Experimental Study of Rubble Stone Masonry Specimens

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ABSTRACT: Some experimental tests were performed within the scope of Portuguese national research project, SEVERES, to characterize the shear behaviour of old masonry buildings in Lisbon. Diagonal compression, triplet and static cyclic tests were performed and the results obtained are presented in this paper. Seventeen masonry specimens with different dimensions (depending of the type of test) were built using traditional techniques and materials. Two types of mortar were used: air lime and hydraulic lime mortar, with traditional lime stone. Based on the results achieved different masonry characteristics were assessed: i) diagonal tensile strength via diagonal compression tests, ii) initial shear strength and coefficient of friction by triplet tests, and iii) shear strength through static cyclic tests. Moreover, load-displacement diagrams and expected collapse mechanism are presented. According to the results obtained it can be concluded that the values reached are inside the range of ones obtained by other researchers for similar masonry specimens.

Keywords: Rubble Stone Masonry, Shear Strength, Cohesion, Diagonal Compression Test, Triplet Test, Cyclic Static test

NOTATION

- τ shear stress;
- P applied load;
- A_n net area of the panel;
- n percent of the unit's gross area;
- f_{vo} initial shear strength (cohesion);
- f_t tensile strength;
- f_V shear strength;
- $f_{v,avg}$ average shear strength;
- μ coefficient of friction;
- σ compressive stress;
- $F_{v,max}$ maximum force;
- G shear modulus
- F_v vertical force
- $F_{H,max}$ maximum horizontal force
- d_{max} corresponding displacement
- $F_{H,crack}$ value of the horizontal force at first crack
- d_{crack} corresponding displacement
- $F_{H,failure}$ horizontal force at failure
- $d_{failure}$ corresponding displacement

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1 INTRODUCTION

In Lisbon and other southern European cities, old masonry buildings with rubble stone masonry walls are generally exposed to a very high seismic risk due to high probability of earthquake occurrence. In urban areas, the percentage of these buildings, their heritage value and the increasing concern about people's safety led to several studies aiming the structural characterization of old masonry buildings. However, until now, there are not many studies (especially for old Portuguese buildings) where these buildings were analysed. Due to this, the main goal of the project is to contribute to characterize the seismic behaviour of traditional rubble stone masonry walls, by means of experimental tests for characterization of the shear strength of rubble stone masonry. These tests involve diagonal compression, triplet and static cyclic test.

In order to evaluate the diagonal tensile strength, diagonal compression tests were performed on four rubble masonry specimens, two with hydraulic mortar (W1H and W4H) and two with air lime mortar (W2A and W3A). The test setup and procedure for diagonal compression test followed the ASTM E519-02 standard [1] and suggestions of other research works [2, 3].

In order to obtain the initial shear strength (cohesion) and coefficient of friction, nine specimens were built and tested by triplet test set-up *following* the major lines of EN 1052-3 standard [4] and of the other works [5,6] related to brick masonry.

Furthermore, in order to define shear strength and the load-displacement diagrams and expected collapse mechanism of masonry walls, four masonry specimens (two based on hydraulic lime, S1H and S2H and two with air lime S3A and S4A) were tested by applying static cyclic horizontal loads on top following the major concepts of ASTM Standard E2126-02a and the work of Vasconcelos [7,8].

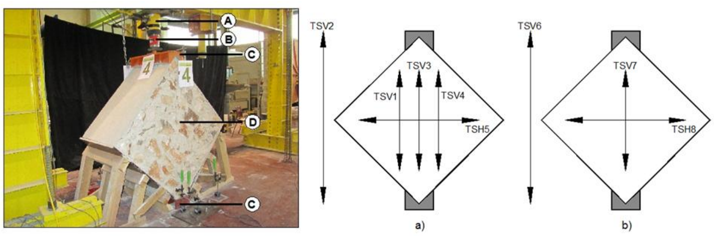
2 TEST DESCRIPTIONS

These tests involved the use of panels of three different dimensions, namely $120\times120\times70$cm for diagonal compression tests, $60\times40\times40$cm for triplet tests and $120\times120\times40$cm for static cyclic tests. All specimens were built in laboratory, especially for this experimental campaign using traditional techniques and materials.

