13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 923

TUFF MASONRY WALLS STRENGTHENED WITH A NEW KIND OF C-FRP SHEET: EXPERIMENTAL TESTS AND ANALYSIS

Ciro FAELLA[1], Enzo MARTINELLI[2], Emidio NIGRO[3], Sergio PACIELLO[4]

SUMMARY

A lot of tuff masonry buildings have been built in the past centuries in Italy and in southern Europe; such buildings are generally dimensioned and detailed for vertical loads; for this reason strengthening upgrade is generally required for horizontal actions.
In the last years composite materials have been utilised for such a purpose instead of more traditional techniques consisting, for example, in casting two thin r.c. plates at both the faces of the masonry wall obtaining a sandwich structure.
The present paper deals with experimental tests carried out on tuff masonry walls strengthened with an innovative composite material consisting in a low-density bidirectional carbon-fiber tissue that can be applied to the masonry wall by means of a special cement-based mortar. A series of masonry walls have been tested under diagonal compression at the Laboratory of Structures of the University of Salerno (Italy), according to the ASTM E519/02 standard. Both unreinforced and reinforced walls have been considered in order to quantify the influence of such a new strengthening technique with respect to the bare masonry behaviour in terms of strength and ductility.
Two different arrangements of the strengthening material have been considered (single side versus double side strengthening) in order to point out the influence of the various parameters on the final behaviour.

INTRODUCTION

Masonry buildings are widely common in Italy, in the Southern Europe and in all the Mediterranean basin where they constitute a great part of the built heritage, often having been built in the past decades (or sometimes in the past centuries) and having historical relevance. Indeed, on one hand the regions

[1] Full Professor of Structural Engineering at the University of Salerno, Italy. Email: c.faella@unisa.it
[2] Post-Doc Scholar at the University of Salerno, Italy. Email: e.martinelli@unisa.it
[3] Associate Professor of Structural Engineering, at the University of Naples "Federico II", Italy. Email: emidio.nigro@unina.it
[4] Doctoral Fellow at the University of Salerno, Italy. Email: sopaciello@unisa.it

mentioned above are characterized by a medium to high seismic activity, on the other hand, a great variety of stone and brickwork arrangements can be observed, but the quality of masonry that one can find in these regions is generally not homogeneous and usually not so good. For this reason masonry building are generally fit for bearing vertical loads, but are not so strong to provide enough strength and ductility to resist the cyclic horizontal actions induced by seismic shaking. The recent earthquakes occurred in Italy, in Greece, in Turkey and in Morocco have pointed out the lack of seismic resistance generally characterizing such structural typology.

One of the first studies aimed to quantify the strength of masonry panel to seismic-like horizontal forces has been carried out by Turnsec and Cacovic [1] which dealt with the issues of masonry strength under both eccentric loads and shear actions. They conducted a series of experimental lab tests and provided some simplified formulae for evaluating the panel strength under the above load conditions.

Various experimental tests can be carried out on masonry panels even for practice purposes and for research issues. Corradi et al. [2] reported the results of a very large experimental campaign carried out on the places of the Umbria-Marche earthquake which struck the central Italy in 1997. In that region masonry is generally constituted by the typical calcareous or travertine stones which can be squared or roughly cut and assembled with various kind of mortar. Laboratory tests have been carried out for quantifying the mechanical properties of the masonry components. In situ experimental work has been carried out for testing masonry panels as a whole. Compression tests have been conducted for characterizing the panel strength under vertical loads, while shear compression tests and diagonal compression tests have been carried out to investigate the masonry behavior under seismic-like actions. It is worth noticing that shear-compression tests provided systematically an higher estimation of the masonry shear strength with respect to the corresponding values obtained by diagonal-compression tests. In a companion paper, Borri et al. [3] conducted the same tests on stonemasonry panels strengthened with FRP. Even in that paper the ratio between the shear strength evaluated by shear-compression tests is generally about twice the corresponding value obtained by diagonal compression tests. These studies seem to point out that the latter test is much more severe that the former one and they emphasized the importance of choosing the best one for simulating the masonry behavior under seismic actions. However, diagonal compression tests have been also carried out by Valluzzi et al. [4] for characterizing the effectiveness of strengthening clay brick masonry panels by FRP. They investigated the influence of various kind of FRP materials (carbon-based, glass-based and Polyvinyl-alcohol based composites) and strengthening patterns (grid set-up and diagonal configuration). In all cases the contribution of FRP strips on the shear behavior of panels seemed not effective at all in the case of single side reinforcement. Moreover, diagonal arrangements provided more effectiveness in terms of shear strength, while specimens with grid set-up pattern of the FRP strips resulted in more ductile failures. The issue of adherence between FRP strips and masonry substrate have been emphasized as well, demonstrating that it is of greater concern as the axial stiffness of the FRP laminate increases. For this reason, utilizing less stiff FRP strips seems to be more appropriate for masonry strengthening, at least if alternative anchoring methods will not be developed. Calibrating a stable formula to quantify the interfacial strength depending on the FRP Young modulus, its thickness and the mechanical (but even chemical) properties of the masonry bricks is a cutting edge issue even utilizing both rods and strips like Tinazzi et al [6] did. Campione et al. [7] focused their interests to investigate the so-called peeling phenomenon occurring at the interface between the epoxy resin utilized for gluing FRP and the stone substrate; such a phenomenon, occurring in FRP-strengthened r.c. beams as well, depends on the brittleness of the stone in tension and can affect the effectiveness of the strengthening/retrofitting intervention with FRP on masonry panels. Pull-out tests on calcarenite bricks have been carried out for studying the peeling and delamination phenomenon; a simplified analysis based on an elastic beam model on elastic springs gave results comparable with experimental data. Campione et al. [7] observed that the rupture phenomenon is substantially governed by the tensile strength of the stone bricks and pull-out ultimate force can be improved by using adequate fixing techniques. Alternatively, Triantafillou [5] faced the same subject by introducing an effectiveness coefficient for taking account limited possibility for FRP to develop its ultimate strain before bonding crisis.

