EXPERIMENTAL BEHAVIOR OF MASONRY COLUMNS CONFINED USING ADVANCED MATERIALS

Marco Di Ludovico[1], Edoardo Fusco[1], Andrea Prota[1], Gaetano Manfredi[1]

[1] Department of Structural Engineering (DIST)
University of Naples "Federico II"
via Claudio 21, 80125 Naples, Italy
e-mail: diludovi@unina.it; e.fusco@unina.it; aprota@unina.it; gamanfre@unina.it.

ABSTRACT
Over last years, Fiber-Reinforced Polymer (FRP) wrapping effectiveness has been clearly confirmed especially with reference to concrete structures. Despite evident advantages of FRP based confinement systems that allow preventing brittle failures of members subjected to compressive overloads due to static or seismic actions, the use of such technique in the field of masonry has not been fully explored. Thus, the potential of both FRP wrapping and of an innovative technique based on the use of FRP grid bonded with cementitious mortar to restore structural safety of masonry members have been investigated in the present paper by an experimental work dealing with 12 square cross-section listed faced tuff masonry columns subjected to uniaxial compression. In particular, three different confinement schemes were experimentally analysed in order to evaluate and compare the effectiveness of the proposed strengthening techniques: 1) uniaxial glass FRP laminates (GFRP); 2) uniaxial carbon FRP (CFRP) laminates; 3) alkali-resistant fibre-glass grid bonded with a cement based mortar. The main experimental outcomes in terms of specimens' mechanical behaviour, stress-axial strain relationships and ultimate strains recorded on the reinforcement in the transverse direction are presented and discussed in the paper. Experimental outcomes showed that the investigated confining systems were able to provide significant gain both in compressive strength and ductility of masonry members.

KEYWORDS: masonry, tuff, confinement, mortar, grid, FRP**.**

1. INTRODUCTION

A large number of existing masonry structures show damages due to a wide range of causes (i.e. inadequate construction techniques and materials, foundation settlements, seismic loads and environmental deterioration). Even when these structures are not affected by strong signals of deterioration, they often need to be upgraded to meet new stringent seismic design requirements or to allow a change of use of the building.
The confinement of masonry columns, traditionally obtained through reinforced concrete jacketing (Kog Y.C. et al., 2001 [1]) or steel jacketing, could allow preventing brittle failure of masonry members subjected to compressive overloads, seismic actions or also static actions, like creep effects.
In order to enhance the potential of the traditional strengthening techniques, numerous studies were carried out in the last decades. The most interesting innovation in this area was the introduction of the Fiber-Reinforced Polymer (FRP) strengthening technique. Numerous researches were carried out in such field to study the benefits given by FRP interventions in both in-plane and out-of-plane behavior of masonry walls (Lissel, 2003 [2], Galati, 2003 [3], Tumialan et al., 2003 [4], ElGawady et al., 2005 [5], Marcari et al., 2007 [6]).
However, a review of the literature state of art demonstrates that only few studies were conducted on the application of FRP laminates to increase both axial strength and deformation capacity of masonry columns through confinement (Krevaikas et al., 2005 [7], Corradi et al., 2007 [8], Aiello et al., 2007 [9]).
Traditional confinement techniques, that were largely used and investigated in the past, may be inadequate in seismic areas where the added mass could generate a significant extra weight that induce an increase of the

seismic actions to be computed. On the contrary, confinement of masonry columns with FRP laminates could imply significant advantages like as a negligible increase of cross-sectional dimensions and member mass as well as the fast and easy installation procedure.
Moreover traditional confinement techniques, generating a significant cross sections increase, seem to be too invasive when it is necessary to preserve the historical value of architectural heritage. In such cases properties like reversibility, compatibility and sustainability could become critical for the selection of the most appropriate strengthening technique.
Although FRP laminates could represent a sound solution to comply such requirements, it is also necessary to underline that their use by means of epoxy resins requires the primer application to ensure a proper gripping into substrate pores; even though studies have already shown that FRP can be removed by heating the surface, Offices for Cultural Heritage Preservation are often not comfortable with the level of reversibility of these resins. A few studies are available about the sustainability and recycling of epoxy resins; however it is clear that the exceeding material has to be treated as a special waste and this requirement about its disposal is not common in the construction industry. Thus, the use of an innovative system based on the use of fibers bonded with cement based matrix could offer interesting opportunities since it could represents an effective technique from both structural and architectural point of view. Indeed, such system combines the above mentioned advantages of FRP systems and those related to the use of inorganic matrix such as reversibility, compatibility, sustainability of the intervention and disposal of the exceeding material.
As result of such considerations, the present paper aims to put in evidence, through the realization of an experimental campaign and its analysis, the potential of masonry confinement by two main techniques: by using FRP laminates (carbon FRP (CFRP) or glass FRP (GFRP)); by using a primed alkali-resistant fibreglass grid bonded with cement based mortar. Moreover the paper goal is to enrich the experimental available data on confinement of masonry members in order to faster the development of effective analytical design equations to predict the behavior of confined masonry columns by using composite material bonded with resins or cement based mortars.