The specimens are identified by a three index code, in which the first index indicates the type of test (W – diagonal compression, T – triplet, S – static cyclic test); the second index is the identification number of the panel, whereas 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 the four masonry specimens in order to evaluate the masonry diagonal tensile (shear) strength and shear modulus. This test was performed on square masonry specimens, which were positioned in the testing machine with a diagonal axis in the vertical direction and loaded in compression along this direction. For diagonal compression tests the test setup is composed of a set of metallic elements, two steel loading shoes, fixed at the two opposite corners of a diagonal of the masonry specimen. The load is applied by an hydraulic jack acting on the loading shoe placed on the top of the panel, and transferred by equilibrium to the other shoe at the panel bottom corner, in contact with the laboratory strong floor (Figure 1).



A – Hydraulic jack; B – Load cell; C – Loading shoes; D – Masonry specimen

Figure 1. Setup for diagonal compression tests.

The shortening of the vertical diagonal and the lengthening of the horizontal diagonal were measured with linear displacement transducers (TSV and TSH), which were placed on both sides of the masonry specimens. The total number of channels used for each specimen was eight (five transducers were installed on one side of the specimen and three transducers were placed on the other side), as can be seen in Figure 1. In order to avoid any damage of the instrumentation, the transducers were removed, when the behaviour of the specimen under load start to indicate that it could be close of failure. Due to this reason, one transducer was placed under the hydraulic jack in order to measure vertical displacement until end of the test.

As already mentioned, one of the most used methodologies to evaluate the shear strength of masonry specimens based on the results of diagonal compression tests is the one proposed on the ASTM specifications [1]. According to this the shear stress can be calculated as:

$$\tau = \frac{0.707 \times F}{A_n} \tag{1}$$

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

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

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

Consequently, the shear strength f_{vo} (f_{vo} according to Eurocode 6 [9]) and the tensile strength f_t are defined as:

$$f_t = f_{vo} = \frac{0.707 \times F}{A_n} \tag{3}$$

where F_{max} is the maximum load applied by the jack.

2.2 Triplet tests

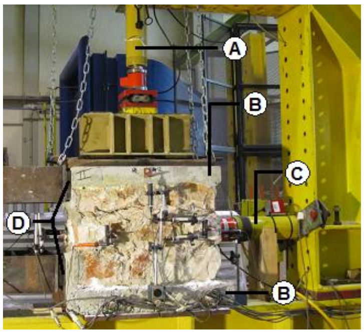
In order to obtain the initial shear strength of horizontal bed joints in rubble stone specimens, triplet tests were performed on nine rubble stone masonry specimens. The specimens were subdivided in two groups depending on the type of mortar, namely hydraulic and air lime mortar.

Following the EN 1052-3 standard [4], all masonry specimens were subjected to a vertical pre-compression load. 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 complete test. The specimens with hydraulic mortar were subdivided into three series: series 1 for a pre-compression level of 0.1 MPa (panels T1H and T2H), series 2 for a pre-compression level of 0.2 MPa (panel T5H) and series 3 for a pre-compression level of 0.3 MPa (panels T3H and T4H). 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 T6A and T7A), series 5 for a pre-compression level of 0.3 MPa (panel T8A) and series 6 for a pre-compression level of 0.5 MPa (panel T9A).

As can be seen in Figure 2, the test setup consists of two horizontal supports to restrain the horizontal movement of the top and bottom stone layers. The horizontal and vertical loading system consisted of two independent 300 kN capacity hydraulic jacks, namely a horizontal jack, which were applying the load at the middle layer and a vertical jack, applying the load 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. 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. The displacements were recorded by thirteen linear voltage displacement transducers (LVDTs) placed on the four specimens faces. The shear strength f_v of horizontal bed joints in rubble stone masonry specimens submitted to a compressive stress σ is given by:

$$f_v = f_{vo} + \mu \times \sigma \qquad (4)$$

where μ and f_{vo} stand for coefficient of friction and cohesion, respectively. As indicated in EN 1052-3 [4], the parameters f_{vo} and μ can be obtained from several triplet tests performed with different compressive stress levels by means of linear regression.



