Experimental Tests on Rubble Masonry Specimens – Diagonal Compression, Triplet and Compression Tests

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SUMMARY
Aiming to characterize the seismic behavior of old masonry buildings in Lisbon some experimental tests were performed within the scope of a Portuguese national research project, the called Seismic Vulnerability of Old Masonry Buildings (www.severes.org). In this paper the diagonal compression tests, triplet tests and compression tests performed are described and the results obtained presented. Depending on the type of tests carried out, different dimensions of masonry specimens were adopted and, for all of the tests, two different types of mortar, hydraulic and air lime mortar were considered. Based on the results obtained it was possible to assess different masonry characteristics, namely: i) shear strength of masonry via diagonal compression test, ii) initial shear strength and coefficient of friction by performing triplet test, and iii) compressive strength and Young modulus of elasticity through compression test. Moreover, for all tests, load-displacement diagrams and expected collapse mechanism are presented.

Keywords: masonry buildings, experimental tests, seismic vulnerability

1. INTRODUCTION

Very few experimental tests have been performed on structural components of the typical Lisbon old masonry constructions, in particular tests on Pombalino's buildings [Cardoso et al., 2005]. The external walls are mostly of rubble lime stone masonry and are similar to the stone masonry walls used in the Gaioleiro [Mendes & Lourenço, 2010] and Placa [Simões & Bento, 2012] typologies that also exist in Lisbon.

The aim of this project is to characterize the seismic behavior of traditional rubble stone masonry walls, including experimental tests for characterization of the shear strength of rubble stone masonry, which is a relevant parameter for the evaluation of seismic behavior of masonry buildings. These tests involve diagonal compression, triplet and compression test.

In order to evaluate the initial shear strength (cohesion), diagonal compression tests were performed on four big rubble masonry specimens, two with hydraulic (W1 and W4) and two with air lime mortar (W2 and W3). The test setup and procedure for diagonal compression test followed the ASTM E519-02 standard [ASTM, 2002] and what is suggested in recent research works [Corradi et al., 2003, Brignola et al., 2008].

Other nine wall prototypes were subjected to triplet tests (in order to evaluate initial shear strength, cohesion and coefficient of friction) following the major lines of EN 1052-3 standard [BS EN, 2002] and of the other works [Prota et al., 2006, Oliveira et al., 2002], on brick masonry.

Two smaller specimens were built to perform compression test and tested in order to assess the compressive strength and Young modulus following the standard [BS EN, 1998].

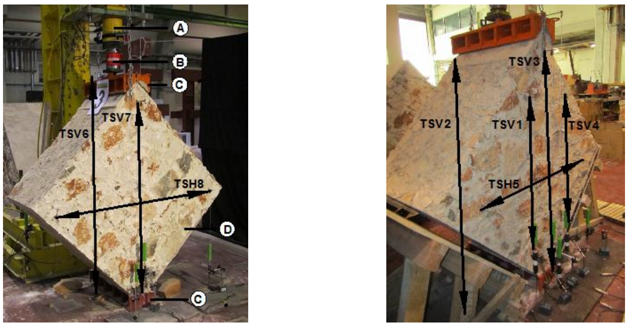
2. TESTS DESCRIPTION

These tests involved the use of panels of three different dimensions, namely 120cm × 120cm × 70 cm for diagonal compression tests, 60cm × 40cm × 40cm for triplet tests and 40cm × 40cm × 40cm for

compression tests. All specimens were built in laboratory, especially for this experimental campaign using traditional techniques and materials. The specimens were tested 8 months after construction to ensure the hardness of the mortars.
The panels are identified by a three index code, in which the first index indicates the type of test (W – diagonal compression, T – triplet, C – compression test); the second index is the identification number of the panel, while the third index indicates the type of mortar (H – hydraulic and A – air lime mortar).

2.1 Diagonal compression tests

Diagonal compression tests were performed on four square masonry specimens in order to obtain the diagonal tensile (shear) strength and the shear elastic modulus. These specimens were placed in the test rig with a diagonal axis in the vertical direction and loaded in compression along this direction.
The test setup is composed of two steel loading shoes, which were fixed on the two opposite corners on the panels. The load is applied to the panel by an hydraulic jack on the steel loading shoes positioned on top of the specimen and transmitted to the other shoe which was placed at the bottom of the specimen, as can be seen in Fig. 2.1(a).



