Seismic Vulnerability of Old Masonry Buildings – SEVERES Project

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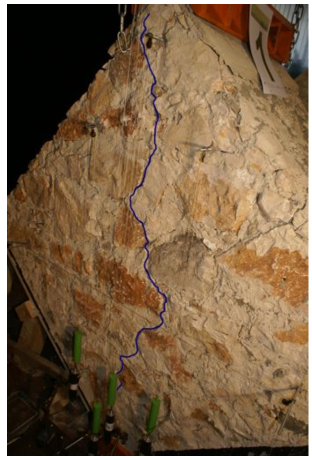
I. Experimental results

This part of the report discusses the experimental results, whereas the description of the performed tests is given in the previous report. All information about description of the tests and positions of transducers can be found in Report 1 - Exterior Walls Tests - Pombalino Buildings. This report presents the experimental results obtained by diagonal compression tests, triplet tests and compression tests.

A. Diagonal compression test

1) Failure mode: The diagonal compression tests on the four rubble masonry specimens (W1, W2, W3 and W4) were characterized by similar failure patterns, as presented in Figure 1. In all tests the main crack developed in the middle of the specimens, continuously propagating towards the upper and the bottom specimens corners and caused the collapse. It should also be mentioned that for all specimens the stones are not damaged and the crack had appeared only through the mortar, dividing the specimen in two almost symmetrical parts.

Due to the different mechanical properties of mortar, the specimens showed different behavior after the collapse, despite of its brittle nature in all cases. The specimens with air lime mortar (W2 and W3) were disintegrated after the collapse, while the specimens, which were built with hydraulic mortar (W1 and W4), broke in two parts, each remaining in one piece. The specimens after collapse can be seen in Figure 2.



(a) Wall made with hydraulic mortar W1

(b) Wall made with air lime mortar W2

(c) Wall made with hydraulic mortar W3

(d) Wall made with air lime mortar W4

Fig. 1. Main crack at the middle of the specimen.

2) Masonry specimens built with hydraulic mortar: The force-vertical displacement diagram (where vertical displacement represents average values of the measurement recorded using LVDTs 3 and 7), for the specimens with hydraulic lime mortar, is presented in Figure 3. As can be seen on this graphic the maximum load for specimen W1 was 372 kN, with a vertical shortening of 1.55 mm (Point 1). In this specimen the collapse occurred later, at a load of 268 kN and with a vertical shortening of 5.29 mm (Point 2). In specimen W4 the point on the collapse was the one at which the maximum load was applied, with a magnitude of 306 kN and a vertical displacement of 3.47 mm (Point 3). It is important to say, that this apparent ductile behavior of specimen W1 is related to the stone arrangement, since the specimen W1 was built with horizontal stone layers, (at 45° to the external inclined surfaces), whereas the other three specimens were built with diagonal layers (45°), to be representative of the real masonry walls.

It is worth to refer, that for safety reasons, the transducers were removed before the end of the test (except the transducer that was placed under the hydraulic jack). In order to define the complete behavior of the walls, the dotted parts of the curves in Figure 3 were obtained by

(a) Specimen W1 made with hydraulic mortar (b) Specimen W2 made with air lime mortar

Fig. 2. Collapse of masonry specimens.

interpolation using the measurement of the transducers under the hydraulic jack.

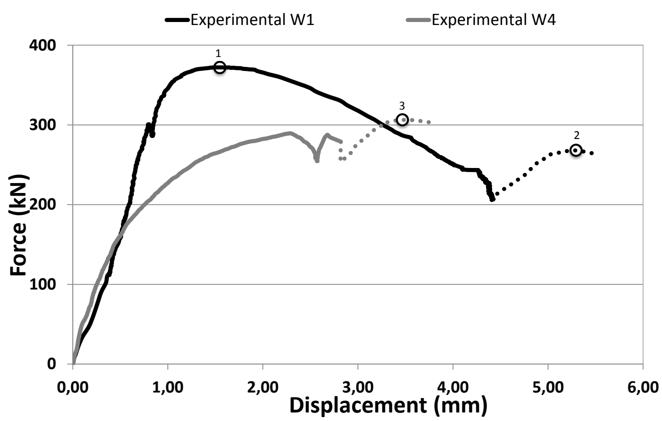


Fig. 3. Experimental results - Walls W1 and W4: Force vs. Vertical displacement diagram (note: vertical displacement measured at the top of the specimen).

The behavior of the tested panels can also be analyzed in terms of shear stress–shear strain curves, as presented in Figure 4, where the shear stress and shear strain were calculated according to ASTM standard [1].Results for diagonal compression test are presented in Table I.

3) Masonry specimens built with air lime mortar: According to the results obtained for masonry specimens, which were built with air lime mortar and diagonal positions of the layers (parallel to the faces), these specimens have much lower strength than the specimens based on hydraulic lime mortar. Namely, the ultimate load for specimen W2 was 29 kN with vertical shortening of 1.58 mm (Point 1) and for the masonry specimen W3, the ultimate load was 28 kN with value

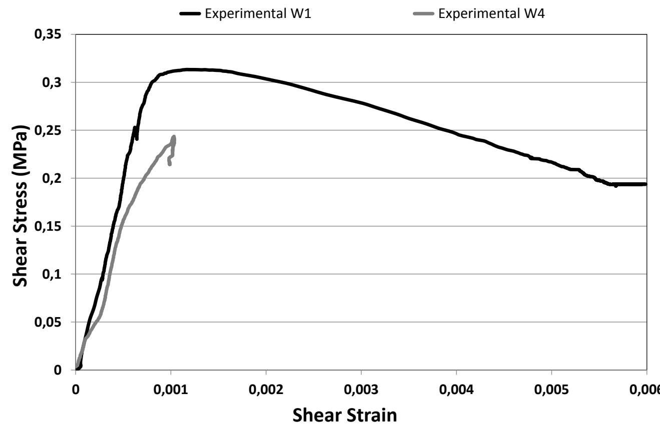


Fig. 4. Experimental results - Walls W1 and W4: Shear Stress vs. Shear Strain diagram.

