3rd Workshop on

The New Boundaries of Structural Concrete

University of Bergamo - ACI Italy Chapter
Bergamo, Italy, October 3 - 4, 2013

Papers, Invited lectures

Editors
Luigi Coppola, Roberto Realfonzo and Paolo Riva

EDIZIONI READY

Experimental Behaviour on Shear Strengthened Masonry Panels

S. Mostosi[1], A. Meda[2] and P. Riva[3]

ABSTRACT: Traditionally a large percentage of the Italian building stock is made of masonry, with walls often made of hollow core clay bricks. These buildings are usually designed only for gravity loads, with no or little concern for seismic actions. Accordingly, they are extremely vulnerable to seismic actions, as shown by the recent earthquakes of L'Aquila (2009) and Emilia (2012).
After the new seismic classification of the Italian territory, a large number of these buildings will need seismic retrofit works in order to be able to meet the new code requirements. Hence, seismic strengthening techniques for masonry buildings are rapidly gaining interest.
In the present paper the effectiveness of a shear reinforcement technique on masonry panels is presented. The specimens were reinforced by using an innovative strengthening system based on the combined use of a steel or glass fiber grid embedded in a base mortar. Such system is composed by two layers applied on both sides of the panels and connected by through joints made of steel bars or glass fiber wires.
A series of one unreinforced masonry panel and four strengthened panels have been subjected to diagonal compression tests. This type of test was chosen to simulate the in-plane shear phenomenon of masonry. Several reinforcement configurations, with different combination of grid type, mortar type and connectors type, have been tested.
Experimental results show the effectiveness of this technique to increase the shear strength and the ductility of the panels. The investigated technique does not significantly modify the stiffness of the structural elements confirming the compatibility of the intervention when used on existing buildings.

1 INTRODUCTION

Traditionally a large percentage of the Italian building stock is made of masonry, with walls often made of hollow core clay bricks. These buildings are usually designed only for gravity loads, with no or little concern for seismic actions. Accordingly, they are extremely vulnerable to seismic actions, as shown by the recent earthquakes of L'Aquila (2009) and Emilia (2012).
After the new seismic classification of the Italian territory, a large number of these buildings will need seismic retrofit works in order to be able to meet the new code requirements. Hence, seismic strengthening techniques for masonry buildings are rapidly gaining interest.
Seismic performance of existing masonry buildings is affected by various failure dealing with either out of plane (bending) and in plane (shear) behavior of walls. The present paper will focus on the shear failure mechanisms.
Seismic in plane behavior of masonry walls can be experimentally simulated by two kinds of tests. On one hand it can be reproduced by the so called "diagonal compression test", ruled by ASTM 519, and, on the other hand, it can be simulated by "shear com-

[1] *Tecnochem Italiana S.p.A, serena.mostosi@unibg.it*
[2] *Associate Professor, Civil Engrg Dept, University of Rome "Tor Vergata", alberto.meda@uniroma2.it*
[3] *Professor, Head, Dept of Engrg, University of Bergamo, paolo.riva@unibg.it*

pression test". Besides other findings gained by the above research, it can be observed that strength values obtained by diagonal compression tests are generally more conservative than those given by shear compression tests. Both tests methods pointed out the general lack in shear strength of those masonry walls. Consequently, masonry structures are generally in need for strengthening in shear and various technique can be adopted with that aim.

Several strengthening techniques have been used for this purpose such as: the use of grout injection; deep re-sealing of mortar joint and the use of composite materials based on carbon or glass fibers. One of the latest technique for shear strengthening of the masonry walls consist of using composite material fiber reinforced polymers (FRP). This reinforcement technique provides a series of advantages, such as the negligible influence of the self weight of the reinforcement on the total mass of the structure and the ease of installation. However, this type of reinforcement has several limitations as the relatively high costs and low fire resistance due to the use of epoxy resins for glueing the fibers to the surface of the walls.

The present paper reports the main results obtained by an experimental campaign carried out at the laboratory of the university of Bergamo on brick masonry panels. In particular, one unreinforced masonry panel and four strengthened panels have been tested under diagonal compression with the main aim of quantifying their shear strength. The aim of this research is to evaluate the effectiveness of a strengthened technique for masonry walls using steel or glass fiber grid embedded in a layer of mortar.

