TECHNICAL ARTICLE

Mechanical Characterization of Masonry Walls With Flat-Jack Tests

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Abstract

The results from an experimental campaign on old masonry buildings from Lisbon are presented and discussed. The tests aim at the evaluation of the masonry deformability properties in compression and the shear strength parameters based on flat-jack testing technique. Tests were carried out in both internal brick masonry walls and external rubble limestone masonry walls. The evaluation of the shear parameters was done according to a new testing technique—shear tests on masonry walls with flat-jacks—involving more than one masonry unit. One of the goals is the calibration and development of this testing technique and to show its first application to the test of rubble stone masonry walls. For that, the experimental technique is fully explained in this paper, and the results of some in situ tests are used to discuss the calibration procedure. Because of the characteristics of the walls, in particular, the great heterogeneity and thickness of the external masonry walls, the application of the flat-jack testing technique involved some uncertainties that are described and debated in this work.

Introduction

The rehabilitation and conservation of historical constructions are fundamental for the renewal of old city centers, but the analysis of these constructions poses several difficulties. One of the main challenges is, in fact, to evaluate adequately the current safety of existing masonry buildings. The structural safety assessment of buildings and the design of strengthening solutions, when required, should be based on an extensive knowledge of the structure and of the materials mechanical characteristics. According to the most recent codes applicable to existing structures—EC8-3[1] and the Italian Code NTC[2]—the type of structural analysis and appropriated confidence factors (i.e. the safety factors) are chosen according to the level of inspection and testing and to the percentage of elements that have been checked for details. Moreover, the geometric survey, inspections and in situ tests are necessary to create a representative model of the structure. There are many experimental tests available to estimate the materials mechanical properties. However, in case of historical buildings, there are several limitations on the type/number of tests that can be carried out in situ and restrictions to the extraction of representative samples for laboratory testing.

For the structural safety assessment of masonry buildings, the most important mechanical parameters are the compressive Young's modulus, the compressive strength and the shear strength of load bearing masonry walls. The evaluation of those mechanical properties requires in situ tests where the boundary conditions are properly taken into account. This type of tests is often very destructive and requires heavy equipment. The flat-jack testing technique provides significant information about the mechanical properties of compressed masonry walls and is considered to be a semi-destructive testing technique, as the damage on the wall is easily repaired after the test.

Usually, the flat-jack test aims to evaluate the state of vertical stress of a wall—single flat-jack test[3,4]—and the Young's modulus (and strength) under compression—double flat-jack test.[5,6] As to the wall shear strength parameters, it is common practise to perform diagonal compression tests, which are very destructive and cause extensive damage to the structure to obtain the test prototype.[7,8] Another possibility is to test single masonry units with flat-jacks which provides a direct measure of the shear strength of mortar joints that can be correlated to the behavior of the wall[9,10] as demonstrated in several research works.[11,12] Caliò[13] proposed, in alternative, the execution of shear tests with the flat-jack technique involving part of the masonry wall. The technique seems to be promising, but an extended calibration process should be done. The analysis of the results obtained by this technique is particularly difficult when the thickness of the wall is higher than the size of the flat-jack, which happens easily on traditional masonry walls.

This paper aims to contribute for the development and calibration of this experimental technique—shear tests on masonry walls with flat-jack—and apply it, for the first time, to the test of rubble stone masonry walls. For that, the experimental technique is fully explained and the results from an experimental campaign are used to discuss the procedure. Simultaneously, the paper aims to enrich the database about mechanical characteristics of masonry walls on old Lisbon buildings.

Experimental Tests with Flat-Jacks

The testing technique to characterize the mechanical behavior of the masonry walls under compression is based on the pressurization of a flat-jack inside a horizontal plane cut in the masonry wall. When a section cut is made on the masonry, the stress release causes the masonry to close the cut partially. During the test, the pressure on the flat-jack is increased until the distance between reference points, positioned on both sides of the cut, is the same as before the cut. The pressure on the flat-jack is equivalent to the previously existing state of stress in the masonry. Based on this simple procedure, it is possible to estimate the local compressive stress level on a masonry load-bearing wall. Placing two flat-jacks into parallel horizontal cuts on the masonry wall, one above the other, it is possible to test the masonry specimen in between under uniaxial compression. By measuring the deformability in compression during the test (stress–strain relationship), one can obtain the masonry Young's modulus in compression.

These testing methods are described on American Society for Testing and Materials (ASTM) and International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) standards[3−6] and have been repeatedly used for the mechanical characterization of masonry walls since the beginning of the 1980's.[14] Most of the research works have been focused on the flat-jack tests on brick and block masonry walls[15−17] and less on irregular masonry walls.[18−20] For the evaluation of the shear strength of masonry walls, ASTM and RILEM standards suggest to correlate it with the shear resistance of the mortar joints.[9,10] The test procedure was designed for the test of brick or block single-leaf masonry walls, in which a masonry unit is subjected to horizontal forces, of increasing magnitude, applied by a cylindrical jack or a small flat-jack. The horizontal force that causes the movement of the masonry test unit (or the change in the slope of the load-displacement curve) provides a measure of the bed joint shear strength. Performing several tests with different vertical confinement stresses (applied by two parallel flat-jacks placed above and below the test site), it is possible to estimate the mortar cohesion and friction coefficient. Nevertheless, this testing technique is not always suitable for the test of rubble stone masonry walls that can be found in several old masonry buildings.

Caliò[13] proposed an alternative testing method for the evaluation of the shear strength of regular brick or block masonry. In this procedure, horizontal flat-jacks are used to apply a vertical state of stress to a masonry specimen, as well as a vertical flat-jack applies an horizontal pressure of increasing magnitude until the shear sliding collapse of the masonry specimen occurs. For that, two vertical and two horizontal cuts are done in the masonry. Two flat-jacks are placed on the horizontal cuts and one flat-jack is placed in one of the vertical cuts. The other vertical cut remains free to accommodate the horizontal sliding movement of the masonry specimen. After performing several tests with different vertical stress levels, it is possible to estimate the masonry cohesion and friction coefficient, as proposed in ASTM and RILEM.[9,10] The main advantage of the proposed method is that it is less intrusive in comparison with traditional tests to determine the shear strength of the masonry: monotonic and cyclic shear-compression tests or triplet tests.[7,8]

Experimental Campaign in Lisbon

In order to assess the mechanical properties of walls from the two most representative Lisbon types of masonry buildings and also to obtain data for the calibration of the flat-jack shear testing technique, several in situ flat-jack tests were performed. The tests were conducted on the external rubble stone masonry walls from a ''Pombalino'' building and