2. EXPERIMENTAL CAMPAIGN

The experimental campaign was carried out at the Laboratory of the Department of Structural Engineering (DIST) of the University of Naples Federico II. The investigation was carried out on 12 square cross-sections listed faced tuff masonry (external tuff blocks and inner core filled with tuff chips and mortar) scaled columns (mass density equal to about 1530 kg/m^3): side average dimension equal to 220mm; and average height of about 500 mm corresponding to 8 courses of tuff bricks (height-width ratio of 2.27). Masonry was made by scaled yellow Neapolitan tuff bricks (50x50x100mm) and a pozzolana (local volcanic ash) based mortar (thickness of 12mm). Masonry columns geometrical details and specimen view during construction phases are depicted in Figure 1.

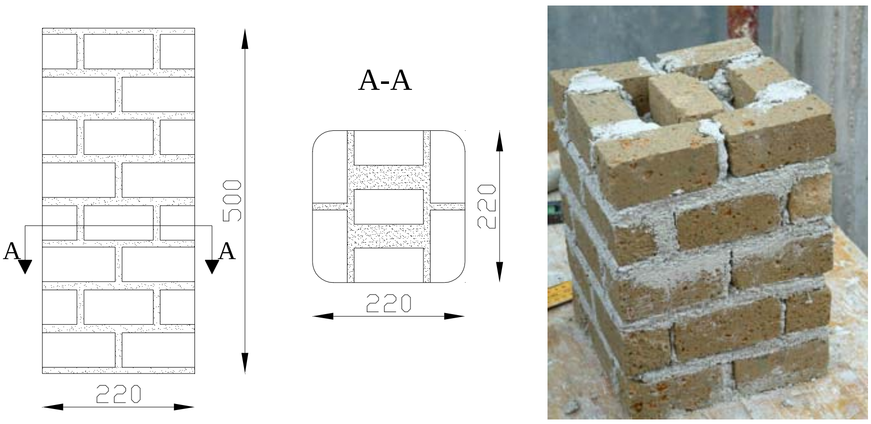


Figure 1. Specimen details (dimensions in mm).

The specimens were divided in four series of three specimens, respectively named Series “U”, “C”, “G”, and “GRM”. The specimens of Series U were used as control specimens and they were tested without wrapping.

Specimens of Series C and Series G were wrapped with one ply of CFRP and GFRP uniaxial laminates, respectively. CFRP laminates were characterized by a unit weight of 300 g/m^2 and a thickness of 0.166 mm/ply, while GFRP laminates by a unit weight of 900 g/m^2 and a thickness of 0.48 mm/ply. Specimens of Series GRM were wrapped with one ply of primed alkali-resistant fiberglass grid (unit weight of 225 g/m^2 and thickness of 0.043 mm/ply), bonded with a cement based reinforced mortar. The corners of specimens of Series C, G and GRM were rounded with a radius of fillet of 20mm in order to allow a proper reinforcement installation procedure. In the case of Series GRM, the reinforcement installation was realized according to the following steps: application of a layer (about 4 mm) of cement based mortar reinforced with short glass fibers; installation of one ply of primed alkali-resistant fiberglass grid; application of a second layer (about 4 mm) of cement based mortar reinforced with short glass fibers. It is noted that the reinforcement provided by the GFRP grid bonded with cement based mortar was applied continuously up to the top and bottom ends of the masonry columns in order to simulate applications in which the external reinforcement is clamped to the structural members connected to the column.
Specimen series and labels are summarized in the first two columns of Table 1; in the third column the product of external reinforcement ratio, ρ_f (ρ_f=4t$_f$/[max(b,d)], with t_f, thickness of reinforcement fibres, *b* and *d* cross-section dimensions of the specimen) and Young modulus of fibers, E_f, are reported for each strengthening system. The amount of CFRP and GFRP laminates used for the strengthening was designed with the aim to obtain a similar value of the product $\rho_f E_f$, and thus to directly compare the performances of wrapping systems based on the use of glass or carbon fibers bonded with epoxy resins.

