonry and vertical and horizontal strains.

4. SHEAR FLAT-JACK TEST

The masonry specimen to be tested under shear load is delimited by to vertical cuts with a distance of 35.0 cm. A flat-jack is placed in one vertical cut while the other cut remains free for the specimen horizontal deformation. This test procedure was first suggested by Caliò (Caliò, 2009); however, in the present work a vertical stress was applied to the rubble stone masonry specimen by a set of horizontal flat-jacks. 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 Eqn. 4.1:

$$F_h = p \text{ x } K_e \text{ x } K_c \text{ x } A_{je} \tag{4.1}$$

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 Eqn. 4.2:

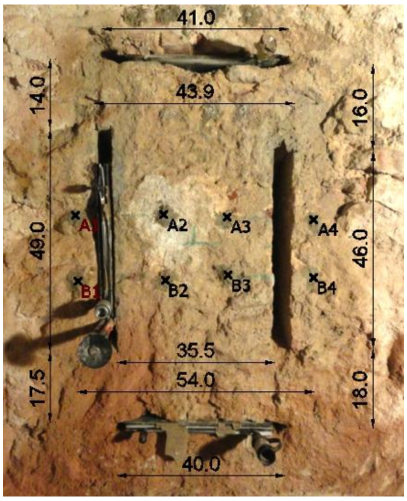
$$F_{h,max} = A_s \text{ x } (\tau_o + \mu \text{ x } \sigma_n) + A_p \text{ x } \tau_o \tag{4.2}$$

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 Eqn. 4.2.
In this experimental campaign, three shear flat-jack tests were carried out to evaluate the shear strength of the masonry. The test results are presented on the following section.

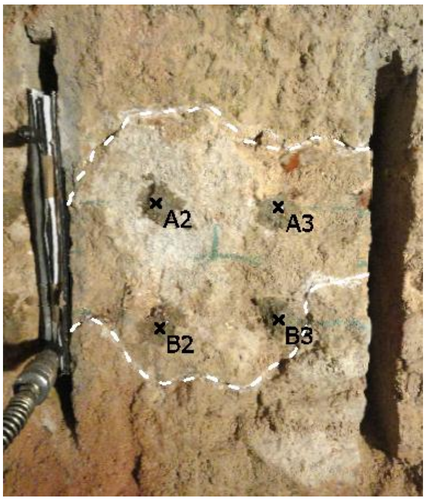
4.1. Shear Test 1

In the first test a set of horizontal flat-jacks imposed a vertical compressive stress to the masonry specimen according with the test setup shown in Figure 5 a). Points A1-A2, A3-A4, B1-B2, B3-B4 are related with the measurement on the horizontal deformation of the specimen and A2-B3, B2-A3 with the diagonal deformation. 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 Figure 5 b). The ratio between the flat-jack pressure and the horizontal and diagonal relative distances of the masonry specimen is plotted in Figure 6.
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). 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 (Eqn. 4.1) is 47.5 kN.



a)



b)

Figure 5. 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.

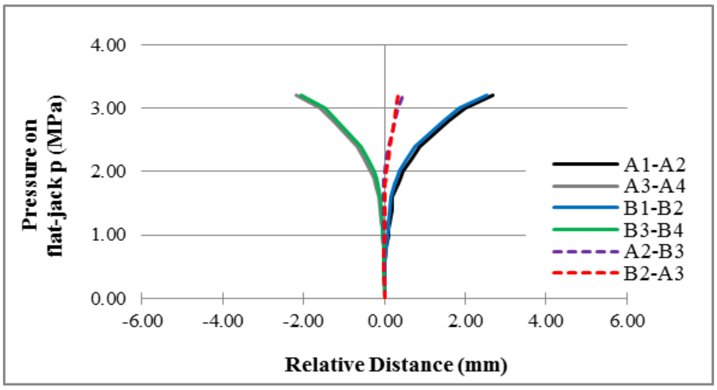
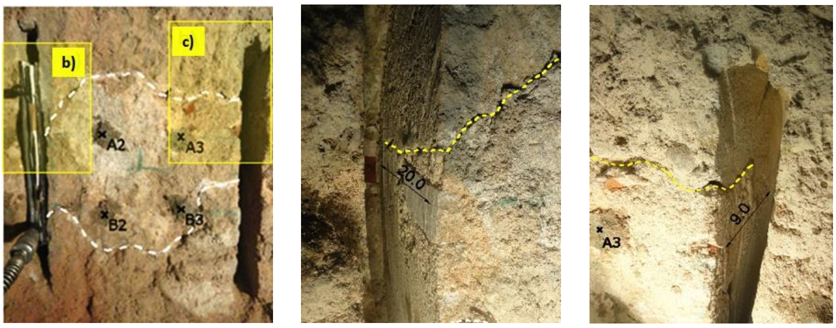


Figure 6. Loading cycle with a vertical pressure of 0.40 MPa.