(a) Specimen front side (b) Specimen bask side

Figure 2.1. Test setup and Position of transducers for diagonal compression test
A – Hydraulic Jack; B – Load cell; C – Loading shoes; D – Masonry specimens

The shortening of the vertical diagonal and the lengthening of the horizontal diagonal under load were measured with linear voltage displacement transducers (named TSV and TSH, respectively) placed on both sides of the specimens. Nine transducers were placed on each specimen (Fig.2.1), namely five transducers on one specimen's side, three transducers on the other side and one transducer to measure vertical displacement under the hydraulic jack. In order to avoid any damage of the instrumentation, the transducers were removed when the behavior of the specimen started to indicate that it could be close to failure. After that the load was continuously applied until the collapse of the specimen.
According to ASTM E519-02 [ASTM, 2002] standard, the shear stress τ and shear elastic modulus G for masonry specimens can be evaluated from the experimental test results assuming that the Mohr's circle is centered in the origin of the Cartesian system of axis and the value of the shear stress τ is equal to the principal tensile stress f_t. The shear stress τ is obtained by Eqn. 2.1:

$$\tau = \frac{0.707 \times P}{A_n} \qquad (2.1)$$

where P is the load applied by the jack and A_n is the net area of the specimen, calculated as follows:

$$A_n = \left(\frac{w+h}{2}\right) \times t \times n \qquad (2.2)$$

where w is the specimen width, h is the specimen height, t is the thickness of the specimen and n is the percentage of the unit's gross area that is solid, expressed as a decimal. In the present work the value n =1 was adopted.

Consequently, the initial shear strength τ_0 (f_{v0} according to Eurocode 6 [EC 6, 1995]) and the tensile strength are defined as:

$$\tau_0 = f_t = \frac{0.707 \times P_{\max}}{A_n} \tag{2.3}$$

where $P_{\max}$ is the maximum load applied by the jack.

2.2 Triplet test

Triplet tests were conducted on nine masonry specimens in order to define the initial shear strength of horizontal bed joints in rubble stone masonry specimens. It worth to refer that, specimens were built with three stone layers and subdivided into two groups depending on the type of mortar used for their construction (first group with hydraulic mortar and second group with air lime mortar).
All specimens were subjected to a vertical pre-compression load, following the EN 1052-3 standard [BS EN, 2002]. Four different vertical stress levels were adopted (0.1 MPa, 0.2 MPa , 0.3 MPa and 0.5 MPa) and were kept constant, as much as possible, during the tests. The specimens with hydraulic mortar were subdivided into three series: series 1 for a pre-compression level of 0.1 MPa (panels T1 and T2), series 2 for a pre-compression level of 0.2 MPa (panel T5) and series 3 for a pre-compression level of 0.3 MPa (panels T3 and T4). Correspondingly, the group of specimens with air lime mortar was subdivided into three series: series 4 for a pre-compression level of 0.1 MPa (panels T6 and T7), series 5 for a pre-compression level of 0.3 MPa (panel T8) and series 6 for a pre-compression level of 0.5 MPa (panel T9).
The setup of triplet test consists of two supports which were used to restrain horizontal movements of the top and bottom stone layers, covering its full height, as depicted in Fig.2.2. The horizontal and vertical loading system consisted of two independent 300 kN capacity hydraulic jacks, namely a jack, that applied the horizontal force at the middle layer and another jack, applying a vertical force at the top of the specimen. To obtain a uniform state of stress, the vertical load was indirectly applied to the specimen through a steel beam to spread the vertical force.

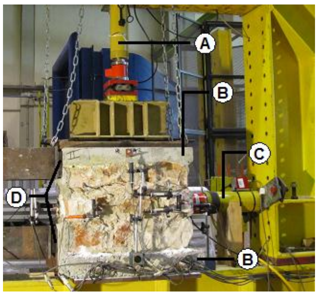


Figure 2.2. Triplet test setup
A – Compressive load; B – Concrete slab; C – Shear load; D – Rigid supports to restrain movements

