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POLYMERIC GRIDS FOR THE REHABILITATION OF MASONRY STRUCTURES

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Abstract

The performance of masonry walls reinforced using polymeric grid embedded into plaster layers as a retrofitting tools for the seismic improvement of masonry buildings have been investigated by experimental tests. A number of quasi-static tests have been carried out for completing and detailing the information from previous tests and checking the effectiveness of the available results for the definition of design criteria. The results of the experimental campaign are presented and discussed. The grid shows its positive effect after the masonry failure, avoiding the collapse of the separated portions and increasing the ductility of both the in-plane and out-of-plane collapse mechanisms.

Keywords: polymeric grid, retrofitting, seismic improvement, masonry buildings

1 Introduction

The retrofitting technique involving the reinforcement of plaster layers in masonry buildings is not an innovative one, as a matter of a fact, starting from the '70s, masonry buildings were strengthened using plasters reinforced with steel grids. The method was largely used in Italy for the rehabilitation of constructions after the 1976 Friuli earthquake and it is still widely applied, even if often criticised for some intrinsic contraindications, i.e. the uncontrolled stiffening of retrofitted panels, the lack of reversibility and the real effectiveness strongly depending on the execution detailing. In the last years, other plaster reinforcements have been proposed in literature and are available on the market, e.g. those using light carbon grids into thin cement plaster layers. Polymeric reinforcements, similar to those used in reinforced soil, could also be employed as a retrofitting tool in the aseismic upgrading of masonry buildings. Therefore, the use of polymeric grid could represent a different retrofitting systems capable of overcoming some deficiencies of the other reinforcement systems (i.e. corrosion of the steel) and being more effective in terms of costs-benefits ratio, while giving, at the same time, a significant strength increment. The underlying idea in the use of polymeric grid is that this reinforcement can improve the performances of the masonry by increasing its strength and its ductility. A pre-requisite for the use of this technology is the assessment of the effectiveness of plaster reinforcement strengthening tool.

In previous experimental studies, a number of tests have been carried out on both simple structural elements and three-dimensional building models, using both static or quasi-static loads and dynamic excitations, but the test protocols did not allow to obtain quantitative evaluations of the parameters controlling the complex system. Only qualitative information could be derived from the abovementioned tests results, demonstrating a generic effectiveness of the retrofitting system. With the aim of completing and detailing the information so far available and to assess the effectiveness of the results for establishing design criteria, a new test campaign has been carried out. The new experimental activities consisted in a series of tests focussed on the estimation of the improvement of the mechanical parameters of the grid reinforced masonry in comparison with the unreinforced one.

2 Seismic behaviour of masonry buildings

Notwithstanding masonry buildings usually represent the most simple configurations of constructions and require a very poor construction technology, their seismic behaviour present elements of complexity, greater than those typical of new structural configurations associated to the modern materials: steel and reinforced concrete frames. This derives from both the structural configuration and the material characteristics.

In masonry constructions, the ordinary structural configuration consists of a three-dimensional assembly of mass-distributed plane elements (panels) that are characterised by a twofold behaviour when horizontal inertia forces are induced by earthquake attacks. The forces in the plane of the panels, combined with those exerted by vertical loads, induce a membrane behaviour with in-plane normal and shear stresses, while the actions orthogonal to the panel induce a plate behaviour with out-of-plane flexure and shear. The stress status in the members is complex and is also complicated by the in-plane extension of the element and by the interaction with the other panels at the borders.

Masonry is indeed a composite material whose behaviour depends, like all the ordinary construction materials, on the macroscopic mechanical characteristics: tensile and compressive strength, elastic and shear modulus. The tensile strength is practically null, therefore the members perform as non-tensile-resisting elements and their flexural and shear behaviours are strongly influenced by the axial force. The absence of tensile strength easily induce cracks on the surfaces subjected to tension, causing a subdivision of the panels into separate portions that can transform sections of the building in kinematisms in which each rigid portion can move with respect to the other till the collapse. These collapse mechanisms can develop either in the plane of the panels as well orthogonally, giving rise, respectively, to the so called *first mode* and *second mode* mechanisms [1], as shown in Figure 1. The first mode mechanisms are prioritary because they are characterised by reduced or absent ductile behaviour and can be developed as a consequence of the lack of continuity in panels cracked by second mode failures; they are the typical failure mechanisms of the large and continuous building complexes of the historic centre.