A – Compressive load; B – Concrete slab; C – Shear load; D – Rigid support to restrain movements

Figure 2. Triplet test setup

2.3 Static cyclic tests

Static cyclic tests were performed on four square masonry specimens in order to define shear strength, load-displacement relationships and expected collapse mechanism. All specimens were vertically pre-stressed with a compressive load (0.3 Mpa - 144 kN), which was applied through four steel bars (cables), each one with an actuator at the top. All the actuators were synchronized in order to apply the same force. The cables connected to the actuators were anchored in the strong floor of the laboratory. A stiff beam on the top of the specimen was was used for the uniform distribution of

the vertical loads. A set of steel rollers on the top of the specimen (Figure 3) allowed horizontal displacements of the top of the specimen with regard to the vertical actuators. After the vertical load was applied, the horizontal load was applied to the top of the wall by means of a of system steel plates that is appropriately connected with steel bars. The horizontal force is recorded in the horizontal double-acting hydraulic jack with capacity 300 kN that was linked to the reaction wall. It is

worth to emphasize that in all tests the vertical load was kept (approximately) constant during the complete test. In order to prevent sliding at the base, the specimens were fixed to a steel profile and clamped down using steel beams, which was vertically presstressed (Figure 3).

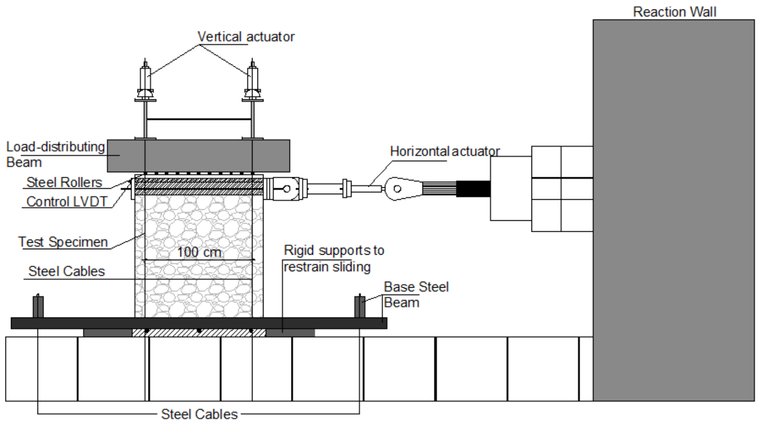


Figure 3 Cyclic test setup

The cyclic tests were conducted under displacement control by means of the horizontal LVDT connected to the left side of the specimen, as can be seen in Figure 5. Each cycle was repeated three times with monotonic increase of the maximum amplitude. The displacement history of horizontal displacement versus time is presented in Figure 4.

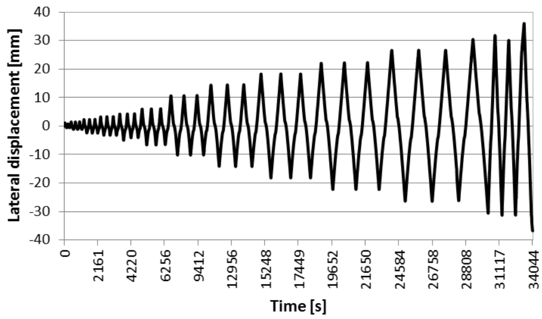


Figure 4. Displacement-time history

The displacements of the wall under cyclic loading were measured through a set of LVDTs indicated in Figure 5. The vertical displacement of the top and bottom of the specimen was measured by the TSV1 and TSV7, respectively, whereas the TSV3 and TSV5 were used to measure vertical displacement on different heights of the specimen. Transducers TSH1, TSH3, TSH5 and TSH7 were instrumented on the specimen to measure horizontal displacements on different heights. The same arrangement of the LVDTs was made on both faces of the wall. As in previous tests, in order to avoid any damage of the instrumentation, all transducers (except the control one) were removed when the behaviour of the specimens started to indicate that it could be close to failure.