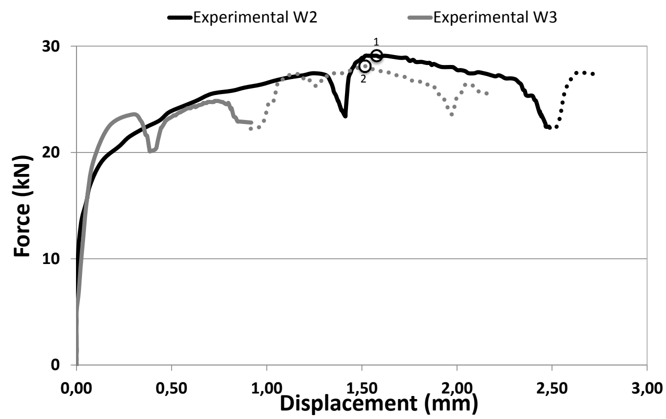


Fig. 5. Experimental results - Walls W2 and W3: Force vs. Vertical displacement diagram (note: vertical displacement measured at the top of the specimen).

of vertical displacement of 1.52 mm (Point 2), where vertical displacement obtained as average values of the measurement recorded using LVDTs 3 and 7 for both walls, as can be seen in Figure 5.

As referred, for walls W1 and W4 for safety reasons the transducers were removed before the end of the test (except the transducer that was placed under the hydraulic jack) and the dotted part of the curves in Figure 5 were obtained by interpolation using the measurement of the transducers under the hydraulic jack.

The differences in results for specimens W1 and W4, which were built with different stone arrangement and the similarity of results the obtained for specimens W2 and W3, built with the same stone arrangement, indicate that the stone arrangement has an influence on strength and deformation capacities of the masonry panels.

The results for these masonry specimens are given in Table I. Furthermore, the curves shear stressshear strain are determined and shown in Figure 6.

TABLE I
RESULTS OF THE DIAGONAL COMPRESSION TEST

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

TABLE II
RESULTS OF THE TRIPLET TEST

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	0.26	0.33
	T2				188	0.39	
Series 2	T5	Hydraulic	0.2	48	213	0.44	0.44
Series 3	T3	Hydraulic	0.3	72	267	0.56	0.57
	T4				279	0.58	
Series 4	T6	Air lime	0.1	24	64	0.134	0.13
	T7				56	0.120	
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

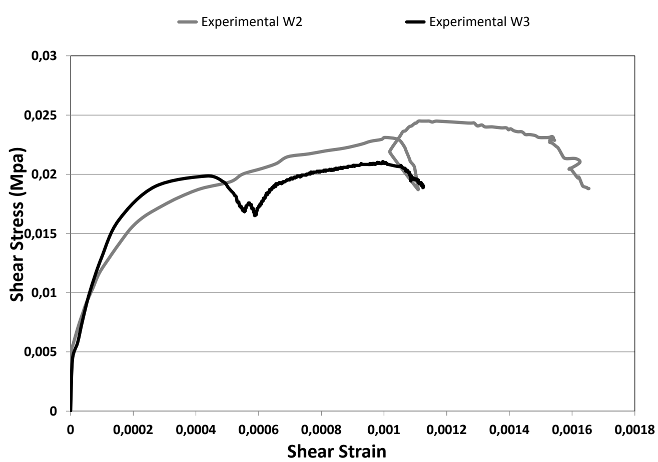


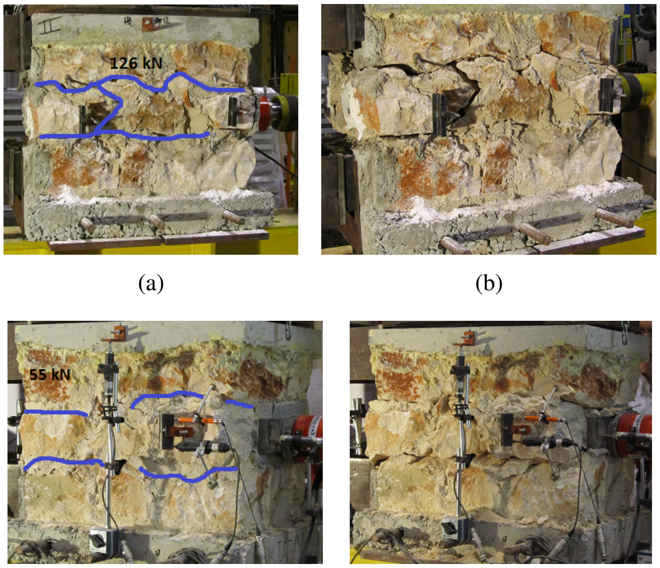
Fig. 6. Experimental results - Walls W2 and W3: Shear Stress vs. Shear Strain diagram.