Moreover the texture of the masonry, associated to the dimensions and the organization of the blocks, can induce other behaviours characterised by the loss of integrity of the structural elements that can collapse for the break-up of the internal links among the blocks.

The seismic behaviour of a masonry building depends on three fundamental behaviours to be granted:

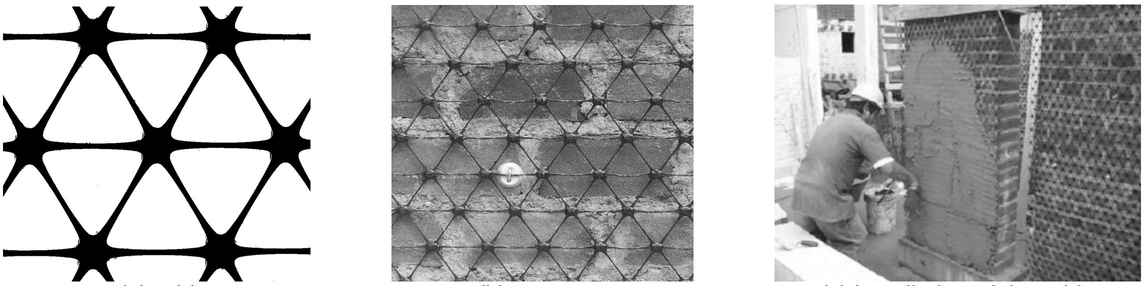
- maintaining the global integrity, without the separation into macro-elements (portions of the buildings behaving as independent structural assembly), allowing a box-like behaviour with a redistribution of the horizontal forces among all the resisting elements;
- the capability of all the members to resist the forces (axial force, shear forces, bending moments) induced by the actions or, better, the capability of sustaining the induced forces without reaching the ultimate displacement, that is, below the ductile capacity;
- the capability of the panels not to develop collapse mechanisms associated to both the evolution of the kinematisms and the loss of integrity.

(a) *first mode* collapse mechanism (overturning) (b) *second mode* collapse mechanism (shear cracks)

Figure 1 - Fundamental failure modalities of masonry elements

3 Reinforcing system description

The retrofitting system simply comprises a polymer grid fixed to the structure by means of special connectors and encased into a 2 cm thick mortar plaster. The grid referred to in the present work is the RichterGard RG TX one, a stiff monolithic polymer grid with integral junctions. The grid is orientated in three directions such that the apertures have a triangular form and the resulting rectangular cross section ribs have a high degree of molecular orientation, which continues through the area of the integral node. Figure 2 shows the grid layout and its installation.



(a) grid (b) connectors (c) installation of the grid

Figure 2 - Characteristics of grid and its installation

4 Outline of the tests

An experimental program was prepared, based on tests aimed at evaluating the actual influence of the grid in the mechanical behaviour of the reinforced element, with particular attention to the response to horizontal actions, therefore focussed on the shear strength of panels and to their capability of avoiding the development of collapse kinematisms.

Four testing campaigns, each one including one or more series of tests, were defined and programmed according to the following list.

Phase 0: a) dynamic tests on 3D whole structures.
Phase 1: b) diagonal compression tests on brick masonry square panels;
Phase 2: c) shear compression tests on brick masonry rectangular panels;
d) out-of-plane tests on brick masonry large panels;
Phase 3: e) shear compression tests on stone masonry;
f) shear compression tests on tuff masonry;
g) shear and flexural tests on complex 3D elements of connections;

The first three series of static tests (b, c, d) have already been performed and their results are resumed and commented in the following chapters. The other tests have been defined and programmed, they will be carried out in the next future.

The experimental campaigns have been supported by theoretical and numerical investigations aimed at interpreting and reproducing the results, defining suitable behaviour models for the design and the correct installation procedures.

5 Diagonal compression tests

5.1 Setup description

Six groups of 3 panels, for a total number of 18 panels, have been manufactured and tested. Each group includes three panels, in order to allow for a minimum statistical significance to the test results, taking into account the typical large scattering of the response data of masonry elements. The tests have been carried out according to the standard ASTM [2]. Panels are made of solid bricks having the maximum dimension equal 26 cm coming from current industrial production. Panels’ dimensions are 1200 x 1200 mm with a thickness of 26 cm. The nominal thickness of the plaster layers is 20 mm, the actual thickness turned out to be varying between 20 and 25 mm. Great attention has been paid to the application of plaster in order to obtain a correct positioning of the grid within the plaster, according to producer's suggestions. Connectors have been installed according to engineering judgement. The joint mortar have been scarified before applying the plaster. Table 1 reports the details of the experimented samples. Figure 3 shows the test setup arrangement.

