CONFINEMENT OF NATURAL BLOCK MASONRY COLUMNS USING FIBER REINFORCED POLYMER REBARS AND LAMINATES

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ABSTRACT

In the last few years, a notable amount of research has been devoted to the use of Fiber Reinforced Polymer (FRP) materials for strengthening and rehabilitation of existing concrete and masonry structures. One of the most interesting applications of FRP is their use to achieve confinement of concrete and masonry columns. However, experimental data regarding confinement of columns with square or rectangular cross-section and confinement of masonry columns is still very limited. The authors are currently carrying out an experimental and theoretical investigation on confinement of non-circular masonry columns. So far, experimental tests have been conducted on columns made of natural masonry blocks, subjected to static compression loads up to failure. Variables such as different FRP strengthening systems and cross section geometry have been investigated. Wrapping with FRP pre-preg laminates was implemented either alone or in combination with the use of AFRP rebars inserted in epoxy-filled slots into the columns. The use of FRP materials appears to be very effective in enhancing strength, stiffness and ductility of the strengthened members, with efficiency that depends on the tested variables.

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INTRODUCTION

Compression members constitute the most critical elements of a building. In fact, a beam failure would normally affect only a local region, whereas a column failure may result in collapse of the entire structure. These dangerous occurrences may be due to static deficiencies caused by wrong design assumptions, overloads emerged by enlargement of the building, construction defects and earthquakes. Unfortunately, typical static problems affecting vertical elements arise and can be visible only in the last damage stages, when the cracking pattern shows the incipient crushing of the materials. Therefore damages and structural deficiencies affecting columns require strengthening and repair actions that should be very fast and effective at the same time.

In the last years Fiber-Reinforced Polymer (FRP) composites were successfully used in-situ for repair and rehabilitation of reinforced concrete columns, and several studies demonstrated that FRP confinement furnishes a significant increase in ductility and load capacity (Saadatmanesh et al., 1994; Nanni et al., 1995; Lavergne et al., 1997; La Tegola et al., 1999; Xiao et al., 2000). It was seen that the effectiveness of the FRP confinement depends on type of loading and associate failure modes; duration of loads; columns geometry and substrate material properties; type of FRP system used; environmental effects. In particular it was observed that the confinement action developed by FRP in circular columns is more effective than in square or rectangular sections.

Even if reinforced concrete members are usually found in modern buildings, masonry columns constitute the most important elements of ancient structures, especially in Europe. Confinement has proved to be a very effective technique to increase strength and ductility of damaged or inadequate masonry columns. Several implementations of the confinement technique using traditional materials such as steel or wood were developed, so active and passive confinement was applied using ties, prestressed external and internal tendons and jackets (Mastrodicasa, 1983). The application of FRP composites to masonry is developing now as a new technique and experimental data regarding confinement of columns with square or rectangular cross-section and confinement of masonry columns is still very limited. Important variables distinguish the behavior of masonry FRP-confined columns from concrete FRP-wrapped members: the nature of the substrate that influences the resin interface, the different mechanical behavior of masonry blocks against a continuous concrete mass. Therefore investigations of the mechanical response of masonry columns retrofitted with FRP is needed in order to use this new materials in masonry columns without loosing structural safety, with the best exploitation of FRPs that are well known as high-strength and light-weight materials.

In this study, the mechanical behavior of masonry columns is experimentally evaluated, when Carbon FRP (CFRP) laminates are used for external wrapping and Aramid FRP (AFRP) rebars are used as internal tendons. Experimental tests have been conducted on columns made of natural masonry blocks, subjected to static compression loads up to failure. The variables investigated were FRP strengthening systems and cross-section geometry. Test procedures and results are outlined in the following.

THE STRENGTHENING CONCEPT

As previously mentioned, two different FRP-based strengthening systems for masonry columns were investigated in this experimental program. The first system consisted of wrapping the column (after rounding the corners to avoid local stress concentration effects and air-blasting the surface to ensure proper bond) with one layer of CFRP pre-preg laminate. This material is characterized by high stiffness and very low thickness and weight: as an example, the laminate used for this program had a Young's modulus of 275 GPa, a thickness of 0.167 mm and a density of 300 g/m^2. While the high stiffness is desirable to achieve a good passive confinement effect, the low weight contributes to the easiness and rapidity of the strengthening operation. Besides, due to the low thickness, wrapping with FRP does not involve any change in the shape and size of the strengthened elements, which is particularly important while repairing historical structures.