Constant vertical compressive load was applied first, by the vertical hydraulic jack and after the horizontal hydraulic jack was used to apply an increasing horizontal load, till the specimen's collapse. It is worth to emphasize that in all tests the vertical load was kept (approximately) constant during the complete test.
The displacements of the specimens were recorded with thirteen linear voltage displacement transducers (LVDTs) placed on four faces of the specimen. Six transducers measured the horizontal displacements on the front and back faces and two transducers were placed on the front and back faces to measure the vertical displacements. On the specimen face where the horizontal load is applied it was placed one transducer at the horizontal actuator and two transducers to measure the horizontal displacements. On the opposite face two other horizontal transducers were placed.
The shear strength τ of masonry under moderate normal stresses is given by the Coulomb criterion [Vasconcelos, 2005, Hamid 1980a)b) & Drysdale, Atkinson et al., 1989, Riddington & Ghazali, 1990]:

$$\tau = \tau_0 + \mu \times \sigma \qquad (2.4)$$

where μ and σ stand for coefficient of friction and vertical stress, respectively. The results of the several triplet tests performed with different σ values were used to define τ_0 and μ by means of linear regression.

2.3 Compression Test

The major goal of the compression test was to determine the compressive strength and Young modulus of the masonry under compression. The tests were performed on two masonry specimens who were centered in the testing machine with the top and bottom width in full contact with the jack plate and were loaded uniformly in compression. The tests were performed with a hydraulic jack with a maximum force of 3000 kN, and two LVDT's were placed on each wall (to measure vertical displacement at each side of the specimen).

3. TESTS RESULTS

3.1 Diagonal compression tests

3.1.1 Failure modes

In this experimental campaign all specimens showed a similar failure pattern. Namely, in all walls the main crack was developed in the middle, propagated towards the top and bottom corner, passing only through the mortar without damaging the stones and dividing the specimens in two parts, almost symmetrically. In Fig. 3.3 one specimen with hydraulic mortar (W4) and one with air lime mortar (W2) can be seen after the tests.

(a) (b)

Figure 3.3. Main crack at the middle of the specimens: (a) specimen W4 and (b) specimen W3

On the other side, the specimens showed different behavior after the collapse, despite brittle nature of the collapse of all specimens. The specimens with air lime mortar disintegrated after collapse, while the specimens with hydraulic mortar had two broken parts which remained in one piece, as in shown in Fig. 3.4.

(a) (b)

Figure 3.4. Masonry specimens after its collapse: (a) specimen W4; (b) specimen W3

3.1.2 Masonry specimens based on hydraulic lime mortar

In Fig. 3.5 the force-vertical displacement diagram is represented (where vertical displacement represents average values of the measurements recorded using LVDTs 3 and 7), for the specimens which were based on hydraulic lime mortar. As in shown in this diagram, the maximum load for specimen W1 was 372 kN, with a vertical shortening of 1.55 mm (Point 1). In this case the collapse of specimen occurred with a load of 268 kN and vertical shortening of 5.29 mm (Point 2). In the case of specimen W4 the point of the collapse was the point with the maximum load applied, and corresponds to a load of 306 kN and a vertical displacement of 3.47 mm (Point 3).

It is important to mention that the specimens W2, W3 and W4 were built with diagonal layers (45º), whereas the specimen W1 was built with horizontal stone layers, which can be the mean reason for apparent "ductile" behavior of this specimen.

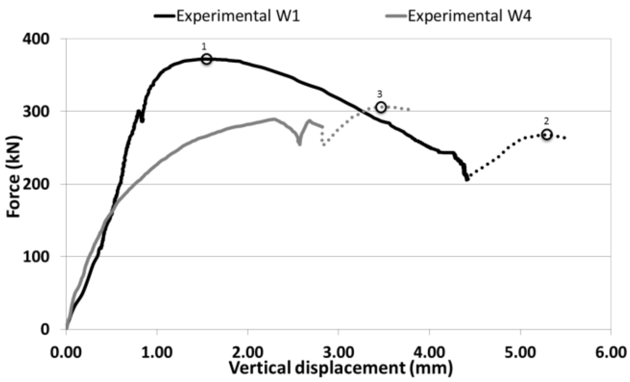


Figure 3.5. Specimens W1 and W4: Force vs. Vertical displacement (Note: vertical displacement measured at the top of the specimens)

As already mentioned, for safety reason, all transducers (except the transducer that was placed under the hydraulic jack) were removed before the end of test. In order to define the complete behavior of the walls, the dotted parts of the curves in Fig. 3.5 and Fig. 3.6 (which is shown below) were obtained by interpolation using the measurement of the transducers under the hydraulic jack.