4) Discussion of the results: Regarding the tested specimens by diagonal compression test, it can be notice that the influence of the type of mortar is very high, as specimens with hydraulic mortar have shear strength about 10 times greater than the specimens built with air lime mortar. Moreover, from these results it can be concluded that stone arrangement indicate some differences in masonry strength and deformation capacity, but anyway this influence is not as huge as the influence of the type of mortar. As can be concluded from the experimental results of diagonal compression test, the wall shear strength is powerfully connected to the mortar resistance, therefore the masonry specimens built with air lime mortar showed a very low shear resistance. Also, it is important to refer that the cracks in all masonry specimens (with hydraulic and air lime mortar) propagated through the joints, without damaging the stones.

For the air lime mortar specimens the maximum compression loads are similar (28 and 29 kN) but the shear elastic modulus G varies significantly. In fact the variation of G for this type of walls is about 38%. The air lime mortar specimens have similar stone arrangements and the reported 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 the variation of the shear modulus G is about 35% and the variation of the maximum compression load is about 18%. The variation on maximum loads can be explained by the different stone arrangement adopted on the hydraulic lime mortar walls. In this case, the variation on G values is connected to both, the stone arrangement and to the measurements errors.

B. Triplet test

Nine masonry specimens were built for triplet tests. Five masonry specimens were built with 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 Figure 7.



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

Fig. 7. Crack pattern (a) and (c) and Collapse (b) and (d) of masonry specimens: (a) and (b) specimen T1 made with hydraulic mortar; (c) and (d) specimen T7 made with air lime mortar

1) Specimens built with hydraulic mortar: The experimental results for the triplet tests on specimens built with hydraulic mortar (series 1, 2, 3) are depicted in Figure 8(a). As can be seen in the load-displacement diagram (displacement was measured with transducer TSH2), the collapse load for specimens tested with a pre-compression of 0.1 MPa, were 126 kN, with an horizontal displacement of 5.56 mm, in specimen T1 and 188kN, with an horizontal displacement of 6.50 mm, in specimen T2. For a compression of 0.2 MPa the collapse load for specimens T5 was 213 kN, with horizontal displacement of 6.09 mm. Two more specimens, T3 and T4, were tested with a 0.3 MPa pre-compression level and the collapse loads were respectively, 267 kN, with an horizontal displacement of 5.95 mm, and 279 kN, with an horizontal displacement of 8.42 mm. As it was expected, higher pre-compression levels produced higher shear resistances.

An important issue regarding shear tests is the dilatant behavior of masonry joints. The dilatancy, i. e. the relation between the vertical and the horizontal strains, has a significant role in numerical modeling and can be much more relevant in rubble stone masonry walls than in brick masonry walls. Figure 8(b) shows the vertical displacement that can be considered measure of dilatancy, as a function of the horizontal displacement. It is important to note that the vertical displacement showed in Figure 8(b) were calculated using the average of displacement recorded by LVDTs 12 and 13 and the corresponding horizontal displacement was recorded using the transducer placed on the horizontal actuator (TSH2).

In Figure 8(a) and 8(b) the points where the linear behavior ends and the points of maximum force are marked. It can be notice that the vertical displacement started to increase after the end of the linear behavior.

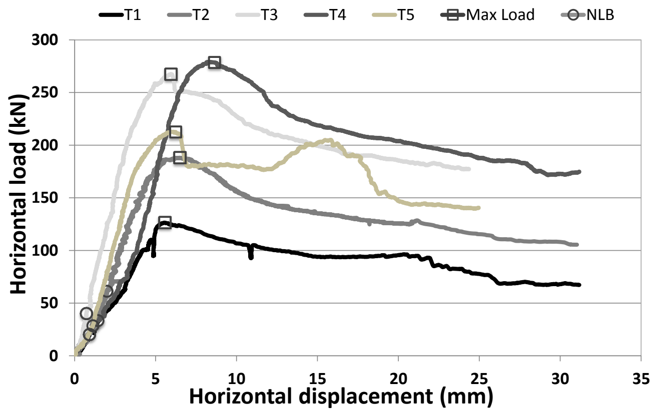
In Figure 8(c) is depicted the relation between vertical load and horizontal displacement, where it can be seen that during the tests the vertical load was almost constant, as was required.

2) Specimens built with air lime mortar: The experimental results for the triplet tests on specimens built with air lime mortar (series 4, 5, 6) are depicted in Figure 9(a). As can be seen in the load-displacement diagram (displacement was measured with transducer TSH2), the collapse load for specimens tested with a pre-compression of 0.1 MPa, were 64 kN, with an horizontal displacement of 13.10 mm, in specimen T6 and 56 kN, with an horizontal displacement of 5.57 mm, in specimen T7. For a compression of 0.3 MPa the collapse load for specimens T8 was 139 kN, with horizontal displacement of 8.23 mm. The last specimen, T9, which was tested with compression of 0.5 MPa, showed the collapse load of 161 kN, with value of horizontal displacement 13.75 mm. Similarly, as in case of hydraulic mortar, higher pre-compression levels produced higher shear maximum loads. As already mentioned, the important issue regarding the shear tests is the dilatant behavior of masonry joints. The relation between the vertical and the horizontal displacements can be seen in Figure 9(b), where vertical displacement represents average values of the measurement recorded using LVDTs 12 and 13. In Figure 9(c) relation between vertical load and horizontal displacement can be seen and also can be noticed that vertical load was almost constant during the tests.