2.1. Material properties and test setup

The average compressive strength of tuff bricks used for specimens realization was equal to 2.55MPa; it was computed by means of compressive experimental tests on 15 orthogonal prisms (50x50x100mm). The mechanical properties of the mortar employed in the realization of columns were determined based on bending and compression testing (according to UNI EN 998-2, [10]): nine 40 x 40 x 160 mm mortar prisms were tested in flexure with three point bending; and eighteen cubes, obtained from failed mortar specimens in flexure, were subjected to compression tests. The 28-day average strength results were as follows: 1.71 MPa for flexion tests and 6.9 MPa for those of compression.
Moreover, CFRP and GFRP uniaxial laminates with a density of 1.8 g/cm^3 and 2.62 g/cm^3, respectively, were used. The following mechanical properties were obtained through experimental tensile tests according to ASTM D3039-3039M, 2000 [11]: ultimate tensile strength, Young modulus, and ultimate strain equal to 3380 MPa, 228 GPa, and 0.015 for CFRP laminates and 1315 MPa, 68 GPa, and 0.020 for GFRP laminates.
A two-component cement based mortar was used to bond fiberglass grid to the masonry substrate and to provide columns jacketing; the mechanical properties were given by the manufacturer: flexural strength of 9 MPa, compressive strength of 25 MPa and Young Modulus equal to 8 GPa. Finally, primed alkali resistant fiberglass grid properties were provided by the manufacturer: ultimate tensile strength equal to 1440 MPa, Young Modulus equal to 72.0 GPa and ultimate strain equal to 0.02.

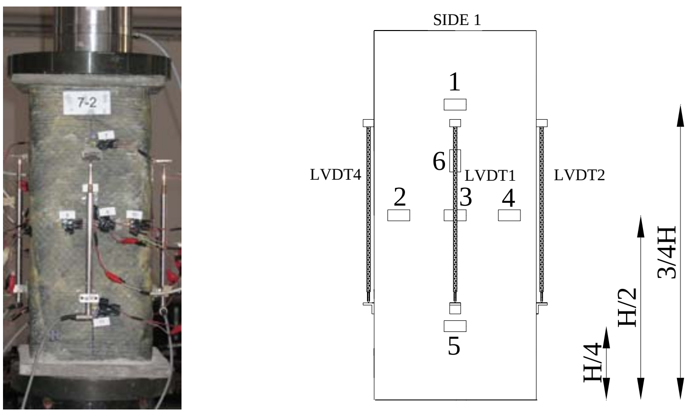


Figure 2. Test set-up and instrumentation layout.

Masonry columns were tested trough monotonically applied axial compressive loading under displacements control mode with a rate of 0.002 mm/s. On each specimen four stringer-type linear variable displacement transducers (LVDTs) and four strain gages, one on each side of the column, were mounted in order to record axial displacements. Furthermore, in order to measure transverse strains on the external reinforcement, 6 strain gages were installed on each side of the confined specimens; details about instrumentation locations on each side of specimens are reported in Figure 2. Finally, two spherical hinges were placed at the ends of the specimens in order to avoid load eccentricity during the test.