The second system consisted of a combination of FRP rebars and laminates. This choice was made as an attempt to increase the portion of the column cross-section that can be considered "effectively confined", see Figure 1. For square and rectangular cross-sections, the "effectively confined" part of the section is usually regarded as delimited by four parabols starting at the four vertexes of the section with given slope. This concept has long been used for both concrete (Mander et al., 1988) and masonry (Mastrodicasa, 1983). In the case of block masonry columns, the internal rebars increase the efficiency of confinement by mechanically interlocking the blocks, thus delaying their expulsion under to the applied compression. Internal steel dowels have been traditionally used for this purpose (Mastrodicasa, 1983). The replacement of steel with FRP materials offers some peculiar advantages. First of all, FRPs have a superior resistance to corrosion, which is particularly important in the case of natural masonry that is a very porous material. Besides, the FRP rebars are characterized by a low transverse stiffness which is very likely to limit the local damage phenomena at the rebar-resin-masonry interface due to the transfer of stresses. Last but not least, the low weight of the FRP rebars makes their installation faster and easier than that of steel dowels.

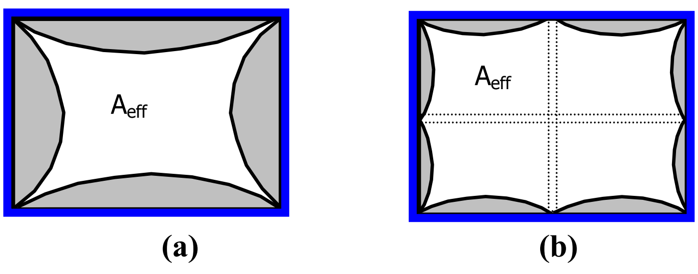

Fig. 1. Effectiveness of FRP confinement for a square or rectangular cross-section: (a) without internal tendons, and (b) with internal tendons

MATERIAL CHARACTERIZATION

Aramid FRP rebars and Carbon FRP laminates were used in the experimental program that will be described in the following. These materials were tested in the laboratory to evaluate their mechanical properties and, in the case of the CFRP laminates, also to ascertain that proper bond with the substrate material could be achieved.

Commercially available AFRP tendons with rectangular 4x30 mm cross-section were used. Tensile test of ten coupon specimens was performed to characterize the mechanical properties of the tendons. An essential requirement for conducting tensile tests on FRP rebars and tendons is a suitable anchor device to grip the specimens without causing slippage or premature local failure during the test (Yan et al., 1999). The conventional method for tensile testing of steel rebars consisting of steel grip jaws is not suitable for tensile testing of FRP tendons, the latter being sensitive to compressive forces in the transverse direction. The stress concentration due to gripping can easily crush the specimen and thus result in premature failure. The grips chosen for these tests consisted of two 2x30x250 mm steel plates, and an epoxy mortar was used to glue the grips to the ends of the coupons. The total length of the test specimens was 700 mm, and the length of the test section was 200 mm, that is, larger than the minimum value suggested by JSCE (1997) and ACI (2001). Tensile tests were performed using a 600-kN load-controlled universal testing machine. The tendons showed a linearly elastic behavior up to failure and experienced tensile failure, which indicated that the tendon had developed its full tensile capacity, and the anchor was efficient. An average tensile strength and elastic modulus of 1026 MPa and 49900 MPa, respectively, were obtained (Aiello and Ombres, 2000).

Commercially available CFRP pre-preg laminates with a nominal thickness of 0.167 mm were chosen. Tensile characterization was performed on five coupon specimens according to JIS K7073, using a 5-kN displacement-controlled universal testing machine. Also these specimens showed a linearly elastic behavior up to failure and experienced tensile failure. Average tensile strength and elastic modulus were equal to 3400 MPa and 275000 MPa, respectively. Both results were in agreement with the manufacturer specifications, that indicated 3400 MPa and 230000 MPa as lower-bound values for tensile strength and elastic modulus, respectively.