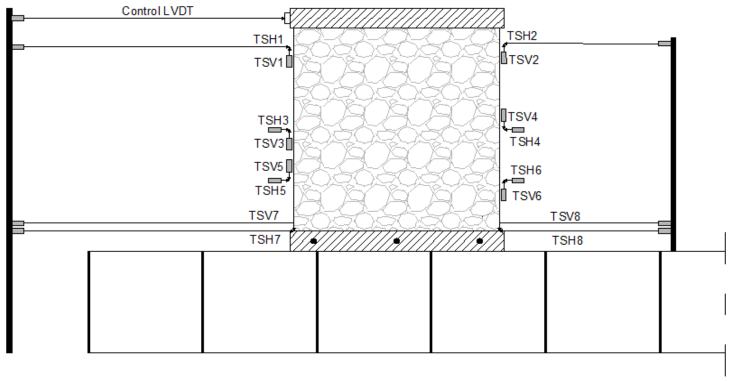


Figure 5. Position of transducers

The shear strength was calculated according to the following equation:

$$f_v = \frac{F_{H\max}}{A} \tag{5}$$

where $F_{H\max}$ is maximum horizontal force and A is cross-sectional area of the specimens.

3 TESTS RESULTS

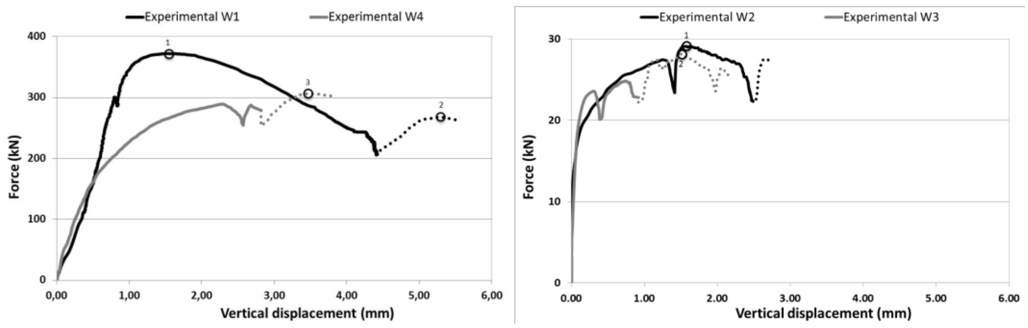
3.1 Diagonal compression tests

In all performed tests, all specimens showed a similar failure pattern: a main crack was developed in the middle of the specimen, continuously propagating from the centre towards the upper and bottom corners. It should be mentioned that in all tests the stones were not damaged and the crack appeared only through the mortar, dividing the specimen in two almost symmetrical parts. In Figure 6 one specimen with hydraulic mortar (W4H) and one with air lime mortar (W3A) can be seen.

(a) (b)

Figure 6. Main crack at the middle of the specimens: (a) specimen W4H and (b) specimen W3A

Despite of the collapse quasi-brittle nature in all cases, the specimens showed different behaviour after the collapse: the specimens with air lime mortar (W2A and W3A) disintegrated, while the specimens with hydraulic mortar (W1H and W4H) broke in two parts, each remaining in one piece. In Figure 7, the load-vertical displacement diagram is represented (where vertical displacement represents the average of the measurements recorded on both sides of the panel) for the specimen W1H and W4H. As can be seen on this diagram the maximum load for specimen W1H 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 W4H the point of the collapse was coincident 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 worth noting that the specimens W2A, W3A and W4H were built with diagonal layers (45º), whereas the specimen W1H was built with horizontal layers, which may have contributed for the apparent ductile behaviour of specimen W1H. Furthermore, experimental results show that the masonry specimens built with air lime mortar showed much lower strength and deformation capacity than the specimens based on hydraulic mortar. As can be seen in Figure 7 collapse load for specimen W2H was 29.1 kN, with a vertical shortening of 1.58 mm (Point 1), and for specimen W3A the ultimate load was 28.1 kN, with a vertical displacement of 1.52 mm (Point 2).



(a) (b)

Figure 7. Force vs. Vertical displacement: (a) W1H and W4H, (b) W2A and W3A

As mentioned above, all transducers (except the transducer that was placed under the hydraulic jack) were removed before the end of tests to avoid damage to the transducers. In order to define the complete behaviour of the walls, the dotted parts of the curves in Figure 7 were obtained by interpolation using the measurement of the transducers under the hydraulic jack. The most important results for the diagonal compression tests are shown in Table 1.