3. EXPERIMENTAL RESULTS

3.1. Stress-strain relationships

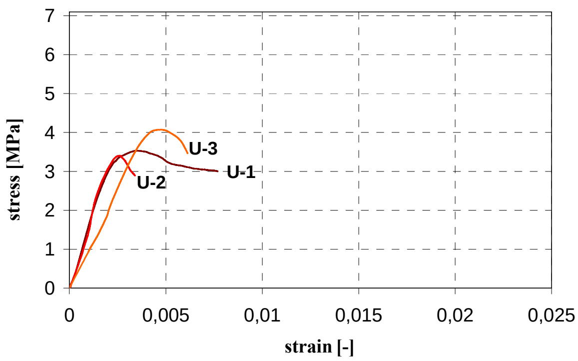
Data recorded by LVDTs applied on each specimen allowed to plot the stress-axial strain relationships for each specimen; such curves are reported for each series in Figure 3. The stress-axial strain relationships of control specimens were characterized by the typical nearly linear progress followed by a second non linear branch up to the peak stress; once peak stress was achieved, a gradual post-peak descending branch was observed that dropped when fracture of specimen occurred. The average peak load recorded was equal to 178 kN, while the average peak stress, f_{m0}, and ultimate axial strain, ε_{m0}, were 3.67 MPa and 0,57%, respectively (see Table 1); it is noted that the ultimate axial strains reported in Table 1 have been computed with reference to 85% of the peak load in the case of stress-strain relationship characterized by a post peak descending branch and to the peak load in the other cases.The failure was due to vertical cracks that become increasingly wide along the specimens, especially at the ends of the columns (see Figure 4 (a)). The cracks pattern recorded during the test showed that the mortar was able to avoid local failure with a corresponding premature collapse of the column.

Table 1 – Experimental results

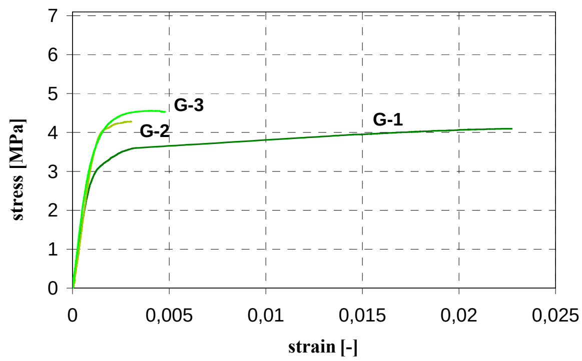
Spec. Series	Spec. label	$\rho_f E_f$	Peak Load	Av. Peak load	Peak stress	Av. Peak stress	Ultimate axial strain	Av. Ultimate axial strain
[-]	[-]	[MPa]	[kN]	[kN]	[MPa]	[MPa]	[-]	[-]
U	U-1	-	170.86	178	3.53	3.67	0.0077	0.0057
	U-2	-	164.82		3.41		0.0034	
	U-3	-	197.10		4.07		0.0061	
G	G-1	600	198.36	209	4.10	4.31	0.0227	N/A
	G-2	600	207.36		4.28		0.0030	
	G-3	600	220.26		4.55		0.0045	
C	C-1	692	206.94	217	4.28	4.48	0.0083	0.0094
	C-2	692	222.96		4.61		0.0109	
	C-3	692	220.44		4.55		0.0090	
GRM	GRM-1	56	300.92	334	5.40	6.00	0.0023	0.0019
	GRM-2	56	310.74		5.58		0.0018	
	GRM-3	56	391.54		7.03		0.0016	

GFRP and CFRP wrapped specimens presented nearly bilinear stress-strain curves (see Figure 3 (b) and (c)). The peak load was very close for all specimens and equal to about 209 kN and 217 kN on average for GFRP and CFRP specimens, respectively (corresponding to average peak stress, f_{mc}, equal to 4.31 MPa and 4.48 MPa, see Table 1). As concerns as ultimate axial strains, ε_{mc}, on GFRP wrapped specimens, G-1 achieved large values of ultimate axial strain up to 2,27% with respect to the other GFRP wrapped columns (i.e. 0.30% and 0.45%, for G-2 and G-3, respectively); such result could be ascribed to the premature failure that occurred on laminates of G-2 and G-3 wrapped specimens due to local stresses concentration at the corners. Therefore the authors believe that an average ultimate axial strain for GFRP wrapped specimens can be not computed from the available experimental data. Whereas on CFRP wrapped specimens, the average ultimate axial strain recorded was about 0.9%. Stress-strain relationships of both GFRP and CFRP wrapped specimens followed the same linear branch recorded for unconfined specimens up to a stress value of about 3.00 MPa; once such stress value was achieved, a transition branch was recorded in the stress-strain diagram that led to a second linear branch having a lower

