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EXPERIMENTAL EVALUATION OF THE SHEAR STRENGTH OF MASONRY WALLS

Jelena Milosevic[1 (*)], António Sousa Gago[2], Rita Bento[3], Mário Lopes[4]
[1, 2, 3, 4] ICIST, IST; Technical University of Lisbon, Portugal
[(*)]*Email:* jelena@civil.ist.utl.pt

ABSTRACT

In this work diagonal compression tests and triplet tests on rubble stone masonry specimens are described and the results obtained presented. For the tests carried out different dimensions of masonry specimens were adopted and two different types of mortar were used in the specimen's construction, namely hydraulic and air lime mortar. The general objectives of the work presented herein are to determine: i) initial shear strength (cohesion) of masonry via diagonal compression test and ii) initial shear strength, or cohesion and coefficient of friction by triplet test. This study was developed within the scope of the national research project SEVERES (www.severes.org).

Keywords: masonry, diagonal compression tests, triplet tests, shear strength, cohesion

INTRODUCTION

Old masonry buildings are integral and very important parts in most of the European cities. These buildings are still being used, for housing and services, as their main function. In Lisbon and other Mediterranean 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.

In order to support simulation of building structural behaviour, for any numerical analysis, it is important to know the mechanical characteristics of the materials. However, until now, there are not many studies where values for shear strength parameters of old masonry buildings can be found, which otherwise is a very relevant parameter for the evaluation of seismic behavior of masonry buildings.

The main goal of the 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. These tests involves of diagonal compression and triplet tests (described in this paper) and cyclic shear test.

To characterize 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), with dimension $120\times120\times70$cm. 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, 2003, Brignola, 2008].

Other nine wall prototypes ($60\times40\times40$cm) were subjected to triplet tests following the major lines of EN 1052-3 standard [BS EN, 2002] and of the other works [Prota, 2006, Oliveira, 2002], since they oriented to brick masonry. Until now triplet tests on rubble stone masonry specimens are not describe in any standard or performed in other experimental campaign. It worth to refer that, specimens were built with three stone layers and subdivided into two groups depending on the type of mortar (first group with hydraulic mortar and second group with air lime mortar).

The tested specimens were specially built for this experimental campaign in order to represent the Portuguese old buildings, using traditional materials and following traditional building techniques. All specimens were tested 8 months after its construction to ensure the hardness of the air lime mortars.

TESTS DESCRIPTION

The experimental campaign described in this paper consists of four diagonal and nine triplet tests. The specimens are identified by a three-index code, in which the first indicates the type of test (W – diagonal compression test and T – triplet test); the second index is the identification number of the panel and the third index indicates the type of mortar (H – hydraulic and A – air lime mortar), as in shown in Table 1.

Table 1 Classification of tested panels by masonry typology

Masonry typology	**Index Code**	**Size [cm]**
Rubble stone	W1H	$120\times120\times70$
	W2A	$120\times120\times70$
	W3A	$120\times120\times70$
	W4H	$120\times120\times70$
Rubble stone	T1H	$60\times40\times40$
	T2H	$60\times40\times40$
	T3H	$60\times40\times40$
	T4H	$60\times40\times40$
	T5H	$60\times40\times40$
	T6A	$60\times40\times40$
	T7A	$60\times40\times40$
	T8A	$60\times40\times40$
	T9A	$60\times40\times40$

DIAGONAL COMPRESSION TEST

Diagonal compression tests were performed on the four panels to evaluate the masonry diagonal tensile (shear) strength and the shear elastic 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 test 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 a 800 kN 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 slab (Fig. 1).