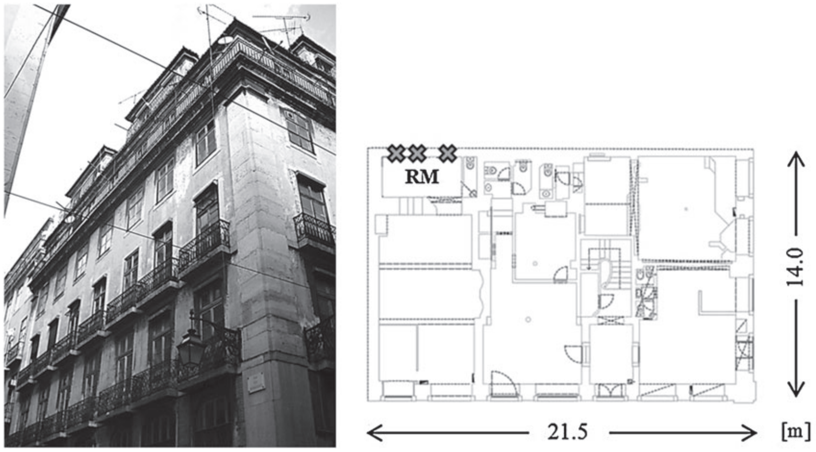


Figure 1 Identification of the ''Pombalino'' building and the test position on RM walls.

a ''Gaioleiro'' building and on the internal brick masonry walls of the ''Gaioleiro'' building. This experimental campaign aimed first to evaluate the masonry deformability properties in compression and to estimate the masonry Young's modulus, making use of the test method proposed in ASTM and RILEM standards.[5,6] The second objective was to estimate the masonry shear strength parameters based on the testing method proposed by Caliò[13] and use it for irregular masonry walls, like the external walls from old buildings in Lisbon.

''Pombalino'' buildings were built after the 1755 Lisbon earthquake that completely destroyed the city center. This typology is characterized by a three-dimensional timber-masonry structure, known as the ''gaiola pombalina'' or cage, intended to withstand the horizontal seismic loads above the first story.[21] ''Gaioleiro'' buildings were built at the second half of the 19th century and the beginning of the 20th century, following the urban development plan from engineer Ressano Garcia.[22] The ''Gaioleiro'' buildings were built with a different design from the ''Pombalino'' style, as the internal structure is made of clay brick masonry walls with air lime mortar and timber floors. The external walls of both types of buildings are made of rubble limestone masonry with air lime mortar; their thickness decreases with the height of the building. The thickness of the walls on the ground floor can vary between 0.8 and 1.2 meters.

One ''Pombalino'' building and one ''Gaioleiro'' building were selected for this experimental campaign. In both cases, the tests were done at the ground floor where the vertical loads are higher. On the ''Pombalino'' building (Fig. 1), one double flat-jack test and three shear flat-jack tests were performed on the back façade rubble limestone masonry (RM) wall. On the ''Gaioleiro'' building (Fig. 2), three double flat-jack tests and three shear flat-jack tests were done

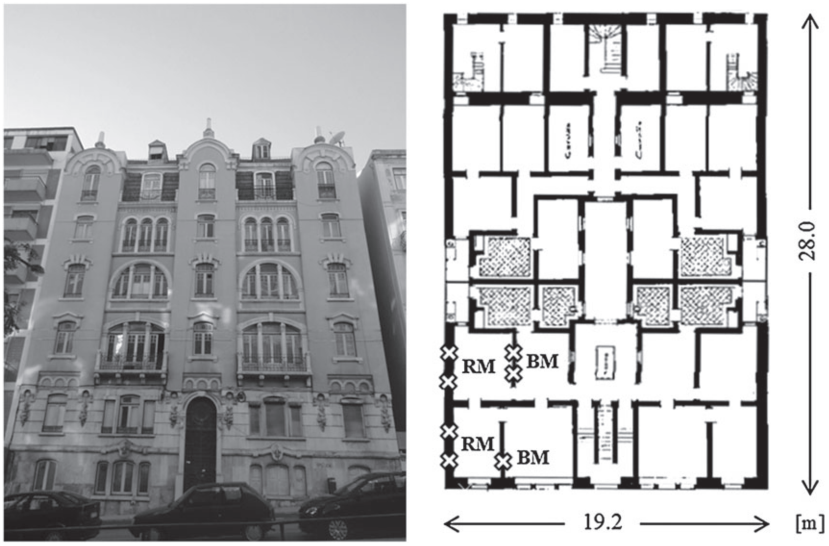


Figure 2 Identification of the ''Gaioleiro'' building and the test position on RM and BM walls.

Figure 3 Test apparatus: (a) test setup; (b) hydraulic pump; and (c) removable mechanical meter.

on the lateral rubble limestone masonry (RM) wall and three shear flat-jack tests were done on internal brick masonry (BM) walls. The external walls selected have no openings and are thick enough to support the cuts perpendicular to their surface without endangering the structure. The tests on the brick masonry walls were carried on the whole thickness of the wall.

Flat-jacks are made of one steel sheet folded in the middle, welded in the edges creating an envelope bladder to be filled with oil. The flat-jack pressure is controlled by a manual hydraulic pump connected to the flat-jack by flexible tubes (Fig. 3). The oil pressure is measured by means of a pressure gauge. As stated in ASTM and RILEM standards,[3−6] flat-jacks have an inherent stiffness, which resists expansion when pressurized. Therefore, the flat-jack oil pressure is greater than the stress that is applied to the masonry wall. According to the test standards,[3−6] the average stress applied to the masonry (σ_m) is equal to the flat-jack pressure (p) multiplied by factors which account for the physical characteristics of the flat-jack, namely, an a-dimensional calibration factor (K_m) and the ratio K_a between the effective area of the flat-jack in contact with the masonry (A_{je}) and the area of the cut (A_{cut}), according to Eq. 1:

$$\sigma_m = p \times K_m \times K_a \tag{1}$$

In this experimental campaign, two flat-jack plan-shapes were used (Fig. 4): semi-circular with A = 345 mm and B = 255 mm for the test of RM walls and rectangular with A = 400 mm and B = 150 mm for the test of BM walls with brick dimensions (depth × height × length): 150 × 120 × 240 mm. The flat-jacks were manufactured and calibrated according to the ASTM and RILEM specifications.[3,4] For the calibration procedure, each flat-jack was placed in a compression machine, pressed between two steel bearing plates to provide full contact and subjected to three pressurized and depressurized cycles with constant pressure increments, maintaining the distance between the machine platens constant during the calibration procedure. The calibration factor (K_m) is obtained from the slope of the regression line between the test machine load (F_M) and the flat-jack load (F_{FJ}) defined as the flat-jack pressure (p) times the gross area of the flat-jack (A_j). Figure 5 plots, as an example, the calibration curve of a semi-circular flat-jack.

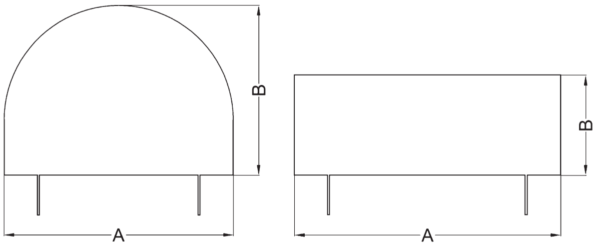


Figure 4 Flat-jack configuration.