The tests results show that the strengthening system present significant benefits in terms of increasing the shear strength and ductility with considerable advantages in the case of a seismic event.

2 EXPERIMENTAL PROGRAM

The experimental program consists of a diagonal compression tests on a total of five brick masonry panels with dimensions of 100x100 cm and thickness equal to 40 cm. Each panel was made of sixteen parallel rows of solid 22.5x10x5 cm bricks. All the panels were built with a cement mortar type M10, according to UNI-EN 998-2.

A panel (PNR), used as a reference specimen, has not been strengthened. On this panel were applied on both side two layers of mortar type M10 (the same mortar used for the construction of the panels) with a thickness of 2.5 cm to simulate the real condition of a plastered masonry inside a building. The total thickness of the un-reinforced specimen was 45 cm.

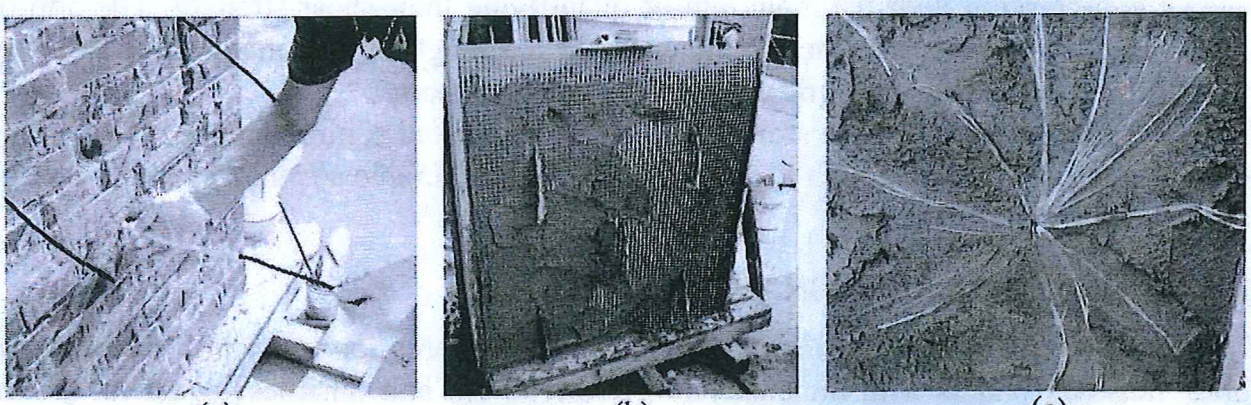
The other four specimens were reinforced by using an innovative strengthening system based on the combined use of a steel or glass fiber grid embedded in a base mortar. Such system is composed by two layers applied on both sides of the panels and connected by through joints made of steel bars or glass fiber wires. Two strengthening panels were reinforced with a cement mortar (BS38/39) and the other two panels with a cement mortar with a lower compression strength (BS37). The different reinforcement configurations, with different combination of grid type, mortar type and connectors type, are shown in table 1.

The procedure for the application of the strengthening technique can be summarized in the following phases: [1] Execution of five through hole with a diameter of 30 mm for the insertion of the connectors. [2] Insertion of the connectors (steel bars or glass fiber wires) and subsequently injection of epoxy resin into the holes to ensure the anchoring of the connectors. [3] Application of a layer of cement rough coat. [4] Application of the

first hand of mortar with a thickness of 15 mm. [5] Positioning of the mesh on both faces of the panels and anchoring to the connectors. [6] Application of the second hand of mortar with a thickness of 15 mm. Five connectors for square meter of panel were placed. The thickness of the strengthening layer for all four reinforced panels is equal to 30 mm for each side for a total thickness of the specimen of 46 cm. Figure 1 and Figure 2 show the different phases for the application of the strengthening layer of the panel PR_G1 and PR_S2, respectively.

