ANALYSIS OF NONLINEAR LOCAL RESPONSE OF RUBBLE MASONRY UNDER CYCLIC LOADS BY DIFFERENT RETROFITTING METHODOLOGIES: AN INNOVATIVE APPROACH FOR TESTING

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ABSTRACT

This work investigates the behaviour of isolated masonry panels under horizontal actions in regions prone to earthquakes. Particular attention to the issue of historical rubbleworks was paid, this which is a rather unexplored branch of construction engineering, although representing a large part of historical structures in Europe. The preservation of existing buildings is essential for future generations to experience culture. In particular, old masonry structures under seismic loads deserve a great deal of attention. Italy is a prime example because it counts numerous cases of historical rubble structures in regions prone to earthquakes. They widely range from independent structures to connected buildings within both monumental and rural housing categories. Solid progress in the theoretical analysis of such structures has been advanced. However, there is still a significant lack of knowledge on this topic, especially for the difficulty in simulating these different kinds of masonries and related reinforcements. Here, these important issues have been approached by means of experimental tests. Destructive tests were performed on reinforced and unreinforced full-scale elements; consequently, the significance of performing validation procedures on existing elements has been shown. Monotonic and cyclic tests were executed with the final outcome of identifying both in-plane and out-of-plane local responses. With regards to out-of-plane responses, an innovative approach for testing was introduced. Its aim was to identify the response of isolated rubble macro-element under alternate cross-horizontal actions. Hence, particular concern to the out-of-plane modes of damage and associated failures under seismic action was given. Different reinforcement strategies were tested, focusing on the influence of cross-sectional elements and small fillers on the global stability of rubbleworks. Throughout the paper, the implications of our findings are discussed and detailed.

Keywords: in-situ cyclic tests, fillers, out-of-plane response, interlocked-masonry, strengthening measures.

1. INTRODUCTION : Rubbleworks with respect to Seismic Hazards

Headers and stretchers are the elements used for providing the strength of masonry against out-of-plane and in-plane seismic loads, respectively [1]. Nevertheless, rubbleworks usually do not feature these components; rather rubbles are randomly displaced and glued by exceedingly large mortar joints (see Fig.1). In the reality, such a rule of setting can be found: rubble sequences are always filled and regularized by small fillers [2]. Hence, small fillers supply to these deficiencies by interlocking rubbles and connecting bigger stones within the courses sequences. Their employment is crucial and essential for the resistance of rubbleworks under seismic actions and due to their *shaped-interlock* they are able to produce extremely hard mechanical connections [3]. The assumption of this last key concept drives any aspect of the presented research; consequently, three progressive goals were addressed: (i) the clarification of the mechanical roles of individual stones within the static of global panels, especially small fillers and their influence on the local response of single panels under horizontal actions. (ii) The design of different reinforcement methodologies aimed at finding specific strengthening measures for rubbleworks. (iii) The derivation of a force-displacement curve for isolated panels, representative of rubbleworks response under cross-cyclic actions.

These issues were pursued by both performing different measures of strengthening on on-site isolated panels and executing out-of-plane validation tests. In the following sections, an overview of the different kind of techniques designed is provided and a particular consideration on the degradation effects produced by cyclic tests is emphasized.

3. THE STRENGTHENING APPROACHES

Strengthening measures and validation tests were applied. They were planned to be assessed throughout two main case studies [3]: the L'Aquila city, which was recently hit by an earthquake, and the Gallico Marina one, in the Reggio Calabria area, which was devastated by catastrophic events in the past [2]. In particular, L'Aquila is a chief example of historical city as it is built by rubble masonry and located in an area with strong and frequent seismic activities.

Recognition of rubble masonry types was the research starting point. As shown in Figure 1, these stoneworks feature the following main characteristics: random setting, small size of stones, regulatory layers made of bricks, no cross-links and exceedingly large mortar joints.

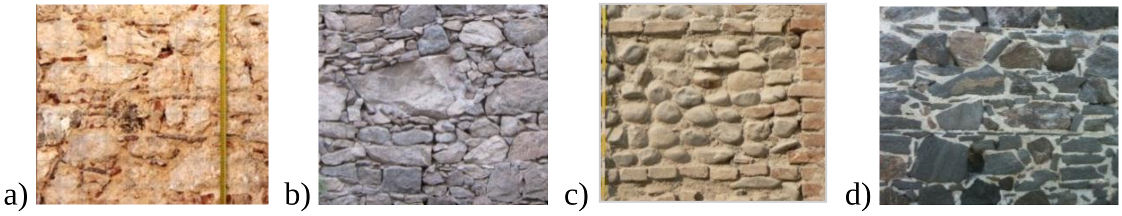


Figure 1: Rubblework types under study. a) L'Aquila experiment: the specimen; b) Uncoursed type: fortified wall of the historical city of Lipari (UNESCO Patrimony, Aeolian Islands); c) Reggio Calabria experiment: the specimen; d) Coursed type: wall of a building placed within the Pumice quarry (Lipari).

Seven different reinforcement strategies were applied: they range from traditional techniques to advanced methodologies (Fig. 2 b). Their design was entirely conceived around two main types of rubbleworks (Fig. 1a,c), made either by regulatory layers of bricks and enclosing elements (Fig. 1c) or built with unsystematic patterns of rubbles (Fig.1,a). According to the basic knowledge stated in Section 2, for the samples in Figure 1, two crucial lacks were noted [5]: (i) absence of cross-tying elements; (ii) local deficit of small fillers or exceedingly large mortar joints. The reinforcement strategies are expected to solve one or both aforementioned faults. In the following an overview of the different types of reinforcements applied is given and two different techniques are presented.

