MASONRY CIRCULAR COLUMNS CONFINED WITH GLASS AND BASALT FIBERS

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Abstract

The mechanical behaviour of masonry columns having a circular cross section, confined with glass and basalt FRP systems was studied in this paper. An extended experimental investigation is presented in order to show the results of axial compression tests on circular masonry columns built with natural calcareous blocks that may be commonly found in Italy and all over Europe in historical buildings. Totally twenty masonry columns were built, instrumented and tested. Different fibres were used including glass and basalt (sheets and grids), different strengthening schemes were applied for confinement of the columns, including complete jacketing and discontinuous FRP strips, different bonding agents were employed including epoxy resin and polymer/cement-based mortar. In four GFRP-confined columns the strengthening action was activated by the presence of Shape Memory Alloys (SMA) filaments immersed in the FRP system. This novel technique is also presented in the paper.

Keywords: Include a concise list up to 7 keywords in alphabetic order.

1. Introduction

Fibre Reinforced Polymer (FRP) composites are widely used for strengthening and conservation of historic masonry, even if research problems are still open. In the last decades Glass, Carbon and Aramidic fibres immersed in an epoxy resin were bonded as external confinement devices devoted to contrast the lateral dilation of axially compressed masonry columns. In the last years new types of natural fibres like basalt were also employed to increase strength and ductility with encouraging results in terms of mechanical behaviour and cost effectiveness. New bonding agents based on cement-based materials were also used.

In the last decade different research work were published in the field, meaning that the engineering problem of structural safety of masonry columns is deeply felt, especially in regions prone to seismic damages. Recent works [1, 2, 3, 4] report the results on the same masonry core used in the present study,. Results are also available for confined clay bricks columns and were used to calibrate analytical models that are in formal accordance to those of FRP-confined concrete [5, 6, 7, 8]. Based on the results collected by early experimental and analytical studies, a design procedure is recommended by the Italian National Research Council (CNR) that was edited in 2004 [9], while a new revised version has been prepared and will be presented in the next year.

From year 2007 researchers from different countries has formed a technical committee within the Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages (RILEM) for the study of FRP-strengthening of masonry structures. The RILEM TC 223 "Masonry Strengthening with Composite Materials" allowed to join different research schools in order to manage a unified effort that may be helpful in the topic of FRP-strengthening of masonry structures. One of the research chapters is dedicated to the study of compressed columns.

In this study experimental results are presented with reference to masonry columns having a circular cross section, that were made by using limestone blocks, strengthened with different composite materials and different strengthening schemes. Unstrengthened columns were tested as reference coupons. Axial shortening of the columns was detected by means of displacement transducers, strain gauges were bonded to fibres in the direction perpendicular to the primary axis of the columns, thus strain profiles were monitored in order to measure the effectiveness of the confining FRP. Experimental results revealed the effectiveness of the glass and basalt FRP-confinement for masonry columns.

A new technique involving the use of Shape Memory Alloys (SMA) was also experienced for the early activation of the confinement action of the glass fibres. The technique aims at producing an active confinement which is not dependent only on the lateral post-strengthening dilation of the columns but also on a pre-existing stress in the composite system. The proposed technology may be very helpful in those real cases in which a pre-cracked columns (earthquakes scenario) needs to be strengthened. In this case not only a recover in load carrying capacity is possible, but also in terms of axial stiffness, which means that structural rehabilitation is provided for both service and ultimate conditions.

A theoretical prediction of the compressive strength was obtained by using the Italian CNR DT 200/2004 recommendations to show an application of the design approach recently proposed in Italy also for new types of fibre like basalt.

2. Specimens and experimental tests

Geometry of specimens and strengthening schemes are described herein, mechanical properties of stone, mortar, masonry and FRPs are also reported.

Mechanical characterization of the materials that formed the final structural system was conducted. Stone blocks were accurately chosen from the natural substrate in order to minimize the high scattering that may be present in mechanical properties. Cubic specimens (70x70x70 mm) were tested under a compression load and an average compression strength of 14.28 MPa was recorded, with a standard deviation of 1.13 MPa, meaning a % coefficient of variation equal to 8%. This result can be seen as very good by considering that natural stone is involved. An hydraulic mortar was used for building the masonry configuration, it is classified as M-3 in the Italian Design Code, which means a compressive strength ≥5.0 MPa. Glass-FRP and Basalt-FRP unidirectional specimens were prepared and tension tested according to ASTM D3039. Testing was performed in displacement-control mode using a