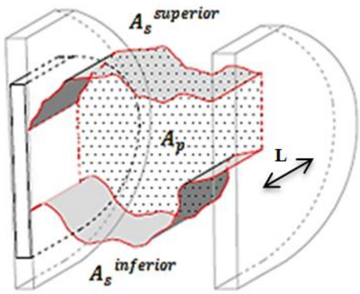
On the flat jack shear tests of brick masonry it is reasonable to assume that the shear failure of the specimen occurs along two horizontal surfaces, coincident with the mortar bed joints, and on the posterior surface of the masonry specimen (Bosiljkov *et al*., 2010). However, for rubble stone masonry specimens the definition of the sliding surfaces is more ambiguous. At the end of the test, two semi-horizontal cracks were clearly visible on the frontal surface of the specimen (Figure 7 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 (Figure 7 b) and a 9 cm long crack on the right side (Figure 7 c). Though, its propagation inside the masonry specimen is uncertain.
In order to define the area of the sliding surfaces, the horizontal surfaces may consider the frontal cracks visible on the masonry (Figure 7 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 (Figure 1), 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 Figure 8 along with the area of the surfaces for both options.



a) b) c)

Figure 7. 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).



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

Figure 8. Test 1 failure surfaces.

4.2. Shear Test 2

On the second shear test a pressure of 0.60 MPa was applied to the horizontal flat-jacks (the test setup is shown in Figure 9 a). Figure 9 b) illustrates 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 end 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.

The ratio between the flat-jack pressure and the horizontal and diagonal relative distances of the masonry specimen is described in Figure 10. 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).

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 (Figure 9 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 (Eqn. 4.1) 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.

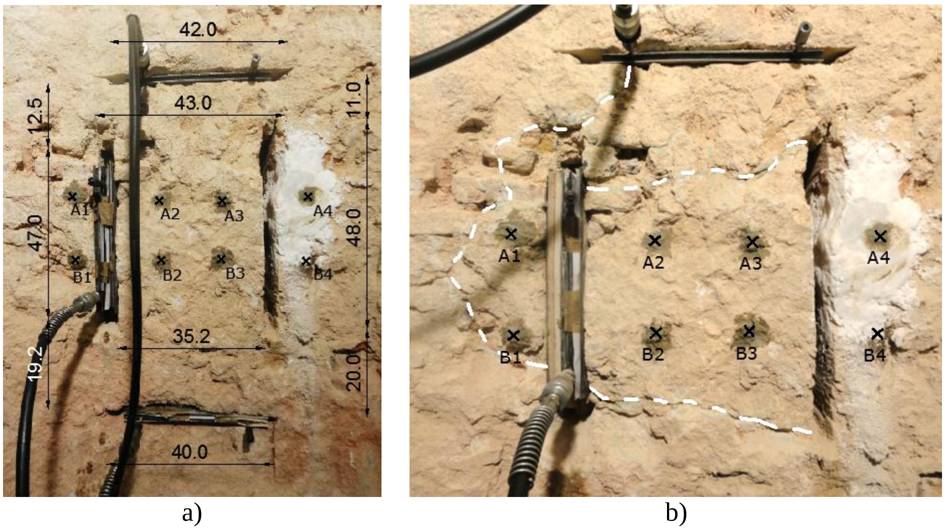


Figure 9. Shear Test 2: a) test setup with a vertical pressure of 0.60 MPa (dimensions in cm); b) frontal cracks on the masonry at the end of the test.

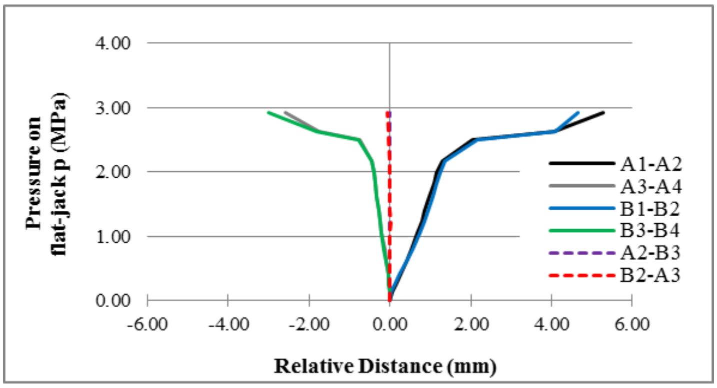
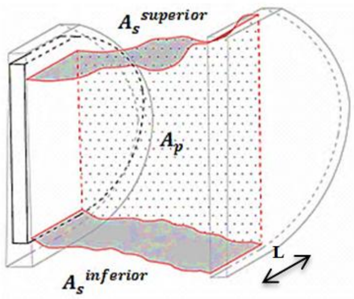


Figure 10. Loading cycle with a vertical pressure of 0.60 MPa.