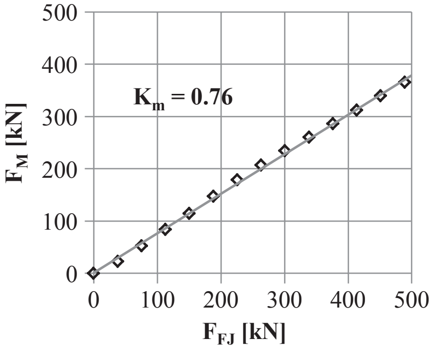


Figure 5 Calibration curve of a semi-circular flat-jack.

The flat-jack when inserted in the cut is packed by steel shims to protect the faces of the flat-jack from irregularities on the masonry surface and in order that the pressure applied by the flat-jack is uniformly distributed as possible on the cut surface. Nevertheless, during the pressurization cycle, the area of the flat-jack in contact with the masonry surface may vary because of the expansion of the flat-jack inside the cut. It is expected that even for higher levels of pressure the area of the flat-jack in contact with the masonry is lower than the gross area of the flat-jack. This fact is particularly important when testing masonry walls with irregular configuration due to the higher probability of having rough surfaces and voids in the masonry. Previous research works have proposed a method to estimate the effective area of the flat-jack in contact with the masonry (A_{je}), which is based on setting between the flat-jack and the masonry a sheet of carbon paper, sandwiched between two sheets of ordinary paper.[14,23] This way, during the test, the paper is marked where contact occurred. In this work, this simplified method to define A_{je} was applied on the test of both rubble stone and brick masonry walls, and the results compared with the ones obtained by considering A_{je} equal to the gross area of the flat-jack (A_j).

During the tests, a removable mechanical meter with 200 mm gauge length was used to measure the distance between reference points (metal discs) glued to the masonry surface (Fig. 3). Three measurements were taken at each pair of points, being the final value the average of the measurements.

The selection of the location for the test is a very important issue for its effectiveness. Cuts should be made away from wall openings or extremities, to guarantee sufficient reaction support during the test. In case of regular or brick masonry walls, the slot cuts should be made at the bed joints. However, in case of irregular stone masonry, cuts have to be partially made within the stone course, which might influence the test results.[15]

Double flat-jack tests

The test method described in ASTM and RILEM standards[5,6] describes the procedure for the assessment of the masonry deformability properties in compression. Two flat-jacks are inserted into parallel (and vertically aligned) cuts with a distance between A and 1.5A (A is the dimension of the flat-jack—Fig. 4). Several loading and unloading cycles should be performed testing the masonry between the flat-jacks under uniaxial compression. In this way, it is possible to perform a compression test on an undisturbed sample of masonry. During the test, the flat-jack pressure (p) and the masonry vertical deformation are recorded allowing the estimation of the masonry Young's modulus (E) according to Eq. 2:

$$E = \sigma_m / \varepsilon_v \tag{2}$$

where σ_m is the average stress applied to the masonry, calculated by Eq. 1. The vertical strain ε_v is the ratio between the variation of the distance between points recorded during the test and the initial distance. On this issue, four equally spaced pairs of vertical reference points and one horizontal pair between the cuts are recommended by the standards.

There is no reference in the RILEM and ASTM standards[5,6] regarding the condition to define the elastic Young's modulus in compression. Thus, the Young's modulus was defined as the secant value to 1/3 of the masonry compressive strength $\left(E_{s(1/3\,f_c)}\right)$ according to EN 1052-1.[24] The stress level applied by the flat-jacks to the masonry is limited by the magnitude of the dead load applied in the wall above the test level. In fact, the load applied by the top flat-jack needs to be reacted and cannot be larger than the dead load on the wall. Thus, the maximum pressure applied during the test is not, in the majority of the situations, the masonry compressive strength. Due to this fact, in this case, the compressive strength was estimated following the suggestion of Lombillo et al.[19,25] by fitting a logarithmic curve on the non-linear region of the envelope loading cycles (stress–strain relationship) and considering the maximum stress associated with a deformation of 3‰ as proposed in.[19,25]

Test on rubble stone masonry walls

A total of four tests were performed on walls made with rubble limestone with air lime mortar: one test on the back façade wall of the ''Pombalino'' building (P.1) and three tests on the side external wall of the ''Gaioleiro'' building (G.1, G.2, and G.3). The test setup (test P.1 as an example) and the relationship between the average stress in the masonry (σ_m) and the average vertical strain (ε_V) for both cycles of pressure are displayed in Fig. 6 for all tests performed. Because of the great thickness of these traditional masonry walls, the depth of the horizontal cuts on the masonry is equal to the flat-jack dimension B (Fig. 4). Therefore, the tests are carried only in a part of the wall thickness (approximately 40%).

The strain value plotted in Fig. 6 corresponds to the average of the four vertical references (1-1′ to 4-4′). It can be noticed that the obtained stiffness for the ''Pombalino'' masonry wall is significantly higher than the stiffness obtained for the ''Gaioleiro''

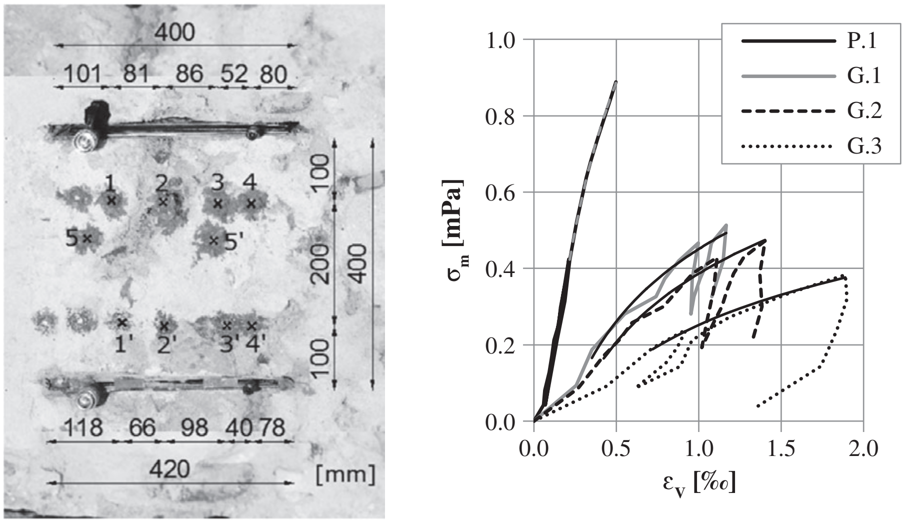


Figure 6 Double flat-jack test setup and results on rubble stone masonry.

Table 1 Double flat-jack test results on rubble stone masonry

Tests	$\sigma_{m,max}$ [MPa]	f_c [MPa]	$E_{s(1/3fc)}$* [GPa]
P.1	0.89	1.89	2.00
G.1	0.51	0.75	0.51
G.2	0.47	0.67	0.42
G.3	0.38	0.47	0.25

*If $A_{je} = A_j$ is considered, $E_{s(1/3fc)}$ is, in average, 19% higher.

building, which may indicate, indirectly, that the ''Pombalino'' masonry wall is more compact and, probably, stronger than the ''Gaioleiro'' masonry wall. The maximum stress obtained on the masonry was, in all tests, conditioned by the insufficient reaction of the upper part of the wall. Therefore, the corresponding stress in the masonry must be regarded as a lower limit of the masonry compressive strength.