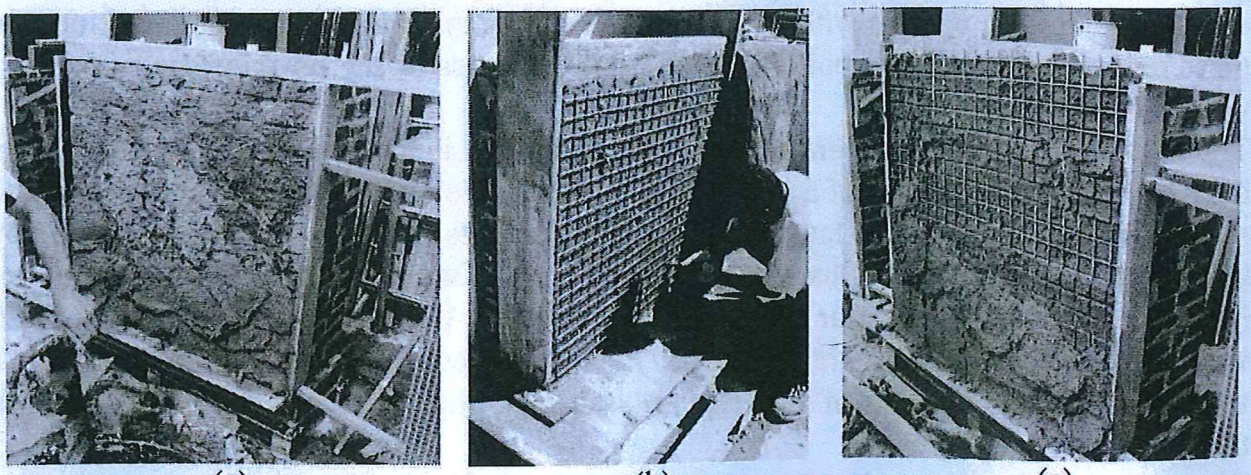
Table 1. Reinforcement configuration for the five panels tested

	Type mortar	Type connector	Type mesh
PNR	M10/UNI-EN 998-2	No connector	No mesh
PR_G 1	BS 38/39	Fiber glass connectors - Ø 10 mm	Fiber glass mesh - 10x8cm
PR_S 1	BS 38/39	Steel connectors - Ø 6 mm	Steel mesh – 50x50 mm Wire diameter 4 mm
PR_G 2	BS 37	Steel connectors - Ø 6 mm	Fiber glass mesh - 10x8cm
PR_S 2	BS 37	Steel connectors - Ø 6 mm	Steel mesh – 50x50 mm Wire diameter Ø 4 mm



(a) (b) (c)

Figure 1. Application of the strengthening layer on the panel PR_G1: a) Insertion of the glass fiber wires; b) Positioning of the mesh; c) Anchoring of the connectors



(a) (b) (c)

Figure 2. Application of the strengthening layer on panel PR_S1: a) Application of the first hand of mortar; b) Anchoring of the steel connectors; c) Second hand of mortar

Table 2. Mechanical values of mortars

Mortar type	Compression strength [N/mm^2]	Flexural strength [N/mm^2]
M10	14	4
BS38/39	40	10
BS37	20	8

The mechanical properties of the mortars, which were used for the construction of the panels and of the strengthening layers, were derived from bending and compression tests (according to UNI EN 998-2; 2004): 40mm x 40 mm x 160 mm mortar prisms were tested in flexure with three point bending tests and 8 cubes, obtained from failed mortar specimen in flexure, were subjected to the compression test. The results of the tests for the three types of mortar used are reported in table 2.
The mechanical properties of steel and fiber glass grids were provided by the manufacturer. For the glass grid the tensile strength was 6600 N/cm and the ultimate tensile strain is 3.5%, for the steel mesh the tensile strength of a single wire is 550 N/mm^2 and the ultimate tensile strain about 10%.

3 TEST SET UP

The diagonal compression load is applied to the corners of the panels by adopting a steel reacting frame (fig 3). The load was applied by means of an electromechanical jack having a loading capacity of 1000 kN with a close loop control system. The tests were conducted under displacement control, in order to record the panels post-peak response, with a constant speed equal to 0.01 mm/sec. The compression load is applied to the masonry through two steel shoes placed in correspondence of two opposite corners of the panels. The test layout follows the requirements of ASTM E 519-81, although some change has been introduced, as the different size of the panels to be tested and of the loading shoes, in order to properly account for the size of the type of masonry to be tested. Between the steel shoes and the specimens has been realized a fast setting shrinkage free mortar bed for a better distribution of the load and in order to avoid a brittle failure of the panels edges.
Potentiometric and LVDT transducer were used for monitoring the in-plane and out-of-plane displacement (fig.3). Two potentiometric transducers were placed on each side of the panels along the two diagonals to record the vertical and horizontal displacement and therefore strains. These transducers had a measurement length of 400 mm. This was based on experimental observations from similar experiments, where it was found that shear cracks developed in the central area of the panels. Two LVDT were installed perpendicularly to the panel surface to measure out-of-plane displacements.
Before setting the instruments, the panels were whitewashed in order to record the crack pattern by means of a high-resolution camera.