3.1 Experiments in L'Aquila City

The first experiment deals with the structures of an ancient building placed in the historical centre of L'Aquila city and damaged by the earthquake on April 6th, 2009 [6]. Due to the extensive damage (Fig. 2,a) the edifice was added to a demolishing program [5]. An experimental program to investigate the load bearing capacity of the panels placed at the first level of the building was planned. Seven panels were separated by each other, following the openings sequence. Five panels were reinforced with different techniques (Fig. 2b) and two unreinforced elements were deemed to be appropriate reference samples. The geometrical dimensions of the obtained panels are: height of 400 cm, thickness of 60 cm and width having variable lengths.

Figure 2: a) The case study after the 2009 April 6th earthquake; b) The in-situ experiments: the panels under reinforcement operations.

3.1.1 Panel n.1

Panel n.1 was reinforced by fibre-reinforced materials. This strengthening methodology is given within the technical literature under the name of “Reticolatus”, designed at the University of Perugia. Its aim is to both provide a cross-interlock especially for rubble masonry types and supply resistance to tensile strength for out-of-plane actions.

In this case study, two different solutions, developed in partnership with the FIBRENET Company, were applied to the same sample and directed to increase the tensile capacity of *Reticulatus* reinforcement (Fig. 3a). A glass-fibre-reinforced polymer (GFRP) plaster covered the inner surface of the sample and this layer was vertically connected to the floor structures by steel bars. A second reinforcement made by a mesh of Dyneema rope was applied to the external surface of the panel (Fig. 3b). The rope was accurately settled by following the masonry pattern. The cross-interlock was obtained by setting transversal metal connectors hooked to both GFRP plaster and the rope mesh (Fig. 3b), which ensure collaboration between the two different reinforcements. Executive details and further information are given in [3,5].

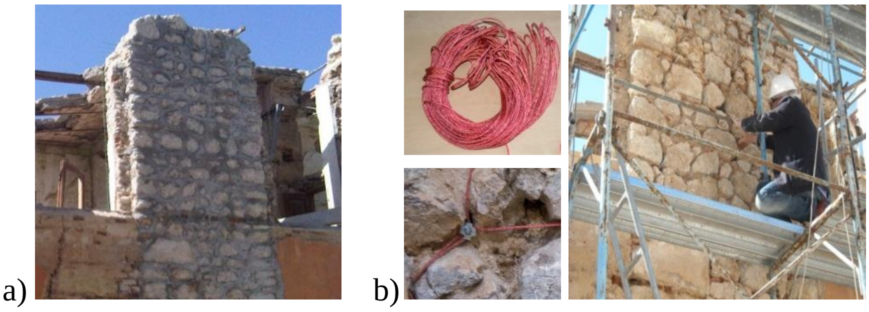


Figure 3: Panel n.1: a) the reinforced panel; b) Dyneema rope mesh and transversal connectors.

3.1.2 Panel n.2

Panel n.2 was reinforced by artificial T-shaped headers. They were designed at the University of Reggio Calabria, its aim is to both provide a cross-sectional interlock and prove the effectiveness of the reinforcement. The practice of cross-interconnecting masonry panels by means of big elements, namely headers (*Diatoni*), is well-known [1]. Despite this, the effectiveness of these elements as reinforcements is still not clearly defined, especially for random settings, which are unable to feature these massive elements. These headers are T-shaped and made out of concrete. During the application of such big transversal elements, four equally distributed boreholes are drilled into the panel surface. Unfortunately, big holes create a weak area in any load bearing element (see Fig. 4a). This issue has to be solved since the application of external device has to be designed with the aim of reinstating the inner equilibrium of the strains. The presented artificial headers were designed to accommodate the external devices shown in Figure 4b. Executive details and further information are given in [3,5].

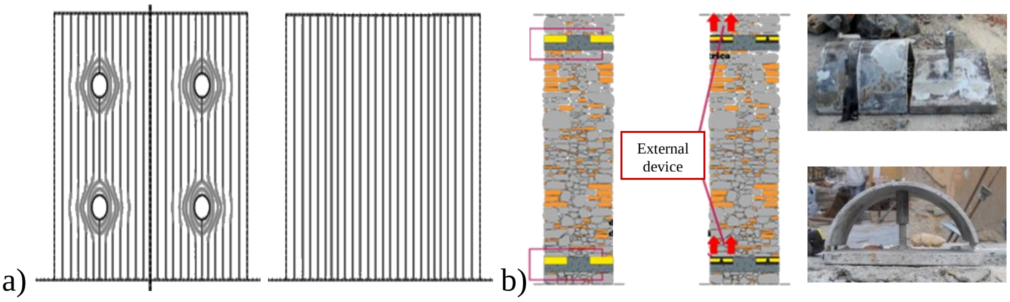


Figure 4: Panel n.2: a) the strains flow; b) the mechanical role and pictures of the external device.

3.1.3 Panels n.3 and n.4

Panel n.3 was reinforced by advanced headers called “*injection anchors with sock*” [7]. This strengthening methodology joins together the system patented by BOSSONG S.p.a. based on injection anchors with sock, with the traditional concept of cross-interlock. The basic idea is to create a transversal connector able to connect the inner masonry patterns, so to consequentially provide a perfect interlock among them. Hence, a steel bar equipped with a deformable sock was applied, in order to both enclose the injection and glue the header to masonry inner surfaces. Further details are given in [3]. In contrast, panel n.4 was reinforced by the common injection technique.

3.1.4 Panel n.5

Headers and small fillers reinforced panel n.5. The aim of this kind of strengthening is to both provide a cross-sectional interlock and prove the small fillers role within the static of rubble masonry elements. Hence, four wooden headers and small fillers in replacement of the mortar joints strengthened the panel. The choice of wooden elements was mainly due to the ancient constructive practice of the L'Aquila territory. Many examples in this area can be found, they widely range from masonry cross elements to entire seismic-resistant systems. Executive details and more information are given in [3,5].