Table 1. Diagonal test results

Masonry typology	**Masonry Specimen**	$F_{v\max}$ **[kN]**	$f_t = f_{v0}$ **[MPa]**	**G [MPa]**
Rubble Stone Masonry Specimens	W1H	372	0.313	389.3
	W2A	29	0.024	57.9
	W3A	28	0.024	92.5
	W4H	306	0.258	252.0

Due to the fact that in these tests the specimen's collapse was achieved without damaging the stones, i.e., the cracks propagated through the mortar joints, it can be concluded that mortar type has a major influence in the specimen's strength. Moreover, from the differences in tests W1H and W4H, whose specimens were built with different stone arrangements, and from the similarities obtained in tests W2A and W3A, specimens of which were built with the same stone arrangement, it can also be concluded that the stone arrangement influences (by a moderate degree) the masonry strength and its deformation capacity. For the air lime mortar specimens (W2A and W3A) the maximum compression loads were similar but the shear elastic modulus G varies significantly. This variation can be due to the fact that the shear modulus is evaluated on the undamaged stage, with small displacements, where measurement errors may have an important influence. For specimens built with hydraulic lime mortar (W1H and W4H) the variation of the shear modulus results can also be explained by the different stone arrangement adopted on the specimens.

3.2 Triplet tests

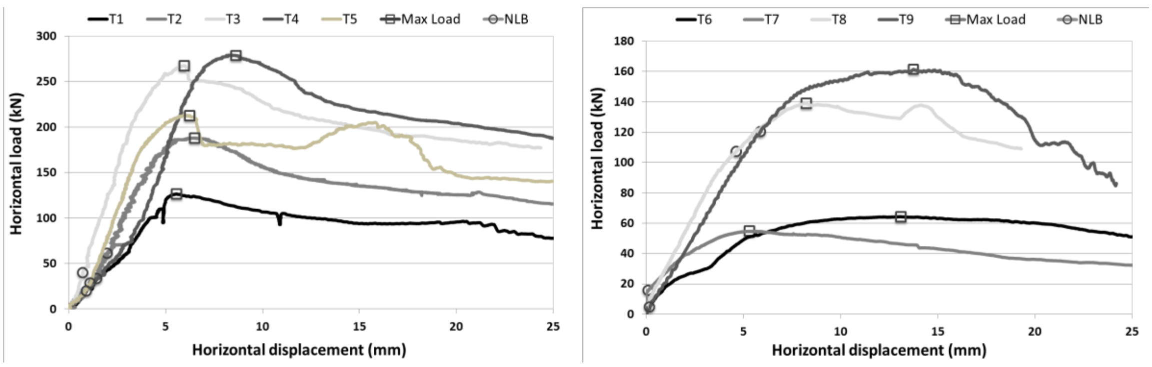
In triplet tests, as expected, all specimens collapsed by sliding of the middle stone layer (Figure 8) and higher shear strength were obtained for higher compression levels. The results are summarized in Table 2 and the force-displacement diagrams are depicted in Figure 9. The transducer, which was placed on the hydraulic actuator, recorded the horizontal displacement plotted in the force-displacement diagrams and the load cell placed next to the horizontal jack measured the force magnitude. The points where the linear elastic behaviour ends and the points of maximum horizontal force are also marked in the force-displacement diagrams.

(a) (b)

Figure 8. Crack pattern of masonry specimens: (a) T1H, (b) T7A

Table 2. Triplet test results

Series	Panel	σ_0 [MPa]	F_v [kN]	$F_{H,\max}$ [kN]	f_v [MPa]	$f_{v,avg}$ [MPa]
Series 1	T1H	0.1	24	126	0.26	0.33
	T2H			188	0.39	
Series 2	T5H	0.2	48	213	0.44	0.44
Series 3	T3H	0.3	72	267	0.56	0.57
	T4H			279	0.58	
Series 4	T6A	0.1	24	64	0.13 4	0.13
	T7A			56	0.12 0	
Series 5	T8A	0.3	72	139	0.29	0.29
Series 6	T9A	0.5	120	161	0.34	0.34



(a) (b)

Figure 9. Horizontal Force (F_H) vs. Horizontal displacement (d). Specimens with: (a) Hydraulic (b) Air lime mortar

Regarding the obtained results, test T6 showed some peculiarities in the specimen's behaviour. The force-displacement diagram shows a relatively long plateau with slight hardening, registering the maximum horizontal force at relatively large horizontal displacement.