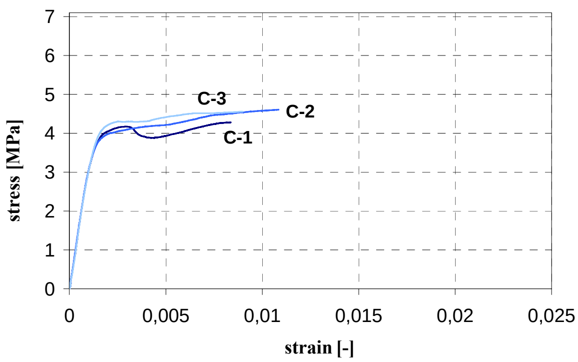
stiffness with a progressive increase of lateral strains. FRP wrapped specimens failed due to reinforcement device rupture in the transverse direction (See Figure 4 (b) and (c)); the longitudinal reinforcement failure started at specimen's corners and then it propagated along the specimen side.
Specimens of Series GRM showed a significant load capacity and stiffness gains (see Figure 3 (d)); indeed the average peak load was equal to about 334 kN, corresponding to an average stress equal to 6.00 MPa (see Table 1). On the contrary, the ultimate axial strain reached average values of 0.19%, significantly smaller than those recorded on control specimens (0.57%).



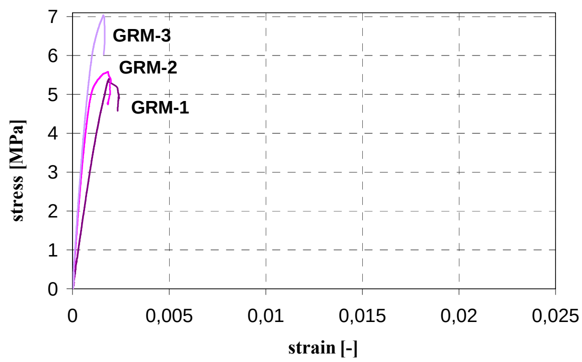
(a) Series U



(b) Series G



(c) Series C



(d) Series GRM

Figure 3. Stress-axial strain relationships.

(a) Series U (b) Series G (c) Series C (d) Series GRM

Figure 4. Specimens' failure mode.

Once peak load was achieved, vertical cracks were detected in the cement based mortar jacket and bulges starting to arise along its sides (see Figure 4 (d)). Because the mortar jacket reinforced by GFRP grid was continuously installed up to the ends of the masonry column, the axial load was applied to the whole cross-section (i.e. masonry core and hollow square mortar jacket) inducing a failure mode strictly related to the axial stiffness ratio between masonry core and external reinforcement jacket. In the case investigated in the present paper, the load distribution between such two resisting systems induced to the masonry core crushing with cracks and evident bulges on the cement based mortar jacket.

The average gains in terms of both peak stresses and ultimate axial strain provided by the different confinement techniques used in the experimental investigation are summarized in Table 2. Standard deviation, SD, and coefficient of variations, COV, are also reported.

Table 2 – Peak stress and ultimate axial strain gains

Spec. label	f_{mc}/f_{m0}	$[f_{mc}/f_{m0}]_{AV}$	$[f_{mc}/f_{m0}]_{SD}$	$[f_{mc}/f_{m0}]_{COV}$	$\varepsilon_{mc}/\varepsilon_{m0}$	$[\varepsilon_{mc}/\varepsilon_{m0}]_{AV}$	$[\varepsilon_{mc}/\varepsilon_{m0}]_{SD}$	$[\varepsilon_{mc}/\varepsilon_{m}]_{COV}$
[-]	[-]	[-]	[-]	[%]	[-]	[-]	[-]	[%]
G-1	1.12	1.18	0.062	5.26	3.96	N/A	1.913	N/A
G-2	1.17				0.52			
G-3	1.24				0.78			
C-1	1.17	1.22	0.048	3.92	1.45	1.64	0.235	14.3
C-2	1.25				1.90			
C-3	1.24				1.57			
GRM-1	1.47	1.64	0.244	14.89	0.40	0.33	0.063	19.0
GRM-2	1.52				0.31			
GRM03	1.96				0.28			