3.1.5 Comparison of results

A comparison among the above-mentioned techniques is shown in Figure 5, where the curves recorded for panels from 1 to 4 subjected to monotonic tests are plotted. Additionally, the curve of the envelopment of the maximum values for Panel n.5 is reported, too [8]. Two main observations are: (i) the influence of headers within the linear phase, which causes an increase of the initial stiffness of the curves; (ii) the different contribution in terms of strength given by the reinforcements in the non-linear phase and the inefficiency of common injections. The experimental behaviours of panels n.2 and n.5, both of them reinforced with headers and experiencing a rigid overturning were compared (Fig.5,b). It is apparent that panel n.5 showed the best performance [3,8]. In addition, by comparing the response of Panels n.2 and n.5, it is possible to clearly identify the influence of small fillers. Four headers reinforced both panels and small fillers strengthened Panel n.5 in addition. Also, by making a comparison between the reference panel and Panel n.5, it is evident that only an increasing force necessary to produce the overturning is noticed (Fig. 6,b). In fact, the use of the traditional reinforcement technique represented by small fillers increases neither the stiffness nor the maximum displacement (see Fig. 5,b).

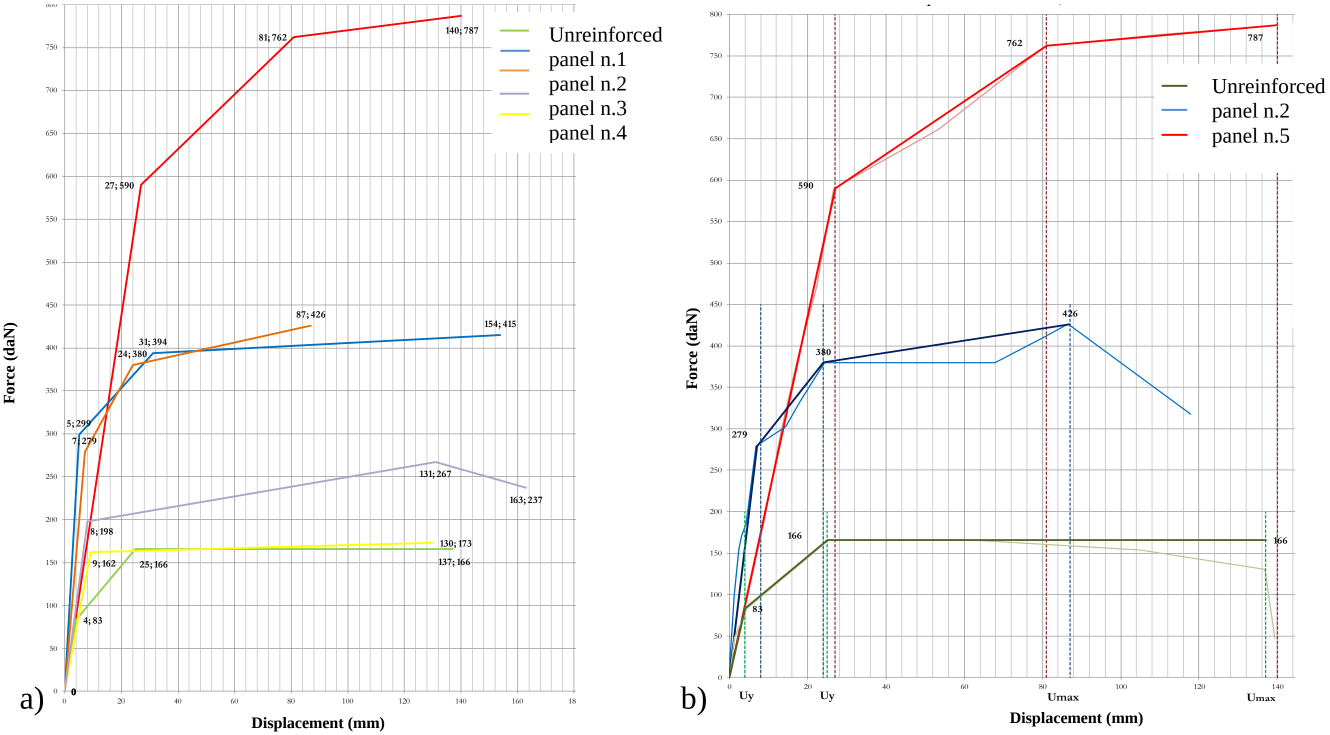
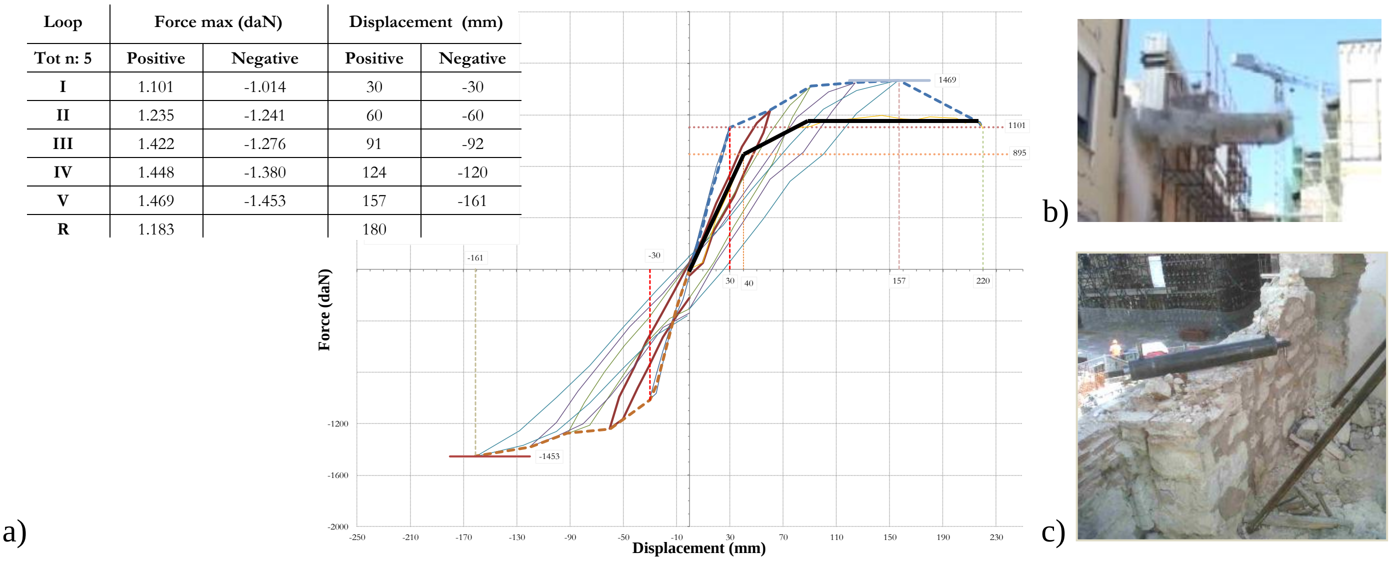