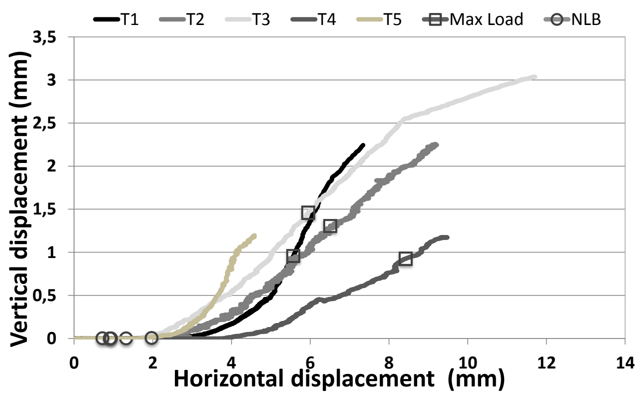
For air lime mortar, as in the case of hydraulic mortar, the points of maximum force and ends of the linear behavior are marked, as can be seen in Figure 9(a) and 9(b). In this case the vertical displacement started to increase after the end of the linear behavior, showing that dilatancy is not relevant at this stage.

In Table II values of the shear strength of the panels, which results in an higher shear strength under increasing pre-compression level are shown.

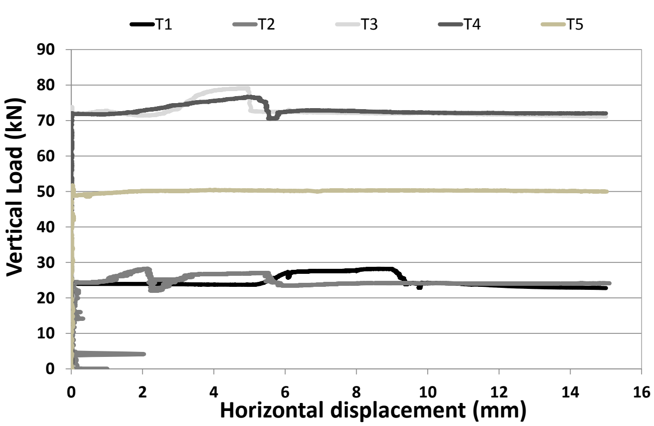
3) Discussion of the results: Figure 10 shows the relation between the normal pre compression stress and the shear strength for all tests. Two straight lines, one for each type of mortar specimens, evaluated by linear regression are also presented in the graphic of Figure 10.



(a) Horizontal load vs. Horizontal displacement; Note: Max Load – maximum load; NLB – end of linear behavior

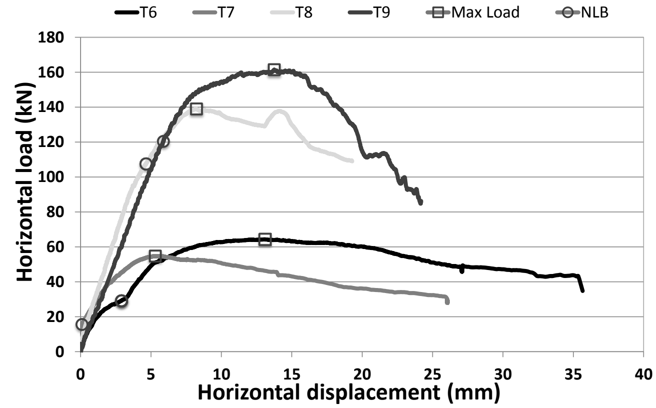


(b) Vertical displacement vs. Horizontal displacement; Note: Max Load – maximum load; NLB – end of linear behavior

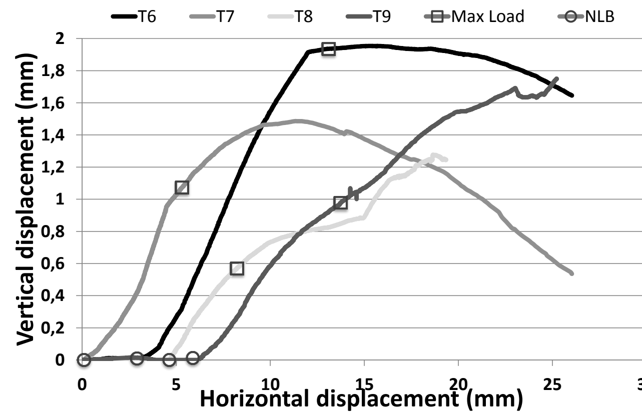


(c) Vertical load vs. Horizontal displacement

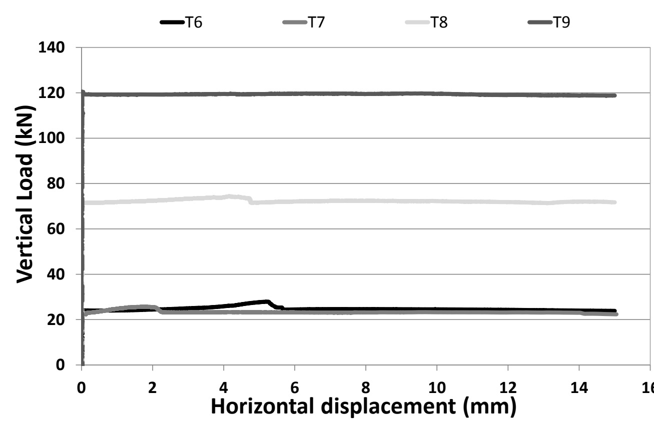
Fig. 8. Experimental Results for Triplet test – Walls T1; T2; T3; T4; T5 (hydraulic mortar).



(a) Horizontal load vs. Horizontal displacement; Note: Max Load – maximum load; NLB – end of linear behavior



(b) Vertical displacement vs. Horizontal displacement; Note: Max Load – maximum load; NLB – end of linear behavior



(c) Vertical load vs. Horizontal displacement

Fig. 9. Experimental Results for Triplet test – Walls T6; T7; T8; T9 (air lime mortar).

