FRG strengthening systems for masonry building

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ABSTRACT: Up to the middle of the last century the main building material was masonry, that is why in most countries there are many masonry buildings and many of these have great historical or social value.
These buildings, located in seismic areas, due to their age are deteriorated by environmental and human factors. This combination of factors causes a very alarming situation that causes a growing interest toward a new strengthening system. Researchers are orientated toward a less invasive and reversible system possibly avoiding resin and organic materials.
Thanks to recent applications, especially on historical buildings, it was possible to realize a strengthening system based on application of FRP grid and mortar matrix (FRG). Much experimentation was conducted to test the effectiveness of this technology on different kinds of masonry.
The present paper resumes the latest tests carried out by the University of Naples on different masonry panels tested under diagonal compression.
Experimental campaign investigated preliminarily on material properties of based component from bricks to reinforcing mortar.
The experimental results confirmed the effectiveness of the investigated strengthening technique to increase the panels shear strength and validated the effectiveness of this reinforcing system on different kinds of masonry.

1 INTRODUCTION

A large number of existing masonry structures shows damages due to a wide range of events (i.e. environmental deterioration, inadequate construction techniques and materials, design for gravity loads only) or, for the same reason, are subject to an high rise. Several strengthening technique are available to reduce the seismic vulnerability of these buildings; however, some of these techniques may be too invasive or expensive. Techniques based on the use of technologies and materials compatible with physical and mechanical properties of masonry are required to enhance performance of such buildings. Among new strengthening strategies, the use of Fiber-Reinforced Polymer (FRP) or Fiber-Reinforced Grouting (FRG) strengthening technique offers a series of advantages as the high strength-to-weight ratios, low influence on global structural mass, corrosion and fatigue resistance, easy handling and installation, and negligible architectural impact.
Effectiveness of this technique was evaluated by means of a different experimental campaign on masonry panels tested under diagonal compression.

The present paper resumes the main experimental results in terms of shear strength, diagonal strains, shear deformation as well as elastic parameters (i.e. modulus of rigidity, G, and Poisson ratio, ν) and ductility are herein presented and discussed with reference to five tuff panels tested under diagonal compression.

2 EXPERIMENTAL CAMPAIGN

During the 3 experimental campaigns, 22 diagonal compression tests are carried out on square masonry panels as summarized in Table 1:

Table 1. Tests Matrix

Cod.	Stone	Sample n°	Matrix	Grid
TN1	Neapolitan Tuff	8	Lime + Cement.	Glass + Basalt
TN2	Neapolitan Tuff	9	Lime	Glass
CA	Limestone	5	Lime	Glass + Basalt

2.1 Material Properties

Mechanical properties of tuff units and mortar as well as matrix to bond FRP reinforcement were determined by means of experimental tests.

According to UNI EN 772-2002 tests were performed on cubic stone units, prisms of 360mm×60mm×90mm were tested in flexure with three point bending in order to evaluate the flexural strength according to UNI EN 14580- 2005.

Prismatic sample of 40x40x1600 mm were tested in flexure and compression tests was been carried out on two resulting half according to UNI EN 1015-11 and UNI EN 998-2.

The mechanical properties of the matrix after 28 days of curing were computed in the same ways; cementitious based mortar has: flexural strength of 14.5 MPa; compressive strength of 30.2 MPa; lime based mortar has: flexural strength of 8.0 MPa; compressive strength of 16.1 MPa. The mechanical properties of GFRP (see Figure 1a) and BFRP (Figure 1b) grids were provided by the manufacturer: tensile 45 kN/m, Young's modulus of 72.0 GPa, and ultimate axial strain of 2.0% for glass grid; and tensile 60 kN/m, Young's modulus of 91.0 GPa, and ultimate axial strain of 2.0% for basalt grid.

Ties are realized with steel fabric (Figure 1c) with tensile strength of 2086 MPa and elastic modulus of 210000 MPa, glued by epoxy putty directly on FRP grid.