100-kN load universal testing machine, with a cross-head displacement rate of 1 mm/min. In particular, five unidirectional GFRP specimens and seven BFRP were tested. Mechanical properties were experimentally evaluated for each specimen and results averaged. An electrical extensometer was used to measure the strain of FRP under tensile force. For GFRP specimens a tensile strength of 1605 MPa resulted from tensile tests, with a standard deviation of 147 MPa. The experimental elastic modulus was 74143 MPa, with a standard deviation of 4683 MPa. For BFRP specimens a tensile strength of 2326 MPa resulted from tensile tests, with a standard deviation of 108 MPa. The experimental elastic modulus was 94100 MPa, with a standard deviation of 2510 MPa. The epoxy-A resin used as adhesive for GFRP system was a low viscosity polymer (Brooksfield viscosity 7000 mPa·s) with a tensile strength of 40 MPa, and a tensile elastic modulus of 3000 MPa. The epoxy-B resin used as adhesive for BFRP system had higher viscosity than the previous system (Brooksfield viscosity 12000 mPa·s), the experimental tensile strength was 70 MPa, with an elastic modulus of 2500 MPa.

Twenty-four full-core masonry columns with circular section were built in a middle-scale configuration. The thickness of the mortar bed was 10 mm. Within each series, specimens were wrapped with one or layer of unidirectional FRP sheets or two layers of FRP grid, that were bonded using two different epoxy adhesive systems. Details about the columns in each series are given in Table 1.

Table 1. Experimental programme

N°	LABEL	DIAMETER	HEIGHT	FRP SYSTEM	STRENGTHENING
1-2-3-4	SC- 1/4	300 mm	600 mm	None	Control specimens
5-6	SC-WG 1/2	300 mm	600 mm	Glass/Epoxy-A unidirectional	Full wrapping
7-8	SC-DG 1/2	300 mm	600 mm	Glass/Epoxy-A unidirectional	Discontinuous strips
9-10	SC-WB 1/2	300 mm	600 mm	Basalt/Epoxy-B unidirectional	Full wrapping
11-12	SC-DB 1/2	300 mm	600 mm	Basalt/Epoxy-B unidirectional	Discontinuous strips
13-14	SC-WB GRID 1/2	300 mm	600 mm	Basalt/Epoxy-B grid 0°/90°	Full wrapping
15-16	SC-DB (?)GRID 1/2	300 mm	600 mm	Basalt/Epoxy-B grid 0°/90°	Discontinuous strips
17-18-19-20	SC-WGSMA 1/4	300 mm	600 mm	Glass/Epoxy-A unidirectional + SMA	Discontinuous strips*
21-22-23-24	SC-DGSMA 1/4	300 mm	600 mm	Glass/Epoxy-A unidirectional + SMA	Discontinuous strips**

** lower distance spacing; ** higher distance spacing*

All specimens were tested under axial compression load by means of a 150-ton hydraulic jack reacting against a closed-loop reaction steel frame. In all tests two LVDTs were used to monitor the displacement of the upper face of the column. LVDTs were also placed to monitor possible displacement of the lower steel beam of the frame, in order to take into account only the displacement of the specimen. Load was recorded by means of a 150-ton load cell, and six electric strain gages were applied on the CFRP sheet in the direction of the transverse fibres at different locations: 100, 300 and 500 mm high from the base of the columns. Load, strains and displacements were all recorded by a data acquisition system. All tests were conducted under the same moisture and temperature conditions in order to minimize the effects due to different hygro-thermal conditions. Figure 1 illustrates the geometry of the FRP-strengthened columns and the position of the strain gages that were placed in the single layer bonded region and along the overlapping region, that was 100 mm long, equal to 16% of the total length of the FRP sheet. All specimens were strengthened by using the manual wet lay-up technique that indicates the use of a low-viscosity epoxy primer prior to FRP-bonding.