The good correlation between the experimental results and the linear regression confirms the initial assumption of a Coulombs friction law for shear strength.

The linear regression provides the shear strength parameters of the Coulombs friction model, namely the initial shear strength, or cohesion, τ_0 and the coefficient of friction μ. For hydraulic mortar specimens the values obtained for cohesion and coefficient of friction were 0.20 MPa and 1.23, respectively. For air lime mortar specimens the obtained values for cohesion and coefficient of friction were 0.08 MPa. and 0.56, respectively. However, according to the EN 1052-3 [2] standard, the characteristic values for cohesion and for the coefficient of friction are about 80% of the experimental values. Thus, the cohesion characteristic values τ_{k0} for hydraulic mortar specimens and air lime mortar specimens are, respectively, 0.16 MPa and 0.07 MPa. The characteristics values for the coefficient of friction μ_k are 0.98 and 0.45 for hydraulic mortar specimens and air lime mortar specimens, respectively.

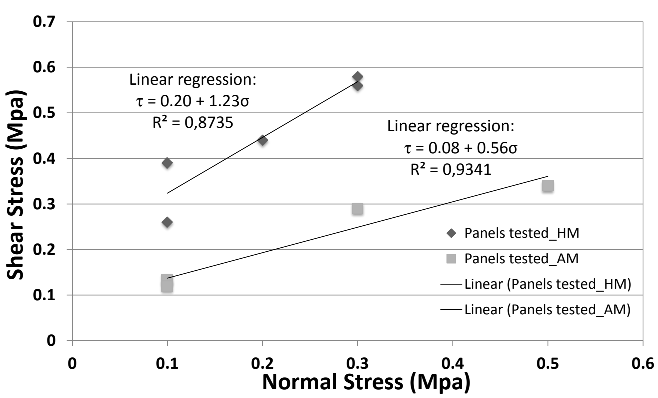


Fig. 10. Relation between shear strength and normal stress

The two groups of specimens (with hydraulic and air lime mortar) differ in terms of initial shear strength, coefficient of friction and ultimate load. As can be noticed in Figure 10, the specimens based on air lime mortar have much lower shear strength: (μ = 0.56, τ_0 = 0.08 MPa) for air lime specimens and (μ = 1.23 and τ_0 = 0.20 MPa) for hydraulic lime specimens. In this type of tests the influence of the mortar composition was bigger than it was in the compression tests. This is due to the fact that the specimens in triplet tests collapsed by sliding of mortar joints without major stone crushing. It is worth to refer that the characteristic values of initial shear strength and coefficient of friction obtained with the samples made with air lime mortar are similar to the values proposed by the [2] for the same type of masonry.

The complete results for all triplet tests are given in Appendix.

C. Compression test

As already mentioned, the compression tests were performed on two small masonry specimen, C1 built with hydraulic lime mortar and masonry specimen C2 built with air lime mortar. The experimental results for the compression tests are depicted in the force-displacement diagram in Figure 11. For the hydraulic lime specimen (C1) the collapse load was 1282 kN, with vertical displacement of 1.53 mm, whereas for the air lime specimen (C2) the collapse load was 1186 kN, with vertical displacement of 6.71 mm. Results for compression test are presented in Table III. The Table III also shows the Youngs Modulus (secant value at 1/3 of the ultimate load). The behavior of tested panel was also analyzed in terms of compressive strength–strain curves, as can be seen in Figure 12.

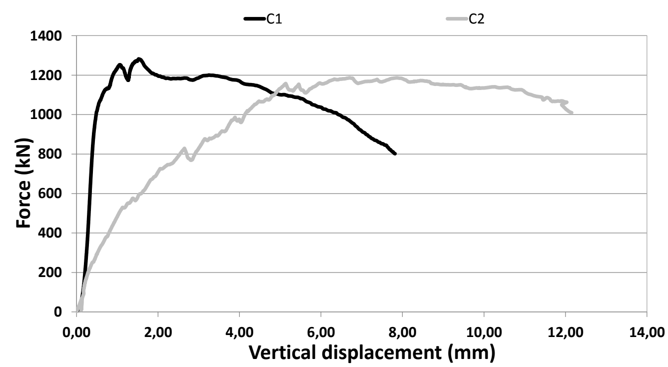


Fig. 11. Experimental results - Walls C1 and C2: Force vs. Vertical displacement diagram .

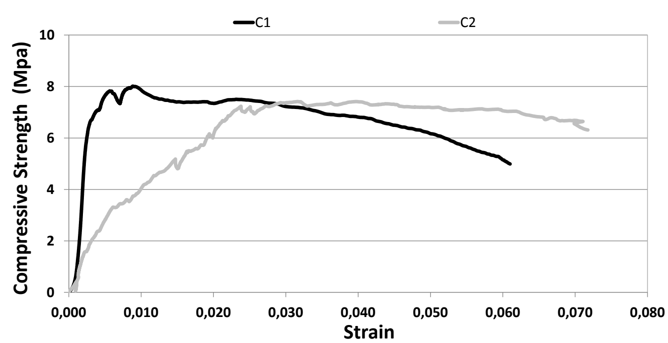


Fig. 12. Experimental results - Walls C1 and C2: Shear Stress vs. Shear Strain diagram.