3.1.3 Masonry specimens based on air lime mortar

As can be seen, masonry specimens built with air lime mortar showed much lower strength and deformation capacity than the specimens based on hydraulic mortar. As in presented in Fig. 3.6 collapse load for specimen W2 was 29 kN, with a vertical shortening of 1.58 mm (Point 1), and for specimen W3 the ultimate load was 28 kN, with a vertical displacement of 1.52 mm (Point 2), where vertical displacement represents average values of the measurement recorded using LVDTs 3 and 7.

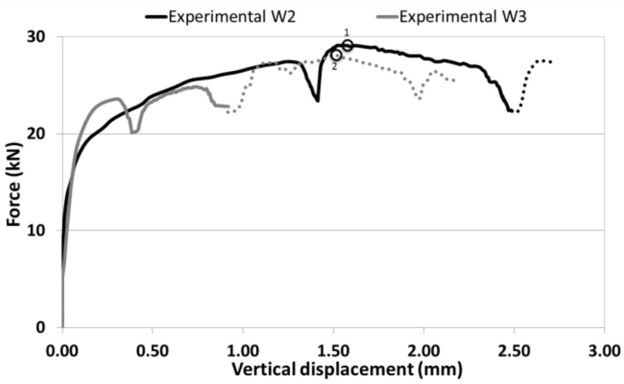


Figure 3.6. Specimens W2 and W3: Force vs. Vertical displacement (Note: vertical displacement measured at the top of the specimens)

All experimental results for diagonal compression tests are given in Table 3.1.

Table 3.1. Results of Diagonal Compression Tests

Masonry typology	**Masonry Specimen**	P_{max} **[kN]**	$\tau_0 = f_t$ **[MPa]**	**G [MPa]**
Rubble Stone Masonry Specimens	W1	372	0.313	389.3
	W2	29	0.024	57.9
	W3	28	0.024	92.5
	W4	306	0.258	252.0

3.1.4 Discussion of the results

The differences in results between specimens W1 and W4, which were built with different stone arrangement, can be noticed. That outcome and the similarity of results of specimens W2 and W3, built with the same stone arrangement, indicates that the stone arrangement has influence on strength and deformation capacities of the rubble stone masonry. However, the influence of stone arrangements is not as significant as the influence of the type of mortar, which is very high, namely specimens with hydraulic lime mortar showed shear strength about 10 times greater than the shear strength of the specimens built with air lime mortar. The fact that the cracks propagated through the joints without damaging the stones can explain the big influence of the mortar resistance on the walls shear strength.
Furthermore, the obtained values for shear elastic modulus G were measured in the elastic regime (1/3 of the maximum load) and the results also vary depending on the type of mortar (Table 2). In this case the values also present a big variation between the specimens built with the same type of mortar. The variation of shear modulus (G) for air lime mortar specimens is about 38% and 35% for hydraulic lime mortar specimens. This variation can be explained by the fact that the shear modulus is evaluated on the undamaged stage, with small displacements, where measurement errors may have an important influence. The variation of the shear modulus G between specimens with hydraulic lime mortar can also be explained by the different stone arrangement adopted (W1 with horizontal and W4 with diagonal layers).

3.2 Triplet tests

3.2.1 Failure modes

As already referred, nine masonry specimens were built for triplet tests. Five masonry specimens based on hydraulic mortar, whereas the remaining four specimens were based on air lime mortar. The specimens were built with three stone layers, which lead to a shear collapse mode by sliding of the medium layer. All specimens followed the expected failure pattern, which is represented in Fig. 3.7.

(a) (b)

Figure 3.7. Collapse of masonry specimens: (a) specimen T1 and (b) specimen T7

3.2.2 Masonry specimens based on hydraulic lime mortar

For specimens built with hydraulic mortar (series 1, 2, 3) the "horizontal force – horizontal displacement diagram" (displacement measured with the transducer placed on the hydraulic actuator) is shown in Fig. 3.8. As can be notice, for specimens tested with a pre-compression of 0.1 MPa, the ultimate load were 126 kN with horizontal displacement of 5.56 mm in specimen T1 and 188 kN with horizontal displacement of 6.50 mm in specimen T2. The ultimate load for specimen T5 with a compression of 0.2 MPa, was 213 kN (horizontal displacement of 6.09 mm). Furthermore, two more specimens, T3 and T4, were tested with a 0.3 MPa pre-compression level and the collapse loads were respectively, 267 kN (horizontal displacement of 5.95 mm) and 279 kN (horizontal displacement of 8.42 mm). As it was expected, higher pre-compression levels produced higher shear resistances.