Table 1 - Characteristics of panels for diagonal compression tests

Group	Number of panels	Panels' number	Plaster	Grid
1	3	#1, #2, #3	No	No
2	3	#4, #5, #6	Yes	No
3	3	#7, #8, #9	Yes	One side
4	3	#10, #11, #12	Yes	Both sides
5	3	#13, #14, #15	Yes	Both sides (*)
6	3	#16, #17, #18	Yes	Both sides (*)

(*) a different grid type has been installed

Each panel has been subjected to cyclic loading grouped in 4 runs as follows:
Run 1: 3 cycles of loading up to 30% of the nominal ultimate load and successive unloading;
Run 2: 3 cycles of loading up to 60% of the nominal ultimate load and successive unloading;
Run 3: 3 cycles of loading up to 80% of the nominal ultimate load and successive unloading;
Run 4: continuous loading up to collapse.

Preliminary tests on brick and mortar have been carried out, giving the results reported in the following. Bricks units showed an average compressive strength of 50.4 MPa. As far as mortar is concerned, different mortars have been chosen for masonry joints and plasters to simulate a hypothetical retrofitting situation where the plaster mortar is stronger than the joint one. Due to the good quality of the currently available materials, the compressive strength of the mortars turned out to be equal to about 8 MPa for the joint mortar and 9 MPa for the plaster mortar.

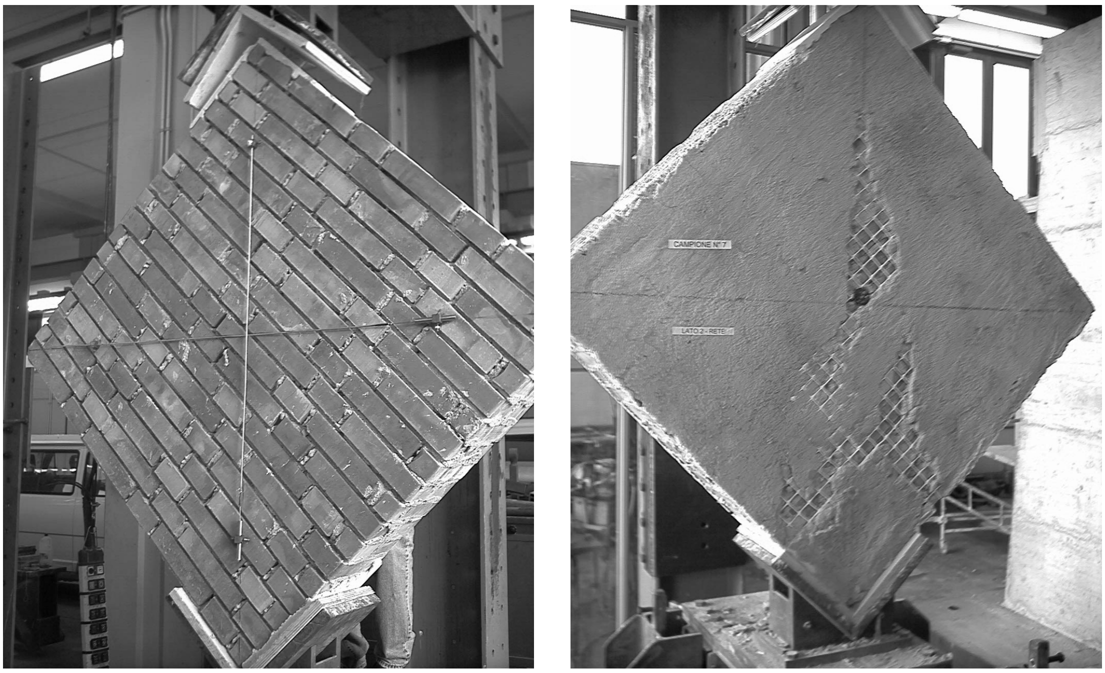


Figure 3 - Setup arrangement of diagonal compression tests: bare panel with LVDT, on the left, and plastered reinforced panel (damaged in the test), on the right.

5.2 Results and comments

For each tested panel, a diagram of shear stress vs. shear distortion has been produced The diagram of panel #3 (bare panel) is reported in Figure 4 as a reference.