Table 1 shows the results obtained on the double flat-jack tests in terms of maximum stress level ($\sigma_{m,max}$), the compressive strength estimated based on Lombillo et al. Refs. 19 and 25, and the secant Young's modulus at 1/3 of the masonry compressive strength $\left(E_{s(1/3\,f_c)}\right)$. The results presented in Table 1 were determined by considering A_{je} with the method based on the sheet of carbon paper, as proposed in Refs. 14 and 23. For these tests, A_{je} was, in average, 84% of the gross area of the flat-jack (A_j). Assuming $A_{je} = A_j$, the masonry Young's modulus would be, in average, 19% higher. Even though these variations may be debatable, the first approach is considered to be more realistic.

Table 2 summarizes the values of compressive strength and Young's modulus obtained in several research programs for rubble stone masonry walls. It is worth mention that the compressive strength estimated for the ''Pombalino'' buildings is close to the results obtained in similar flat-jack tests performed in Portugal on rubble stone masonry by Vicente.[29] In case of the ''Gaioleiro'' building, lower values were obtained, approximately 1/3 of the ones determined for the ''Pombalino'' building.

The Young's modulus obtained from the double flat-jack tests on the ''Pombalino'' building is two times the value obtained by Santos[26] in a shear-compression test performed on a ''Pombalino'' masonry wall. In case of the ''Gaioleiro'' building, tests G.1 and G.2 have similar results, but a much lower Young's modulus was obtained on G.3. This can derive from the fact that the masonry in this segment of wall had a higher percentage of mortar, smaller stones and few pieces of ceramic bricks. This fact highlights that, due to the irregular composition of this type of masonry walls (type of stones, dimension, and workmanship), there are important variations of the masonry mechanical properties within this type of buildings. The Young's modulus from G.1 and G.2 are comparable to the experimental results from Lopes and Azevedo,[27] obtained on a ''Gaioleiro'' building and from Milosevic et al.,[8] obtained on laboratory masonry specimens.

The values proposed by the Italian Code[2] for irregular stone masonry are between the values estimated for the ''Pombalino'' and ''Gaioleiro'' buildings, both in terms of compressive strength and Young's modulus. All in all, the masonry Young's modulus obtained on the ''Pombalino'' building is significantly higher than in ''Gaioleiro'' building, showing the differences between the mechanical behavior of the masonry used on the external walls of these buildings.

Table 2 Rubble stone masonry deformability properties in compression

Reference results for rubble stone masonry			f_c [MPa]	$E_{s(1/3f_c)}$ [GPa]
Shear-compression tests on rubble masonry and air lime mortar walls	Santos[26]		–	1.0
	Lopes and Azevedo[27]		–	0.66
Compression test on rubble masonry and air lime mortar specimens	Milošević et al.[8]		–	0.56
	Moreira et al.[28]		1.60	1.0
Irregular stone masonry	Italian Code[2]		1.00–1.80	0.69–1.05
	Andreini et al.[20]		0.80–1.20	0.40–0.80
Double flat-jack test on rubble masonry and air lime mortar (in situ)	Vicente[29]		0.87–1.76	2.08
	This work	"Pombalino" building	1.89	2.00
		"Gaioleiro" building	0.63	0.39

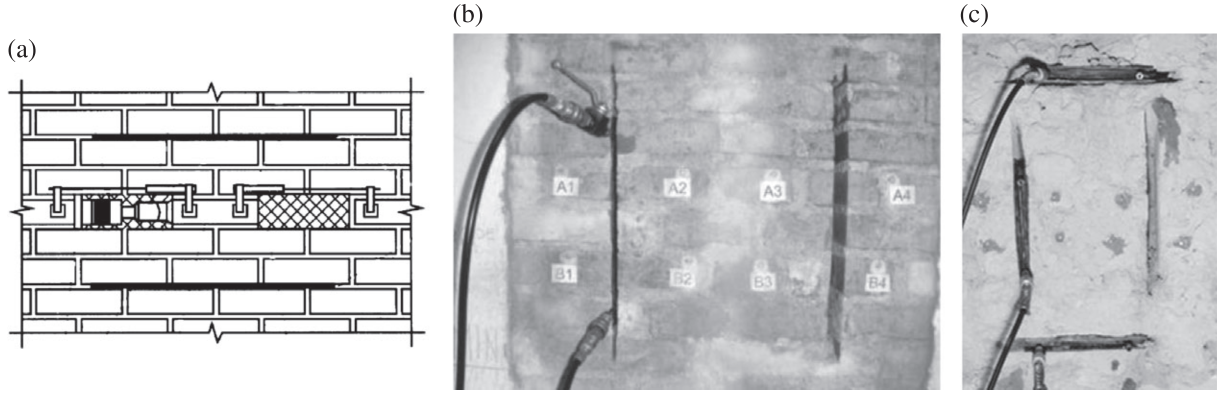


Figure 7 Shear flat-jack test setup: (a) ASTM and RILEM standards[9,10]; (b) Caliò[13]; (c) this work.

However, additional experimental in situ tests have to be conducted to generalize these conclusions.

Shear flat-jack tests

The shear flat-jack test aims to determine the masonry shear strength parameters: cohesion and friction coefficient. The test procedure described in ASTM and RILEM standards[9,10] is defined for brick masonry elements involving the test of only one brick unit (Fig. 7 (a)). A different procedure was suggested by Caliò[13] for the test of masonry specimens under shear load (Fig. 7 (b)). In this work, the procedure proposed by Caliò in Ref. 13 was first applied to test brick masonry walls and then adjusted to test rubble stone masonry walls (Fig. 7 (c)). In addition, a vertical compressive stress was applied to the test specimen by a set of horizontal flat-jacks.

In the flat-jack shear test, the masonry specimen is delimited by two vertical and two horizontal cuts. A flat-jack is placed in one vertical cut, while the other cut remains free for the specimen horizontal deformation. Two flat-jacks are placed on the horizontal cuts, and the pressure on the horizontal flat-jacks is increased and kept with a constant value (σ_v). The pressure on the vertical flat-jack is then gradually increased until the maximum reaction capacity of the masonry above and below the specimen is reached. The horizontal load applied by the vertical flat-jack to the masonry (F_H) is obtained from the flat-jack pressure (p), according to Eq. 3, where A_j is the gross area of the flat-jack and σ_m the averaged stress applied to the masonry by the vertical flat-jack.