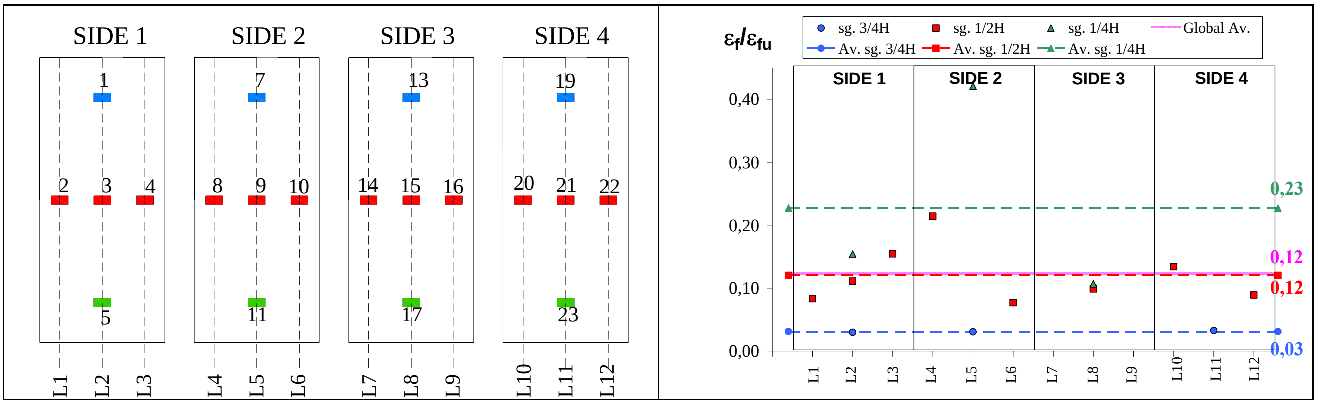
Table 2 shows that similar benefits were provided in terms of strength increase by GFRP and CFRP laminates (peak stress gains ranging between 18% and 22%, respectively); a low dispersion was recorded for such experimental data (less than 5%). About 64% (3.5 and 2.8 times larger) was the peak stress gain provided by the combined use of GFRP grid and cement based mortar. Considering that, in this case, the mechanical amount of reinforcement (expressed by the product $\rho_f E_f$) was significantly less than in the case of GFRP or CFRP wrapping, such result could be explained by considering the combined action of three main effects: the benefits provided by the lateral pressure induced by the GFRP grid; the effects of lateral pressure due to the cement based mortar jacket up to its tensile failure (that is delayed by the GFRP internal grid that allows distributing the acting loads due to masonry expansion); the axial strength increase due to the added cross-section provided by the external reinforced jacket (axial load is shared on masonry core and external reinforced jacket proportionally to their axial stiffness). On the other hand, the use of such strengthening system led to a decrease of ductility: the ultimate axial strain was reduced by an average factor of 0.33 with respect to unconfined specimens. However, it is noted that, due to installation procedure need, the thickness of the mortar jacket was not reduced even if scaled columns were tested; thus the axial strength and stiffness increases produced by the external jacket have been particularly marked on the GRM specimens performances restraining the benefits provided by confinement itself. In any case, in order to improve the ductility of specimen wrapped by the combined use of fiber grids and cement based mortars, it appears necessary to use mortars with higher value of tensile strength and ultimate strain; in this way it could be possible to delay the jacket failure inducing a more ductile global behavior.

3.2. Effective ultimate strain of the external reinforcement

In order to analyze the experimental results reported in Table 2, in this paragraph the transverse strains recorded at failure load (peak load or 85% of peak load in the case of descending branch on the stress-strain relationship) on the reinforcement devices are reported with reference to one specimen of each series experimentally investigated. In particular, specimens that showed maximum ultimate axial strain gains have been selected to the analysis (i.e. specimen G-1, C-2 and GRM-1).

In Figure 5 (a) the location of strain gauges horizontally applied to measure reinforcement transverse strains during the tests are reported; the dashed lines represent the strain gages vertical alignments (named "Li" where L=line and i=number of line from 1 to 12). In Figure 5 (b), (c) and (d) the transverse strains at failure in the reinforcement (effective strain, ε_{fl}) divided by the ultimate axial strain of the reinforcement provided by flat coupon tests (ε_{fu}) are reported for each strain gage on each vertical line (on L2, L5, L8 and L11 where three strain gages were applied, at ¼, ½ and ¾ of the specimen height, three $\varepsilon_{fl}/\varepsilon_{fu}$ values are reported). Moreover dashed lines indicate the average $\varepsilon_{fl}/\varepsilon_{fu}$ values recorded at failure by strain gages applied at ¼H, ½ H and ¾H on the four sides of each specimen.