Figure 5: The L'Aquila on-site experiments: comparison among reinforcements. a) Any methodology; b) Panels n.2 and n.5.

In particular, Panel n.5 was tested by means of an out-of-plane cyclic test. This was executed in displacement control. A single hydraulic device with maximum stroke of 700 mm applied cyclic actions in the panel centre of gravity. These actions are comparable to the earthquake loads and they were applied with steps of displacement of 30 mm per loop and the data recording was assured by computer software. The testing methodology was successfully introduced, since the application of this technique provided a better observation of the rocking effects. Additional remarks can be drawn from direct observation of the experimental results in terms of both the force-displacement constitutive curve (Fig. 6a) and the achieved overturning mechanisms (Figs 6b and 6c). However, in light of the subsequent tests the execution of this check was incomplete, once the peak force was reached, the test was concluded. Despite this, the comparison between the overturning curve (in Fig. 6 in black) and the curve of the envelopment of the maximum values (Fig. 6 in light blue) gave the chance to observe a progressive development of inelastic deformations within the reacting portions.



Loop	Force max (daN)		Displacement (mm)	
Tot n: 5	Positive	Negative	Positive	Negative
I	1.101	-1.014	30	-30
II	1.235	-1.241	60	-60
III	1.422	-1.276	91	-92
IV	1.448	-1.380	124	-120
V	1.469	-1.453	157	-161
R	1.183		180	

Figure 6: The L’Aquila in-situ experiments: a) cyclic response and (b) final overturning of the panel n. 5; c) the panel breaking.

Additionally, curves with similar trend described the response of the other panels (Fig. 5,a). This significant experimental evidence is in contrast with the theoretical idea of a rigid block overturning. The theoretical bilinear force-displacement curve, with no dependence on the applied reinforcement, turns into form of three-linear curve with a marked non-linear trend. In particular, the latter is always described by curves with significantly large displacements, despite a negligible decrease of resistance (See Fig. 6,b).

3.2 Experiments in the Reggio Calabria district

The second experiment deals with the remaining structures of an ancient building placed in the historical centre of Gallico Marina (district of Reggio Calabria) [3,9] (Fig. 7a). This small Italian city was settled after the earthquake on 1783 February 5th. The existing building under investigation, which belongs to one of the eighteenth-century *insulae* of the city (Fig. 7b), due to its minor historical value (Fig. 7c) was added to a demolishing program.

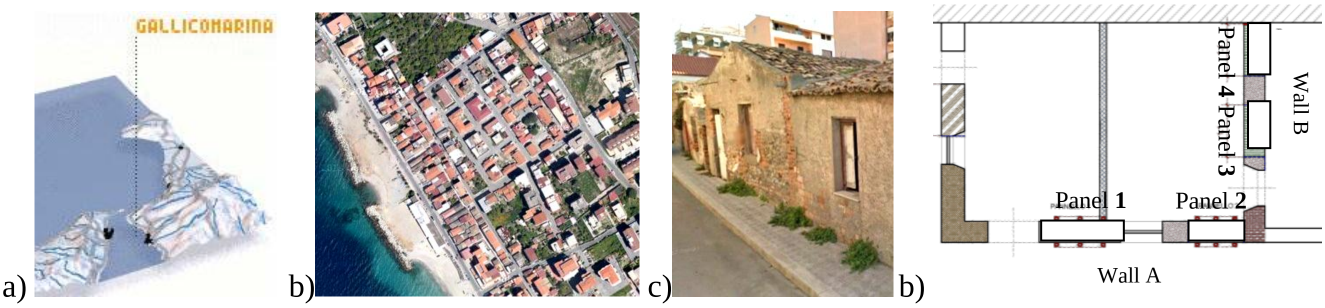


Figure 7: Experiments in Gallico Marina (Rc) Italy: a) the geographical placement; b) the ancient city of Gallico Marina; c) the case study; d) The building plane: (Wall A) the unreinforced panels [1 and 2] and (Wall B) the reinforced ones [3 and 4].