These studies devoted to FRP strengthening of masonry panels pointed out mainly that utilizing those materials for masonry upgrading needs to take care to some detail aspects. First of all, the adherence issue that often controls the failure of masonry panels due to the low tensile strength of masonry bricks; moreover, bricks can be constituted by a great variety of materials range from the weakest tuff stone up to the calcarinite and travertine rock. So it is generally complicated to state a stable correlation between brick mechanical properties and the bonding resistance of the epoxy resin interface, usually utilized for gluing FRP strips to the stone substrate. On the contrary, it seems more rational trying to control premature failures due to loss of interface bonding by reducing the stiffness of the FRP material utilized for strengthening. For this reason, utilizing FRP strips, firstly developed for reinforced concrete, seems not so suitable for masonry; a mesh-like carbon FRP tissue, characterized by a material density much lower than the usual FRP uni/bi-directional sheets, has been developed for shear strengthening of masonry panels. Even epoxy resin seems not so suitable for realizing a good interface between a so-thin material, like an FRP sheet, and a generally irregular substrate constituted by regular bricks or roughly squared stones assembled with variably thin mortar beds. Furthermore, the above mentioned C-FRP meshes can be applied to masonry face by means of a suitable mineral mortar that is generally much more fit to fill the voids between two bricks and the possible irregularities on their faces. A material characterizing by these two properties dealing with FRP density and adherent properties has been recently developed for strengthening FRP panels and improving its shear capacity. Barbieri and Di Tommaso [8] tested this innovative FRP-based strengthening system on clay brick masonry walls. They carried out a laboratory experimental program on nine walls, two unstrengthened and seven strengthened ones; diagonal compression test have been conducted, even if specimens dimensions were smaller than those provided by the ASTM Standard [9]. However, the specimens have been prepared by considering both single-face and double-face strengthening; in the first case both single and double layer of the mesh have been considered, while in the second case only a double layer (alternatively oriented at 0°/90° and ±45°) has been analyzed. The authors observed an increment in the shear strength ranging between 50% to 250% for the panels strengthened according to the different possible arrangements described above. Moreover, they observed that strengthening brick panels by means of the FRP mesh described above results in changing their failure mechanism, that switch from the characteristic diagonal crack propagating throughout the mortar joint to a failure involving both mortar and bricks. Finally, it has been worth underlying that only in few cases peeling phenomena occurred.

Starting from the background briefly outlined above, the present paper describes an experimental campaign conducted at the Laboratory of Structures of the Department of Civil Engineering of the University of Salerno (Italy). The aim of such an experimental activity consists in testing the effectiveness of an FRP-mesh-mineral-mortar system, like that considered by Barbieri and Di Tommaso [8] for strengthening masonry wallets made of tuff masonry bricks. Tuff masonry is generally much weaker than clay brick masonry especially for seismic purposes. For this reason, various specimens have been prepared considering as a reference the unstrengthened ones and analyzing the effect of both single side and double side strengthening. Diagonal compression tests have been carried out for quantifying the effects of the strengthening intervention; such tests have been carried out according to the ASTM 519-02 [9] Standard and will be described in detail in one of the following paragraphs.

Test results have been utilized for obtaining information about the reliability of some code provisions dealing with masonry shear strength; both italian (DM LL.PP., 1987 [11] and Circolare 1981 [12]) and european (Eurocode 6 [10]) standards will be taken into account for this purpose.

Simplified numerical analyses will be finally proposed for simulate the mechanical behavior of the tested wallets.

SPECIMENS DESCRIPTION AND PREPARATION PROCEDURE

Six tuff masonry panels have been assembled according to a texture like that represented in Figure 1.

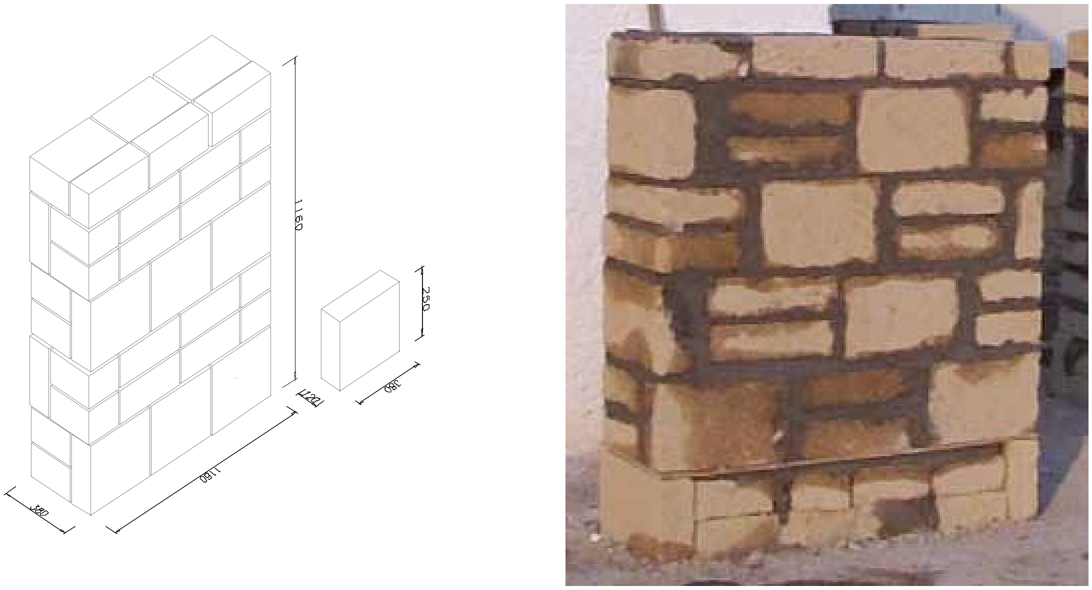


Figure 1: Masonry panel texture

After panels assembling, the FRP mesh has been applied by means of the plaster-like mortar, whose first layer is also useful for regularizing the rough face of the panel. The second mortar layer spread upon the wallet surface is needed to fix and cover the FRP mesh (Figure 2).