Experimental values of $\varepsilon_{fl}/\varepsilon_{fu}$ reported in Figure 5 clearly show that transverse strain profiles were in each case deeply non uniform along the reinforcement perimeter; such result confirms that increasing the axial loads, the resulting axial stresses on the reinforcement may be not homogeneous due to local internal cracks as well as to the quality of the confinement execution, that is one the most important parameter especially in the case of hand lay-up applications. In each case a localized peak value of $\varepsilon_{fl}/\varepsilon_{fu}$, definitely larger than its average value, was recorded by the strain gages located closeness to the zone where the reinforcement failure started ($\varepsilon_{fl}/\varepsilon_{fu}$ peak values of about 0.42, 0.83 and 0.45, corresponding to effective strains of about 8.4‰, 1.2% and 9.0‰ were recorded for GFRP, CFRP and glass grid bonded with cement based mortar confinement systems, respectively).
The average values of ratios $\varepsilon_{fl}/\varepsilon_{fu,}$ computed with reference to the twenty strain gages applied in the transverse direction (reported in the graph by a continuous horizontal line), recorded on GFRP and CFRP wrapped specimens were significantly less than 1 and equal to about 0.12 and 0.29, respectively. This phenomenon, already observed in other experimental campaigns [12] can be due to different reasons [13]: quality of confinement execution wrapping, misalignments or wavings may lead to different stretching of the fibres inducing the failure of those overstretched before the average transverse strain can achieve the laminate ultimate strain (starting from such rupture, the phenomenon progresses to the second most stretched fibre and so on up to the failure of the reinforcement); multi-axial stress state in the reinforcement due to the part of the axial load transmitted to the laminates by means of bond stresses at the FRP-substrate interface; as well as local stresses concentration due to masonry cracking.



(a) strain gauges locations and labels

(b) G-1

(b) C-2

(b) GRM-1

Figure 5. Transverse strain in the reinforcement at failure load: (a) strain gauges locations; (b) strains profile on G-1; strains profile on C-2; strains profile on GRM-2

Quality of confinement execution may have been represented the key parameter to explain the reduced average values of $\varepsilon_{fl}/\varepsilon_{fu}$ recorded on GFRP wrapped specimen with respect to CFRP wrapped one; indeed by increasing the unit weight of laminates (GFRP laminates unit weight was three times that of CFRP ones) the fibres impregnation quality is clearly poorer and thus a premature local failure is facilitated. Such consideration could also explain the very low ultimate axial strain recorded on specimens G-2 and G-3 as above discussed (see Figure 3 (b)). Furthermore, it is noted that both GFRP and CFRP confined masonry columns showed average values of ratio $\varepsilon_{fl}/\varepsilon_{fu}$ significantly less than those typically found by experimental tests on concrete members, typically ranging on average between 0.40÷0.60 (Di Nardo et al., 2007, [14]). Such effect may be attributed to the premature development of internal cracks in the tuff masonry columns with respect to concrete members leading to a non-homogeneous deformations and local stresses in the FRP jacket. Finally Figure 5 (d) shows that even less average values of $\varepsilon_{fl}/\varepsilon_{fu}$ were measured on the specimen reinforced with GFRP grid bonded by cement based mortar. Such result indicates that, in that case, the confinement benefits were mainly due to the mortar jacket lateral pressure; the internal GFRP grid allowed delaying the mortar tensile failure by distributing the tensile stresses due to the masonry expansion.