$$F_H = p \times K_m \times K_a \times A_j = \sigma_m \times A_j \tag{3}$$

According to ASTM and RILEM standards,[9,10] the masonry shear strength (τ) is obtained from Eq. 4:

$$\tau = \frac{F_{H,max}}{A_s} \tag{4}$$

where $F_{H,max}$ is the maximum horizontal force resisted by the specimen and A_s is the area of the horizontal sliding surfaces (in case of tests on the whole thickness of the wall). Assuming a Mohr–Coulomb formulation, the masonry shear strength (τ), when submitted to a vertical compressive stress (σ_v), is given by Eq. 5:

$$\tau = \tau_0 + \mu \times \sigma_{\mathrm{v}} \tag{5}$$

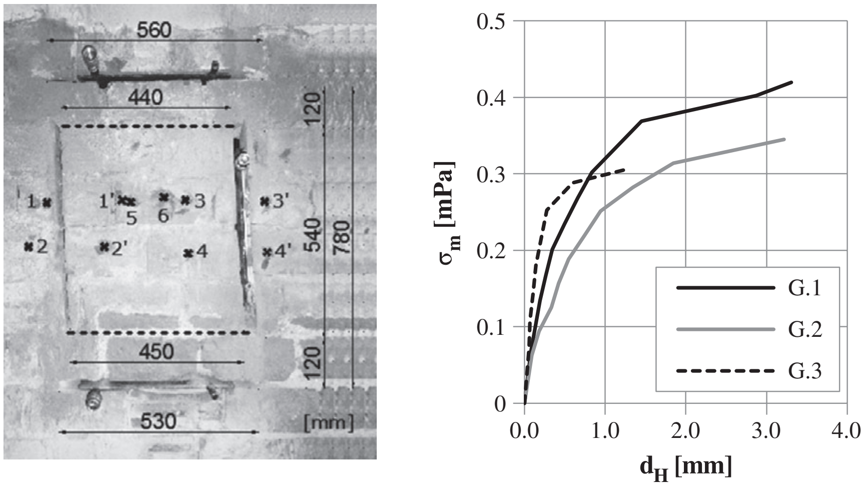


Figure 8 Shear flat-jack test setup and results on brick masonry.

where τ_0 is the masonry cohesion and μ the friction coefficient. As stated in the ASTM and RILEM standards,[9,10] these shear parameters have to be calculated from several shear tests with different vertical compressive stress levels by means of linear regression.

In what concerns the test setup and the dimension of the masonry specimen to be tested, it mainly depends on the size of the flat-jack, on the dimension of the vertical cuts and on the type of masonry wall.[13] The vertical cuts must be at a distance between A and 1.5A (A is the dimension of the flat-jack—Fig. 4) and a length between 500 and 550 mm.[13] In the present experimental work, the test site was limited by horizontal cuts placed between 100 and 150 mm apart from the vertical cuts in order to control the vertical stress on the specimen during the shear test (in some cases using two horizontal flat-jacks). Two horizontal pairs of reference points were attached aside both vertical cuts to monitor the horizontal displacement of the specimen. The points were positioned also to measure the deformation on the diagonal direction.

Table 3 Shear flat-jack test results on brick masonry

Tests	σ_V [MPa]	$\sigma_{m,max}$ [MPa]	$F_{H,max}$ [kN]	τ [MPa]
G.1	0.09	0.42	25.2	0.19
G.2	0	0.35	20.7	0.13
G.3	0	0.31	18.4	0.12

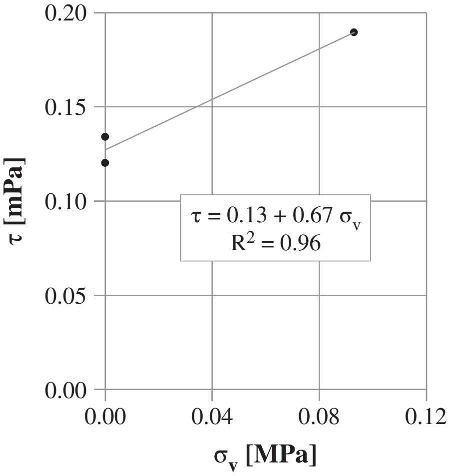


Figure 9 Relationship between shear strength and vertical compression stress.

Tests on brick masonry

Three shear flat-jacks tests were performed on two internal brick masonry walls from the Gaioleiro building (G.1, G.2, and G.3). The test setup is exemplified in Fig. 8 for test G.1. Reference points 1-1′ to 4-4′ are related with the control of horizontal deformation and 2′-6 and 4-5 with diagonal deformation.

In all cases, a horizontal cut was performed above and below the specimen to eliminate the vertical stress on the specimen. Only the test on position G.1 was carried out with a constant vertical level of stress, equal to 0.09 MPa (equivalent to the weight of 4.5 m of wall), imposed by two horizontal flat-jacks. The failure of the specimens occurred along two horizontal surfaces coincident with the mortar bed joints, as depicted on Fig. 8. The test results are summarized on Fig. 8 which displays the average horizontal displacement (d_H) for all specimens tested and Table 3 which presents the maximum values of stress/force imposed by the flat-jacks to the specimens.

Figure 9 depicts the relation between the shear strength (τ) and the vertical compressive stress

Table 4 Shear strength parameters for brick masonry

Reference results for brick masonry		τ_0 [MPa]	μ
Shear tests on solid brick masonry with lime mortar	Krzan et al.[30]	0.16–0.33	0.40 (assumed)
	Atkinson et al.[31]	0.13–0.21	0.64–0.70
Triplet tests on solid brick with cement mortar specimens	Zimmermann et al.[32]	0.03	0.64
		0.21	0.71
Triplet tests on hollow brick with cement mortar specimens	Gabor et al.[33]	0.48	0.83
Triplet tests on granite units with lime mortar specimens	Vasconcelos and Lourenco[34]	0.36	0.63
Shear flat-jack tests on hollow brick masonry (in situ)	This work*	0.13	0.67

*If $A_{je} = A_j$ is considered, cohesion τ_0 is equal to 0.15 MPa and μ is equal to 0.59.

applied to the tested specimens (σ_V) and the linear regression to the tests results (R^2 is the correlation coefficient of the linear regression). Based on this, it was obtained for the hollow brick masonry with air lime mortar 0.13 MPa for the cohesion (τ_0) and 0.67 for the friction coefficient (μ) with a correlation factor (R^2) of 0.96; moreover, it is important to state that this relation was determined with basis on only three tests and only in one case a vertical stress level was imposed to the specimen. For these tests, A_{je} was, in average, 71% of the gross area of the flat-jack (A_j). If A_{je} was considered to be equal to A_j, the shear strength parameters would result 0.15 MPa for the cohesion (τ_0) and 0.59 for the friction coefficient (μ) with a correlation factor (R^2) of 0.95.

More tests have to be carried out to support the evaluation of masonry' shear strength parameters. Comparing the tests results with others from experimental tests on brick masonry walls[30−34] presented in Table 4, it can be said that the masonry's cohesion and friction coefficient herein obtained are close to the results from Atkinson et al.[31] and Zimmermann et al.,[32] albeit both were obtained from tests on solid bricks.

Test on rubble stone masonry

In this experimental campaign, a total of six shear flat-jacks tests were carried out: three on the back façade wall of the ''Pombalino'' building (P.1, P.2, and P.3) and three on the side façade wall of the ''Gaioleiro'' building (G.1, G.2, and G.3). On the shear tests P.1, P.2, and G.3, a vertical state of stress was applied to the masonry specimen. As referred in section ''Double flat-jack tests'' due to the high thickness of these traditional masonry walls, tests were carried out in only part of the wall thickness.