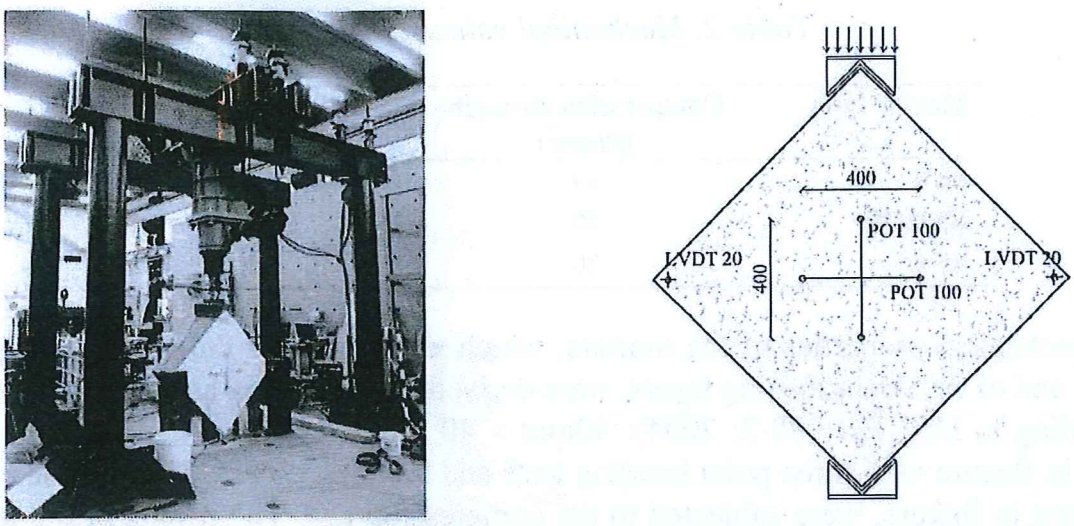
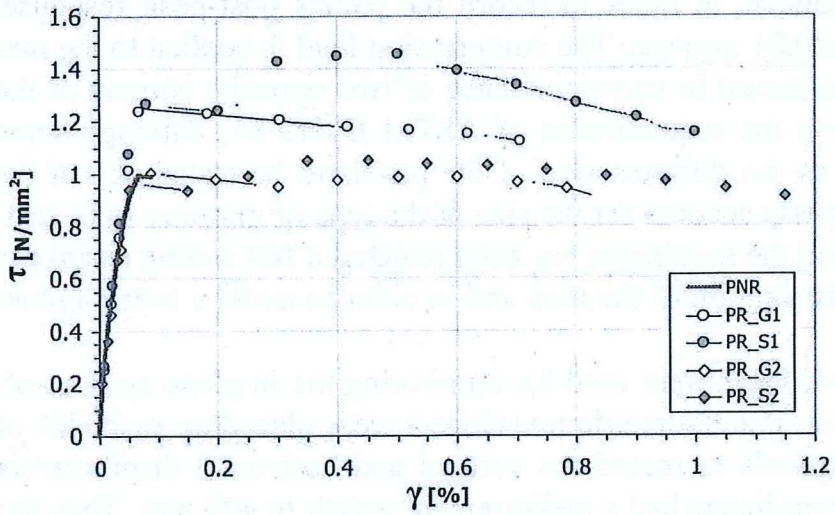


Figure 3. Steel frames used for the diagonal compression test (left) and instrumentation device (right).