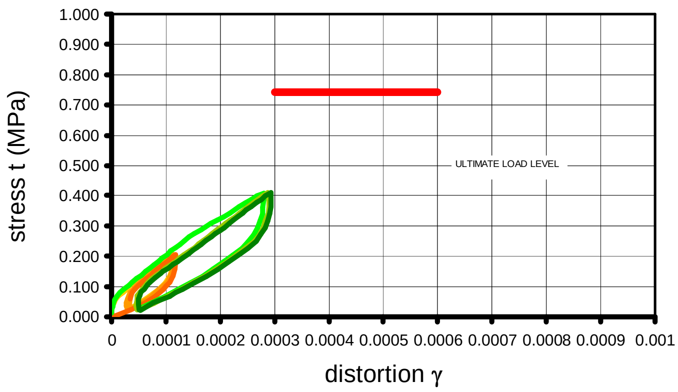


Figure 4 - Diagram of shear stress vs. distortion for panel #3.

The plastered panels (Group 2) showed a significant increase of the ultimate shear strength with respect to the bare panels, these results have been attributed mainly to the contribution of the plaster to the global strength. In terms of stress, the strength was almost the same (Figure 5a). The reinforced panels (Group 4) showed ultimate shear stresses practically equal, with a slight increase given by the presence of grid that added a positive contribution to the panel strength. The main grid role is played on the ultimate deformations of the panels, that resulted to be strongly influenced by the presence of the reinforcement as it clearly appears from the diagram reported in Figure 5b. The ultimate distortion is increased by a factor of 2 to 3 , thanks to the grid presence. The grid, therefore, increased the global ductility of the wall. The mechanism allowing for this significant ductility increase consists in the connecting effect given by the grid crossing the fracture paths. The grid maintains into contact the portion of the walls separated by the cracks, that, otherwise, would collapse, and, thanks to a mechanism of friction exerted between the contact indented surfaces of the wall portions, maintain a significant lateral resistance.

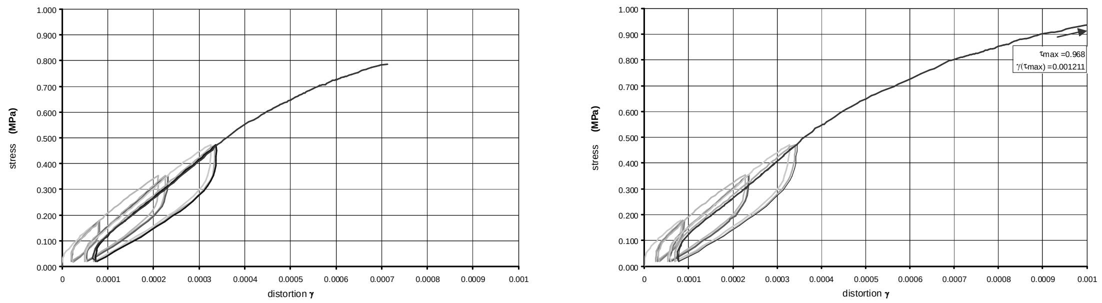


Figure 5. Diagrams of shear stress vs. distortion of panels #6 (plastered unreinforced) and #12 (double reinforcement).

Considering the cyclic characteristic of the seismic response, an important factor for the protection of structural elements is their ability of dissipating energy. The absolute value of the energy dissipated in a single cycle does not constitute a representative parameter for comparisons among different specimens. A more representative parameter is given by the so called "Cycle Dissipating Efficiency", CDE=Ac/Ar, computed as the ratio of the area of the cycle, Ac, to the area of the rectangle external to the cycle, Ar (see Figure 6). From the analysis of the data it was found that the grid does not increase the energy dissipation capability of the panels for the load cycles carried out, lower than the 60% of the actual ultimate load of the panel: in testing conditions the grid is still performing in the elastic range and the cracks are quite closed.

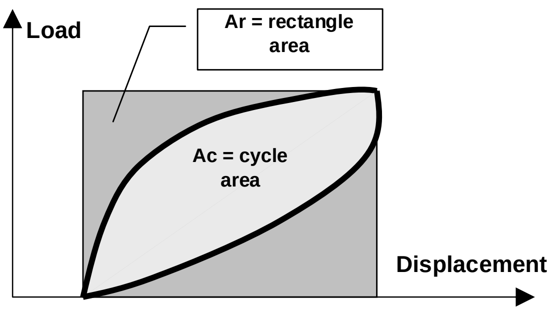


Figure 6 : Graphic representation of the CDE energy factor (Cycle Dissipating Efficiency).