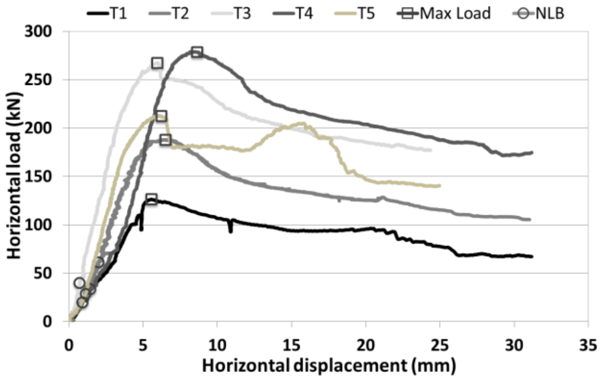


Figure 3.8. Specimens T1, T2, T3, T4 and T5: Horizontal load vs. Horizontal displacement (Note: Max load – maximum load; NLB-end of linear behaviour)

It should be mentioned that in Fig. 3.8 and Fig. 3.9 (shown below), the points where the linear behavior ends and the points of maximum force are marked.

3.2.3 Masonry specimens based on air lime mortar

In Fig. 3.9 the experimental results on specimens built with air lime mortar (series 4, 5, 6) can be seen. As shown in the "horizontal load – horizontal displacement diagram" (displacement measured with the transducer placed on the horizontal actuator), the ultimate load for specimens tested with a pre-compression of 0.1 MPa, were 64 kN with horizontal displacement of 13.10 mm in specimen T6 and 56 kN with horizontal displacement of 5.57 mm in specimen T7. For specimens T8, which was tested under compression of 0.3 MPa the collapse load was 139 kN with horizontal displacement of 8.23 mm. The last specimen, T9, tested with a compression of 0.5 MPa, an ultimate load of 161 kN can be noticed (horizontal displacement of 13.75 mm). Also, as in case of hydraulic mortar specimens, higher pre-compression levels produced higher shear maximum loads.

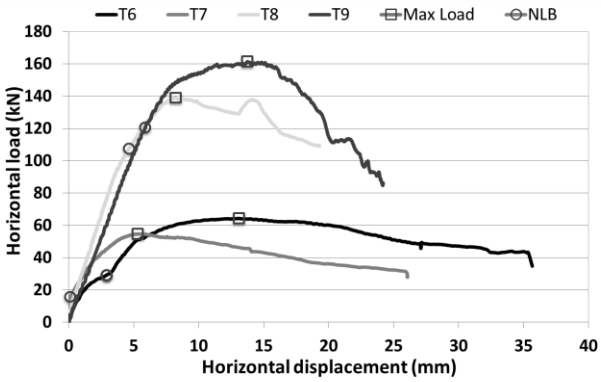


Figure 3.9. Specimens T6, T7, T8 and T9: Horizontal load vs. Horizontal displacement (Note: Max load – maximum load; NLB-end of linear behaviour)

In Table 3.2 the values of shear strength of the panels can be seen.

Table 3.2. Results of Triplet Tests

Series	Panel	Type of mortar	Precompressive stress σ_0 [MPa]	Vertical force F_v [kN]	Maximum horizontal force [kN]	Shear strength τ_0 [MPa]	Average shear strength [MPa]
Series 1	T1 T2	Hydraulic	0.1	24	126 188	0.26 0.39	0.33
Series 2	T5	Hydraulic	0.2	48	213	0.44	0.44
Series 3	T3 T4	Hydraulic	0.3	72	267 279	0.56 0.58	0.57
Series 4	T6 T7	Air lime	0.1	24	64 56	0.134 0.120	0.13
Series 5	T8	Air lime	0.3	72	139	0.29	0.29
Series 6	T9	Air lime	0.5	120	161	0.34	0.34