Results from test P.1 are included in Fig. 10: (a) the test setup, (b) the specimen displacement during the test (reference points from 1-1′ to 4-4′ are related with horizontal deformation and 1′-4 and 2′-3 are related with diagonal deformation), and (c) the frontal cracks on the masonry at the end of the test. In this test, a vertical stress of 0.16 MPa (equivalent to weight of 8 m wall) was applied to the specimen.

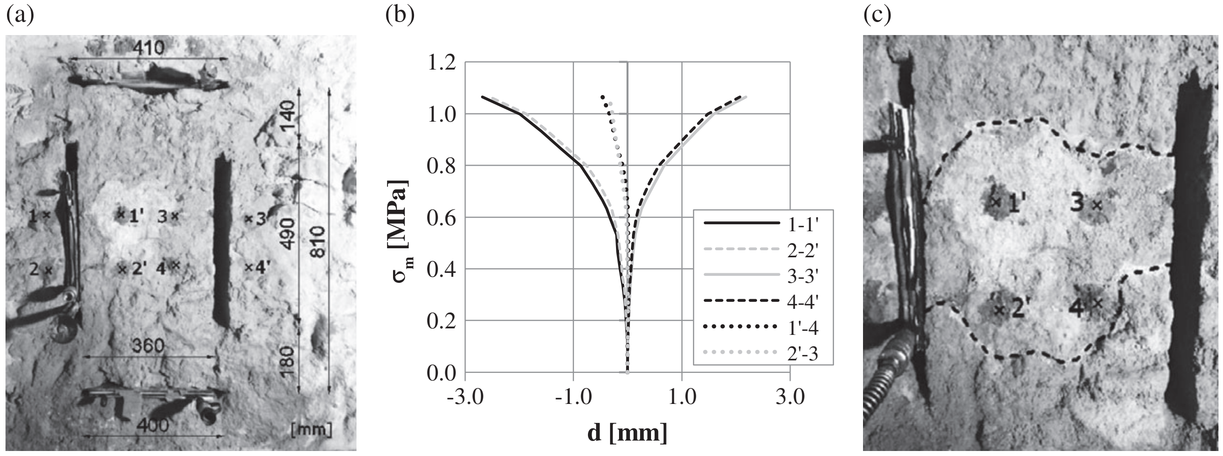
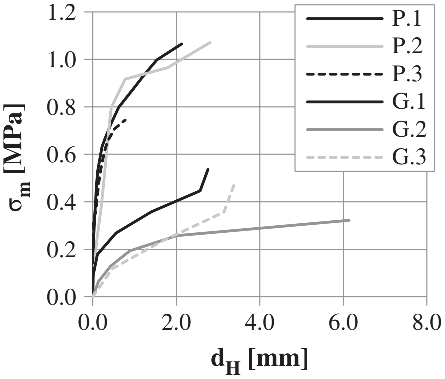


Figure 10 Shear test P.1 with a vertical stress of 0.16 MPa: (a) test setup; (b) deformation of the specimen during the test; and (c) frontal cracks on the masonry at the end of the test.



Tests	σ_v [MPa]	$\sigma_{m,max}$ [MPa]	$F_{H,max}$ [kN]
P.1	0.16	1.03	80.0
P.2	0.24	1.07	80.6
P.3	0	0.74	56.0
G.1	0	0.54	40.3
G.2	0	0.32	24.3
G.3	0.12	0.48	35.7

Figure 11 Shear flat-jack test results on rubble stone masonry.

Referring to Fig. 10 (b), it can be noticed that the displacement between the reference points 1-1′ and 2-2′, next to the vertical flat-jack, is slightly higher than between points 3-3′ and 4-4′ placed next to the vertical cut that accommodates the deformation of the specimen. The higher value of displacement attained in the first case is related to the deformation of the flat-jack and of the reaction wall. The maximum horizontal stress in the masonry was equal to 1.03 MPa for an average 2.13 mm horizontal displacement, which emphasizes the sliding of the specimen. In fact, in the end of the test, it was possible to identify two sliding cracks along the specimen mortar joints identified in Fig. 10 (c).

It is also visible from Fig. 10 (b) that after achieving a horizontal stress of 0.7 MPa, there is some diagonal deformation of the specimen. The control of the specimen (diagonal) deformation is necessary to confirm that the horizontal stress is uniformly applied and causing the sliding of the specimen and not its rotation. This verification is particularly important in case of the test in rubble stone masonry due to the irregularity of the wall and distribution of the stress in the specimen.

Figure 11 presents the test results in terms of the average horizontal displacement (d_H) for all specimens tested and the maximum values of stress/force imposed by the flat-jacks to the specimens. At current stage of the shear flat-jack tests on rubble stone masonry, it is important to make a few comments to the tests performed that justify some of the results obtained.

In case of test P.2, the shear failure occurred for a horizontal stress on masonry of 1.07 MPa, when the specimen was under a vertical stress of 0.24 MPa (equivalent to the 12 m of wall). However, the results from this test may not be completely accurate as the masonry specimen was previously loaded (a previous shear test was aborted due to a rupture on the flat-jack). In addition, during the test, the masonry against which the vertical flat-jack reacted suffered a local crush (Fig. 12 (a)), which conditioned the

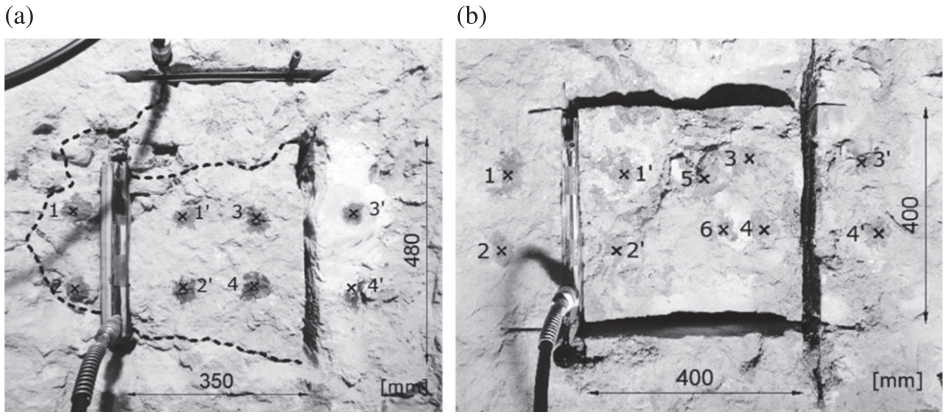


Figure 12 Shear tests: (a) frontal cracks on the masonry at the end of the test P.2; (b) setup of test P.3.