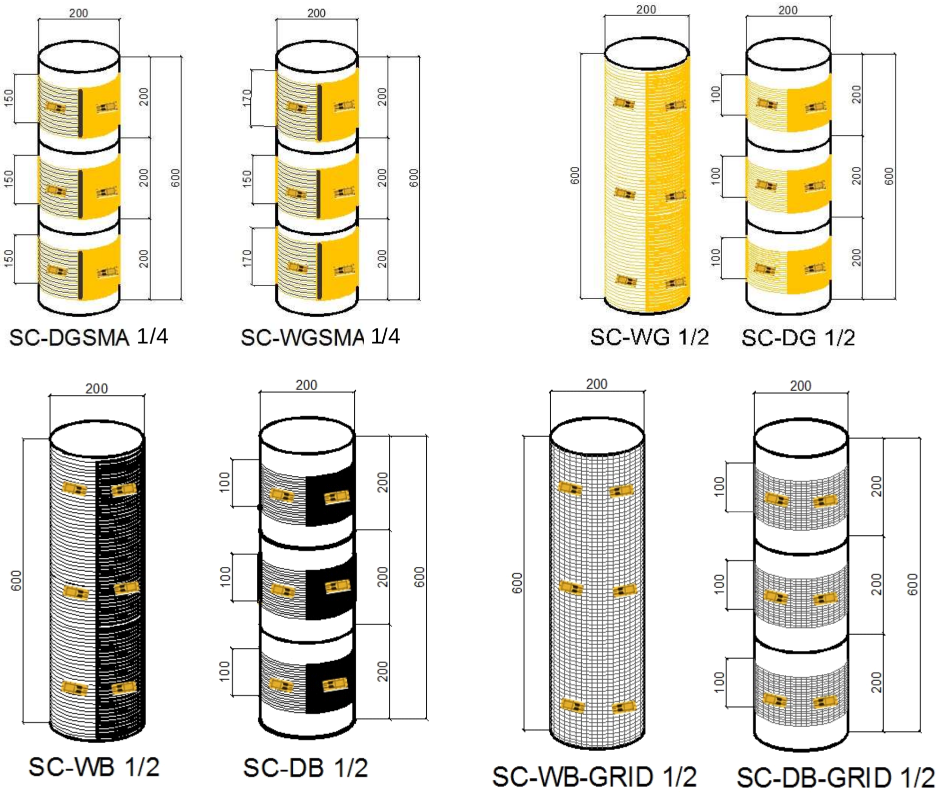

Figure 1. Geometry of masonry columns and strengthening schemes - distances in (mm)

3. Results and discussion

All the four control specimens SC1-4 exhibited a brittle failure mode with a maximum average load of 150 kN, which means a compressive strength of 4.8 MPa. Vertical cracks formed at low load level, then they propagated along the principal axis of the column in directions that were almost parallel to the loading direction. Specimen SC-1 exhibited a lower strength due to the presence of a fossil shell inside the stone core, that acted as a discontinuity structural region. Specimens SC-WG 1-2, externally wrapped with one layer of GFRP along the total height of the column, as theoretically expected, showed the largest increase in terms of carrying capacity. A high increase was recorded also in terms of strain retention after peak load, which means that the specimen had a significant ductility in a cracked state after the peak load. This occurrence is not appreciable in plain masonry that suddenly crushed in a brittle fashion. The increase in terms of compressive strength was equal to 324% by comparing the average values. Rupture was due to fibre collapse under transverse tensile stresses that are activated by the lateral dilation of the masonry core. When discontinuous GFRP strips were bonded, the structural behaviour of SC-DG 1/2 specimens changed respect to full wrapping, since failure mode was due to fibre rupture but in a combined mode that also involved the crushing of the masonry unconfined regions laying between the FRP strips. In this case the increase in terms of strength and ductility reduced up to 40% respect to the case of fully wrapped columns. All experimental results in terms of average values, standard deviation and coefficient of variation are reported in Table 2. The same structural behaviour in terms of load carrying capacity and ultimate strain was observed for SC-DGSMA specimens, that had the same strengthening scheme, but with the confinement being activated by the action of SMA wires embedded in the composite in the same direction of the glass fibres. The stress-strain curves show that the slope of the first branch of the curves increases when SMA alloys are introduced. For the specimens confined with a discontinuous scheme, with a gap of 100 mm between the strips, the stiffness increased of about 40%. Larger increase in this sense was evidenced by SC-WGSMA specimens after compression tests. The narrow gap between the SMA-activated GFRP hoops in SC-WGSMA reduced the height of the cracked regions due to unconfined plain masonry, thus the active confinement produced a 68% higher stiffness respect to SC-DGSMA. The peak load was 24% higher respect to SC-DGSMA. After peak load the column was able to retain the load until failure of glass fibres accompanied by stone crushing all along the height of the column.