3.2.4 Discussion of the results

Fig. 3.10 shows the relation between the normal pre compression stress and the shear strength for all tests and two straight lines, one for each type of mortar specimens, evaluated by linear regression. The correlation coefficient R^2 of the linear regression is 0.8735 for the hydraulic mortar specimens and 0.9341 for air lime mortar specimens, which indicates good correlations in both cases. The linear regression indicates for hydraulic mortar specimens initial shear strength or cohesion τ_0 of 0.20 MPa and a coefficient of friction μ equal to 1.23. For air lime mortar specimens the obtained values for cohesion (τ_0) and coefficient of friction (μ) were 0.08 MPa and 0.56, respectively. Furthermore, according to the EN 1052-3 standard [BS EN, 2002], the characteristic values for cohesion and for the coefficient of friction are about 80% of the experimental values. Thus, the characteristic value for cohesion τ_{k0} for hydraulic mortar specimens is 0.16 MPa, whereas for air lime mortar specimens are 0.07 MPa. The characteristic value for the coefficient of friction μ_k is 0.98 for hydraulic mortar specimens and 0.45 for air lime mortar specimens.

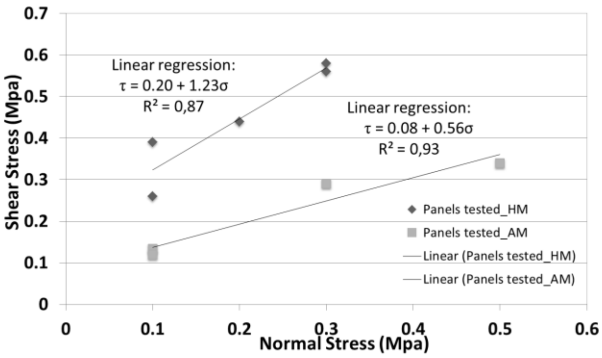


Figure 3.10. Relation between shear strength and normal stress for hydraulic and air lime mortar

Similarly to the diagonal compression tests, in the triplet tests the specimens based on hydraulic mortar presented much higher shear strength as the specimens built with air lime mortar (Fig. 3.10). In the case of triplet tests the specimens collapse also occurred without major stone crushing and the mortar composition had big influence in the sliding resistance of the joints.

3.3 Compression tests

Compression tests were performed on two masonry specimens built with hydraulic mortar (C1) and with air lime mortar (C2). As can be seen in Fig. 3.11 for the specimen C1 the ultimate compressive load was 1282 kN, with vertical displacement of 1.53 mm, whereas for the specimen C2 the ultimate load was 1186 kN, with vertical displacement of 6.71 mm. The Young's modulus was 1.639 GPa and 0.563 GPa for hydraulic and air lime mortar, respectively.

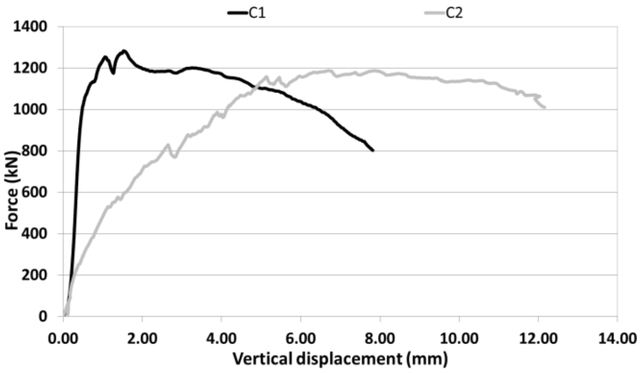


Figure 3.11. Experimental results-Specimens C1 and C2: Force vs. Vertical displacement

The experimental results for these tests showed an unexpected similarity between the strength of the hydraulic and air lime specimens. This can be explained by the specimen's failure mode, which involves in both cases the stone crushing (Fig. 3.12). However, different thicknesses of mortar layers and different stone arrangements could result in different ultimate loads, as it was obtained in previous work [Carvalho, 2008].

(a) (b)