The building facades (Wall A-B) were cut into four panels separated from the surrounding structures in order to evaluate their behaviour both in the original conditions and after undergoing retrofitting interventions (see

Fig. 7d). The geometrical dimensions of the obtained panels are as follows: height of 275 cm, thickness of 40 cm and different width values. Similarly to the experiments performed in the L'Aquila city, two unreinforced panels were deemed to be appropriate reference samples, whereas two panels were reinforced with different techniques (Fig. 7d).

Since the overall aim was to investigate rubble masonry out-of-plane modes of damage and their failures, the influence of cross interlocked elements was analyzed. This issue was investigated by performing different measures of strengthening; in particular, different typologies of cross-elements were applied, commonly, they are namely: traditional and artificial. Their main role is supposed to be: (i) equally distribute the vertical loads along the cross-section, and (ii) locally supply resistance to tensile strength during the overturning phases. With regards to masonry panels made by separated vertical layers, the introduction of these kinds of interlocked elements is expected to provide resistance for shear stress along the inner surfaces of the different layers. In fact, under horizontal actions, vertically-layered masonries suffer from potential sliding of separated walls due to unequal overturning. Consequently, the reinforcements were advanced in order to provide the whole-sectional panel resistance against alternate horizontal actions by tying-cross the layers.

Special attention was paid to the issue of the replacement of degraded mortar joints especially during masonry rocking, when the mortar resistance is lost as the increase of the compression pressures becomes greater at the base.

3.2.1 Panel n.3

In the first reinforcement system a particular type of anchors supplies a gradual control of the injection with an innovative drilling system and additional pre-stress. The holes are not regularly spaced in order to improve the cross-interlock and their diameter decrease, as the hole becoming deeper. Despite this, an additional application of a pre-stress action was considered, aiming at creating a transversal compression pressure.

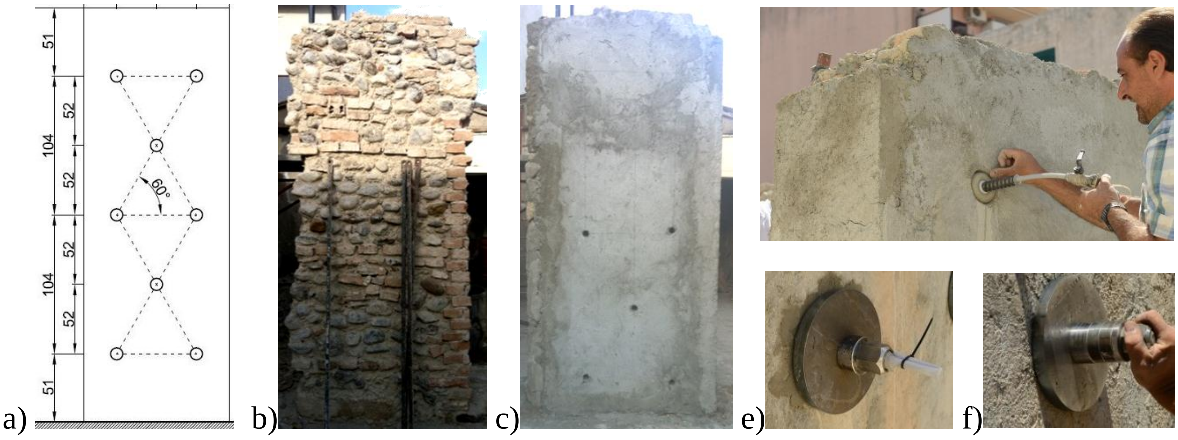


Figure 8: Panel n.3: a) layout of the perforations; b) demolition of the external plaster; c) application of new support made out of concrete; d) injection; e) closing of the injection; f) tightening of the bolt.

The executive steps of the intervention are: 1. to demolish the external plaster and to clean the mortar joints (Fig. 8,b); 2. to apply a new plaster made out of concrete, in order to avoid the extended process of aging of the hydraulic mortars (Fig. 8,c); 3. to drill 8 boreholes by following the scheme shown in Fig. 8,a; 4. to set transversal steel anchors wrapped by a special sock patented by Bossong S.p.a.; 5. to apply the mortar for injection with a pressure of about 2.5 bar (Fig. 8,d); 6. to close the injection tube by a specific device, in order to avoid the injection leak (Fig. 8e); 7. to apply both the steel plate and bolts for tightening (Fig. 8,f); 8. to tie the bolts with a tightening torque equal to 40 Nm. In the experimental test, the theoretical behaviour of the panel as a rigid block was noticed. The diagram shows a bilinear trend with a symmetric response. This behaviour is mainly due to the application of a support made out of concrete. Despite this, the effectiveness over time cannot be stated due to the obvious degradation of the concrete itself due to ageing.

3.2.2 Panel n.4

The second system deals with the new concept of rubble masonry as interlocked-stonework. It aims at clarifying the influence of small fillers within rubble masonry constituents. The employment of these elements is crucial for the settlement and lock of bigger stones and their influence has been stated with

respect to the headers effect. Because of this, the panel was reinforced by means of small fillers only. The five main executive steps of this intervention are: 1. to remove plaster and to strip the flesh from rubbles (Figure 9,a); 2. to analyse the masonry setting (Figure 9,b); 3. to wash the surfaces and to inject fine hydraulic mortar (Figure 9,c); 4. to replace mortar joints by small fillers made out of bricks (Figure 9,d); 5. to repoint joints by hydraulic mortar (see Figure 9,e).
Before the experimental test, an early damage of the reinforcement on the right surface was caused. The interlock among the elements, which belongs to the right side of the panel, was affected. During the experimental test, this evidence is clearly observed in the diagram of the Figure 10.