a) first mortar layer **b) application of FRP mesh** **c) second mortar layer**

Figure 2: Specimen preparation phases

MATERIAL CHARACTERIZATION

The resulting strength of masonry hugely depends on the behavior of the various materials which constitutes bricks, mortar and FRP strengthening system. Moreover, interactions between FRP reinforced layer and tuff masonry represents a critical point because the bonding issue is certainly of concern. For this reasons a wide experimental campaign has been carried out for estimating the mechanical properties of the various materials.

Tuff stone bricks

Compression tests have been carried out on the 12 tuff 100x100x100 mm^3 specimens represented in Figure 3 for quantifying the compression strength f_b, reported in Table 1: the experimental values of f_b range between 3.4 and 4.6 MPa.

Figure 3: Compression tests on tuff elements: specimens set and test execution

In the light of the experimental results an average value $\bar{f}_b = 4.06\,\text{MPa}$ can be assumed.

Table 1: Results of compression tests on brick elements

Specimen #	P_{max} [N]	f_b [MPa]
01	33800	3.419
02	45780	4.643
03	37200	3.737
04	38560	3.899
05	45320	4.566
06	45160	4.573
07	37820	3.820
08	41280	4.195
09	37240	3.786
10	38980	3.941

Table 2: Results of three-point-bending tests on brick elements

Specimen id	b [mm]	h [mm]	L [mm]	F_{max} [N]	$f_{b,t}$ [MPa]
TU01	3.6	4.1	16.2	436	1.48
TU02	3.9	3.6	16.5	454	1.49
TU03	3.7	3.8	16.3	369	1.28
TU04	3.6	4.2	16.6	495	1.64
TU05	4.0	4.0	16.2	456	1.28
TU06	3.6	4.0	16.3	390	1.35

Bending tests for determining the tuff brick tensile strength have also been carried out on six specimens whose dimensions can be read in Table 2. The same table reports the test results in terms of maximum force F_{max} measured in the bending tests and the corresponding values of the tensile strength $f_{b,t}$, whose mean value can be assume equal to $f_{b,t} = 1.42\,\text{MPa}$. Even if brick compressive strength is generally more important for modeling the behavior of masonry as a whole than tensile strength, in this case the latter quantity has been reported because its value can be useful for describing the interface behavior with respect to the bonding issue that is generally deemed of concern in FRP strengthening.

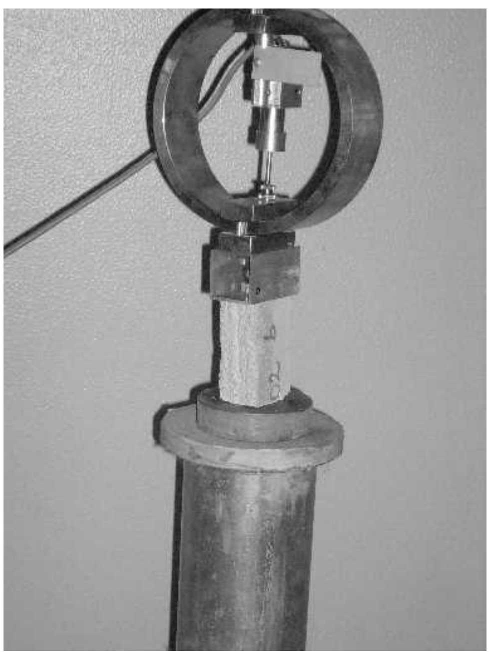
Mortar

Mortar composition is reported in Table 3; it has been chosen according to the typical mortars utilized in the past. According to the classification proposed by the Italian Codes of Standards about masonry [11], mortars can be ranked in four categories from M1 to M4, based on their mechanical properties. The mortar utilized in assembling the panels has been obtained according to the mix proportioned as in Table 3.

Table 3: Mortar Composition

		Composizione				
Class	Mortar type	Cement	Lime	Hydraulic lime	Sand	Pozzolana
M4	*Pozzolanic*	-	1	-	-	3

Compression and bending tests have been carried out on mortar samples to verify that the resulting mechanical properties of the mortar were compatible with the values supposed on the basis of the mortar composition; 40x40x70 mm^3 mortar samples have been utilized for compression tests while bending tests have been carried out on mortar specimens whose dimensions was 40x40x150 mm^3. Figure 4 and Figure 5 report the results of compression and bending tests on mortar samples.



Specimen number	$f_{m,c}$ [MPa]
M01-A	0.879
M01-B	0.846
M02-A	0.709
M02-B	0.834
M03-A	1.210
M03-B	1.117
M04-A	1.295
M04-B	1.115
M05-A	1.086
M05-B	0.914
M06-A	1.296
M06-B	-
M07-A	1.073
M07-B	0.983