This hardening behaviour may be attributed to a stronger interlocking effect of the stones along the nearly horizontal failure surface. As observed in test T7 (Figure 9(b)), without this hardening effect the maximum load would be slightly smaller and would have been registered at a much smaller horizontal displacement.

Figure 10 shows the relation between the vertical compression stress and the shear strength for all tests. Two straight lines, one for each type of mortar specimen, evaluated by linear regression are also presented in the graph. It is worth mentioning the good correlation between the experimental results and the linear regression lines, which confirms the initial assumption of Coulomb's friction law for the shear strength of horizontal bed joints in rubble stone masonry specimens. For hydraulic lime mortar specimens the values obtained by linear regression for cohesion and coefficient of friction were 0.20 MPa and 1.23, respectively. For air lime mortar the obtained values were 0.08 MPa for cohesion and 0.56 for coefficient of friction.

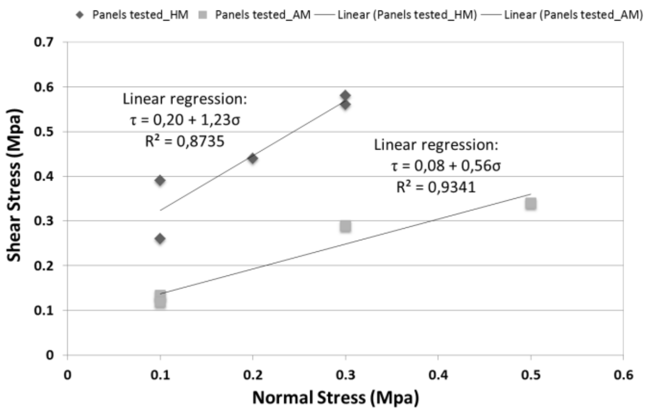


Figure 10. Relation between shear stress and normal stress for hydraulic and air lime mortar specimens (R is correlation coefficient of the linear regression)

3.3 Static cyclic tests

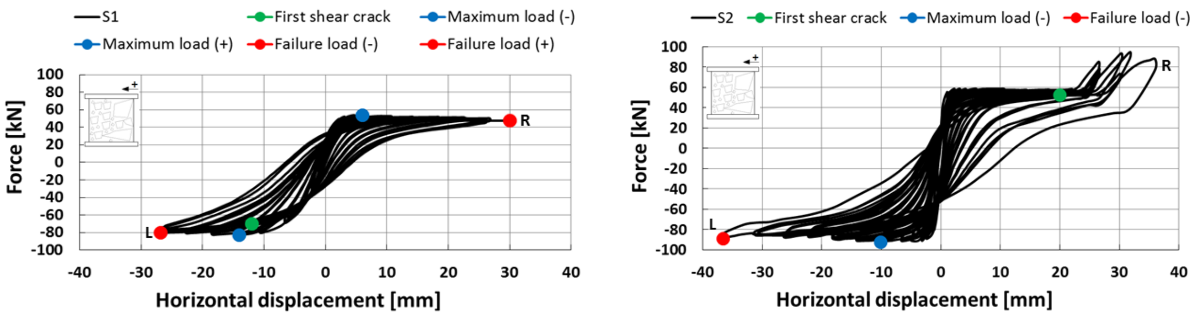
The crack pattern of specimens S1H and S2H is composed by flexural cracks at the base of the specimens (rocking) for small lateral displacements. As the lateral force increases, the opening of these cracks reaches larger values. The first diagonal crack developed due to the failure of stone-unit mortar interface in the middle of the specimen's side (Figure 11), for a lateral displacement of approximately -12mm, for specimen S1H and around 20 mm for specimen S2H. Crack damage in the stones was not found along the shear crack. Crushing of the stones occurred only in the bottom corners. As can be noticed, the collapse mode is different for these two specimens. Namely, for specimen SH1, shear failure mode can be noticed, whereas specimen SH2 was more characterized by flexural pattern. Since these two specimens were built with the same mortar (hydraulic lime) and the same type of stones (lime stones), differences for the failure pattern can be explained by orientation of main mortar joints and by interlocking between the stones.