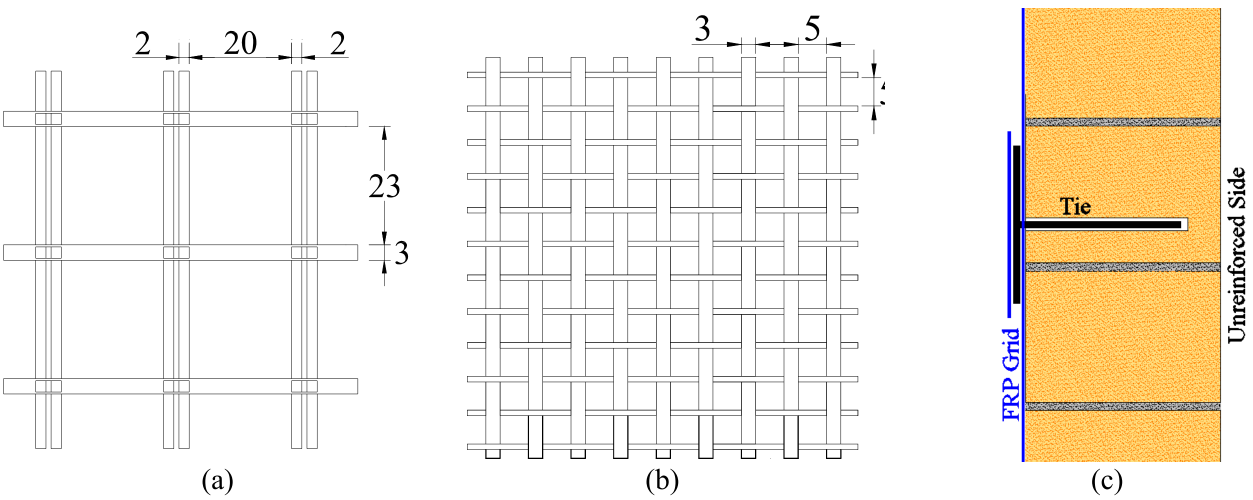


Figure 1. Glass (a) and Basalt (b) grid ; scheme of steel tie (c)

2.2 Reinforcement Scheme

The strengthening system installation procedure involved the following steps: a first layer of mortar (thickness of about 6mm) was applied; FRP grid was applied above this and the second layer of mortar (thickness of about 6 mm) was applied covering the grid. Details about installation process are depicted in **Figure 2**.

The construction procedure of the IMG strengthening system with SFRP ties was approximately the same. Five squared pockets were left in the second matrix layer and 200 mm deep and 20 mm large holes were drilled to install SFRP ties of 500mm length, which were previously impregnated with epoxy resin. Inside the hole was cleaned and prepared with epoxy primer, half of each tie was inserted in the hole and another side was spread with in the squared pocket over the grid. Another layer of FRP grid was applied above tie spread and finally, squared pockets were filled with mortar. The number and size of SFRP ties were selected to strengthen both the central and peripheral parts of the specimen.

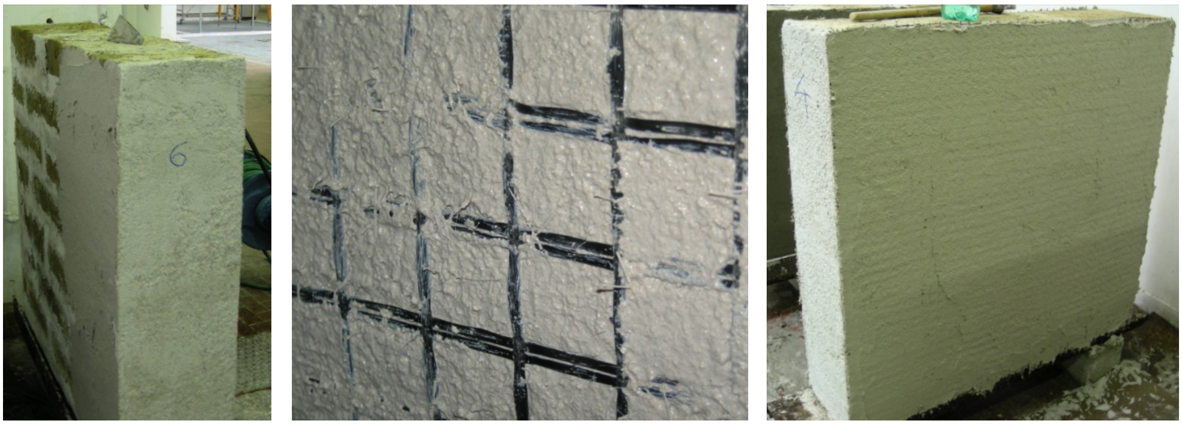


Figure 2. Strengthening system installation procedure

2.3 Test Setup

The panels were tested in a four column testing frame, characterized by a 1000 mm wide and 4000 mm long steel base floor, capable of testing specimens which are more than 4 m high. Its load capacity is 3000 kN both in tension and in compression with a total stroke equal to 150 mm.