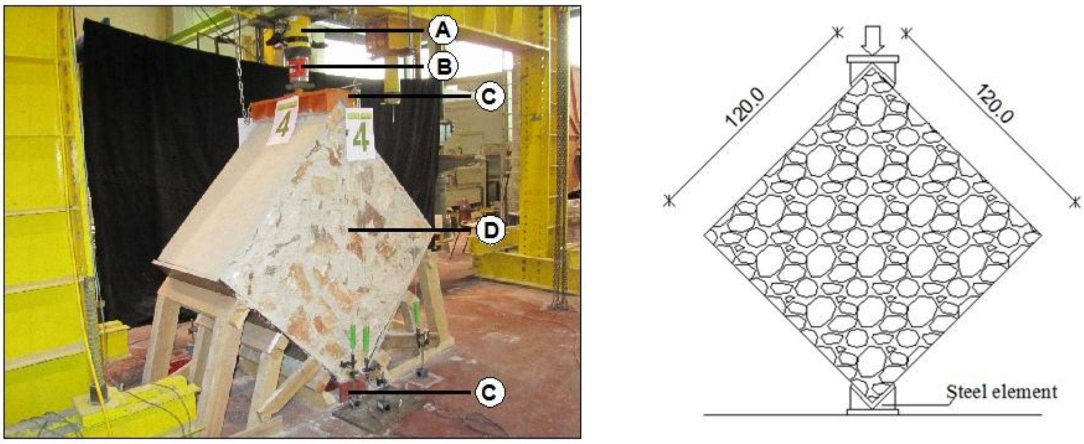

Fig.1 Test setup for diagonal compression test (dimension in [cm])
A – Hydraulic jack; B – Load cell; C – Loading shoes; D – Masonry specimen

The shortening of the vertical diagonal and the lengthening of the horizontal diagonal were measured with linear displacement transducers (TSV and TSH, respectively), 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). It is worth noting, that one transducer was placed under the hydraulic jack in order to measure vertical displacement. For both type of masonry specimens, with hydraulic and air lime mortar, the load was applied gradually with increments rates of 10 kN/s. In order to avoid any damage of the instrumentation, the transducers were removed, when the behavior of the specimen under load start to indicate that it might be close of failure. After that, load was continuously applied until the collapse of specimen.

According to ASTM E519-02 [ASTM, 2002] standard, the shear stress τ and modulus of rigidity (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:

$$\tau = \frac{0.707 \times P}{A_n} \qquad (1)$$

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

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

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:

$$\tau_0 = f_t = \frac{0.707 \times P_{\max}}{A_n} \qquad (3)$$

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

The shear elastic modulus G is obtained by:

$$G = \frac{\tau_{1/3}}{\gamma_{1/3}} \qquad (4)$$

where $\tau_{1/3}$ is the shear stress for a load of 1/3 of the maximum load $P_{\max}$ and $\gamma_{1/3}$ is the corresponding shear strain.

TRIPLET TEST

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

According to the EN 1052-3 standard [BS EN, 2002], all 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 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).

As it can be seen in Fig. 2, where the test setup is depicted, two supports covering the full height of the top and bottom stone layers were used to restrain its horizontal movements. 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.

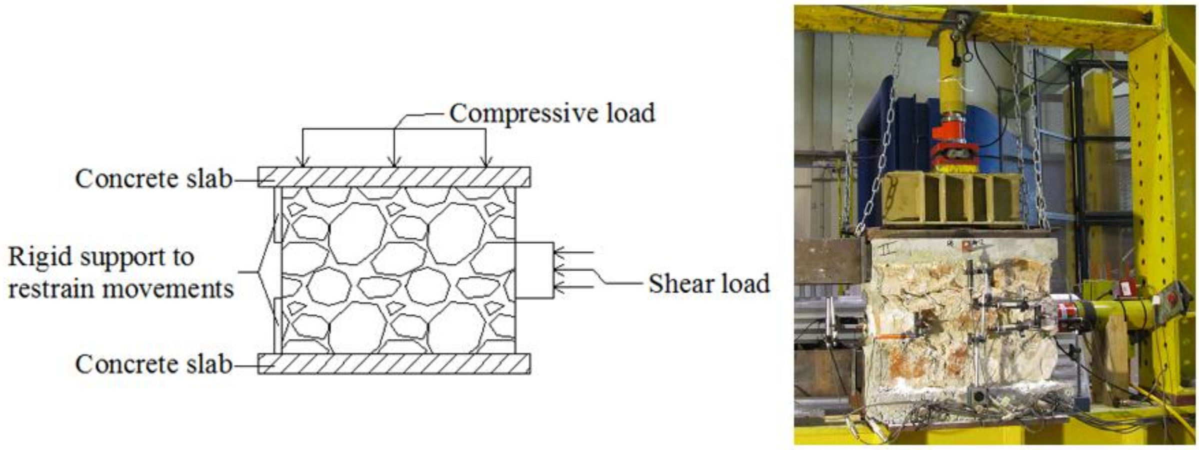

Fig.2 Triplet test setup – general view

Firstly, a constant vertical compressive load was applied by the vertical hydraulic jack and after the horizontal hydraulic jack was used to apply and 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 by means of some small unloading steps.