Figure 4: Compression tests on mortar: test layout and results

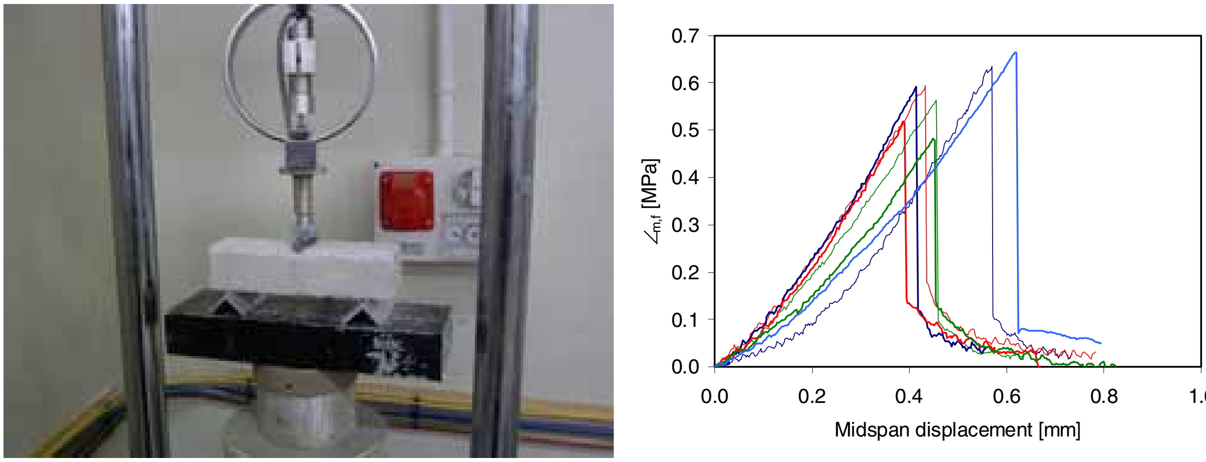


Figure 5: Bending tests on mortar: arrangement and results

According to the results obtained in compression and bending tests, the following values can be assumed for the mortar compression and tensile strength, respectively:

$$f_{m,c} = 1.03\,\text{MPa} \qquad\qquad f_{m,t} = 0.564\,\text{MPa}\,. \tag{1}$$

Despite the mix has been designed according to the Italian Code provisions with the aim of obtaining an M4 mortar, the same code states that the minimum value allowable for raking a mortar in class M4 is 2.5 MPa, that is significantly higher that the experimental value $f_{m,c}$. Nevertheless, the mortar utilized for assembling the panels is representative of a material that has been widely used in the Southern Italy during the past decades.

Tuff masonry as a whole

After diagonal compression tests that will be described in the next section, a masonry sample has been extracted from the integer part of the tested wallet in order to perform a compression test on the tuff masonry as a whole.

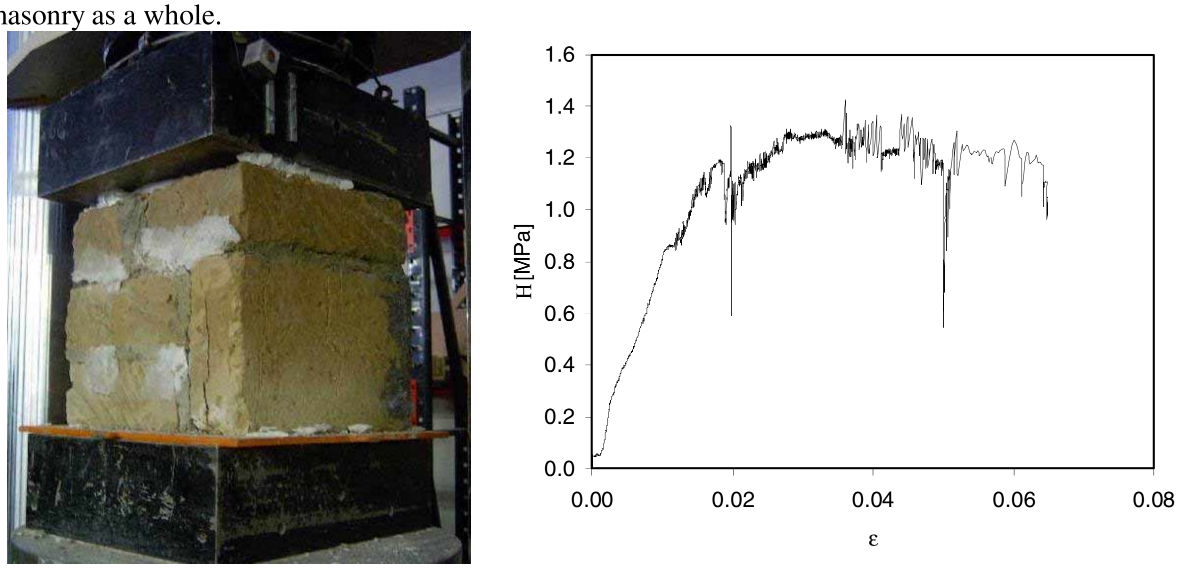


Figure 6: Compression tests a wallet sample: test arrangement and results

The results of such a test is shown in Figure 6 in terms of average compression stress versus average axial strain. A value $f_{w,\exp} = 1.30\,MPa$ of the compression strength measured during the experiment on the wallet sample can be assumed.
It is interesting to relate this strength value to the corresponding values measured for mortar and bricks and reported in the previous sections. Different relationships can be found in the scientific literature and have been adopted by code of standards, sometimes in the shape of synthetic tables. In the following, we refer to the formula adopted by Eurocode 6 for relating the masonry compressive strength f_w to the corresponding ones of mortar and bricks:

$$f_w = k \cdot f_b{}^{0.65} \cdot f_m{}^{0.25} \tag{2}$$

being k a coefficient depending upon the masonry texture and strength characteristics; $k = 0.60$ can be assumed for the present case. According to equation (2) a value $f_{w,th} = 1.41\,MPa$ should be assumed that is very close to the experimental one.

Fiber mesh system

As already told, the FRP strengthening system is based upon an innovative FRP mesh-like tissue that can be applied on the wallet face by means of a mineral mortar. Table 4 and Table 5 report the values that can be assumed for mechanical characteristics of FRP mesh and mineral mortar as taken from the technical sheets provided by the producer firm.