4 EXPERIMENTAL RESULTS

Figure 4 show the shear stress – shear strain curves for the five panels tested.
Shear strength τ, reported in figure 4, for the various panel tested, can be obtained on the basis of the current experimental load P, according to ASTM E 519-81, with the following conventional formula:



	Type mortar	Type grid
PNR	M10	/
PR_G1	BS38/39	G
PR_S1	BS38/39	S
PR_G2	BS37	G
PR_S2	BS37	S

G Fiber glass mesh
S Steel mesh

Figure 4. Shear stress-shear strain relationship for the panels tested

$$\tau = 0.707 \frac{P}{A_n} \tag{1}$$

where A_n is the net section area of the un-cracked section of the panels.
The average strains, ε_v and ε_h, can be calculated on the basis of the average displacements on the two sides of the panels:

$$\varepsilon_v = \frac{\Delta V}{g} \qquad \varepsilon_h = \frac{\Delta H}{g} \tag{2}$$

where ΔV and ΔH are the vertical shortening and horizontal extension along the compressive and tensile diagonal, respectively, and g is the vertical gage length (400mm)
The shear strain value, γ, which is reported in figure 4, is computed as:

$$\gamma = \varepsilon_v + \varepsilon_h \quad (3)$$

The unreinforced specimens (PNR) presented a brittle failure due to the rupture of the bricks and the mortar beds along the loaded diagonal. The average failure load, used as reference value for the comparison with the strengthened specimens results, is equal to 631 kN and the ductility factor is 1.3%. The PNR panel before and after the diagonal compression test is shown in figure 5.

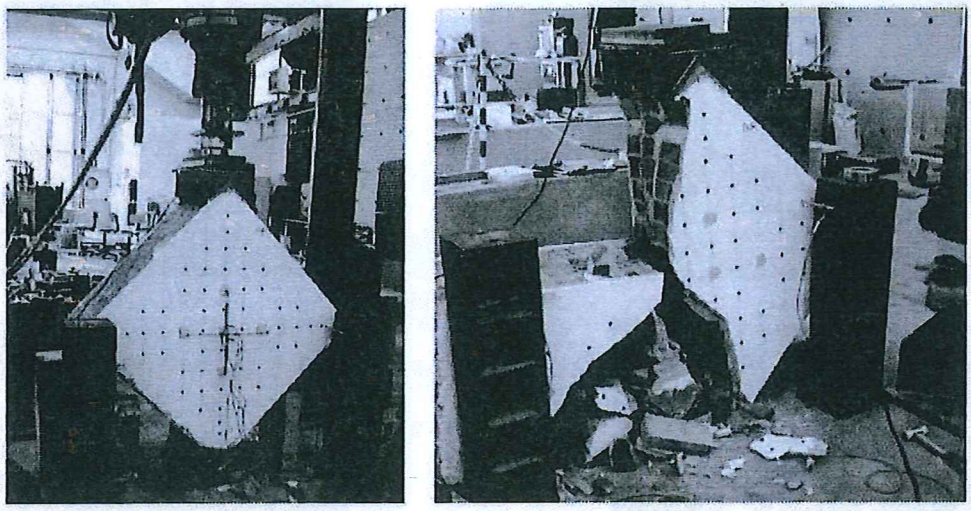


Figure 5. PNR panel before (right) and after (left) the diagonal compression test

The two panels strengthened with a BS38/39 layers show an increase of the maximum load with respect to the unreinforced panels. For the specimen with a fiber glass grid (PR_G1), the maximum load exhibits an increase of 29% compared to the peak load of the unstrengthened panels, while for the specimens with a steel grid (PR_S1) the increase is equal to about the 50%. For the two panels strengthened with a BS37 mortar, that shows a lower compression strength, the increase of strength is smaller: the increase of maximum load is only of 3% for the specimen with a fiber glass grid (PR_G2), while for the specimens with a steel grid (PR_S2) the increase is about 9%.

The presence of the strengthened layers on the both sides of the specimens has considerably increased the ductility for both types of reinforced panels.

The two walls strengthened with a steel grid (PR_S1 and PR_S2) showed greater ductility. After the onset of a first vertical crack, the load begun to increase again and several vertical cracks appeared along the compression diagonal. The tests were stopped when the load dropped below 80% of the maximum load, to avoid the collapse of the panels and damage to the instrumentation. The panels strengthened with steel grid have reached shear strain in the order of 1% and the ductility factor is 11.60 for the wall with a BS38/39 layers and 18.61 for the panel with a BS37 mortar, values more than ten times higher than those of the non-reinforced panel. Even panels strengthened with glass fiber mesh (PR_G1 and PR_G2) showed a moderate increase in ductility. After reaching the maximum load the two panels have achieved shear strains equal to about 0.8%. The collapse occurred due to the opening of a single vertical crack which run through bricks and mortar beds by ripping the fiber glass mesh. The ductility factor for both panels is equal to 9.6%, a value 7.5 times grater than the one shown by the panel without strengthening layers. The panels at the end of the tests are shown in Figure 6.