The displacements of the specimens were recorded with thirteen linear 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.

According to EN 1052-3 [BS EN, 2002] standard the specimen shear strength τ_0 (initial shear strength without any vertical stresses, known as cohesion) can be calculated as follows:

$$\tau_0 = \frac{F_{i,\max}}{2 \times A_i} \qquad (5)$$

where $F_{i,\max}$ is the maximum horizontal force (shear load), that has to be divided by the two (equal) shear surfaces and A_i is the corresponding cross-sectional area.

The shear strength τ of masonry under moderate normal stresses is given by the Coulomb criterion [Vasconcelos, 2005, Hamid, 1980a, Hamid, 1980b, Atkinson, 1989, Riddington, 1990]:

$$\tau = \tau_0 + \mu \times \sigma \qquad (6)$$

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.

RESULTS OF DIAGONAL COMPRESSION TESTS

As already mention, diagonal compression tests were conducted on four rubble masonry specimens, which were built with hydraulic (W1 and W4) and air lime mortar (W2 and W3). In all the performed tests the specimen's collapse was characterized by similar failure patterns. In Fig. 3 one specimen with hydraulic mortar (W4) and one with air lime mortar (W3) are presented. In all tests a main crack developed in the middle of the specimens, propagated towards the upper and the bottom specimen's corners and caused the collapse. It is worth noting that this crack, in all specimens, developed through the mortar with no damage on the stones and divided the specimen in two almost symmetrical parts.

(a) (b)

Fig.3 Main crack at the middle of the specimens: (a) specimen W4 and (b) specimen W3

In all cases the specimen's collapse was fragile, but the specimens showed different behavior at collapse due to the different mechanical properties of mortar. The specimens W2 and W3, which were based on air lime mortar, were disintegrated after the collapse whereas in the case of hydraulic mortar specimens, W1 and W4, each of the two broken parts remained in one piece, as can be seen in Fig. 4.

(a) (b)

Fig.4 Masonry specimens after its collapse: (a) specimen W4; (b) specimen W3

The results for the diagonal compression tests performed on hydraulic lime mortar specimens are depicted in Fig. 5, where the load-vertical displacement diagram is represented (in this diagram the vertical displacement represents the average of the measurements recorded on both diagonals of the panel). As can be seen on this diagram the maximum load for specimen W1 was 372.1 kN, with a vertical shortening of 1.55 mm (Point 1). In this case the collapse of specimen occurred with a load of 267.99 kN and vertical shortening of 5.29 mm (Point 2). In the case of specimen W4 the point of the collapse was coincident with the maximum load applied, and corresponds to a load of 306.24 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, (at 45º to the external inclined surfaces), which can be the reason for apparent “extra strength” and “ductile” behavior of this specimen.

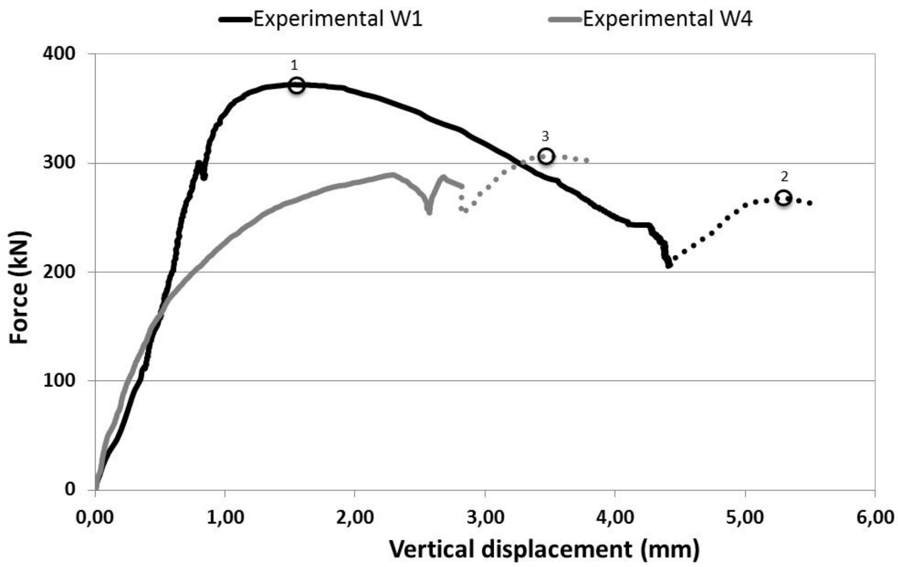

Fig.5 Walls W1 and W4: Force vs. Vertical displacement (Note: vertical displacement measured at the top of the specimens)