At the end of the test, cracks were visible on the frontal surface (Figure 9 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. The specimen sliding surfaces presented in Figure 11 were defined in accordance with the hypothesis referred in section 4.1 for the shear test 1.



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

Figure 11. Test 2 failure surfaces.

4.3. Shear Test 3

The third shear 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. The 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 Figure 12, as well as the gage point's position. 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.

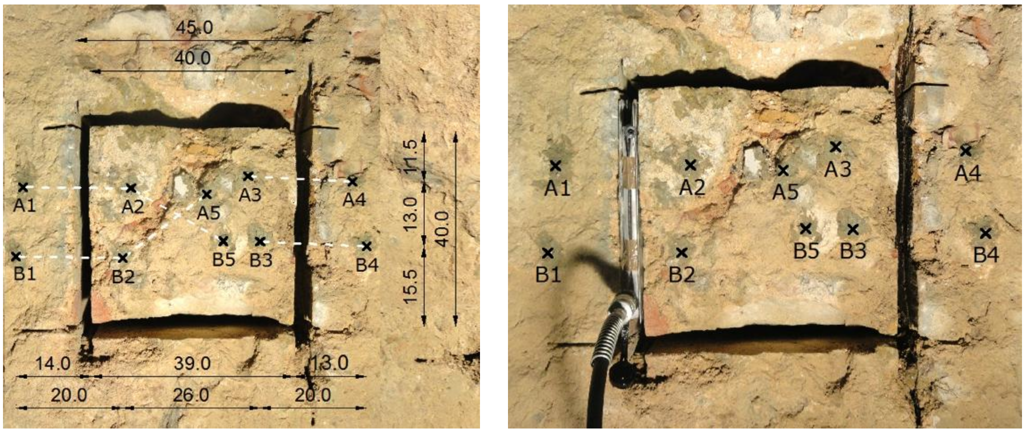


Figure 12. Shear flat-jack test setup and gage point's position (dimensions in cm).

The relation between the flat-jack pressure and the horizontal and diagonal relative distances on the masonry specimen is described in Figure 13. 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.

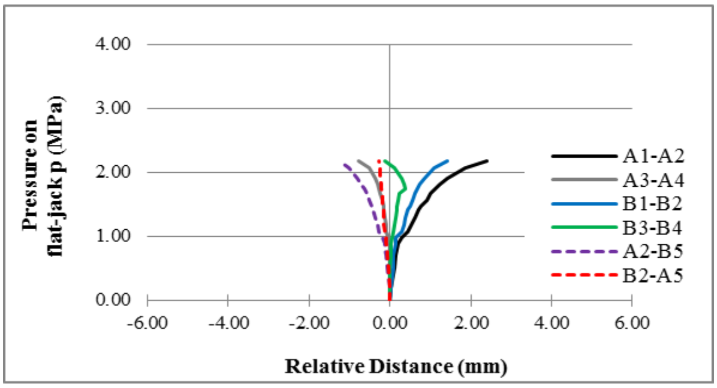


Figure 13. Loading cycle without vertical pressure.

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.

4.4. Discussion of the Shear Tests Results

Within the research project SEVERES (www.severes.org) several tests were carried out in the laboratory to assess the shear strength parameters of traditional rubble stone masonry (Milošević *et al.*, 2012). Several 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. From the diagonal compression tests on masonry and air lime mortar specimens a value of 0.024 MPa was obtained for the cohesion. From the triplet tests on masonry and air lime mortar specimens it was defined for the cohesion a value of 0.082 MPa and a coefficient of friction of 0.558.
Despite the fact that Portuguese masonries do not exactly fit the Italian masonry typologies the values proposed by the OPCM 3431 (2005) can be used as indicative values. For masonry typologies that may be related with the present masonry the standard OPCM 3431 (2005) 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 Figure 8 and Figure 11 respectively for test 1 and 2, values for the shear parameters (cohesion and coefficient of friction) obtained with Eqn. 4.2 are significantly different from the expected, particularly the coefficient of friction which resulted greater than 1.0 (Table 1).

Table 1. 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. 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.

5. 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 far as the shear strength parameters concern, 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 regarding shear tests with flat-jacks (ASTM C 1531-03 and RILEM MS-D.6) were developed for regular block masonry where the cuts cross the entire thickness of the wall completely, isolating the specimens from the remaining masonry. Due to the great thickness of the traditional masonry walls the cuts do not cross the entire thickness of the wall resulting in different boundary conditions, which have a major influence on the test results. Further studies have to be conducted to define calibration parameters, the shear failure surfaces and to quantify the influence of the posterior surface of the specimen.

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