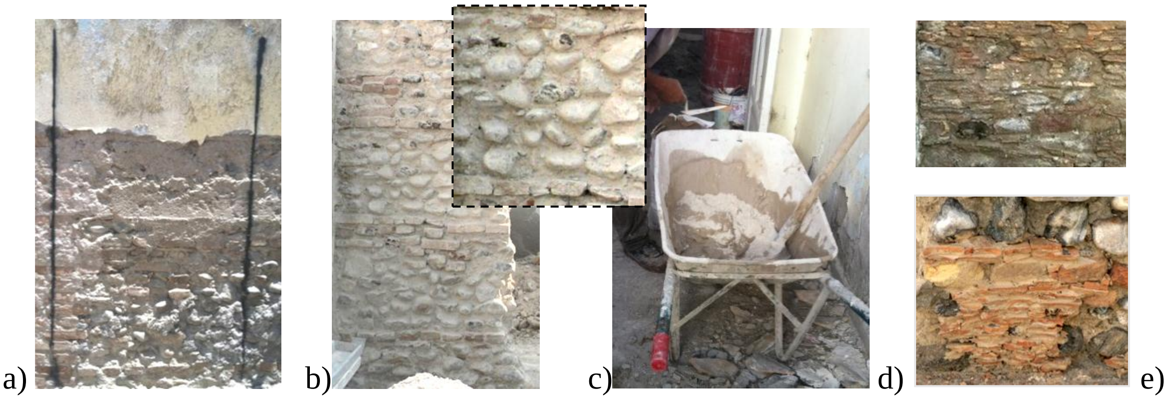
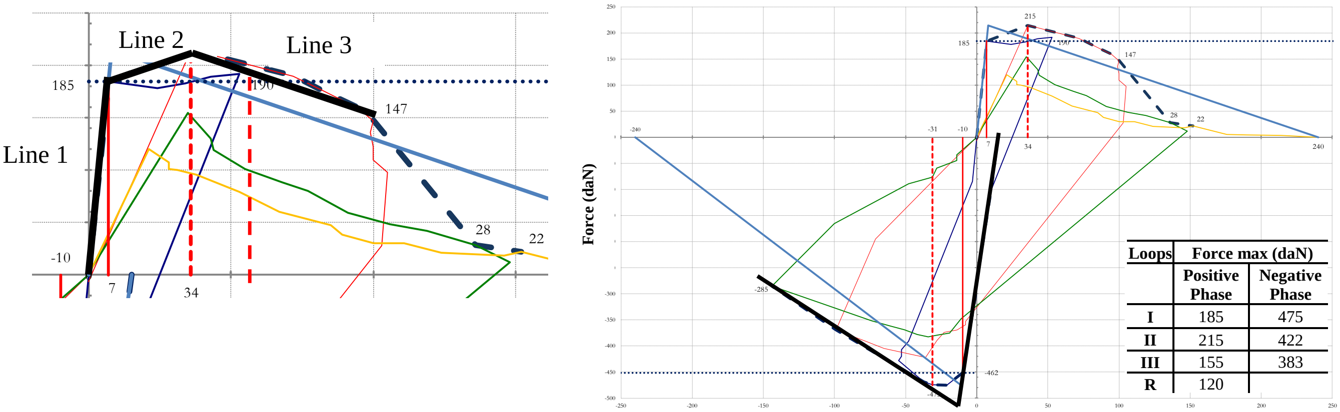


Figure 9: Preparation of the panel n.4 for testing: a) removal of the plaster; b) analysis of the masonry setting; c) preparation of the hydraulic mortar; d) replacement of the old and degraded mortar by small fillers; e) locking the small fillers by hydraulic mortar (repointing).



Loops	Force max (daN)	
	Positive Phase	**Negative Phase**
I	185	475
II	215	422
III	155	383
R	120	

Figure 10: Out-of-plane cyclic test on Panel n.4.

Positive and negative loops gave two different force-displacement curves. It is mainly due to the fact that each loop stresses elements which alternatively belong to right and left side. Concerning the positive phase, the theoretical bilinear curve is replaced by a three-linear one (see Figure 10), instead the negative phase remarks the classic bilinear drift. This result theoretically certifies the effectiveness of the reinforcement and the significance of small fillers within the global resistance of the panel against horizontal actions. In the subsequent section additional explanations and proofs for this surprising result are given by an illustrative case study.

4. THE VALIDATION TEST PROCEDURE: APPLICATION AND RESULTS

4.1 The cyclic test standard procedure

A new testing methodology was introduced, its aims is to simulate the panel resistance loss in consequence of masonry cross-rocking since the out-of-plane modes of damage are the primary cause of building collapse under seismic actions.
The test standards were entirely conceived on the hypothesis of a changing of rubble panels' constitutive curves due to degradation effects of alternate actions. These actions are always applied to the barycentre of the panel and the test is performed with displacement control by growing steps of 15 mm each. Case by case,

this range can be increased up to 50 mm on the basis of both the panel geometrical dimensions and the on-site difficulties. An ultimate monotonic action is applied with the aim of plotting a final degraded curve to be compared with the general trend of the earlier loops. Consequently, two main curves are derived: (i) one resulting from the envelopment of the peak values of different loops and (ii) one associated to the overturning phase. The gap between the peak values of these two curves provides the final response of the panel due to the strength loss. Accordingly, the limit of displacement is defined by following the degradation trend of both curves. The interpolation of the violet and the yellow curves gives the maximum limit of displacement of the panel. To better clarify this concept the example of a rubble masonry isolated panel is reported in Figure 11 and detailed within the next section.