As already mentioned, all transducers (except the transducer that was placed under the hydraulic jack) were removed before at the end of test for safety reason. In order to define the complete behavior of the walls, the dotted parts of the curves in Fig. 5 and Fig. 6 (which is shown below) were obtained by interpolation using the measurement of the transducers under the hydraulic jack.

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 Fig. 6 collapse load for specimen W2 was 29.1 kN, with a vertical shortening of 1.58 mm (Point 1), and for specimen W3 the ultimate load was 28.1 kN, with a vertical displacement of 1.52 mm (Point 2), where vertical displacement represents average values of the measurement recorded using transducers which were instrumented on both diagonal of the panel.

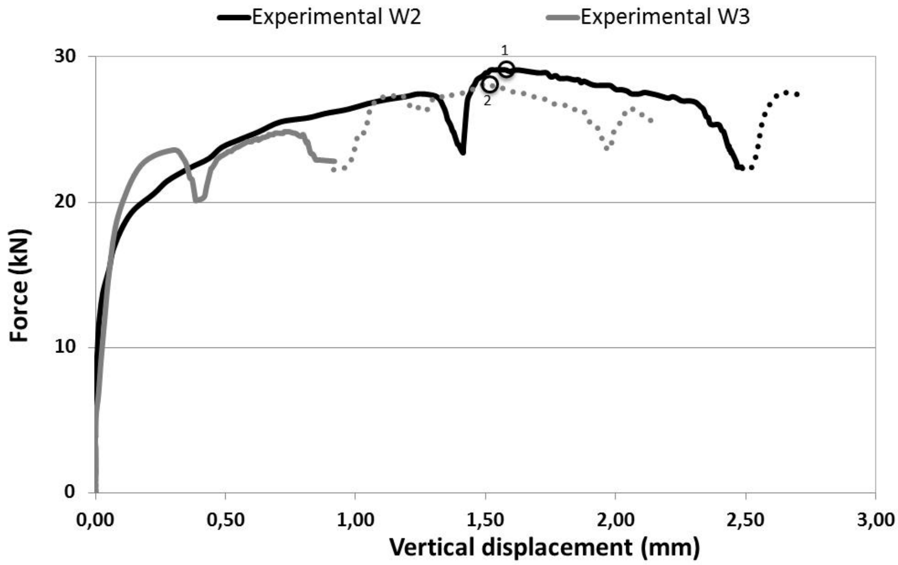

Fig.6 Walls W2 and W3: Force vs. Vertical displacement (Note: vertical displacement measured at the top of the specimens)

The experimental results obtained with the four masonry specimens are given in Table 2.

Table 2 Diagonal compression tests

Masonry typology	**Masonry specimen**	$P_{\max}$ **[kN]**	$\tau_0 = f_t$ **[MPa]**	**G [MPa]**
Rubble stone masonry specimens	W1	372.1	0.313	389.3
	W2	29.1	0.024	57.9
	W3	28.1	0.024	92.5
	W4	306.2	0.258	252.0

Considering the results obtained by diagonal compression tests, it can be concluded that different stone arrangements result in some differences in masonry strength and deformation capacity. Nevertheless, the influence of stone arrangements is not as important as the influence of the type of mortar, which is very high: specimens with hydraulic lime mortar showed a shear strength about 10 times greater than the shear strength of the specimens built with air lime mortar. The big influence of the mortar resistance on the wall shear strength can be explained by the fact that cracks propagated through the joints without damaging the stones.

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).

RESULTS OF TRIPLET TESTS

As mentioned, 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. 7.

(a)

(b)

Fig.7 Crack pattern (left) and Collapse (right) of masonry specimens: (a) specimen T1 and (b) specimen T7

The “horizontal force – horizontal displacement diagram” (displacement measured with the transducer placed on the hydraulic actuator) for specimens built with hydraulic mortar (series 1, 2, 3) is shown in Fig. 8. As can be notice, for specimens tested with a pre-compression of 0.1 MPa, the ultimate load were 126.39 kN (horizontal displacement of 5.56 mm) in specimen T1 and 187.96 kN (horizontal displacement of 6.50 mm) in specimen T2. The ultimate load for specimen T5 with a compression of 0.2 MPa, was 212.8 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, 267.35 kN (horizontal displacement of 5.95 mm) and 278.83 kN (horizontal displacement of 8.42 mm). As it was expected, higher pre-compression levels produced higher shear resistances.