Four masonry blocks were tested to verify the effectiveness of the bond between CFRP sheets and masonry substrate. The blocks were made of natural masonry of the same type to be used for the experimental tests. The dimensions of the blocks were 150x150x300 mm. Two blocks were tested in compression without any FRP reinforcement. Two more blocks were cut into two pieces along one diagonal. A CFRP sheet was then applied to reconnect the two parts together and reconstruct the original geometry. The blocks were then tested in compression to evaluate failure load and mode of failure in comparison to those of the virgin blocks. The ultimate load of the "repaired" blocks was very close to that of the virgin ones, and even slightly higher. However, the displacement (reduction in length) of the repaired blocks at failure was ten times higher, as can be seen in Figure 2 which illustrates all specimens after failure. The reason is that the presence of the glued surface along the block diagonal forced the cracks to deviate from their initial trajectories and follow different paths, thus dissipating a larger amount of energy.

Finally, three 70-mm size cubes made of the same masonry material were tested in compression to evaluate the material compressive strength, that resulted to be 17 MPa.

Figure 2 – Specimens for Bond Tests between CFRP Sheets and Masonry Blocks

EXPERIMENTAL TESTS

Specimens and Procedure

Six columns made of natural masonry blocks were constructed and tested in the laboratory to investigate the effect of AFRP rods and CFRP laminates on their performance under compression loads. The specimens were built with no mortar, just positioning the blocks on each other. The AFRP rods and CFRP laminates were the same previously described.

Two variables were investigated: cross section geometry and type of FRP strengthening system. As for the first variable, three specimens had rectangular cross-section with dimensions 200x300x600 mm whereas the other three had square cross-section with dimensions 300x300x600 mm. Both types of columns were constructed using 100x150x50 mm and 100x200x50 mm blocks (Figure 3). The cross-sectional shape was expected to affect the efficiency of the confining action exerted by the FRP, due to the different distribution of the confinement pressure within the cross-section.

Three specimens of each cross-sectional geometry were tested. One unstrengthened specimen was tested to serve as a baseline comparison, to evaluate the enhancement in strength and ductility provided by the FRP. One specimen was externally wrapped along its entire length with one layer of CFRP laminate having the principal fiber direction perpendicular to the column axis. The application procedure of the FRP laminate involved the following steps. First of all, the corners of the column were rounded up to a curvature radius of approximately 30 mm in order to avoid stress concentrations that could lead to premature rupture of the laminate. Then, the lateral surface of the specimen was air-blasted clean and the FRP laminate was applied according to the manufacturer's specifications. In the third specimen, both AFRP rods and CFRP laminates were used in combination. For the sake of simplicity, the slots in which the AFRP rebars had to be placed were preformed in the blocks prior to construction of the columns rather than drilled into them as it would be necessary in a real application. These slots were filled with a commercially available two-component low-viscosity epoxy paste and the AFRP tendons were subsequently inserted into them. Two tendons were placed in each block layer, in alternate directions, so that the vertical distance between two consecutive tendons of the same direction was 100 mm.

In the following, specimens will be referred to with a two-digit code as illustrated in Table 1. All specimens were tested under compression load by means of a 100-ton hydraulic jack reacting against a closed-loop reaction frame. An LVDT and a dial gage were used to monitor the displacement of the upper face of the column, an additional dial gage measured the displacement of the support beam to derive the net deformation. Load was recorded by means of a 150-ton load cell, and electric strain gages were applied on the CFRP sheet at different locations (Figure 3). Load, strains and displacements were all recorded by a data acquisition system. Figure 4 is a picture of the test setup.