TABLE III
RESULTS OF THE COMPRESSION TEST

Masonry typology	Type of mortar	$P_{(max)}$ [kN]	σ_0 [MPa]	E [GPa]
Random rubble	Hydraulic	1282	8.0	1.639
stone masonry	Air lime	1186	7.41	0.563

The experimental results showed an unexpected similarity between the strength of the hydraulic lime and the air lime specimens. This can be explained by the specimen's failure mode, which involves in both cases the stone crushing (Figure 13). In this case the mortar strength and stiffness did not influence the specimen's strength (which collapsed by stone to stone contact) but only the specimen's initial stiffness. However, different thicknesses of mortar layers and different stone arrangements could result in different ultimate loads, as it was obtained in previous work [3] where the stones settlement during the construction of the samples was not done with as much care as in the cases reported in this paper.

(a) Crack of the specimen C1

(b) Collapse of the specimen C1

(c) Crack of the specimen C2

(d) Collapse of the specimen C2

Fig. 13. Crack and collapse of masonry specimens: (a) and (b) wall with hydraulic; (c) and (d) wall with air lime mortar.

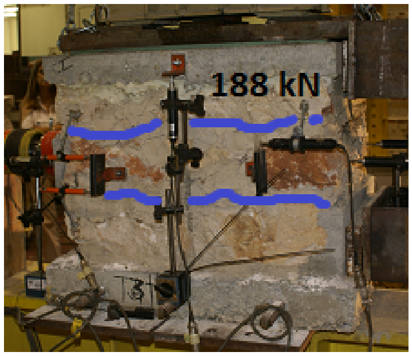
References

[1] A. Standard, "ASTM E519-02, Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages," *ASTM International, West Conshohocken, PA*, 2002.

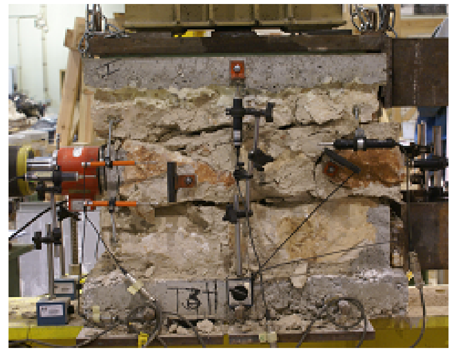
[2] PCM, "3274," *Ordinanza del Presidente del Consiglio dei Ministri n 3274 del 20 Marzo 2003: Allegato 2: - Norme tecniche per il progetto, la valutazione e ladeguamento sismico degli edifici, Italy*, 2003.

[3] J. Carvalho, "Caracterização mecânica de paredes resistentes em alvenaria de pedra através de ensaios não destrutivos," Master's thesis, Instituto Superior Técnico, 2008.