The tests were carried out under displacement control, in order to record the panels post-peak response; the displacement rate was 0.015 mm/sec for all tests. Tests were stopped when the reduction in strength with respect to the peak value was of about 50%. Two steel loading shoes placed on two diagonally opposite corners of the panels were used in order to apply the compression load; the test layout conforms with ASTM E 519-81. Some changes were introduced in order to adapt the ASTM requirements to the masonry blocks dimensions. To avoid a premature splitting failure of panel edges, the spaces between the specimen and steel plates were filled with fast setting and shrinkage free mortar.

Five linear displacement variable transducers over a gauge length of 400 mm were used to monitor in-plane and out-of-plane displacements: two LVDTs were placed on each panel side along the diagonals to record the shortening and elongation of vertical and horizontal diagonals, respectively; one more LVDT was installed perpendicularly to the panel surface to measure out-of-plane displacements..

3 RESULTS ANALYSIS

The shear strength, τ, is computed on the net section area A_n of the uncracked section of the panels , according to ASTM E519-81 standard test method; in general the shear stress can be obtained as $\tau = 0.707\frac{V}{A_n}$, where V is the current experimental load. The average strains, ε_v and ε_h, have been computed as the average displacement on the two sides over the gauge length (400 mm) along the compressive and tensile diagonals, respectively.

As-built specimens suffered stair-stepped cracking involving both bed and head joints along their compressed diagonal. First cracking is shown generally along mortar – bricks interface due to low strength of mortar adhesion bond. Crack pattern is characterized by few and wide cracks while no cracks are visible along load direction or on the edge of the panel near load application. No significant out-of-plane deformations were observed on them.

FRG reinforcement changes cracking propagation toward a more dissipative scheme. In fact strengthened specimens were characterized, independently by the type of grid adopted as reinforcement, by a more uniform crack pattern; several cracks less wide than those achieved on control specimens were attained on the mortar reinforced by FRP grids.

Significant out of plane deformations were observed on one side reinforced panels due to the different deformation of the two sides. However this deformation takes a significant value after post peak load, so at load value is never reached by non-reinforced panel.

3.1 **One Head Neapolitan Tuff**

The experimental program consists in 9 diagonal compression tests on masonry panels. Masonry was made of yellow Neapolitan tuff bricks (360mm x 250mm x 115 mm) and a pozzolan (local volcanic ash) based mortar (thickness 10 mm). Each panel was eight courses high and one tuff block wide; with mortar joints of 10-15 mm thick the resulting dimensions were 1000×1000×250mm.

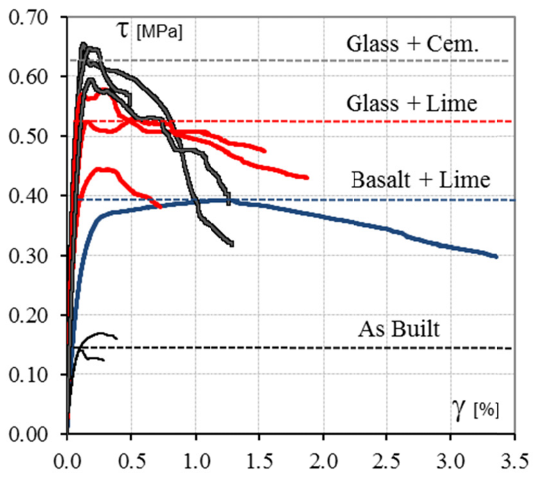
Tuff bricks have a compression strength of 4.0 MPa and flexural strength of 2.6 MPa, mortar joint has a compression strength of 3.72 MPa and flexural strength of 1.3 MPa. Tests layout is two as built and 6 reinforced panel. Three of them are reinforced with cementitious matrix and glass grid, three with lime matrix and glass grid and one with lime matrix and basalt grid.