(a) (b) (c) (d)

Figure 11. Failure pattern of specimens: (a) S1H, (b) S2H, (c) S3A, (d) S4A

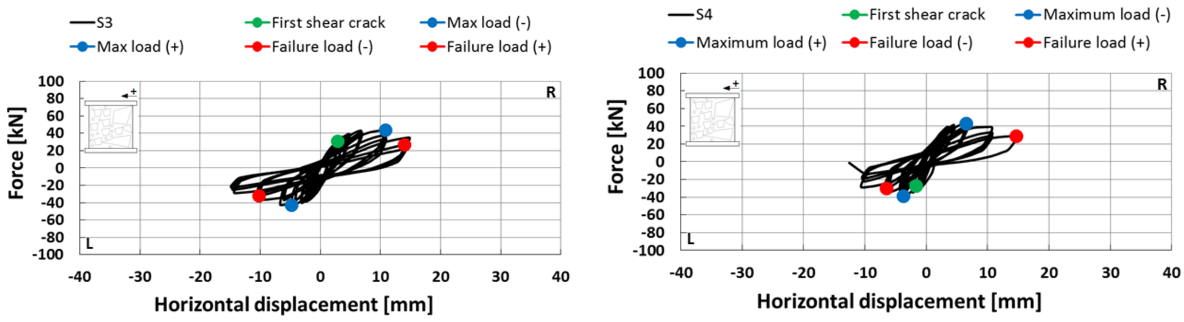
In case of specimens with air lime mortar (S3H and S4H), the first shear crack appeared on both sides of the specimen with very small lateral displacement (around 4 mm), leading to the occurrence of a high number of small cracks distributed throughout of the specimens. During the test, crack damage in the stone was not found along the cracks and comparing to the specimens with hydraulic mortar, where crushing of the bottom corners took place, in the specimen with air lime mortar (S3H and S4H), crushing of the bottom corners did not occur. In the final stage, as can be seen in Figure 11, the specimens were split in several parts.

In addition to the failure patterns, the lateral force-lateral displacement diagrams provide valuable information on the lateral in-plane behaviour needed to evaluate the seismic performance. The results are summarized in Table 3 and the lateral force-lateral displacement diagrams (where the lateral displacement is the measurement recorded using control LVDT), for hydraulic lime and air lime mortar specimens are presented in Figure 12 and Figure 13, respectively. It is important to mention that for all specimens, the failure load was considered as 80 % of the maximum reached horizontal load (Table 3). Regarding the diagram of specimen S2H (Figure 12 (b)), some irregularities can be noticed on the positive slope of the curve: during the test, due to the movement and deformation of the specimen, one vertical actuator reached his maximum stroke. This led to the increase of the axial force on that jack which in turn created a bending moment, applied on top of the wall. Therefore the horizontal force increased to counteract this effect. If it was not for this the behaviour would be expected to be similar to the one registered in the opposite direction and in all other tests.



(a) (b)

Figure 12. Horizontal Force (F_H) vs. Horizontal displacement (d): Specimens: (a) S1H (b) S2H



(a) (b)

Figure 13. Horizontal Force (F_H) vs. Horizontal displacement (d): Specimens: (a) S3A (b) S4A

Table 3. Static cyclic test results

Specimen	Left						Right						
	F_{crack} [kN]	d_{crack} [mm]	$F_{\max}$ [kN]	$d_{\max}$ [mm]	$F_{failure}$ [kN]	$d_{failure}$ [mm]	F_{crack} [kN]	d_{crack} [mm]	$F_{\max}$ [kN]	$d_{\max}$ [mm]	$F_{failure}$ [kN]	$d_{failure}$ [mm]	f_v [MPa]
S1	70.24	12.0	82.69	14.0	80.32	26.84	-	-	53.86	6.0	47.57	30.0	0.17
S2	-	-	92.44	10.13	89.24	36.59	52.38	19.98	Not relevant				0.19
S3	-	-	42.84	4.75	31.88	10.14	30.72	2.90	43.79	10.84	26.60	13.97	0.09
S4	33.82	2.21	38.94	3.74	30.21	6.45	-	-	42.68	6.52	29.03	14.73	0.09