Looking at the load-displacement path for the separate instruments on the two faces of the Group 3 panels, those reinforced on a single side, it can be noted a significant difference on the response of the instruments on the two faces that can be attributed to the different stiffness shown by the two plaster layer. The reinforced layer is probably stiffer because of the presence of the grid and the accidental increment of its thickness for the grid inclusion. The ultimate load decreases due to the load eccentricity causing a non uniform stress status within the panel.

6 Shear-compression tests

6.1 Setup description

Three groups of 4 panels, for a total number of 12 panels, have been manufactured and tested. For each group, two panels were subjected to 0.50 MPa axial load and two panels to 0.75 MPa. Table 2 reports the characteristics of the experimented specimens. The dimensions of panels are 1200 x 1200 mm with a thickness of 220 mm. Panels are made of solid bricks having dimensions 110x220x70 mm. The mortar for the layers was a mix of cement, lime and coarse sand in a 1:2:7 volume proportions, with an average strength of 4.21 MPa. The nominal thickness of the plaster layers is 20 mm. The mortar for the plaster was a mix of cement, lime and coarse sand, with a volume proportion of 1:1:5 and an average compressive strength of 7.12 MPa. Figure 5 shows the scheme and setup of the test.

Panels were subjected to horizontal cyclic loads, applied under displacement control, constant vertical load and top rotations constrained. The first run consist of three cycles up to 50% of the estimated ultimate load. The cycle amplitude is increased by 30% for each subsequent triplet of cycles. After the third triplet, the load is increased up to panel failure.

Table 2 - Characteristics of panels for shear-compression tests

Group	Number of panels	Panels' number	Plaster	Grid	Compression stress [MPa]
1	2	#1, #2	No	No	0.50
	2	#3, #4	No	No	0.75
2	2	#5, #6	Yes	No	0.50
	2	#7, #8	Yes	No	0.75
3	2	#9, #10	Yes	Both sides	0.50
	2	#11, #12	Yes	Both sides	0.75

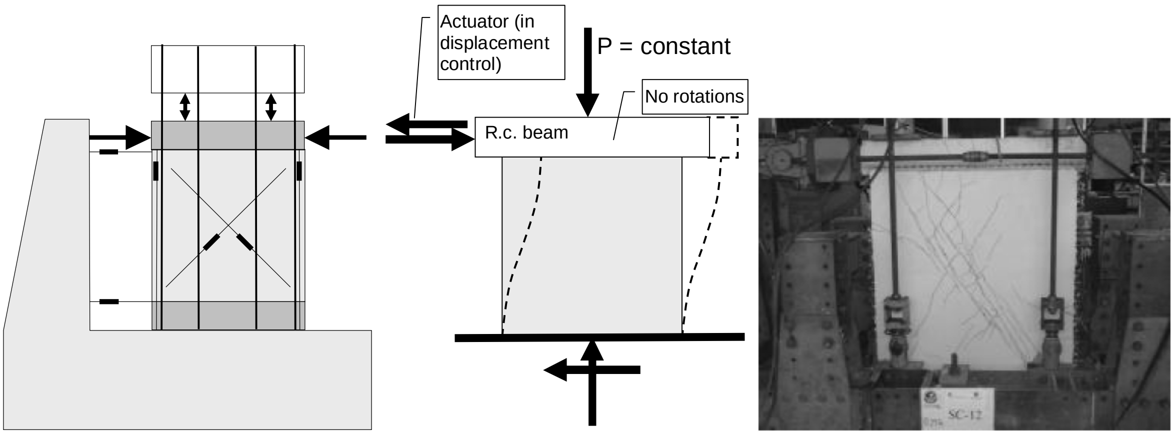


Figure 5 - Test layout, load scheme and setup of the shear-compression tests

6.2 Results and comments

The results from shear-compression tests basically confirmed those from the previous diagonal-compression tests carried out.