The maximum shear stress (τ_{max}) (see Table 2), recorded on the reinforced panels was significantly higher than that achieved on control panels with an increase that can reach 300%. Increase is also clear in ultimate shear strain (τ_{ulti}) that is post peak strain at 80% of ultimate load. Reinforcement in post peak phase always produces a great increase of shear strain (γ_u).

Table 2. Tests Results

Sample ID	Grid	Reinforcement	Matrix	V_{max} [kN]	τ_{max} [MPa]	τ_u [MPa]	γ_{max} [%]	γ_u [%]	ΔV_{max} [%]
P1	-	-	-	49.98	0.14	0.11	0.10	0.53	
P2	-	-	-	60.00	0.17	0.14	0.27	0.46	
PGG1	Glass	2 Sides	Lime	157.31	0.44	0.36	0.23	1.12	233
PGG2				187.55	0.53	0.42	0.53	1.91	
PGG3				204.60	0.58	0.46	0.28	1.64	
PGG1C	Glass	2 Sides	Cement.	228.81	0.65	0.52	0.18	0.50	307
PGG2C				231.62	0.66	0.52	0.12	0.81	
PGG2C				210.53	0.60	0.48	0.19	1.00	
PBB1	Basalt	2 Sides	Lime	138.78	0.39	0.31	1.23	2.98	152

Crack patterns, according to the test results, show few, wide and scaling cracks for non-reinforced panel and, many little and vertical cracks for reinforced panel. **Figure 3** shows a moderate increase in stiffness for a strengthened specimens only in correspondence to a load value greater than peak value of non-reinforced panel. More details can be found on Balsamo et al.2010.



(a) (c)

Figure 3. Stress - Strain Behavior of Samples (a) and Cracks Pattern (b)

3.2 Two Heads Neapolitan Tuff

The 9 tuff masonry, two blocks wide panels were tested and were 310×1200×1200 mm in size. Tuff masonry was made of tuff blocks with dimensions 100×150×300 mm and mortar joints of thickness 10 mm. Diagonal compression tests were carried out on 3 as-built specimens and 6 strengthened specimens reinforced with single-side, single-side strengthening with ties and double-side strengthening layout.

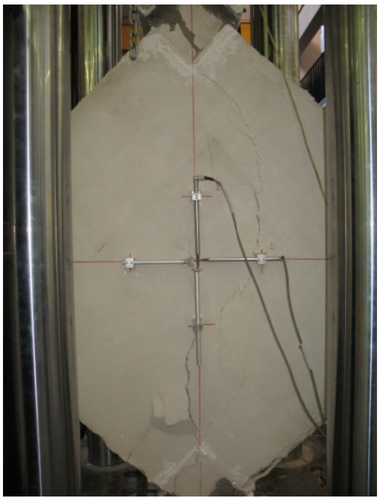
Tuff stones had a unit weight of 11.72 kN/m^3, compressive strength of 4.13 MPa, tensile strength of 0.23 MPa and elastic modulus of 1.54 MPa. Premixed hydraulic mortar with mean unit weight 16.92 kN/m^3 was used for tuff masonry joints; it was composed by natural sand with 1:6.25 water/sand ratio by weight and pozzolana-like reactive aggregates. It has a compressive strength of 2.50 MPa, tensile strength of 1.43 MPa and elastic modulus of 8.54 MPa

The results, summarized in **Table 3**, show a good increase in shear strength from single to double-side strengthened specimens. The presence of SFRP ties produced both shear strength increasing and a significant improvement in terms of ductility.

Table 3. Tests Results

Sample	Grid	Reinforcement	Matrix	V_{max} [kN]	τ_{max} [MPa]	τ_u [MPa]	γ_{max} [%]	γ_u [%]	ΔV_{max} [%]
P1	-	-	-	112.48	0.21	0.17	0.04	0.06	-
P2	-	-	-	84.40	0.19	0.15	0.11	0.41	
P3	-	-	-	119.32	0.27	0.22	0.20	0.37	
PG1	Glass	1 Side	Lime	244.40	0.45	0.36	0.07	0.17	122
PG2	Glass	1 Side	Lime	222.62	0.41	0.32	0.10	0.31	
PG1c	Glass	1 Side + Ties	Lime	288.17	0.53	0.43	0.05	0.68	170
PG2c	Glass	1 Side + Ties	Lime	281.72	0.52	0.42	0.18	1.18	
PGG1	Glass	2 Sides	Lime	328.34	0.71	0.57	0.85	1.09	206
PGG2	Glass	2 Sides	Lime	317.45	0.68	0.55	0.20	1.12	