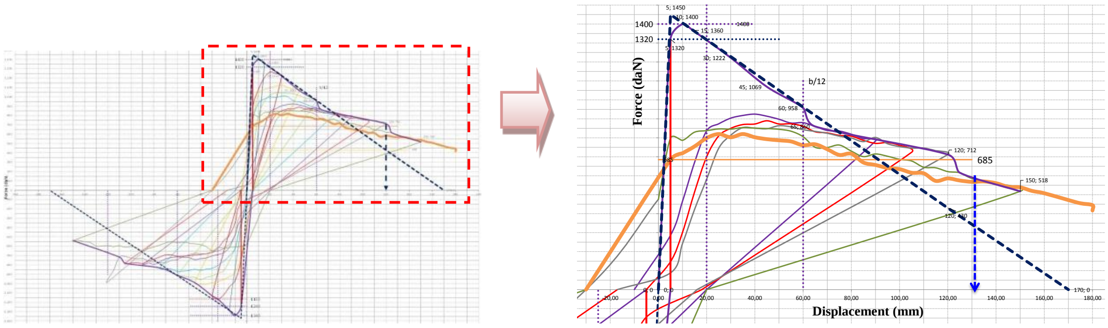
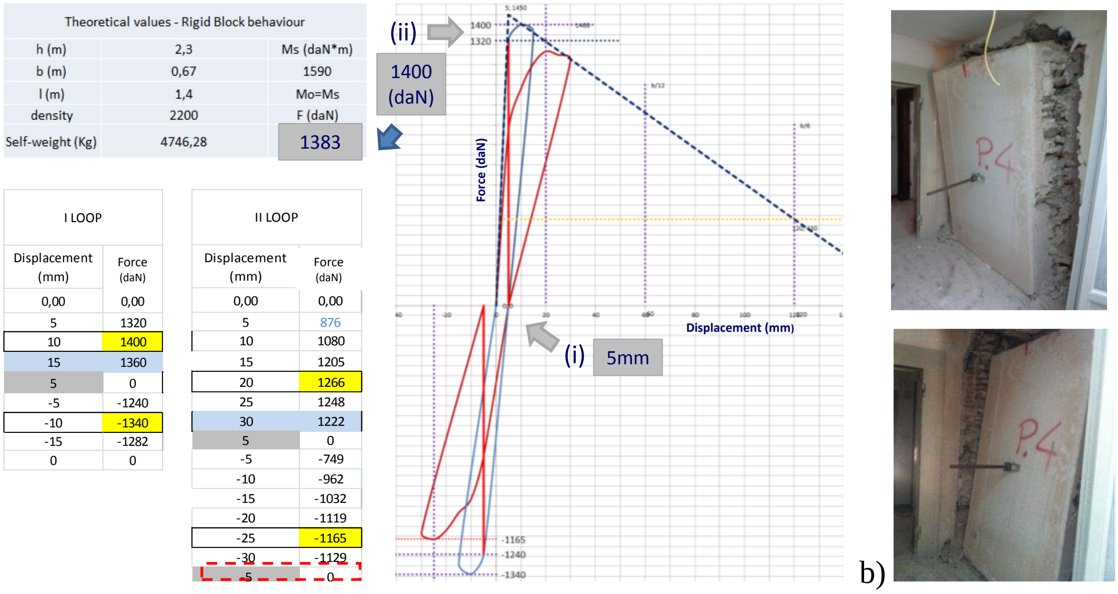


Figure 11: Out-of-plane cyclic test on a rubble masonry panel placed in L'Aquila city.

4.2 The sample of an isolated panel

The sample of an isolated panel placed within an historical Palace in the L'Aquila city was tested according to the new implemented testing methodology. A cyclic tests with quasi-static alternate actions based on steps of 15 mm was performed. In particular, the panel was subjected to nine load cycles and a subsequent monotonic overturning phase with a maximum displacement of 180 mm.



Theoretical values - Rigid Block behaviour		
h (m)	2,3	Ms (daN*m)
b (m)	0,67	1590
l (m)	1,4	Mo=Ms
density	2200	F (daN)
Self-weight (Kg)	4746,28	1383

I LOOP	
Displacement (mm)	Force (daN)
0,00	0,00
5	1320
10	1400
15	1360
5	0
-5	-1240
-10	-1340
-15	-1282
0	0

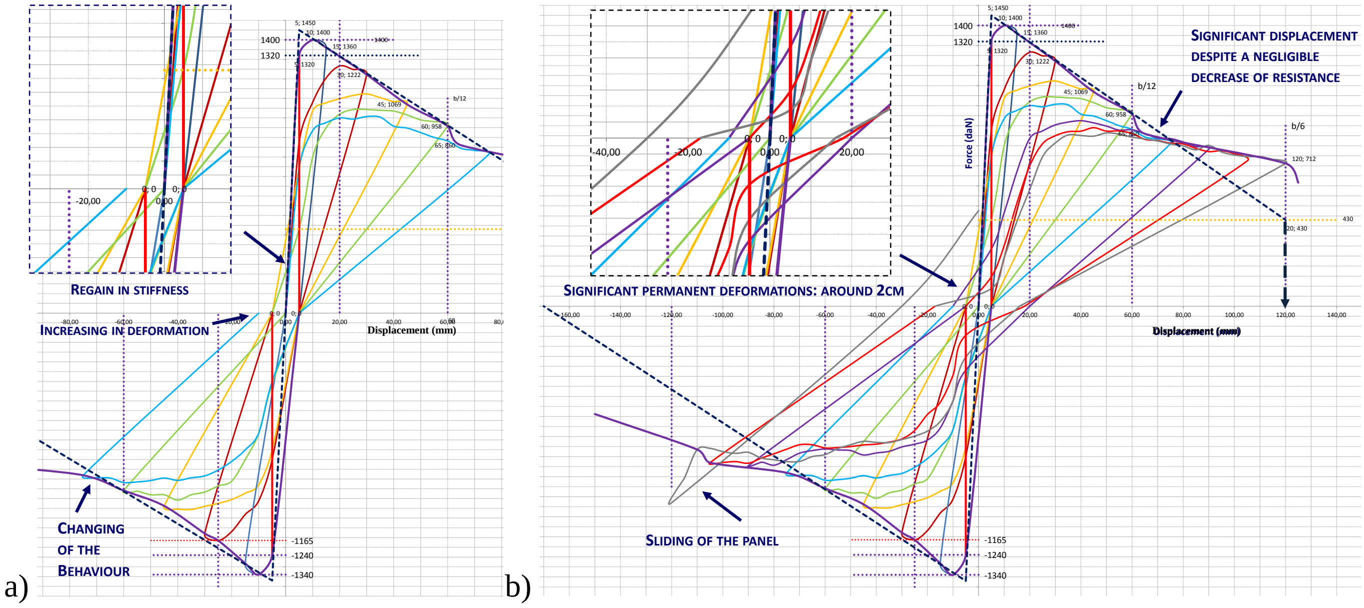
II LOOP	
Displacement (mm)	Force (daN)
0,00	0,00
5	876
10	1080
15	1205
20	1266
25	1248
30	1222
5	0
-5	-749
-10	-962
-15	-1032
-20	-1119
-25	-1165
-30	-1129
-5	0