Table 1. Test Specimens and Results

Specimen Code	Cross-section Geometry	Strengthening pattern	Ultimate Load (kN)	Percent Increase (%)	Ultimate Stress (MPa)
R1	Rectangular	Unstrengthened	170	-	2.83
R2	Rectangular	FRP Laminates	400	135	6.67
R3	Rectangular	FRP Laminates + Tendons	628	269	10.47
S1	Square	Unstrengthened	190	-	2.11
S2	Square	FRP Laminates	443	133	4.92
S3	Square	FRP Laminates + Tendons	656	245	7.29

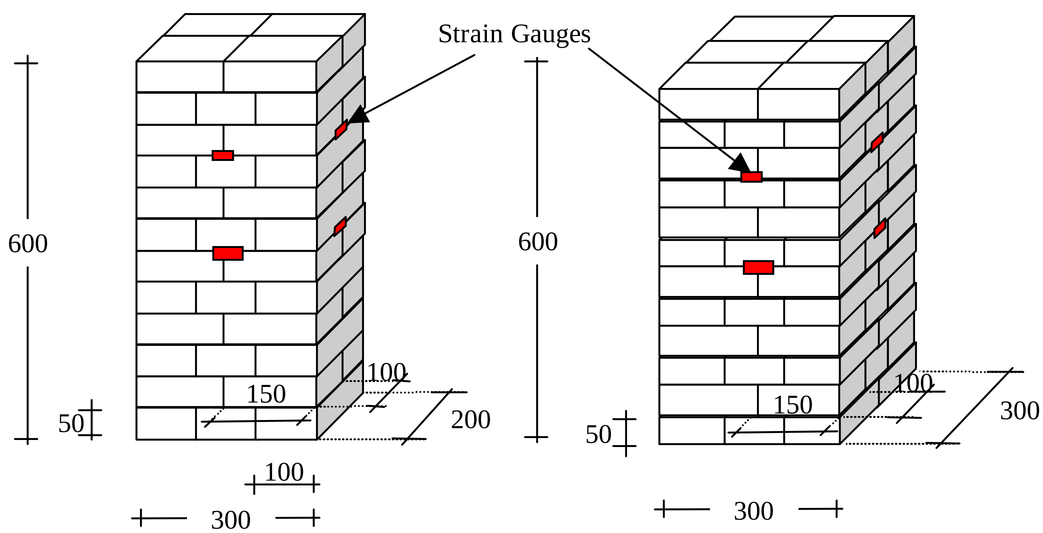

Fig. 3. Geometry of the rectangular and square masonry block columns used for tests (all dimensions in mm)

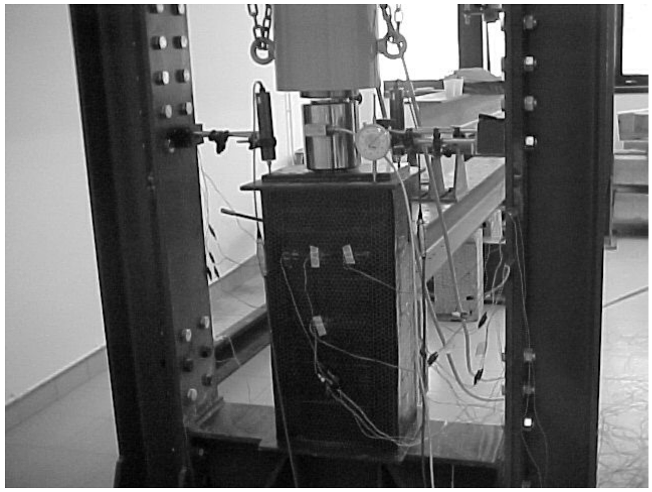

Figure 4 – Test Setup

RESULTS

The control specimens R1 and S1 failed at a load of 170 kN and 190 kN, respectively, corresponding to an ultimate compressive stress of 2.83 MPa and 2.11 MPa. Vertical cracks formed in the specimens, increased in number and propagated as the applied load increased until failure. Vertical and transverse deformation were very limited and failure occurred in a brittle fashion. The crack pattern at failure is shown in Figure 5.