In Figure 4 it is evident how the reinforcement performed on both facings is more effective than the other two; moreover it is clear as the use of the ties improves the effectiveness of the 1 side reinforcement system. Furthermore, note how the use of connectors, while showing effectiveness in relation to the increase of resistance, significantly improves the post peak thanks to the ability of the reinforcement to remain adherent to the surface for further deformation.



(a)

(b)

Figure 4. PG1 Panel after test, reinforced (a) and unreinforced (b) side; Stress - Strain Behavior of the Samples (c)

As Figure 4b shows, 1 side reinforced panel reaches high values of damage on non-reinforced side while on reinforced one the integrity of the panel is held by the reinforcement.

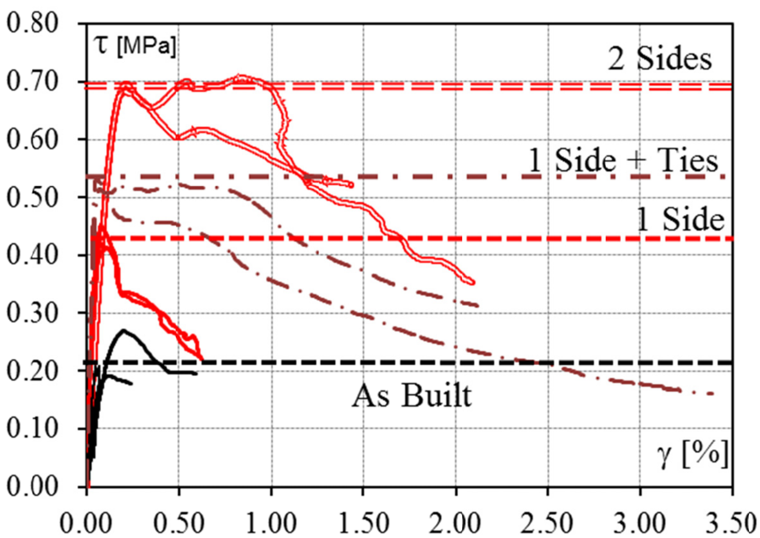


Figure 5. Stress - Strain Behavior of Samples

The use of ties produces an increase in effectiveness on the reinforcement intervention on one side (see **Figure 5**). This effectiveness is particularly evident respect to flexibility which, in the case of reinforced panels with connectors, is also greater than that of the reinforced panels on 2 sides. More details can be found on Parisi et al. 2013.