An important consideration can be drawn by looking at the panels conditions at failure of the reinforced panels with respect to the bare and unreinforced ones. Even if the failure modalities are similar, related to the formation of diagonal cracks, bare and unreinforced panels show very "clean" cracks approximately along two diagonal of the panel, while the reinforced panel is characterised by a widespread net of cracks (Figure 6). This effect suggests that the panel collapse requires the formation of a large number of failure surface, with an higher value of the ultimate strength

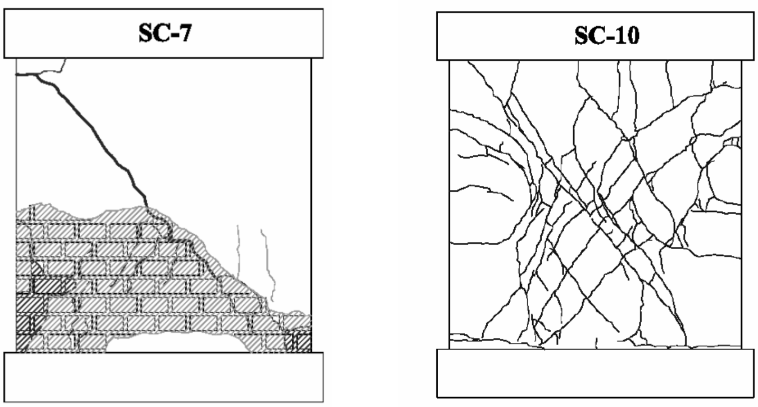


Figure 6 – Crack pattern in panel SC-7 (unreinforced) and in panel SC-10 (reinforced)

The shear-compression tests confirmed the positive effect of the grid on the ductility of panels, effect already evidenced in the diagonal compression tests. The analyses of the shear-displacement curves of the reinforced panels showed an extremely good ductile behaviour of the panels subjected to cycling loadings as well as a significant energy dissipation capacity.

7 Stability tests

7.1 Setup description

Six groups of 2 panels, for a total number of 12 panels, have been manufactured and tested. Each group includes two panels, for a minimum accounting of the typical large scattering of the masonry response. Table 3 reports the details of the experimented samples. The panels are 800 mm wide, 1600 mm high, and 220 mm thick. The materials and construction techniques are similar to those already described for the shear-compression tests. Figure 7 shows the scheme, with the LVDT instrumentations, and the actual setup of the test. The tests reproduce out-of-plane collapse mechanisms explicitly provided by the last Italian seismic guidelines [3].

Table 3 - Characteristics of panel for out-of-plane tests.

Panel	Plaster	Grid		Plaster	Grid
F1	Both sides	No	F7	Both sides	Tension side
F2	Both sides	No	F8	Both sides	Tension side
F3	No	No	F9	Both sides	Tension side
F4	No	No	F10	Both sides	Compression side
F5	Both sides	Tension side	F11	Both sides	Tension side overlap.
F6	Both sides	Tension side	F12	Both sides	Tension side overlap.

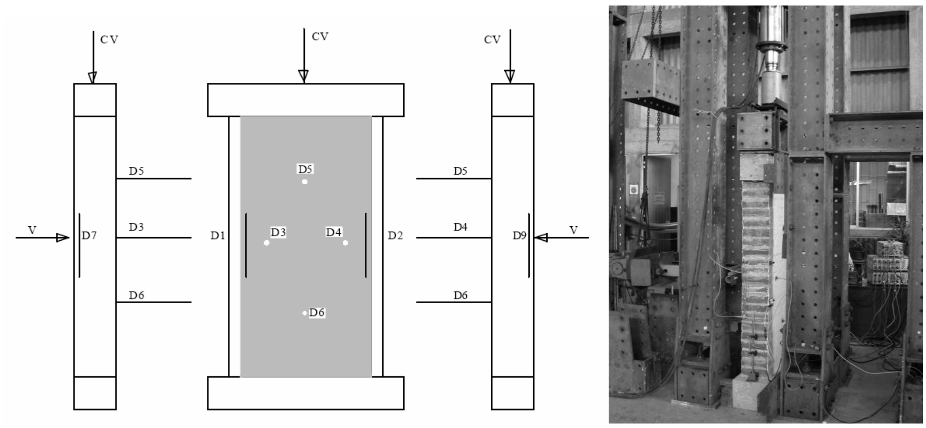


Figure 7 - Scheme and setup of the flexural tests

7.2 Results and comments

The tests carried out clearly demonstrated the positive effects of the grid reinforcement on all the significant mechanical parameters of the panels, i.e. on ultimate load, ultimate displacement (availability of ductility in the collapse mechanism) and energy dissipation (associated to the cyclic loading-unloading hysteretic paths, which simulate the actual seismic conditions). The spread distribution of the crack patterns, already observed in shear compression tests, put into evidence the beneficial contribution of the grid, related to the mitigation of the damage peak and to the increase in energy dissipation due to the spreading of the damaged areas.