4. CONCLUSIONS

The experimental work allowed investigating on the effectiveness of FRP wrapping of masonry members but also of an innovative strengthening technique based on the replacement of organic resins with inorganic matrices such as cement-based mortars. The experimental outcomes showed that GFRP and CFRP jackets led to similar gains both in terms of compressive strength and ductility of tuff masonry columns under axial loads. However, the presence of voids and protrusions on listed faced tuff masonry members as well the use of high values of laminates unit weight may significant reduce the effectiveness of FRP wrapping systems on masonry members with respect to concrete ones. Innovative confinement systems based on the use of GFRP grids and cement based mortars allowed significant strength gains but reduced the global ductility; such effects were emphasized due to the scaled dimensions of columns specimens as opposed to the mortar jacket ones, imposed by installation procedure need. Nevertheless, the use of mortars characterized by higher value of tensile strength and ultimate strain may allow increasing the benefits due to the confining pressure induced by both internal grid reinforcement and mortar jacket. Work is in progress at University of Naples in order to experimentally investigate on: the influence of the scale factor on the specimens' global behavior, the performances of specimens reinforced by a cement based mortar jacket only; the confinement effect provided by GFRP grids bonded with different types of mortar. Further experimental investigations could allow confirming and validating the potential of such strengthening technique that could become a promising confining solution to overcome some limitations of FRP related to the typically used epoxy resin.

ACKNOWLEDGMENTS
The experimental activities presented in the paper have been developed within the research work of "Laboratories University Network of Seismic Engineering" - ReLUIS (Research Line 8) - Executive Project 2005-2008.

REFERENCES

[1] Kog Y.C., Ong K.C.G., Yu C.H., and Sreekanth P.V., (2001). Reinforced Concrete Jacketing for Masonry Columns with Axial Loads. *ACI Materials Journal*, Vol. **98,** No. **(2)**, pp. 650-658.

[2] Lissel. S.L. (2003). The use of FRP's in masonry: a state of the art review. *Proc. of the International Conference on Performance of Construction Materials in the New Millennium (ICPCM)*, Cairo, Egypt, 18-20 Feb. 2003, Vol. **2**, pp.1243-1252.

[3] Galati N. (2003). Out-of-Plane behaviour of masonry walls strengthened with FRP materials. PhD Thesis, Univ. of Lecce, pp. 196.

[4] Tumialan. J.G.. Galati. N., and Nanni. A. (2003). FRP Strengthening of UMR Walls Subject to Out-of-Plane Loads. *ACI Structures Journal*, Vol. **100,** No. **(3)**, pp.312-329.

[5] ElGawady. M., Lestuzzi. P., and Badoux M. (2005). In-Plane Seismic Response of URM Walls Upgraded with FRP. *Journal of Composites for Construction*, Vol. **9,** No. **(6)**, pp. 524-535.

[6] Marcari. G.; Manfredi. G.; Prota A., and Pecce M. (2007). In-plane shear performance of masonry panels strengthened with FRP. *Composites: Part B*, Vol. **38**. pp. 887-901.

[7] Krevaikas T.D., Triantafillou T.C. (2005). Masonry confinement with Fiber-Reinforced Polymers. *Journal of Composites for Construction*, Vol. **9,** No. **(6),** pp. 128-135.

[8] Corradi M, Grazini A, Borri A. (2007). Confinement of brick masonry columns with CFGRP materials. *Composite Science and Technology*; Vol. **67, pp.**1772-1783.

[9] Aiello M.A., Micelli F., Valente L., (2007). Structural upgrading of masonry columns by using composite reinforcemens. *Journal of Composites for Construction ASCE*, Vol. **11**, No. **(6)**, pp. 650-658.

[10] UNI EN 998-2 (2004). Specification for mortar for masonry- Masonry mortar.

[11] ASTM D 3039/D 3039M (2000). Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials.

[12] De Lorenzis L., and Tepfers R., (2003). Comparative Study of Models on Confinement of Concrete Cylinders with Fiber-Reinforced Polymer Composites. *Journal of Composites for Construction ASCE*, Vol. **7**, No. **(3)**, pp. 219-237.

[13] Matthys S., Taerwe L., and Audenaert K. (1999). Tests on Axially Loaded Concrete Columns Confined by Fiber Reinforced Polymer Sheet Wrapping. *Proc. FRPRCS-4*, Baltimore, pp. 217-228.

[14] Di Nardo A., Faella C., Realfonzo R., Salerno N., (2007). Modellazione del calcestruzzo confinato con FRP. *Atti del XII Convegno Nazionale "L'Ingegneria Sismica in Italia"*, 2007, Pisa, Italia.