a) b)

Figure 12: a) Early phases I and II loops; b) The investigated panel.

Figure 12 describes the first two loops. From these loops, it is relevant to observe the permanent deformation at the end of the first loop (Fig. 12 [i]) and a progressive strength decreasing in accordance with the theoretical bilinear curve of rigid block (Fig. 12 [ii]). Figure 13a shows the loops 3 and 4. A change of behaviour of the panel is evident. The decrease of the force does not match with the rigid block curve. In fact, the panel starts to fail and the motion between the inner elements produces an interlock between the sequences of rubbles which is mainly due to the irregularity of the rubbles' surfaces.

By examining and comparing these loops with additional ones, greater displacements were attained despite a modest decreasing of force (see Figure 13,b). A sliding of the panel was observed and eventually, the panel was exposed to a global overturning mechanism. By comparing the two original curves (in blue and violet) with the degraded curve (in yellow) the change of the inner interlocks was confirmed (Fig.11). In particular, by comparing the response of Panel n.4 tested in Gallico Marina with the present sample, a strong similarity has to be stated. The early loops display the same behaviour of Panel n.4 within the negative loading phase (see Figure 10). In contrast, the degraded curve (see yellow curve in Figure 11) shows approximately the same response recorded for the positive response of Panel n.4.



a)
b)

Figure 13: a) Early four loops; b) The eight loops.

5. FINAL OUTCOMES

In this paper we have been investigated the influence of the different types of reinforcements on rubble panels and a promising technique for testing has been detailed. The effect of out-of-plane rocking was evidenced, and the novel concept of interlocked masonry was described and proofed. Accordingly, the mechanical function of *small fillers* has been clarified; they are crucial for the settlement and lock of bigger stones. In particular, under seismic actions, fillers are able to locally avoid out-of-plane bending effects and deformations with respect to the courses track. However, during masonry rocking, their effect is limited at fillers loss. This loss is negligible for the stability of a panel as long as interlock failures are not present in bigger stones. Hence, such a limit of the fillers influence has been stated in respect of headers effect. Because of this, the cyclic response of reinforced and unreinforced existing panels was presented and new methodology for testing shown.

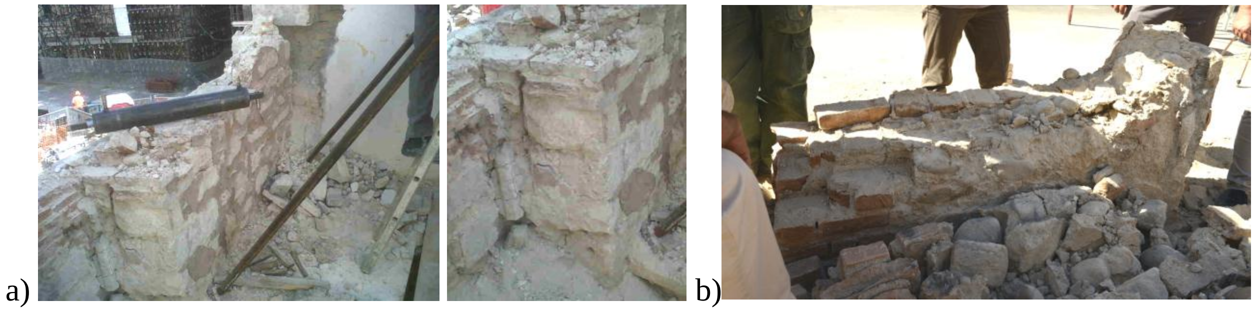

a)
b)

Figure 14: Out-of-plane test, the failures: a) on panel n. 5, L'Aquila; b) on panel n.1, Reggio Calabria.

The rethink conclusion of the present research is the statement of a different response between the linear and early non-linear phases with respect to the non-linear one. This last denotes a trend typical of elements subject to shear actions [10,11,12]. Hence, a changing of the response under orthogonal horizontal actions has to be stated accordingly to different levels of degradation although the early-response is typical of out-of-plane behaviour. The force-displacement curve will denote a three-linear trend with a starting pseudo-elasticity, and a consecutive pseudo-ductility due to a breaking of the panel along an irregular surface (see Fig.14). This breaking goes with a reduction of the resistant-cross area caused by both internal sliding-decohesion (Fig.14,a) and a progressive development of inelastic deformations in reacting panel portions up to the attainment of shaped-interlock among elements (Fig.14,b) [13].

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