The stability of the post-elastic pattern of the force-displacement curve produced by the plastered reinforced panels is shown by the graph reported in Figure 8; in the same figure are reported, for comparison, the curve from a bare unreinforced panel. The analysis of the experimental data confirmed the expected beneficial effects of the grid on the out-of-plane behaviour of the panel, allowing for a significant enhancement of the resistance against the collapse mechanisms.

An interesting result, even if coming from a single test and therefore requiring other investigations, comes from the test on panel F-10 where the grid is located only into the plaster layer on the compression side. The graph in Figure 9 shows the good behaviour presented by the panel, with a post-elastic pattern exceptionally long, proving the effectiveness of the grid in restraining the collapse mechanisms also when it is located on the compression side. The effect derives from a sort of "bandage effect" similar to those given by the application of FRP strips on the compression side of the elements (i.e. the extrados of the vaults): the tension resistant "bandage" prevent the evolution of the cinematic movement leading to the collapse.

The tests carried out on panels where the reinforcing grid was overlapped for a length of 150 mm showed an increment of the bending resistance of approximately 30%.

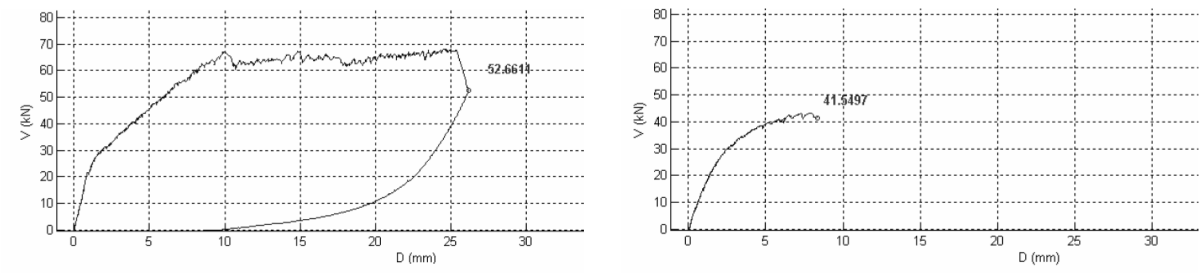


Figure 8 - Horizontal force vs. displacement curves for the plastered reinforced panel (left) and the bare panel (right)

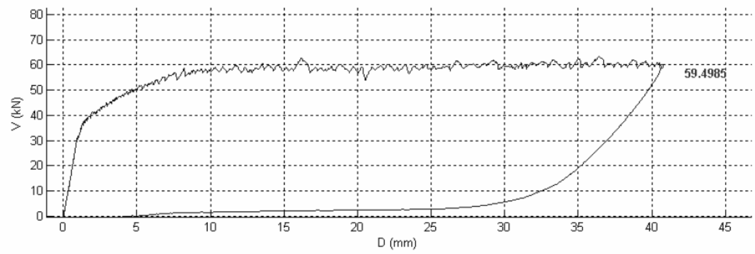


Figure 9 - Force vs. displacement curve for the plastered reinforced panels with reinforcement on the compressed side

8 Conclusions

Plasters reinforced with polymeric grid could be a low-cost solution for the seismic improvement and the cracking protection of existing buildings.

The presence of grid does not seems to improve the shear strength of the masonry panels, even if a certain influence has been shown by the shear-compression tests. The most significant contribution consists in the increase of the ultimate deformation, i.e. in a ductility improvement of the in-plane collapse mechanisms

It has been proved that the main contribute of the grid to the masonry performances relies on the fact that collapse and crumbling is inhibited. It has been observed that the grid starts its positive effect after the masonry failure, avoiding the collapse of the separated portions with rigid body mechanisms. It was also observed a positive increase of ductility due to the connecting effect of the grid crossing the fracture paths. The grid contribution is important in reducing the collapse factor of the so called "1st type collapse", i.e. the collapse with out-of-plane displacements.

Based on structural analysis principles, analytical interpretations of experimental results have been proposed. Design methods easily accounting for the grid contribution in the safety evaluation procedures provided by codes have also been developed. They are the subjects of dedicated publications currently under preparation.

A first pilot application in the retrofitting and seismic enhancement of a tuff building has already been completed while two other applications to stone buildings have been designed and are currently in progress.

Acknowledgment

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