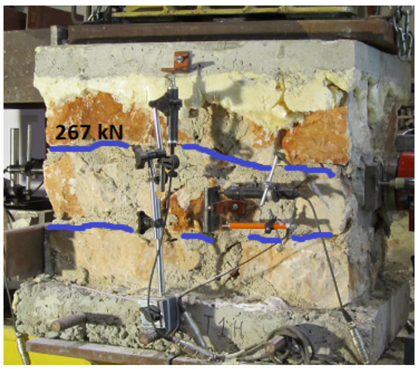
APPENDIX
ALL RESULTS FOR TRIPLET TEST



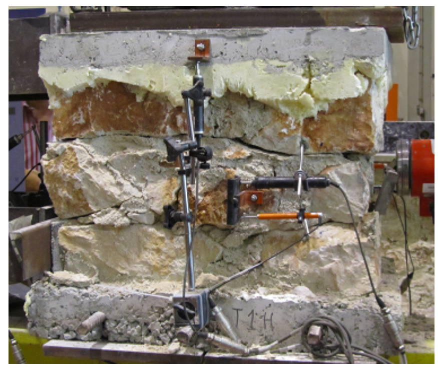
(a) Crack pattern of the specimen T2



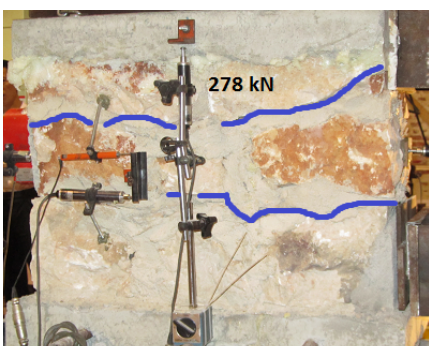
(b) Collapse of the specimen T2



(c) Crack pattern of the specimen T3

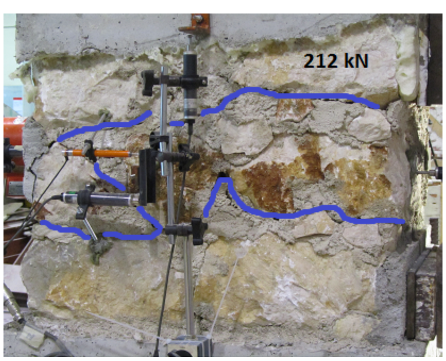


(d) Collapse of the specimen T3



(e) Crack pattern of the specimen T4

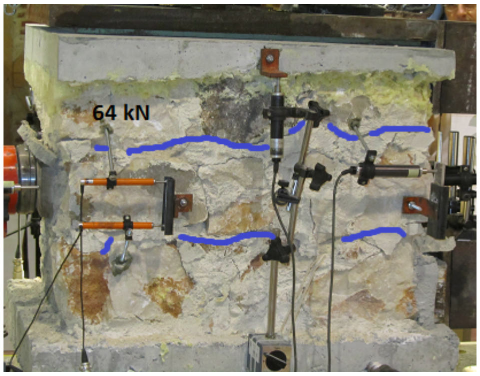
(f) Collapse of the specimen T4



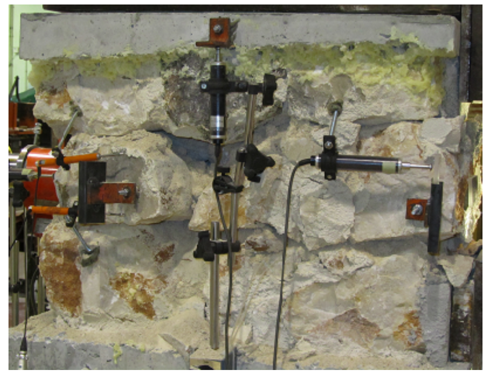
(g) Crack pattern of the specimen T5

(h) Collapse of the specimen T5

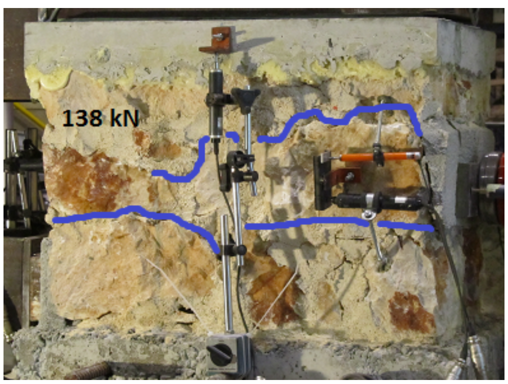
Fig. 14. Crack pattern and Collapse of masonry specimens made with hydraulic mortar



(a) Crack pattern of the specimen T6

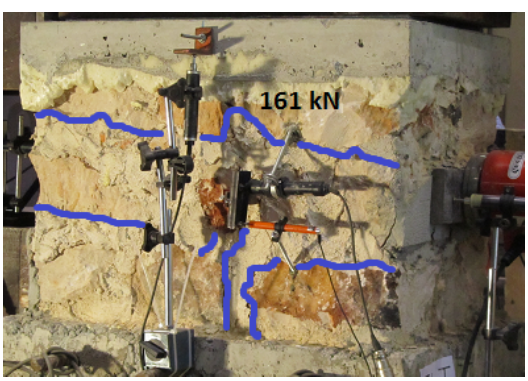


(b) Collapse of the specimen T6



(c) Crack pattern of the specimen T8

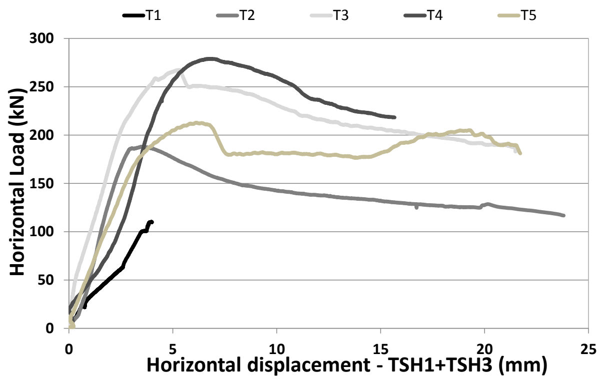
(d) Collapse of the specimen T8



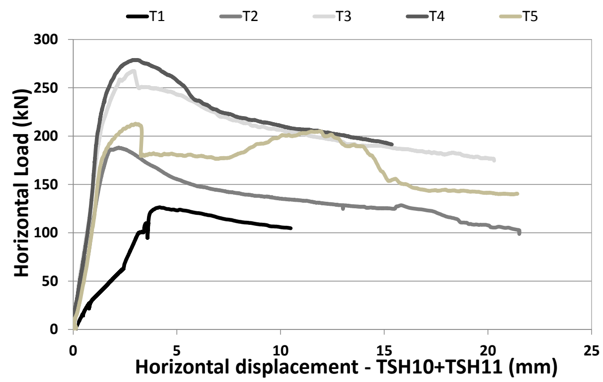
(e) Crack pattern of the specimen T9

(f) Collapse of the specimen T9

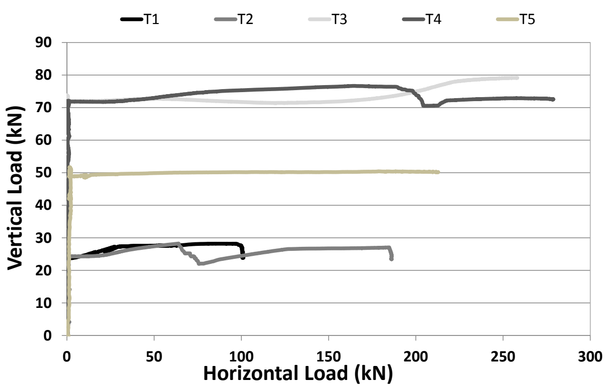
Fig. 15. Crack pattern and Collapse of masonry specimens with air lime mortar.



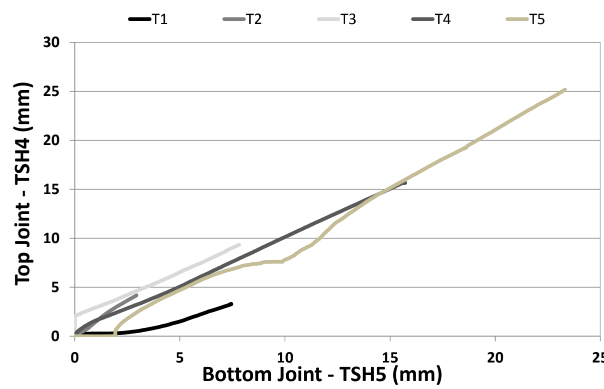
(a) Horizontal load vs. Horizontal displacement-TSH1 and TSH3