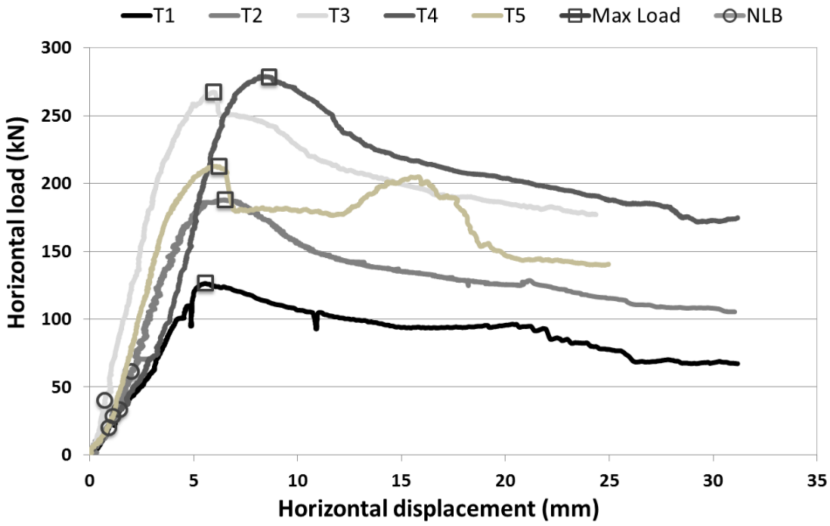

Fig.8 Walls T1, T2, T3, T4 and T5: Horizontal load vs. Horizontal displacement
(Note: Max Load- maximum load; NLB-end of linear behavior)

It should be mentioned that in Fig. 8, the points where the linear behavior ends and the points of maximum force are marked.

In Fig. 9 are depicted the experimental results on specimens built with air lime mortar (series 4, 5, 6). 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 64.3 kN (horizontal displacement of 13.10 mm) in specimen T6 and 55.8 kN (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 138.9 kN (horizontal displacement of 8.23 mm). The last specimen, T9, tested with a compression of 0.5 MPa, an ultimate load of 161.4 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.

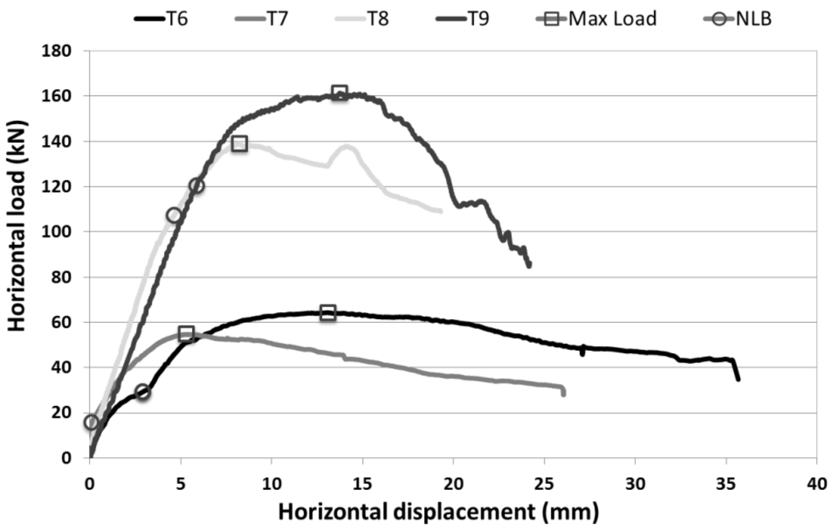

Fig.9 Walls T6, T7, T8 and T9: Horizontal load vs. Horizontal displacement
(Note: Max Load- maximum load; NLB-end of linear behavior)

For air lime mortar, as in the case of hydraulic mortar, the points of maximum force and ends of the linear behavior are marked in the “horizontal load – horizontal displacement diagram” (Fig. 9).

In Table 3 the values of shear strength of the panels can be seen.