The two strengthened systems studied in this research display considerable increase in ductility without, however, producing significant changes in the shear stiffness of the

structure. Therefore, this type of strengthening intervention does not change the static scheme of the structure neither cause redistribution of stiffness in the building.

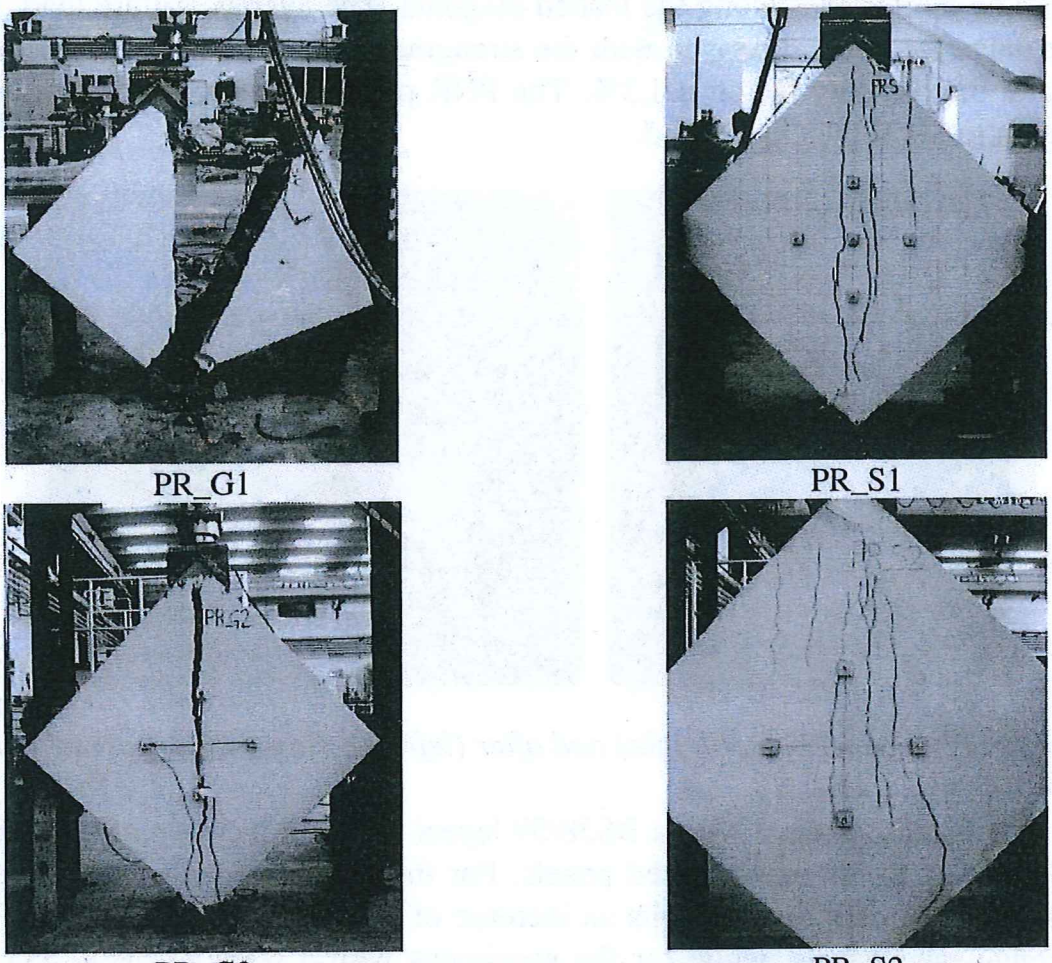


Figure 6. Strengthened specimens at the end of tests

The main results for the tests are summarized in table 3. The values of τ_{max}, γ_{max}, $\varepsilon_{v,max}$, $\varepsilon_{h,max}$ are the stress and strain values evaluated at the maximum load and the τ_u, γ_u are the stress and strain values evaluated when the load drops at the 80% of the maximum load.