Specimens R2 and S2, externally wrapped with CFRP sheets, had an ultimate load of 400 kN and 443 kN, respectively, that is, 135% and 133% higher than the corresponding virgin specimens. Although the crack pattern could not be observed because of the wrapping, the progressive damage was indicated by a typical noise. Failure occurred in a very ductile fashion: after the maximum load was reached, displacement kept on increasing while the load remained approximately constant. It was decided that the test would be stopped when the relative displacement of the column faces would be equal to 18 mm, that is, when the average axial compressive strain would be equal to 3%. Then, the CFRP wrap was cut in order to inspect the state of the inner material. All blocks appeared severely damaged, and some of them had broken into small pieces (Figure 6a).

Specimens R3 and S3, strengthened with a combination of FRP rods and sheets, failed at a load of 628 kN and 656 kN, that is, 269% and 245% higher than the respective virgin specimens and 57% and 48% higher than the respective wrapped ones. Failure occurred again in a very ductile fashion, with the external load remaining constant while displacement increased, and the same displacement limit was set in order to stop the test. From the inspection of the blocks after failure it was evident that the AFRP rods had been effective in connecting the blocks together and enhancing the confinement effect (Figure 6b). On the upper face of the specimen, parabolic-shaped cracks indicated the trajectories along which the confinement stresses had spread along the cross-section.

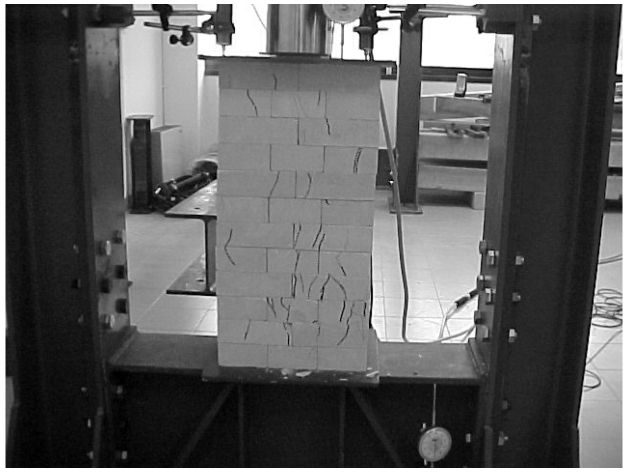

Figure 5 – Control Specimen R1 after Testing

(a) (b)

Fig. 6. Columns after failure and cutting of the FRP jacket: specimen R2 confined with FRP laminates (a) and specimen R3 confined with tendons and laminates (b)

DISCUSSION

The load-displacement curves of all tested columns are reported in Figure 7.

The overall behavior of all strengthened specimens shows a first approximately linear phase followed by a perfectly plastic branch in which load remains constant while displacement increases. Very good consistency exists between the slope of the linear branch of all specimens. Also the strength values are consistent, those of the square columns being just as higher than those of the rectangular ones as justified by the larger cross-sectional area. No effect of the different section geometry was observed, as can be concluded comparing the strength percent increases due to confinement in the couples of specimens with same strengthening pattern.

External wrapping with CFRP laminates resulted in a remarkable increase in stiffness, strength and ductility of the masonry columns. The use of AFRP tendons in combination with the external wrapping resulted in a further strength enhancement, whereas stiffness remained approximately the same of the wrapped specimens and nothing can be concluded about ductility, since test was stopped for all specimens at 3% of average axial strain.

Specimen S2 deserves a special mention, since testing of this specimen was not stopped before complete failure was achieved. The reason for this decision was that the load-deflection behavior of this specimen was showing a slight positive slope in the second plastic branch. In fact, the maximum load was reached at about 36 mm of axial displacement (Figure 8a) and failure occurred by tensile rupture of the FRP laminate (Figure 8b). It is worth noting that a 50-mm overlap was provided when closing the FRP wrap to ensure that no debonding would occur at the closing point.