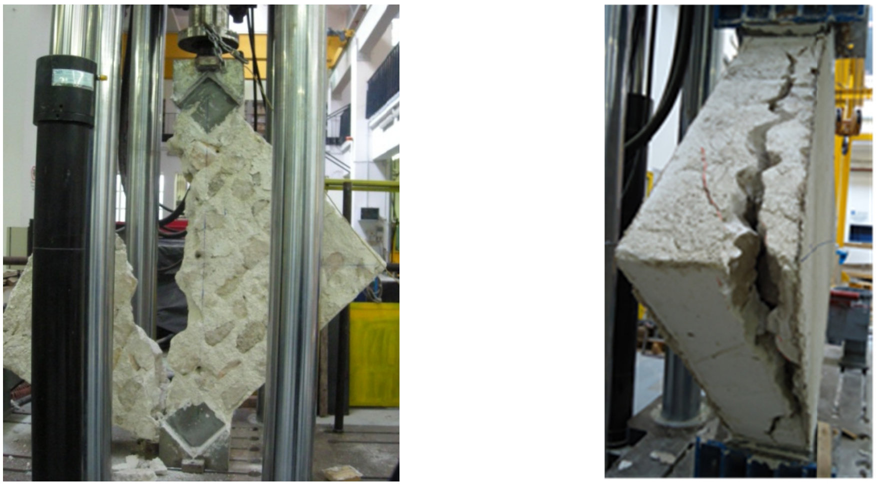
3.3 **Limestone Panel**

The experiment was conducted on 5 panels 1250x1250x250 mm of size elements made of irregular texture, with irregular actions, without connecting transverse and mortar with poor mechanical properties thus reproducing the typical make of masonry buildings existing in the area of L 'Aquila (Italy). For the specimens packaging limestone with a resistance of 6.16 MPa and a 18.45 kN/m^3 weight per unit of volume was used. The mortar has a compressive strength of 3.50 MPa and a flexural strength of 1.10 MPa. All panels have a 2 sides reinforcement with lime matrix, two of them have basalt grid and other two have glass grid.

Table 4. Tests Results

Sample ID	Grid	Reinforce	Matrix	V_{max} [kN]	τ_{max} [MPa]	τ_u [MPa]	γ_{max}	γ_u	ΔV_{max} [%]
P1	-	-	-	53.79	0.13	-	-	-	
P1BB	Basalt	2 Sides	Lime	141.18	0.33	0.27	1.32	0.60	202
P2BB				183.86	0.43	0.27	0.28	0.11	
P1GG	Glass	2 Sides	Lime	138.29	0.33	0.26	0.24	0.37	146
P2GG				126.88	0.30	0.28	0.41	0.13	

As built panels show a very low shear strength value, probably due to the chaotic texture of masonry and the poor mechanical properties of the mortar. However, as shown in **Table 4**, even in this case it shows a strong increase of the shear strength reinforced panel that reaches increases of 200% in the case of reinforcement with basalt and 146% in the case of reinforcement with glass. It has not been possible to record the ultimate strain of the non-reinforced panels because of the sudden collapse of the panel.



(a) (b)

Figure 6. Panels failure as built (a) and reinforced (b)

In **Figure 6**, which shows the panel after the test, we note the sharp failure of non-reinforced panel which endures a distinctly fragile break. Regarding the reinforced panels, for this type of masonry there has always been a rupture inside the veneer, as shown in **Figure 6**b. This type of failure is probably due to the low quality of the mortar compared to the strong surface resistance conferred by the facing reinforcement. However as can be seen in **Figure 7** the panels stiffness remains unchanged.

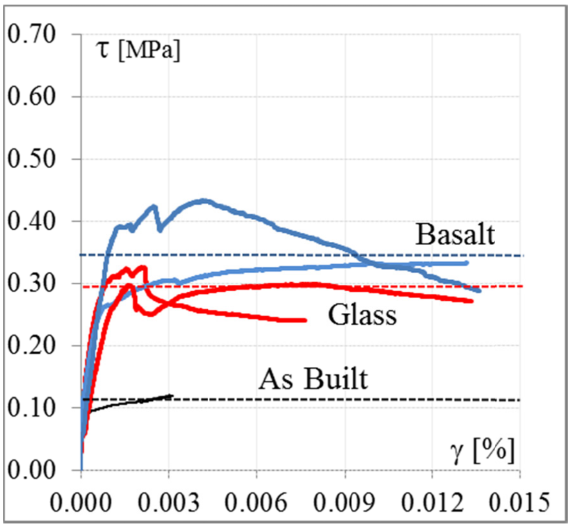


Figure 7. Stress - Strain Behavior of the Samples

4 CONCLUSION

The results obtained and briefly described in this paper show that the application of the FRP system generates a sharp improvement in the ability of the resistant strain and masonry regardless of the medium on which it is applied.

Such effectiveness is demonstrated both in reference to the configuration of reinforcement on a single side and on two sides .

It is also demonstrated how the use of ties generates a significant increase in both resistances and deformation in particular for the configuration with reinforcement on single side, resulting in less effective for the configuration with reinforcement on both sides . These have a particular effectiveness in the disorderly masonry for which the break is triggered by injury contained on the wall surface.

An important consideration, also, is that this intervention does not produce significant changes of mass or stiffness in the walls on which it is applied; accordingly it is possible to include among the local interventions with the chance to also run on a limited portion of the building.

Based on these results FRG systems can be considered as a valid alternative to the traditional techniques of reinforcement of masonry structures , considering the high mechanical performance obtained with this method of intervention as well as the simplicity of implementation and low level of specialization required for the implementation of the intervention itself.

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