Table 4: Mesh properties

Fiber density [g/m^2]	168
Nominal thickness [cm]	0.047
Strength (for a width of 1 cm) [N/cm]	1600

Table 5: Mineral Mortar properties

Compressive strength [MPa]	38
Bending strength [MPa]	7.5
Young modulus [MPa]	15000

Figure 7 shows the fiber mesh layout emphasizing the main dimensions and representing the consistency of such a material.

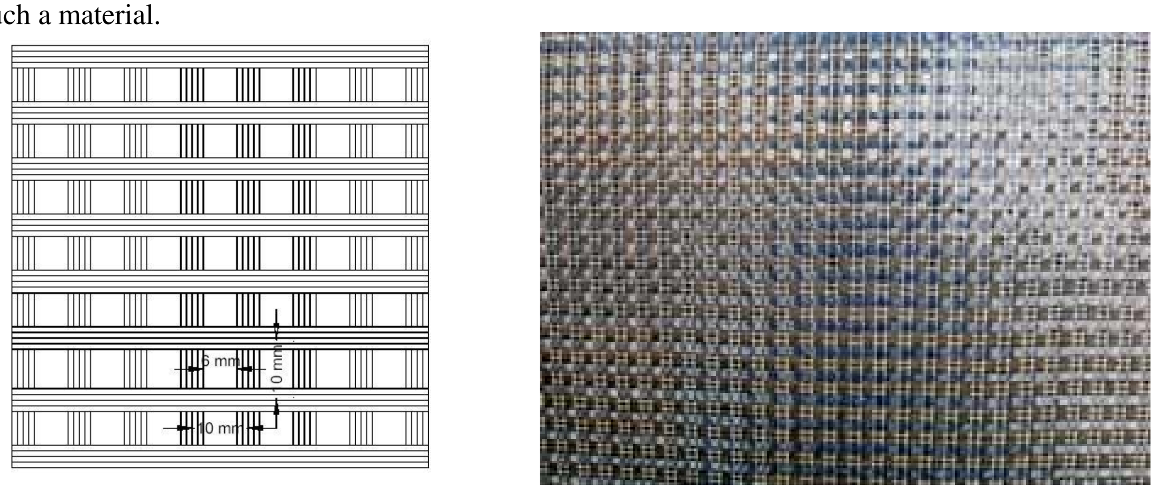


Figure 7: Carbon Fiber Mesh

DESCRIPTION OF THE EXPERIMENTAL CAMPAIGN

The present section is devoted to describe the experimental tests conducted on six tuff masonry wallets listed in Table 6.

Table 6: Tested tuff masonry panels

Specimen Number	B	L	t	Notes
1	1206	1155	393	Unstrengthened
2	1201	1145	390	Unstrengthened
3	1210	1153	405	Single side strengthening
4	1207	1148	388	Single side strengthening
5	1207	1159	390	Double side strengthening
6	1197	1153	388	Double side strengthening

The above specimens have been tested under diagonal compression (Figure 8); the test has been carried out by means of a 350 kN oil jack and the current load has been measured by a load cell.

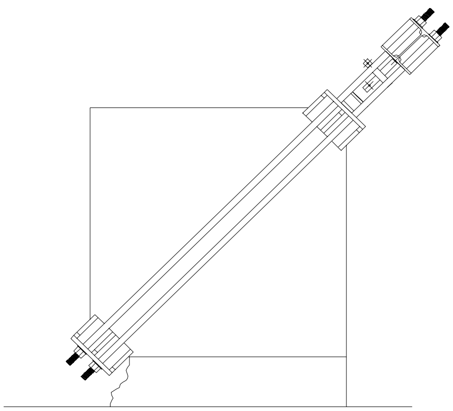


Figure 8: Test procedure

Diagonal displacements in both parallel and transverse direction have been monitored by means of four wire sensors, placed on both sides; one more sensor has been mounted to monitor the out-of-plane displacement of the panels during test process (Figure 9).

Figure 9: Measurement system: Oil jack, Wire Sensor and Load cell.

Experimental measurements in terms of both force and displacement has been recorded continuously by means of a data acquisition system.

EXPERIMENTAL RESULTS

In the present section, the experimental results in terms of the main measured quantities is presented. First of all, Figure 10 shows the Load-Displacement curves obtained in the six experimental tests.