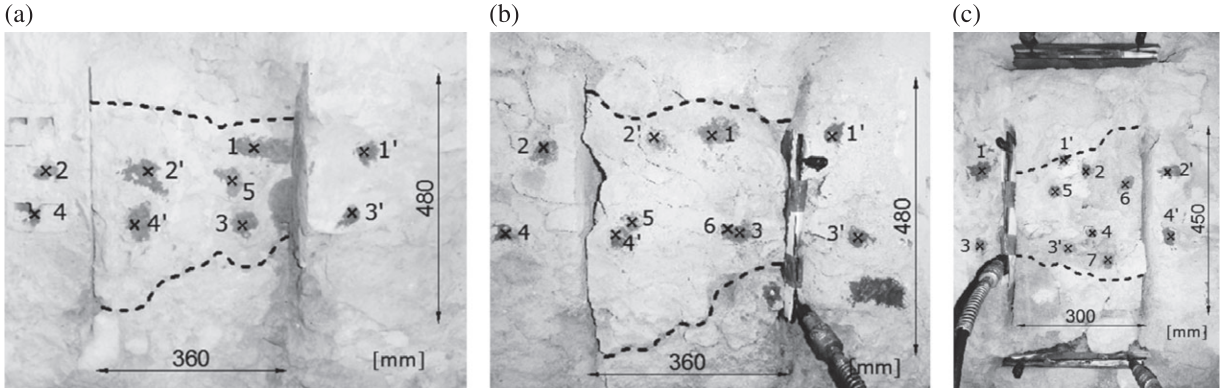


Figure 13 Frontal cracks on the masonry at the end of test: (a) G.1; (b) G.2; and (c) G.3.

pressurization of the flat-jack and induced the end of the test. This premature failure may explain the fact that the maximum horizontal force applied on the flat-jack is only slightly superior to the one applied on test position P.1, in which a lower vertical stress was imposed (Fig. 11).

The shear test P.3 was performed after the double flat-jack test described on section ''Double flat-jack tests'' hence, the specimen size (Fig. 12 (b)) differs from the pre-defined shear test setup (Fig. 10 (a)). In this specific case, two vertical cuts were made adjacent to the already existing horizontal cuts, defining a specimen 400 mm high and 400 mm large, connected to the masonry wall only on the back surface. Because of the boundary conditions, it was impossible to observe the cracked surface of the wall (frontal and lateral). The test was stopped with horizontal shear stress on masonry of 0.74 MPa, as the support was not offering enough reaction to continue with the test. This result should be considered with some reservations due to the differences on the test configuration.

Figure 13 depicts the tests configuration, position of the reference points and the frontal cracks on the masonry specimen at the end of the tests on the ''Gaioleiro'' building. The shear tests G.1 and G.2 were performed without imposing a vertical state of stress, being the masonry specimen vertically unloaded. Test G.3 was carried with a constant vertical state of stress of 0.12 MPa. It was first planned to perform one more test imposing a vertical state of stress on the ''Gaioleiro'' building; however, later it was decided not to because the horizontal displacement in test G.3 was greater than the obtained on the ''Pombalino'' building—tests P.1 and P.2—where higher vertical stresses were applied (Fig. 11). It was decided not to perform a test in the ''Gaioleiro'' building with higher vertical stress in order to limit the damage on the building. Contrary to the first expectations, with or without an imposed vertical stress to the specimen, the test results in the ''Gaioleiro'' building in terms of horizontal stress and force are close and it is not possible to define a strength pattern (Fig. 11). This fact is in part consequence of the heterogeneity of the material and of the distribution of stresses in the wall.

The results obtained show the need of performing more shear tests in rubble stone masonry walls with similar boundary conditions but also the need of testing the entire thickness of the wall, whenever is possible (e.g. laboratory tests with flat-jack tests on masonry specimens with representative thickness) in order to calibrate the test procedure and to get satisfactory correlating factors. In fact, the definition of the specimen sliding surfaces (A_s – Eq. 4) is very ambiguous due to the high heterogeneity of the masonry. For instance, at the end of the test, it was possible to identify sliding cracks on the masonry specimen (depicted in Figs. 10, 12, and 13), but it was impossible to know how these frontal cracks propagate along the specimen thickness. Moreover, the performed in situ tests mobilized only part of the wall thickness and the boundary conditions (connection of the specimen to the wall) have significant influence on the test results.

In order to overcome these uncertainties, Caliò[13] carried out two shear flat-jack tests on a brick masonry wall to understand the influence of the vertical surface that connects the back of the specimen to the rest of the wall. In one case, the vertical cuts, which define the masonry specimen, crossed the whole thickness of the wall, and, on the other case, the cuts were limited to part of the wall thickness. Based on the results obtained, it was proposed to determine the shear

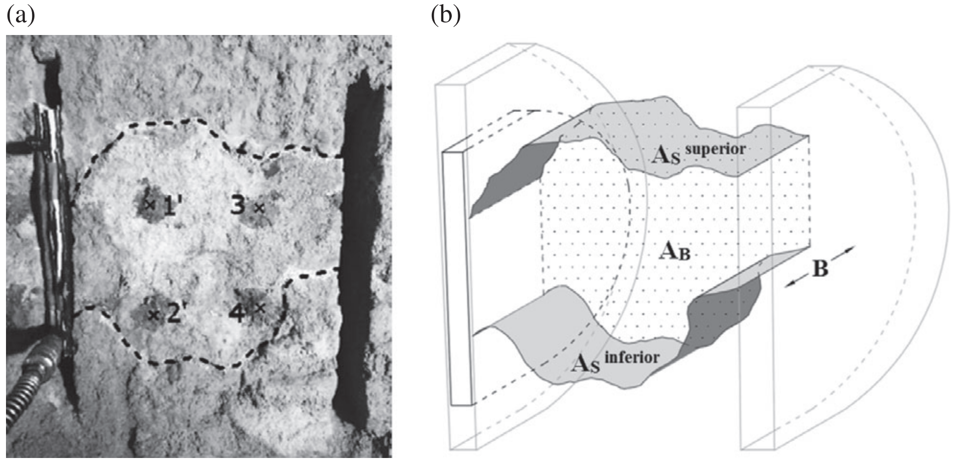


Figure 14 Shear test P.1: (a) frontal cracks on the masonry; and (b) sliding surfaces hypothesis.

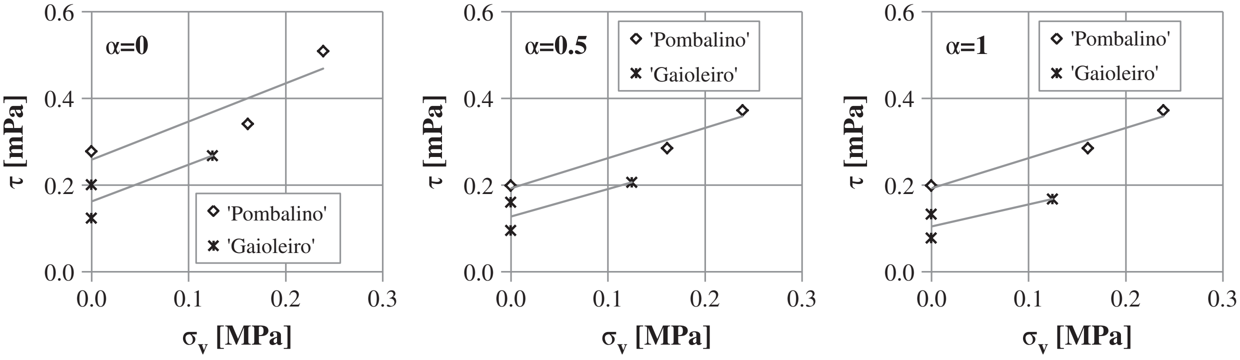


Figure 15 Relationship between shear strength and vertical compression stress.