Table 3 Triplet tests

Series	**Panel**	**Type of mortar**	**Precompressive stress [MPa]**	**Vertical force [kN]**	**Maximum horizontal force [kN]**	**Shear strength [MPa]**	**Average shear strength [MPa]**
Series 1	T1	Hydraulic	0.1	24	126.39	0.26	0.33
	T2				187.96	0.39	
Series 2	T5	Hydraulic	0.2	48	212.8	0.44	0.44
Series 3	T3	Hydraulic	0.3	72	267.35	0.56	0.57
	T4				278.83	0.58	
Series 4	T6	Air lime	0.1	24	64.3	0.134	0.13
	T7				55.8	0.120	
Series 5	T8	Air lime	0.3	72	138.9	0.29	0.29
Series 6	T9	Air lime	0.5	120	161.4	0.34	0.34

Fig. 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 lime mortar specimens an initial shear strength or cohesion τ_0 of 0.201 MPa and a coefficient of friction μ equal to 1.225. For air lime mortar specimens the obtained values for cohesion (τ_0) and coefficient of friction (μ) were 0.0815 MPa and 0.558, 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 0.160 MPa, whereas for air lime mortar specimens are 0.065 MPa. The characteristic value for the coefficient of friction μ_k is 0.980 for hydraulic mortar specimens and 0.447 for air lime mortar specimens.

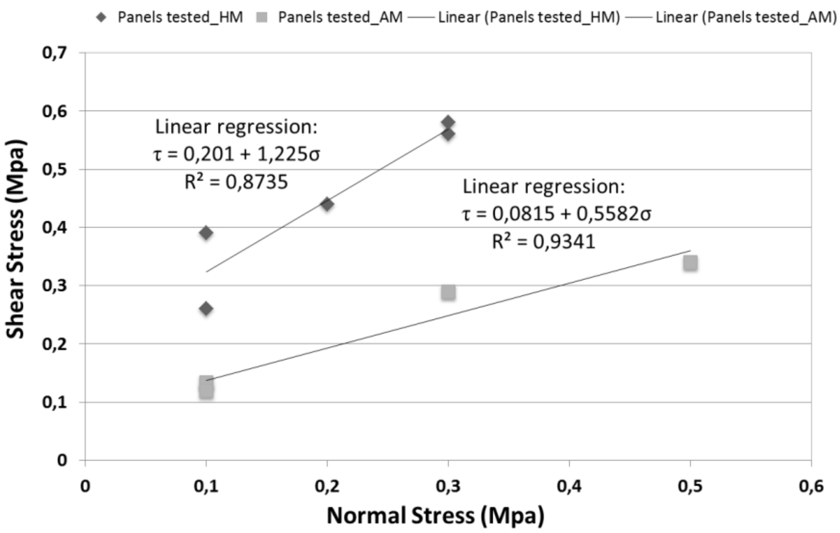

Fig.10 Relation between shear strength and normal stress for hydraulic and air lime mortar

As happen in the case of the diagonal compression tests in the triplet tests the specimens based on hydraulic mortar presented much higher shear strength than the specimens built with air lime mortar (Fig. 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.

CONCLUSIONS

The experimental program presented and discussed in this paper consists of two types of tests, diagonal compression and triplet tests. Masonry specimens were specially built for this experimental campaign using materials and techniques similar as used in old buildings in Portugal.

Four masonry specimens, two based on hydraulic and remaining two based on air lime mortar have been subjected on diagonal compression test in order to obtain initial shear strength. The obtained results showed differences in terms of shear strength depending on the type of mortar (hydraulic or air lime) and can be noticed that specimens with air lime have much lower strength than specimens with hydraulic lime.

Furthermore, nine more specimens (five with hydraulic and four with air lime mortar) were also 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 obtained in all specimens.

Different values for initial shear strength were obtained with the two types of shear tests. In particular for air lime specimens the differences were significant. That variations between the results of the diagonal compression tests and of triplet tests can be connected to the differences in the manufacturing of the specimens, to the different specimen's sizes used on the two types of tests and, mainly, by the 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 on diagonal compression tests, 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 important to mention that the results of triplet tests for the coefficient of friction are similar to the values proposed by the Italian standards [PCM 3274, 2003] for the same type of masonry.

It is also worth noting that, until now triplet test on rubble stone masonry are not described in any standard or work, neither performed in other experimental campaign.

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