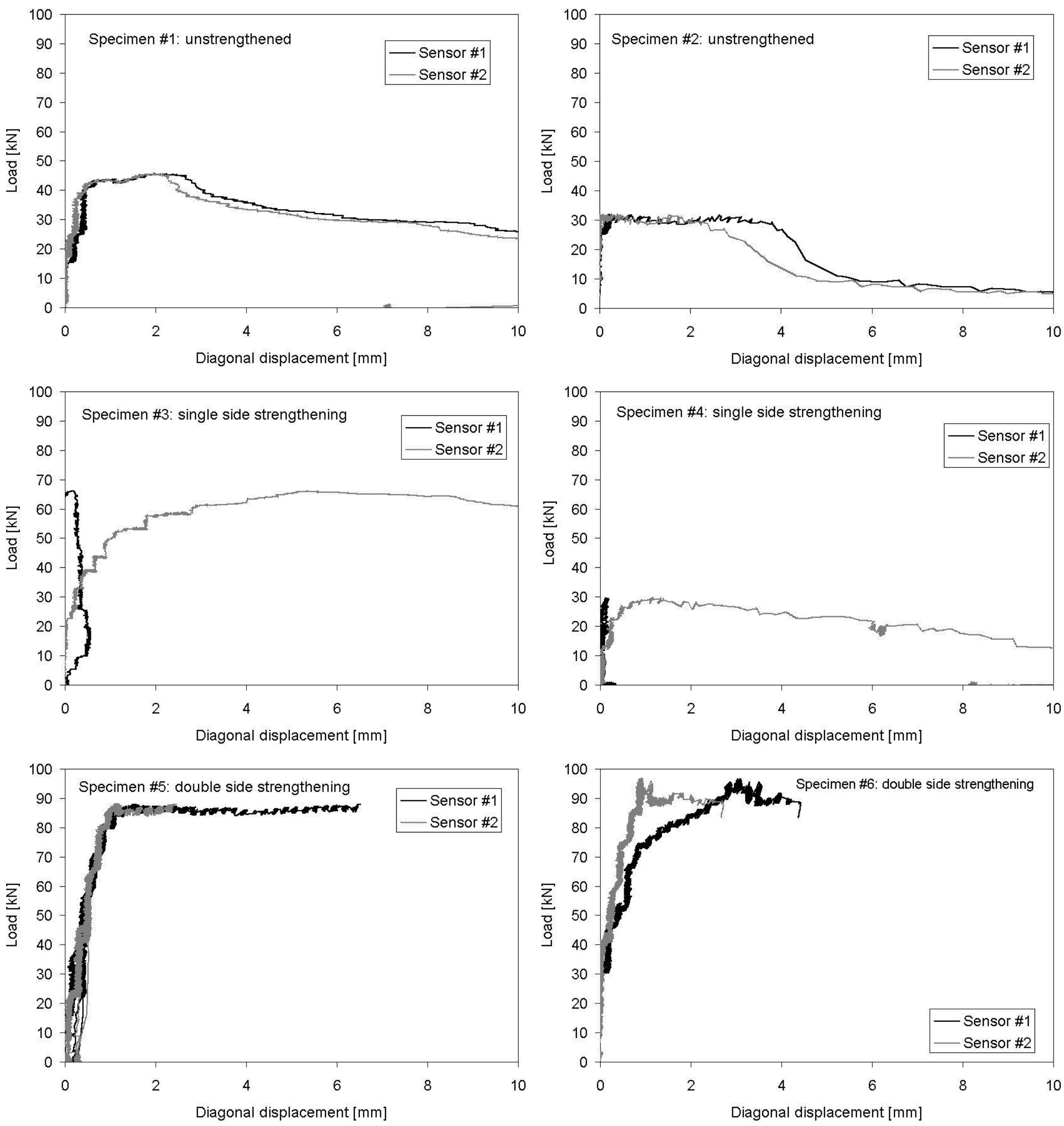


Figure 10: Experimental results: Compressive load versus diagonal displacement

In such figures, it is possible to notice that shear strength generally increases as FRP strengthening increase, as it would be possible to expect even before carrying out the experiments. The only test excepting this general trend is the one carried out on specimen #4. Indeed, specimens #3 failed at a load not so higher than the ultimate one for unstrengthened masonry (numerical values of the ultimate load will be also reported in Table 7). Both specimens #3 and #4 failed after large out-of-plane deviations, just induced by the presence of the FRP plate on only one side. Figure 10 witnesses this phenomena because in the graphs dealing with specimens #3 and #4 the sensor placed in the same direction on the opposite faces gave two measures very far one another. On the contrary, in the other tests both measures were quite close one another, diverging only after the peak load. The same observation holds for transverse diagonal displacements represented in Figure 11.