strength (τ) according to Eq. 6 where the influence of specimen back surface (A_B in Fig. 14 (b)) is function of a coefficient α. In addition, it was concluded in that $\alpha = 0.5$ was a good correlation factor between the test results for that case.

$$\tau = \frac{F_{H,max}}{A_s + \alpha A_B} \qquad (6)$$

Nevertheless, while testing rubble stone masonry specimens, the definition of the specimen sliding surfaces is more uncertain than in the case of brick masonry specimens. Taking advantage of the results from this experimental campaign, the specimen's horizontal sliding surfaces (A_s) were defined based on the frontal cracks visible on the masonry specimen and assuming that these cracks propagate along the specimen thickness, which is equal to the cuts depth (and equal to the flat-jack dimension B), as defined in Fig. 14. The specimen back sliding surface (A_B) was considered coincident with the area between the frontal cracks.

Based on this assumptions, Fig. 15 shows the relation between the shear strength (τ) and the vertical compression stress (σ_v) for all tests, considering, in addition, different values for α in order to present different limit conditions: (1) $\alpha = 0$, the case in which the influence of the specimen back surface is neglected; (2) $\alpha = 0.5$, the calibration factor determined by Caliò[13] for brick masonry, but that may also be considered in case of rubble stone masonry, or in other types of masonry, due to the interconnection of the masonry units on the wall thickness; and (3) $\alpha = 1$, the case in the which the masonry specimen slides over the back surface. Considering all these cases, Table 5 shows the results from the linear regression to the tests performed on the ''Pombalino'' building and on the ''Gaioleiro'' building determined by considering A_{je} based on the sheet of carbon paper, as proposed in Refs. 14 and 23.

From the tests performed on the ''Pombalino'' building, it can be estimated that the rubble stone

Table 5 Shear strength parameters on rubble stone masonry

	$\alpha = 0$			$\alpha = 0.5$			$\alpha = 1$		
Tests	τ_0 [MPa]	μ	R^2	τ_0 [MPa]	μ	R^2	τ_0 [MPa]	μ	R^2
"Pombalino" building*	0.26	0.88	0.81	0.19	0.70	0.96	0.15	0.58	0.99
"Gaioleiro" building†	0.16	0.85	0.71	0.13	0.63	0.66	0.11	0.50	0.63

*If $A_{je} = A_j$ is considered, cohesion τ_0 is 66% higher and μ is 12% lower.

†If $A_{je} = A_j$ is considered, cohesion τ_0 is 28% higher and μ is 43% lower.

Table 6 Shear strength parameters for rubble stone masonry

Reference results for rubble stone masonry			τ_0 [MPa]	μ
Shear-compression tests on rubble masonry and air lime mortar	Chiostrini et al.[35]		0.11	0.23
			0.05	0.35
	Vasconselos and Lourenco[36]		0.11	0.19
Triplet tests on rubble stone masonry with air lime mortar specimens	Milosevic et al.[8]		0.08	0.56
Shear flat-jack tests on rubble stone masonry with air lime mortar (in situ)	This work	"Pombalino" building	0.15	0.58
			0.26	0.88
		"Gaioleiro" building	0.11	0.50
			0.16	0.85

masonry is characterized by cohesion between 0.15 and 0.26 MPa and friction coefficient between 0.58 and 0.88. However, taking the condition $A_{je} = A_j$, it would result that cohesion τ_0 is 66% higher and μ is 12% lower (this variation is justified as in these tests A_{je} is 62% of A_j). In case of the "Gaioleiro" building, the obtained rubble stone masonry cohesion is between 0.11 and 0.16 MPa, and the friction coefficient is between 0.50 and 0.85. Following the condition $A_{je} = A_j$, cohesion τ_0 is 28% higher and μ is 43% lower (here A_{je} is 82% of A_j).

The friction coefficient determined in both experimental campaigns is significantly higher than the results considered in the literature (Table 6). As far as masonry cohesion is concerned, a lower value was estimated with the tests on the "Gaioleiro" building than on the "Pombalino" building. This result was expected, taking into account the quality of the construction of these typologies of buildings. In addition, the tests on the "Gaioleiro" building were made on the side external walls, while on the "Pombalino" building they were made on a façade wall, where usually the masonry has better quality.

Comparing the obtained masonry cohesion with reference values for rubble stone masonry (Table 6), the results herein presented are much higher. Nevertheless, the masonry shear strength parameters estimated based on the hypothesis where both the horizontal and back vertical surfaces are accounted for the determination of the shear strength ($\alpha = 1$) are closer to the reference values. These preliminary results show the possibility of making in situ shear flat-jack tests on rubble stone masonry. However, the results also show the need of carrying additional tests with similar boundary conditions and tests in which the entire thickness of the wall is tested in order to calibrate the test procedure and to determine correlating factors.

Final Comments

An experimental campaign with flat-jacks was carried out in order to assess the mechanical properties of old masonry buildings in the historical center of Lisbon. The campaign included tests on external rubble stone masonry walls from a "Pombalino" building and a "Gaioleiro" building and on the internal brick masonry walls from the "Gaioleiro" building. The tests performed aimed at the evaluation of the masonry deformability properties in compression and the shear strength parameters.

From the double flat-jack tests, it was possible to estimate the masonry Young's modulus in compression. The test results on rubble stone masonry walls are comparable with experimental results obtained on similar buildings. The masonry Young's modulus on the "Pombalino" building is significantly higher than on the "Gaioleiro" building.

The evaluation of the shear parameters of the masonry walls was done according to a new testing technique with flat-jacks that requires calibration which is one of the main objectives of this work. The masonry shear strength parameters estimated for brick masonry walls are coherent with other reference experimental tests, but significant deviations were obtained on the tests with rubble stone masonry walls. This fact is mainly related to the boundary conditions of the specimen and the high heterogeneity of the material. Further studies have to be conducted to define calibration parameters, the shear failure surfaces and to quantify the influence of the back surface of the specimen. Nevertheless, it is important to emphasize that the shear flat-jack testing technique is certainly less invasive than the traditional shear tests and therefore, after disclosing the above mentioned uncertainties, it may be a powerful tool for the in situ estimation of the masonry shear strength. In fact, a good agreement with results from other authors was obtained for brick masonry walls, and, in this case, there were no uncertainties related with the definition of the sliding areas as the tests affected the whole thickness of the wall.

All in all, it can be concluded the tests results are highly dependent on the composition of the wall (type of stones, dimension, and workmanship) and on the site conditions (boundary conditions and existing stresses on the structure), which may explain the variability of results. Another important issue is the difference between the mechanical properties of the rubble stone masonry from the ''Pombalino'' building and the lower results obtained on the ''Gaioleiro'' building, which emphasizes the differences between the mechanical behavior of the masonry used in these building typologies. However, additional experimental in situ tests have to be conducted to confront and support the obtained values.

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