Table 3. Experimental results

Specimen	P_{max} [kN]	τ_{max} [N/mm²]	$\varepsilon_{v,max}$ [%]	$\varepsilon_{h,max}$ [%]	γ_{max} [%]	τ_u [N/mm²]	γ_u [%]	G [N/mm²]	μ [%]
PNR*	631.3	0.992	0.044	0.026	0.070	0.980	0.090	3217	1.283
PR_G1	814.8	1.252	0.050	0.024	0.074	1.122	0.707	2569	9.59
PR_S1	948.9	1.458	0.095	0.397	0.492	1.167	0.957	2693	11.60**
PR_G2	652.3	1.003	0.050	0.036	0.086	0.918	0.827	2644	9.65
PR_S2	687.7	1.057	0.111	0.266	0.377	0.894	1.194	2512	18.61**

*For the panels showing a brittle failure, the values of τ_u and γ_u have been evaluated at the end of the tests

Evaluated using the first cracking load (γ_{max}=γ_{fl})

The modulus of rigidity, G, is calculated as the secant modulus between the origin and the stress equal to 30% of the peak stress. The local panel ductility, μ, has been computed by the following equation:

$$\mu = \frac{\gamma_u}{\gamma_{max}} \tag{4}$$

where γ_{max} is the shear strain corresponding to the maximum load and γ_u is the shear strain at 80% of the maximum load (or at the end of the test for the panels that show a brittle failure).

CONCLUSIONS

The possible use of an innovative strengthening technique for masonry walls based on the combined use of a steel or glass fiber grid embedded in a base mortar has been investigated. Diagonal compression tests were conducted on five masonry panels to confirm the effectiveness of this seismic strengthening technique.
On the basis of the experimental results the following conclusions can be drawn:
- The strengthened panels show a significant increase of ductility: the two specimens strengthened with steel mesh exhibit the highest ductility and have reached shear strains in the order of 1% (more than ten times higher than the un-reinforced panel); the walls strengthened with a glass fiber mesh show a moderate increase of ductility and have achieved shear strains equal to about 0.8%.
- The strengthened system studied in this research does not modify the shear stiffness of the structure; therefore it does not change the static scheme of the structure neither cause redistribution of stiffness in the buildings.
- The crack pattern demonstrates a very good adhesion between bricks masonry and reinforced mortar.

ACKNOWLEDGEMENTS

This research project was financially supported by Tecnochem Italiana s.p.a. The Authors would like to thank Mr. Dario Rosignoli for his continuous support and valuable suggestions.

REFERENCES

Borri, A., Castori, G. and Corradi, M. (2011). "Shear behaviour of masonry panels strengthened by high strength steel cords", *Construction and Building Materials, 25* 494-503.

Corradi, M., Borri, A. and Vignoli, A. (2008). "Experimental evaluation of the in-plane shear behaviour of masonry walls retrofitted using conventional and innovative methods", *Journal of the British Masonry Society*, 21(1), 29-42.

Faella, C., Martinelli, E., Nigro, E. and Paciello, S. (2010). "Shear capacity of masonry walls external strengthened by a cement-based composite materials: An experimental campaign", *Construction and Building Materials, 24,* 84-93.

Gabor, A., Bennani, A., Jacquelin, E. and Lebon, F., (2006). "Modelling approaches of the in-plane shear behaviour of unreinforced and FRP strengthened masonry panels", *Composite Structures*, 74, 277-288.

Marcari, G., Manfredi, G., Prota, A. and Pecce, M., "In-plane shear performance of masonry panels strengthened with FRP", *Composites Part B: Engineering*, 30(7-8), 887-901.

Valluzzi, M.R., Tinazzi, D. and Modena, C., "Shear behaviour of masonry panels strengthened by FRP laminates", *Construction of Building Materials*, 16(4), 409-416.

ASTM E 519-81. (1981). "Standard test Method for Diagonal Tension (Shear) in Masonry Assemblages". *American Society of Testing Materials.*

UNI EN 998-2 (2004). "Specification for mortar for masonry-Masonry mortar".