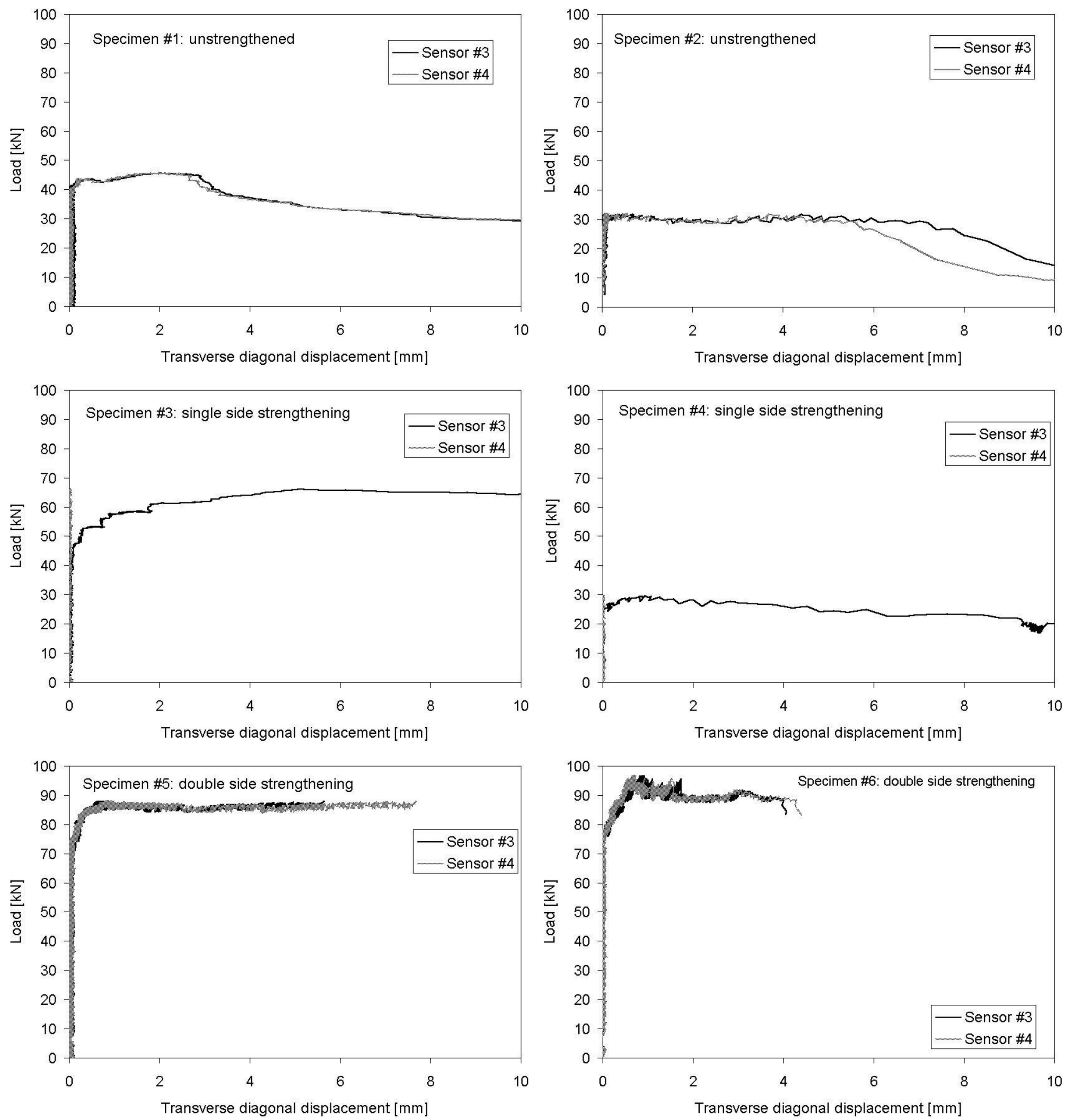


Figure 11: Experimental results: Compressive load versus transversal diagonal displacement

Therefore, the most efficient solution for strengthening this kind of masonry walls is surely the double side strengthening, resulting in high and stable increase in shear strength. In both cases, specimens failed prematurely due to loss of bonding at the FRP-to-masonry interface. In such cases the phenomenon has been very clear resulting in peeling failure of the interface. Figure 12 shows the masonry track left on the bonded side of the FRP-reinforced mortar layer after peeling occurring: as you can see, a complete separation between the supporting mortar and the substrate occurred.

Figure 12: FRP plate peeled off after interface delamination

For this reason the weak link in the strengthening system lies in the masonry-to-FRP interface that is very weak especially for tuff masonry, whose tensile strength is generally low as demonstrated in bending tests reported in Table 2.

ANALYSIS OF THE EXPERIMENTAL RESULTS

The experimental values obtained for the failure load on the wallets can be utilized for estimating the shear strength f_v according to the following conventional formula suggested by the ASTM code provisions:

$$f_v = \frac{0.707 P_u}{A_n} \tag{3}$$

being P_u the ultimate value of the applied load and A_n the net area of the specimen defined in [8] as follows:

$$A_n = \left(\frac{w+h}{2}\right) \cdot tn \tag{4}$$

where *w*, *h* and *t* are the dimensions of the masonry specimen, while *n* is the percentage of the gross area (equal to unity for tuff masonry). Numerical results are reported in Table 7, even for unstrengthened and strengthened wallets. Table 7 also shows the ratios between the shear strength f_{v0} and the average value $f_{v0,U} = 0.060\,MPa$ of the same quantity determined for the naked masonry specimens.

Table 7: Experimental values of the masonry shear strength

Specimen number	Load [N]	f_{v0} [MPa]	$f_{v0,m}$ [MPa]	$f_{v0}/f_{v0,U}$
1	45563	0.071	0.060	-
2	31938	0.050		-
3	66063	0.102	0.074	1.701
4	29563	0.045		0.755
5	88063	0.134	0.139	2.236
6	96688	0.143		2.380

In Table 8 the corresponding values provided by the Italian Code of Standards [11] and [12] for naked masonry: the latter one have to be utilized as a suggested value for untested masonry while the former one provide the masonry strength depending on mortar and brick properties.

Table 8: Experimental versus code provided values for the shear strength: unstrengthened specimens

Specimen	f_{v0} [MPa]	$f_{v0,DM87}$ [MPa]	$\tau_{k,Circ81}$ [MPa]
1	0.071	0.1	0.1
2	0.050		

Experimental values are lower than the ones provided by the Italian Codes of Standards for two main reasons. On one hand, diagonal compression tests is generally more severe than the other tests, as we said in the introductory section; on the other hand, mortar strength has been tailored to be very low for representing the materials usually utilized in existing masonry structures in the Southern Italy.

In Table 7 the shear resistance of the strengthened masonry panels can be evaluated by means of the following formula provided by Eurocode6 [10]:

$$V_{Rd} = f_{vk} \cdot t \cdot d + 0.9 \cdot \rho_{FRP} \cdot f_{fu} t \cdot d \qquad (5)$$

being t and d the dimensions of the wall section, ρ_{FRP} the FRP ratio computed on the wall section and f_{fu} the ultimate tensile stress for FRP. Equation (5) can be utilized for obtaining a simple formula to evaluate the shear strength $f_{v0}{}^{FRP}$ for the strengthened wallets; in fact, interpreting physical quantities as average values, the following deterministic relationship between the shear strength $f_{v0}{}^{FRP}$ and the shear strengthening due to FRP system can be stated:

$$f_{v0}{}^{FRP} = f_{v0} + 0.9 \cdot \rho_{FRP} \cdot f_{fu} \qquad (6)$$

Table 9 shows a comparison between the results obtained by equation (6) and the experimental values of the shear strength $f_{v0}{}^{FRP}$.

It is possible to notice that the experimental values are largely lower than the corresponding analytical ones. Indeed, these experimentally observed values can be explained because specimens failure is generally due to loss of adherence between the thin FRP reinforced mortar layer and the masonry substrate, rather than to a fiber rupture; Figure 12 has already shown the peeling phenomenon arising at the FRP-masonry interface. Equation (5) can be applied to different kind of masonry, maybe stronger than tuff one, that is characterized by low adherence strength.

Table 9: Shear strength for FRP-reinforced walls: Experimental vs. Analytical comparison.