Columns confined with basalt fibres also exhibited differences depending on the strengthening scheme and type of reinforcement (grid or unidirectional sheet). Fully wrapped columns had an average peak strength of 11.1 MPa, which was 2.3 times that of unconfined columns, while at the same time the axial ductility was almost seven times larger, when a comparison between the ultimate axial strain is considered. Compared to glass fibres, the BFRP-confined columns had a lower strength and a comparable ductility, showing a collapse due to fibre rupture. Columns confined with continuous grid having fibres oriented at 0°-90° respect to primary axis of the column showed the same behaviour of columns confined by discontinuous BFRP-unidirectional sheets in terms of peak load and ultimate strain. The load carrying capacity increased from 33% to 46%, but failure modes were different; in columns wrapped with discontinuous sheets failure was due to fibre rupture when crushing process started in the regions without confinement that showed the expulsion of small stone pieces; columns totally confined with basalt grid showed a progressive failure due to fibre rupture in the 90° direction respect to the axis of the column, which was less brittle and sudden respect to the previous cases. When columns were confined with discontinuous basalt grid, unexpected strength values were found. In fact, both the tested specimens showed a peak strength even higher than that recorded for columns confined with a continuous basalt grid (9.1 MPa and 7.4 MPa for the specimen SC-DBGRID 1 and SC-DBGRID 2, respectively). . This occurrence may be due also to the scattering that is present in the masonry itself. The failure mode observed in this specimens was tensile rupture of the transverse fibres accompanied by a diffusive cracking all along the height of the column due to compression forces.

Important comments may be added when all curves are compared and when additional information come from strain readings along the FRP hoops. Independently from the material used as FRP it is clear that full wrapping furnishes the highest benefit in terms of maximum strength and strain enhancement. It is also noted that full wrapping dramatically changed the stress-strain law of compressed masonry since an hardening branch is always appreciable, followed by a sudden drop in terms of load. The elastic pressure exerted by the fibres all along the height avoided the crushed to come out from the confining "bag" and the ultimate strength of the fibres results the limit condition at failure. The circular shape also allows to apply an uniform confining elastic pressure in the cross section, so the circular fully wrapped columns had the whole masonry volume subjected to an ideal tri-axial state until large cracks develop inside the core of the column.

The readings of the electrical train gages placed as shown in Figure 1 were collected and compared. In all case the strain increased linearly with the load as expected from theory; in most of the cases the ultimate strain of the fibres was reached in different regions of the column, meaning that confinement acted without stress-concentration. Regions that showed FRP failure were always those interested by the highest strain readings. Totally wrapped columns had a uniform strain profile when compared to other specimens, in these cases failure started from the central region of the column than propagated along the height. Discontinuous wrapping showed failure that sometimes departed far from the central region, due to the unconfined regions that generated a different cracking state along the height of the column. All specimens that exhibited the highest peak loads, including the columns wrapped with discontinuous grid, showed a uniform strain distribution along the columns, while in all other cases a stress concentration in the upper or lower region prevailed and local fibre rupture announced the ultimate limit state of the column.

Table 2. Experimental results - average values

SPECIMEN	σ_{MAX} (MPa)	ε_{ULT} %	$\sigma^f_{MAX} / \sigma^0_{MAX}$ %	$\varepsilon^f_{ULT} / \varepsilon^0_{ULT}$ % %
SC- 1/4	4.8	0.52	-	-
Standard deviation	1.3	0.25	-	-
Variation coefficient	26.5 %	48.0 %	-	-
SC-WG 1/2	15.5	3.61	324.3	713
Standard deviation	0.5	0.05	10.0	10.0
Variation coefficient	3.1 %	1.4 %	3.1 %	1.4 %
SC-DG 1/2	8.7	2.36	182.0	450
Standard deviation	0.0	0.85	0.0	162
Variation coefficient	0.0 %	36.0 %	0.0 %	36.0 %
SC-WB 1/2	11.1	3.46	231.7	661
Standard deviation	0.4	0.34	8.0	65
Variation coefficient	3.6 %	9.8 %	3.6 %	9.8 %
SC-DB 1/2	6.4	1.79	133.0	342
Standard deviation	0.2	0.23	4.0	45
Variation coefficient	3.4 %	12.8 %	3.4%	13.1 %
SC-WB GRID 1/2	7.0	2.20	146.6	421
Standard deviation	1.2	0.10	26.0	19
Variation coefficient	17.5 %	4.5 %	17.7 %	4.5 %
SC-DB GRID 1/2	8.3	0.74	173	141
Standard deviation	1.2	0.15	26.0	28
Variation coefficient	14.8 %	20.2 %	14.8%	19.9%
SC-WGSMA 1/4	10.1	5.34	211.0	1010
Standard deviation	1.6	0.01	32.1	96
Variation coefficient	15.5%	10.2 %	15.2 %	9.5 %
SC-DGSMA 1/4	8.2	0.03	170.8	548
Standard deviation	1.2	0.02	25.8	286
Variation coefficient	14.9 %	52.7 %	15.1 %	52.2%

A comparison between the experimental results and theoretical predictions obtained by applying the analytical model of the CNR DT 200/04 [9] without the influence of the safety design coefficients, is briefly described for the studied columns, except for SMA-activated confinement, which is not considered in the model.