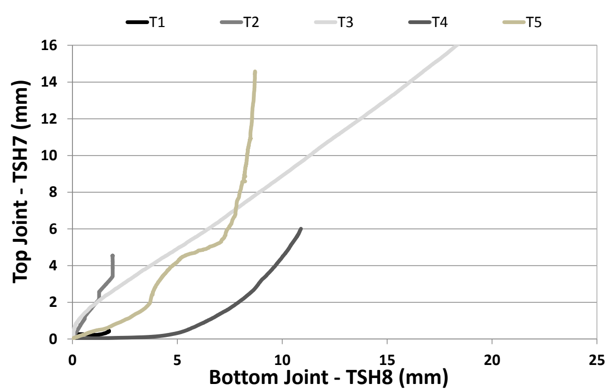
(b) Horizontal load vs. Horizontal displacement-TSH10 and TSH11



(c) Vertical load vs. Horizontal load

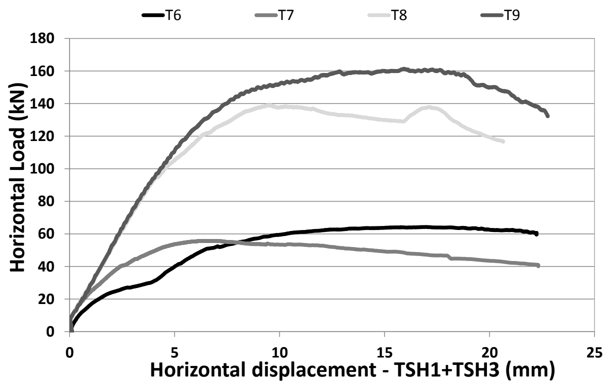


(d) Relation between the horizontal displacement of the joints-TSH4 and TSH5

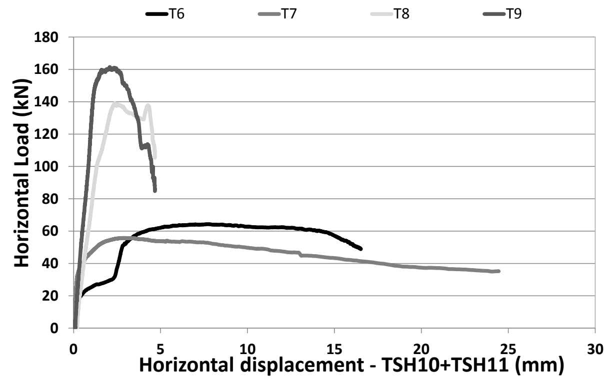


(e) Relation between the horizontal displacement of the joints-TSH7 and TSH8

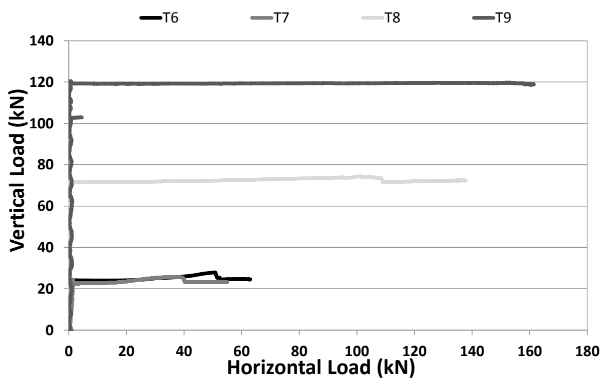
Fig. 16. Experimental Results for Triplet test – Walls T1; T2; T3; T4; T5 (hydraulic mortar).



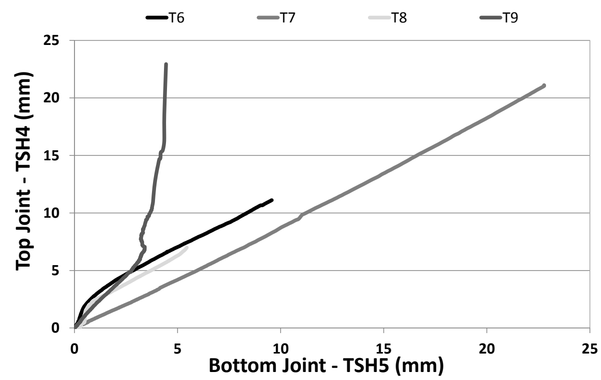
(a) Horizontal load vs. Horizontal displacement-TSH1 and TSH3



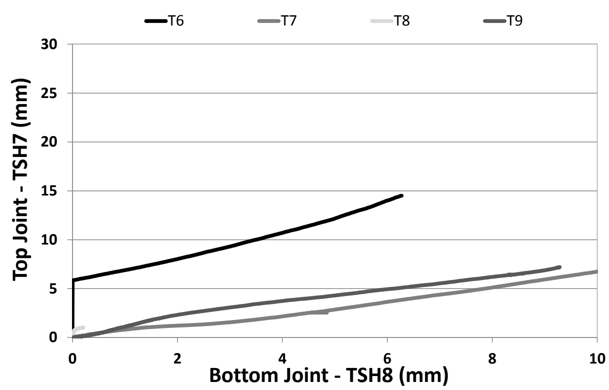
(b) Horizontal load vs. Horizontal displacement-TSH10 and TSH11



(c) Vertical load vs. Horizontal load



(d) Relation between the horizontal displacement of the joints-TSH4 and TSH5



(e) Relation between the horizontal displacement of the joints-TSH7 and TSH8

Fig. 17. Experimental Results for Triplet test – Walls T6; T7; T8; T9 (air lime mortar).