Strengthening type	ρ_{FRP}	$f_{v0,th}$ [MPa]	$f_{v0,exp}$ [MPa]
Single side	0.001205	0.429	0.074
Double side	0.002356	0.782	0.139

An alternative formula can be introduced by considering that bonding crisis instead of FRP rupture controls the specimen failure :

$$f_{v0}{}^{FRP} = f_{v0} + 0.4 \cdot n_{FRP} \cdot \frac{L_{eff} \cdot \tau_{ad}}{t}, \tag{7}$$

being L_{eff} the effective bonding length, τ_{ad} the FRP-masonry adherence strength and n_{FRP} is the number of FRP layers; in other words, the term $L_{eff} \cdot \tau_{ad}$ represents the maximum stress per unit length in FRP layer resulting in loss of bonding. For this reason the quantity $L_{eff} \cdot \tau_{ad}$ is a characteristic parameter mainly depending upon the mechanical properties of masonry. Equation (7) can be calibrated by using the experimental results in terms of shear resistance $f_{v0,\exp}$ obtained for the strengthened wallets reported in Table 7.

Table 10: Calibration of mechanical parameter in equation (7)

Strengthening type	$L_{eff}\,\tau_{ad}$ [N/mm]
Test #3 - Single side	41.03
Test #4 - Single side	-14.35
Test #5 - Double side	36.45
Test #6 - Double side	41.94

The obtained values are listed in Table 10; excepted for test #4, in which a premature failure occurred resulting in a final strength lesser than the unstrengthened one, the other values range between 36.45 and 41.94 N/mm and an average value $\left(L_{eff}\tau_{ad}\right)_{av} = 39.81\,N/mm$ can be derived. However, further studies need to be carried out for confirming and better calibrating equation (7), even considering other type of masonry, for obtaining a reliable design relationship for FRP strengthening of tuff masonry.

CONCLUSIONS

An innovative FRP mesh-like tissue has been tested that seems to be particularly suitable for masonry strengthening due to the fact that a mineral mortar, instead of the usual epoxy resin, is utilized for applying it on the panel faces.

Different strengthening arrangements have been considered; single side solution resulted in scattered and variable shear strength increases reaching 70% as a maximum value. On the contrary, more stable and effective strengthening effect has been observed for double side reinforced panels: the average value of such a strengthening reached 130% with respect to the unstrengthened masonry.

Existing relationships for evaluating the increase in wallet strength induced by FRP strengthening does not seems suitable at all for foreseeing the effect of such intervention on tuff masonry panels due to the premature failure generally occurring in tuff masonry strengthened panels for bond crisis at the FRP-to-masonry interface.

For this reason an alternative formula has been calibrated, for designing both single side and double side strengthening intervention: in both cases a mechanical parameter has been pointed out for interpreting the FRP effectiveness. Such a parameter depends only upon mechanical properties of the FRP-to-masonry interface: in fact, substantially constant values has been determined for such parameter for all the tested specimens, even singly and doubly strengthened.
Other experimental tests and theoretical analyses are in progress in order to confirm and extend the preliminary results reported in this paper.

REFERENCES

1. Turnsek, V., Cacovic, F.: “Some Experimental Results on the Strength of Brick Masonry Walls”, Proceedings of the Second International Brick Masonry Conference, Stoke-on-Trent, England, 12-15 April, 1970.
2. Corradi M., Borri A., Vignoli A.: “Experimental study on the determination of strength of masonry walls”, Construction and Building Materials 2003, 17: 325 – 337.
3. Borri A., Corradi M., Vignoli A.: Strengthening techniques tested on masonry structures struck by the Umbrian-Marche earthquake of 1997-1998. Construction and Building Materials 2002, 16(4): 229 – 239.
4. Valluzzi M. R., Tinazzi D., Modena C.: “Shear Behavior of masonry panels strengthened by FRP laminates”, Construction and Building Materials 2002, 16(4): 409 – 416.
5. Triantafillou T. C.: “Strengthening of masonry structures using epoxy-bonded FRP laminates”, Journal of Composite for Construction ASCE 1998, 2(2): 96 – 104.
6. Tinazzi, D., C. Modena, and A. Nanni, "Strengthening of Masonry Assemblages with FRP Rods and Laminates,” International Meeting on Composite Materials, PLAST 2000, Proceedings, Advancing with Composites 2000, Ed. I. Crivelli-Visconti, Milan, Italy, May 9-11, 2000, pp. 411-418.
7. Campione G., Cucchiara C., La Mendola L, Zingone G.: “Interfacial phenomena in masonry members reinforced with FRP”, Proceedings of the 12th European Conference on Earthquake Engineering, London, 9 – 13 September 2002, Paper Reference 609.
8. Barbieri A., Di Tommaso A.: Relazione sulle prove di compressione diagonale su provini di muratura rinforzati e non, condotte al LaRM di Bologna, Internal Report (in Italian), 2002.
9. ASTM. Standard test method for Diagonal Tension (Shear) in Masonry Assemblages, ASTM E 519 – 02. American Society for Testing Materials, 2002.
10. Eurocode 6: Design of masonry structures – part 1-1: Genaral rules for buildings – rules for reinforced and unreinforced masonry. ENV 1996-1-1: 1995.
11. D.M. LL. PP. Norma tecniche per la progettazione, esecuzione e collaudo degli edifici in muratura e per il loro consolidamento, (in Italian) 20 November 1987.
12. Circolare LL.PP. Normativa per le riparazioni ed il rafforzamento degli edifici danneggiati dal sisma nelle regioni Basilicata, Campania e Puglia. G.U. 21/07/1981, n.198 (in Italian).

ACKNOWLEGDEMENTS

The authors wish to acknowledge the support of the Company Ruredil S.p.A. (Milan, Italy) in supplying composite materials for specimens tested in the experimental campaign.