Figure 3.12. Collapse of masonry specimens: (a) specimen C1 and (b) specimen C2

4. CONCLUSIONS

As noticed, masonry specimens were built especially for this experimental campaign and tested under three types of tests, diagonal compression, triplet and compression tests. Four masonry specimens (W1H, W2A, W3A, and W4H) were subjected to diagonal compression tests in order to obtain the initial shear strength and shear modulus. The results showed that the stone arrangement leads to some differences in masonry strength and deformation capacity, but the influence of stone arrangements is not as important as the influence of the type of mortar, as the specimens built with air lime mortar have 10 times lower strength than the specimens based on hydraulic mortar.
Furthermore, five specimens based on hydraulic lime and four specimens based on air lime were tested by triplet tests. The values obtained for shear strength parameters of the specimens based on air lime mortar are lower than the values obtained for the specimens with hydraulic mortar, as it was expected. Also, typical failure modes were identified in all tests. Moreover, compression tests allowed the evaluation of compression strength and the Young modulus for traditional stone masonry specimens.
As mentioned, different values for initial shear strength were obtained with the two types of shear tests. That variations between the results of these shear tests can be due to differences in the manufacturing of the specimens, to different specimen's sizes and, mainly, to differences in the failure surfaces. In triplet tests the failure surface was imposed to be parallel to the stone layers and the

specimens showed higher resistance than the equivalent specimens tested under diagonal compression, where the failure surface was free to develop.

In the case of diagonal compression tests the failure surface is chosen by “the wall itself” and, tends to take place along the least resistance surface. These tests can be considered to be representative of general situations and the results of triplet tests representative of situations where the failure occurs by sliding surfaces parallel to the stone layers.

It is also worth noting that to the best of our knowledge there are no standards or scientific works that experimentally evaluate the rubble stone masonry with triplet test procedure.

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REFERENCES

Cardoso, R., Lopes, M. L. and Bento, R. (2005). Seismic Evaluation of Old Masonry Buildings. Part I: Method Description and Application to a Case-Study. *Journal of Engineering Structures* **27**, 2024–2035.

Mendes, N. and Lourenço, P. B. (2010). Seismic Assessment of Masonry “Gaioleiro” Buildings in Lisbon, Portugal. *Journal of Earthquake Engineering* **14:1**, 80-101.

Simões, A. and Bento, R. (2010). Characterization and Classification of Lisbon Old Masonry Buildings, *Report DTC nº 01/2012, ICIST*, Technical University of Lisbon, Portugal.

ASTM (2002). ASTM E 519-02, Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages. *ASTM International, West Conshohocken, PA*

Corradi, M., Borri, A., Vignoli, A. (2003). Experimental study on the determination of strength of masonry walls. *Journal of Construction and Building Materials* **17:5**, 325–337.

Brignola, A., Frumento, S., Lagomarsino, S., Podestà, S. (2008). Identification of shear parameters of masonry panels through the in-situ diagonal compression test. *International Journal of Architectural Heritage* **3:1**, 52–73.

BS EN (2002). BS EN 1052-3, Methods of test for masonry-Part 3: Determination of initial shear strength.

Prota, A., Marcari, G., Fabbrocino, G., Manfredi, G. and Aldea, C. (2006). Experimental in-plane behavior of tuff masonry strengthened with cementitious matrix-grid composites. *Journal of Composites for Construction* **10**, 223.

Oliveira, J.T., Lourenço, P.B. and Barros, J.O. (2002). Shear testing of stack bonded masonry. *Report no. 02-DEC/E-10*. University of Minho, Portugal, 33.

BS EN (1998). BS EN 1052-1, Methods of test for masonry-Part 1: Determination of compressive strength.

EC 6 (1995). Eurocode 6 - Design of masonry structures, part 1-1: general rules for buildings - rules for reinforced and unreinforced masonry. *ENV 1996-1-1:1995.*

Vasconselos, G. (2005). Experimental investigations on the mechanics of stone masonry: characterization of granites and behavior of ancient masonry shear walls. *Phd Thesis*, University of Minho, Portugal.

Hamid, A. A. and Drysdale, R.G. (1980a). Behavior of brick masonry under combined shear and compression loading. *Proc. 2nd Canadian Masonry Conference*, 57-64.

Hamid, A. A. and Drysdale, R.G. (1980b). Concrete masonry under combined shear and compression along the mortar joints. *ACI Journal* **77:5**, 314-320.

Atkinson, R.H., Amadei, B.P., Saeb, S. and Sture, S. (1989). Response of masonry bed joints in direct shear. *Journal of Structural Engineering* **115:9**, 2277-2296.

Riddington, J.R. and Ghazali, M.Z. (1990). Hypothesis for shear failure in masonry joints. *Proc. Instn. Civ. Engrs.* **89**, 89-102.

Carvalho, J. (2008). Mechanical characterization of loadbearing masonry stone through non-destructive testing (in Portuguese). *Master’s thesis*, Instituto Superior Técnico, Lisbon.