As expected, specimens built with air lime mortar showed lower strength than the specimens built with hydraulic lime mortar. In case of rubble masonry specimens with hydraulic mortar, the role of the textural variability on the lateral response is well evidenced in Figure 12, where the force-lateral displacement diagrams for the specimens S1H and S2H are displayed. Concerning specimen S1H, the hysteresis diagram is associated with the mixed deformation composed of flexural and shears cracking, what is in agreement with the failure pattern.

The lateral response of the specimen S2H is governed more by a flexural pattern and is well described by an expressive pinching effect on the hysteresis loops. As can be noticed, for the two specimens (S1H and S2H), the differences in the maximum lateral strength are minimal. Additionally, in larger amplitude cycles after the maximum load, there is a little strength degradation for both specimens. As already mentioned, in both specimens the hysteresis loops are asymmetric, which to a certain extent can be related to the textural scatter that is intrinsic to the construction of these walls.

On the other hand, comparing to the specimens with hydraulic mortar, the reduced deformation capacity and lateral resistance becomes clear from the analysis of the force-displacement diagrams for specimens made with air lime mortar (S3A and S4A), displayed in Figure 13. Comparing to the specimens with hydraulic mortar, where degradation of the strength is almost negligible, in case of specimens with air lime mortar, ultimate strength is almost half values of maximum lateral strength, and differences in the maximum lateral strength between specimen S3A and S4A are insignificant.

Moreover, the collapse of the specimen was achieved without damage the stones, i.e., the cracks propagated only through the mortar joints, which is one more fact that shows the influence of the mortar type on the strength of the specimen.

4 CONCLUSIONS

As previously mentioned, due to the lack of studies in the literature targeting old Portuguese buildings ("Pombalino", "Gaioleiro" and "Placa") their seismic behaviour is generally unknown, thus the main scope of this experimental study was focused on analysing the most important mechanical parameters and for proposing appropriate techniques for rehabilitation of these buildings. Namely, seventeen specimens were specially built with two different types of mortar, air lime and hydraulic lime and traditional limestone in order to simulate load bearing walls on rubble stone masonry. The experimental program performed on the specimens and discussed in this paper was focused on three types of tests: diagonal compression, triplet and static cyclic 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 tests have shown 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 lower strength than the specimens based on hydraulic mortar. Furthermore, five specimens built with 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. Additionally, four specimens (S1H, S2H, S3A, and S4A) were tested by static cyclic tests. According to the results obtained, as in diagonal compression tests, it can be concluded that mortar strongly influences the strength of the specimens, since the specimens with air lime mortar showed lower strength comparing to specimens with hydraulic mortar. Furthermore, for specimens built with hydraulic mortar, the strength was not equal for both loading sides, what can be attributed to variability in construction.

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 with geometrical constraints.

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.

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REFERENCES

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

[2] Corradi, M.; Borri, A. & Vignoli, A.: Experimental study on the determination of strength of masonry walls. Construction and Building Materials 2003, 325-337.

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

[4] EN 1052-3 Methods of test for masonry-Part 3: Determination of initial shear strength 2002.

[5] Prota, A.; Marcari, G.; Fabbrocino, G.; Manfredi, G. & Aldea, C.: Experimental in-plane behaviour of tuff masonry strengthened with cementitious matrix-grid composites. Journal of Composites for Construction 2006, 3-223.

[6] Lourenço, P.B, Barros, J.O, & Oliveira J.T.: Shear testing of stack bonded masonry. Construction and Building Materials, 2004, 125-132.

[7] ASTM E 2126-02a Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Walls for Buildings. ASTM International. West Conshohocken, PA 19428-2959.

[8] Vasconcelos, G: *Experimental investigations on the mechanics of stone masonry: characterization of granites and behaviour of ancient masonry shear walls*. PhD Thesis, University of Minho, Portugal 2005.

[9] Eurocode 6 Design of masonry structures, part 1-1: general rules for buildings - rules for reinforced and unreinforced masonry 1995. ENV 1996-1-1:1995