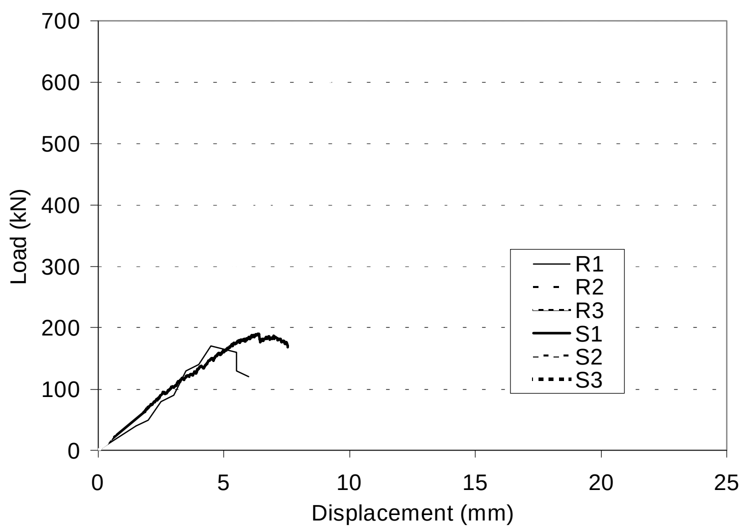

Fig. 7. Load-displacement Curves of the Tested Specimens

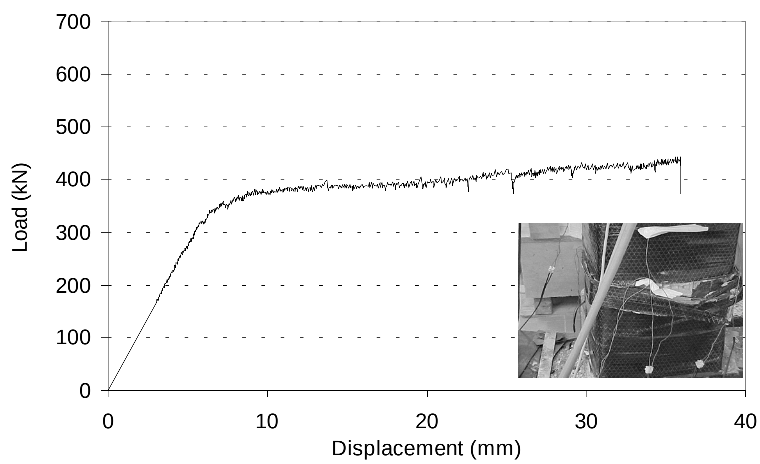

Fig. 8. Complete Load-displacement Curve and Picture after Failure of Specimen S2

CONCLUSIONS

Confinement has proved to be a very effective technique to increase strength and ductility of damaged or inadequate masonry columns. On the other hand, in the last years FRP composites were successfully used in-situ for repair and rehabilitation of reinforced concrete columns, and several studies demonstrated that FRP confinement furnishes a significant increase in ductility and load capacity. The application of FRP composites to masonry is developing now as a new technique and experimental data regarding confinement of columns with square or rectangular cross-section and confinement of masonry columns is still very limited. In this study, the mechanical behavior of masonry columns was experimentally evaluated, when Carbon FRP (CFRP) laminates are used for external wrapping and Aramid FRP (AFRP) rebars are used as internal tendons. Experimental tests were conducted on six columns made of natural masonry blocks with no use of mortar, subjected to static compression loads up to failure. The variables investigated were FRP strengthening systems and cross-section geometry.

External wrapping with CFRP laminates resulted in a remarkable increase in stiffness, strength and ductility of the masonry columns. The use of AFRP tendons in combination with the external wrapping resulted in a further strength enhancement, whereas stiffness remained approximately the same of the wrapped specimens. The overall behavior of all strengthened specimens showed a first approximately linear phase followed by a perfectly plastic branch in which load remained constant while displacement increases. Test was stopped for all specimens at 3% of average axial strain, except for one specimen that reached the maximum load at about 36 mm of axial displacement. In this case, complete failure was achieved by tensile rupture of the FRP laminate. Although the cross-sectional shape was expected to affect the efficiency of the confining action exerted by the FRP, no effect was observed.

The use of FRP materials appears to be a very effective technique to enhance strength, stiffness and ductility of masonry columns. FRPs peculiar characteristics allow to couple strengthening efficiency with easiness and speed of implementation of the technique. Further research is needed for a systematic assessment of all the significant variables and for theoretical prediction of the behavior of the strengthened columns.

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