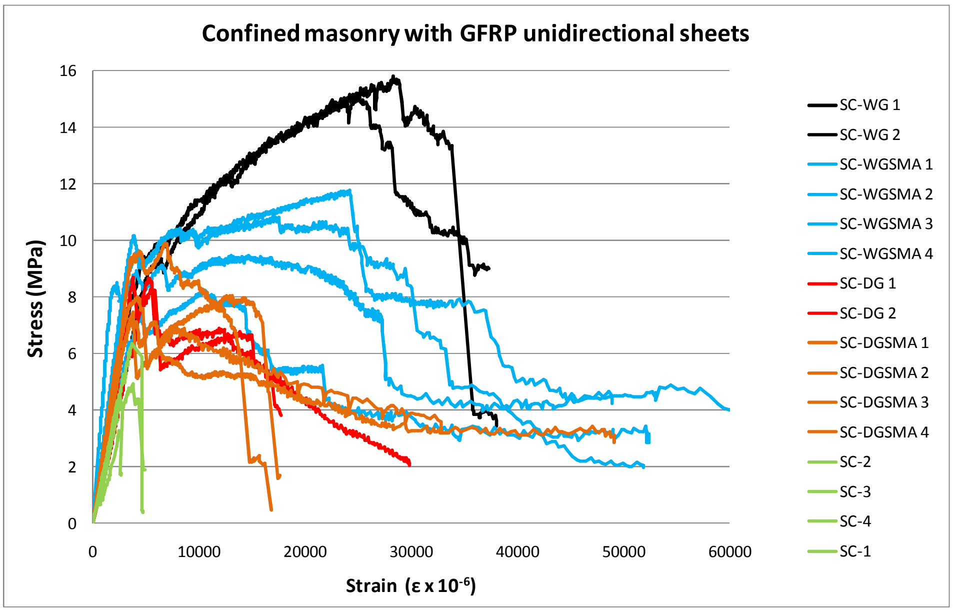

Figure 1. Experimental stress-strain curves for GFRP-confined masonry

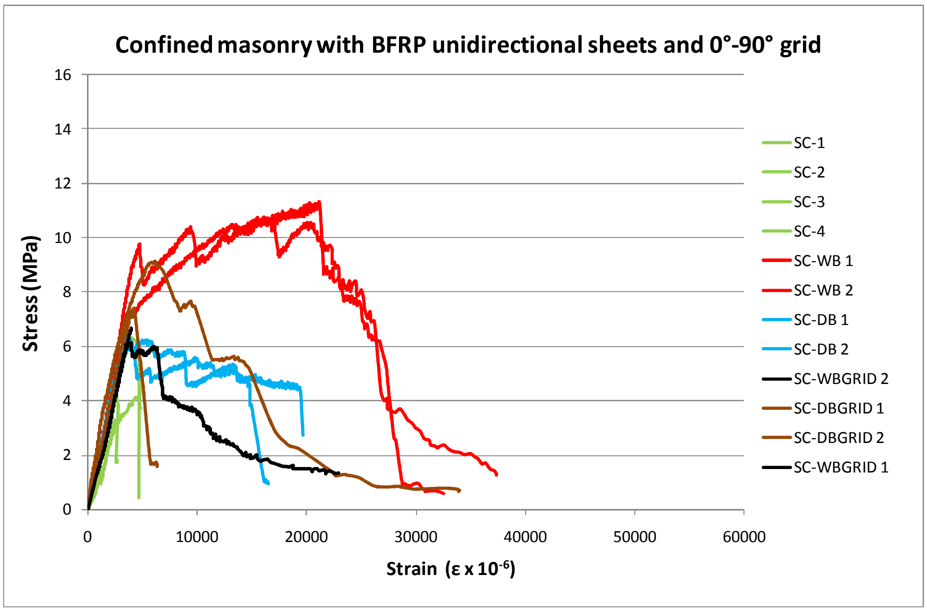

Figure 2. Experimental stress-strain curves for BFRP-confined masonry

The CNR model was found to be accurate in predicting the peak load of confined masonry: for fully wrapped columns SC-WG, SC-WB and SC-WBGRID the experimental strength was respectively 0.95, 1.38 and 1.14 times respect to that predicted theoretically. The same range of error was maintained for SC-DG and SC-DB columns wrapped with discontinuous strips, showing an experimental strength respectively 1.08 and 1.12 times respect to theoretical. A larger error was found for SC-DBGRID columns that had an experimental peak strength 60% higher if compared to theoretical prediction.

4. Final remarks

A research study on the behaviour of FRP-confined masonry was presented. Two types of FRP materials were investigated: glass and basalt, the first in forms of unidirectional sheets, the second in forms of unidirectional sheets and 0°-90° grid. Different strengthening schemes

were tested, discontinuous and full wrapping; eight columns wrapped with GFRP sheets were also provided with SMA filaments embedded in the FRP layer in order to produce an active confinement prior to large dilations that produce the tensile strain of the transverse fibres.
In all cases the confinement acted as a significant benefit for the compressed masonry, either in terms of load carrying capacity, or in terms of ultimate axial strain. The presence of full wrapping with unidirectional basalt and glass sheets produced the highest values of strength and ductility, with failure due to tensile fibre rupture and strain gages showing an uniform strain field along the height of the columns. Discontinuous wrap, which results necessary in many in-field applications, produced a significant upgrade of the mechanical properties, even if the presence of unconfined regions, that are prone to local crushing, caused lower strength enhancement and a softening descending branch after the peak load. Unexpectedly from theory, discontinuous wrapping with basalt grid produced higher mechanical properties of the confined masonry respect to the other cases with higher FRP amount.
A comparison between experimental results and equations proposed in CNR DT-200 guidelines was conducted, disregarding the design safety coefficient. The results obtained from this study testify that the equations reported in the Italian document CNR DT200-2004 can be considered reliable in describing the behaviour of FRP-confined masonry for the tested columns. The results of numerical simulations showed that the use of a safety coefficient model should be prescribed as done in the present form of the guidelines. New information and recommendations are easily drawn from the presented research work, which can be used by researchers and practitioners involved in the strengthening design of masonry columns.

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6. References

[1] AIELLO M.A., MICELLI F., VALENTE L., "Structural upgrading of masonry columns by using composite reinforcements" *ASCE Journal of Composites for Construction*, Vol.11, N.6, 2007, pp. 650-658.

[2] AIELLO M.A., MICELLI F., VALENTE L. "FRP-Confinement of square masonry columns", *ASCE Journal of Composites for Construction*, Vol.13, N.2, 2009, pp.148-158.

[3] FAELLA C., MARTINELLI E., PACIELLO S, CAMORANI G., AIELLO M.A., MICELLI F., NIGRO E., "Masonry columns confined by composite materials: experimental investigation" *Composites: Part B*, Volume 42, Issue 4, 2011, pp. 692-704.

[4] FAELLA C., , MARTINELLI E., CAMORANI G., AIELLO M.A., MICELLI F., NIGRO E., "Masonry columns confined by composite materials: Design formulae", *Composites: Part B*, Volume 42, Issue 4, 2011, pp. 705-716.

[5] CORRADI M., GRAZINI A., BORRI A., "Confinement of brick masonry columns with CFRP materials", *Composites Science and Technology*, 67, 2007, pp.1772-1783.

[6] KREVAIKAS T.D. AND TRIANTAFILLOU T., "Masonry Confinement with Fiber-Reinforced Polymers" *ASCE Journal of Composites for Construction* Vol. 9 N.2, 2006, pp.128-135.

[7] MASIA, M.J. AND SHRIVE, N.G., "CFRP Wrapping for the Rehabilitation of Masonry Columns", *Canadian Journal of Civil Engineering*, Vol. 30, N.4, 2003, pp.734-744.

[8] SHRIVE, N.G., "The Use Of Fibre Reinforced Polymers To Improve Seismic

Resistance Of Masonry", *Construction and Building Materials*, 20 (4), 2006, pp.269-277.

[9] CNR – Italian National Research Council, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures", Technical Document 200/2004, Advisory Committee on Technical Recommendations for Construction of National Research Council, Rome, Italy, 2004, 144 pp.