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# Experimental program on large-scale reinforced concrete columns strengthened with carbon FRP jackets

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ABSTRACT: One of the most attractive applications of FRP composite materials is the confinement of concrete columns to increase both the strength and ductility. Numerous experimental studies have been carried out, most of them on small scale cylindrical specimens. Further experimental research needs to be conducted on large-scale columns, very limited to date. Several empirical models have been proposed and adopted by the design guides published in various countries.

It is well known that the confinement of square or rectangular columns is less efficient than the confinement of circular columns. In the theoretical analysis of rectangular sections, models found in current design guides are usually based on models created for circular columns and then modified by a shape factor.

This paper presents the results of tests carried out on full scale CFRP confined columns subjected to axial compression load. Four columns have been tested: three specimens strengthened with carbon FRP and one control specimen (unstrengthened). The columns have a height of 2400 mm and cross section of different aspect ratios. The tests´ results show that the FRP confinement can increase the strength and ductility of concrete columns of rectangular section with rounded corners. The stress-strain behaviour and strength gain depends on the aspect ratio. The hoop rupture strain of the FRP jacket is much lower than the material ultimate tensile strain obtained from flat coupon tests. The proposals of different design recommendations are reviewed and compared with the experimental results of this work ACI-440.2R-17 (2017), Concrete Society TR55 (2012), CNR-DT 200 R1/(2013).

## 1 INTRODUCTION.

The use of fiber reinforced polymers (FRP) jackets for the strengthening of concrete structures has proven to be a very effective technique to improve the ductility and load capacity of the members subjected to compression.Early investigations on FRP confinement tried to use the analytical models previously developed for the confinement by steel but soon it was found that inadequate results were obtained, as FRP materials have an elastic behavior until failure.

Many researchers have shown that the reinforcement mechanism in rectangular sections loses effectiveness compared to circular columns [De Luca A, et al. (2011), Lam et al. (2003a), Nisticò et al. (2013), de Diego et al. (2019)]. Therefore to produce a reduction of the cutting edge effect on the confining sheets, it is common to round the corners of the columns.

To date, studies in large-scale square and rectangular columns are scarce [Toutanji et al. 2010, Zeng et al. (2018), Rocca et al. (2007)] compared to those that exist on a small scale [Chaallal et al. (2003), Lam et al. (2003), Maalej et al. (2003), Rocchette et al. (2000), Wang et al. (2001)]. As a result, from these studies and those obtained from circular columns, theoretical models modified by a shape factor were formulated [Lam et al. (2003); Pham et al. (2003b); Wu et al. (2015)] that have been incorporated into the guidelines and design recommendations published in recent years in various countries [ACI-440.2R-17, (2017); CNR-DT200_R1. (2013); TR55, (2012); fib Bulletin 14, (2001)]. Therefore, there is a gap with respect to the calibration of the models and their applicability to FRP-confined large-scale rectangular RC columns.

Some studies have shown the variability of the behavior between rectangular columns of small and large scale [De Luca et al. (2011), Masia et al. (2004), Rocca et al. (2007)], and there is significant uncertainty when applying existing stress-strain models for FRP-confined concrete in rectangular columns based on studies in small-scale columns.

This work involves a test program with the aim of research the behaviour of large scale FRP confined reinforced concrete columns with square and rectangular cross sections.

## 2 EXPERIMENTAL PROGRAM

### *2.1 Description of experimental program and main parameters*

Axial compression tests were performed on 4 large-scale concrete prismatic specimens with square and rectangular section. 3 of them have been externally strengthened with CFRP (polymer reinforced with carbon fibres) and one specimen has been tested without reinforcement as a reference. The specimens have minimum steel internal reinforcement, made up of 12 mm longitudinal bars, placed as shown in figure 1.

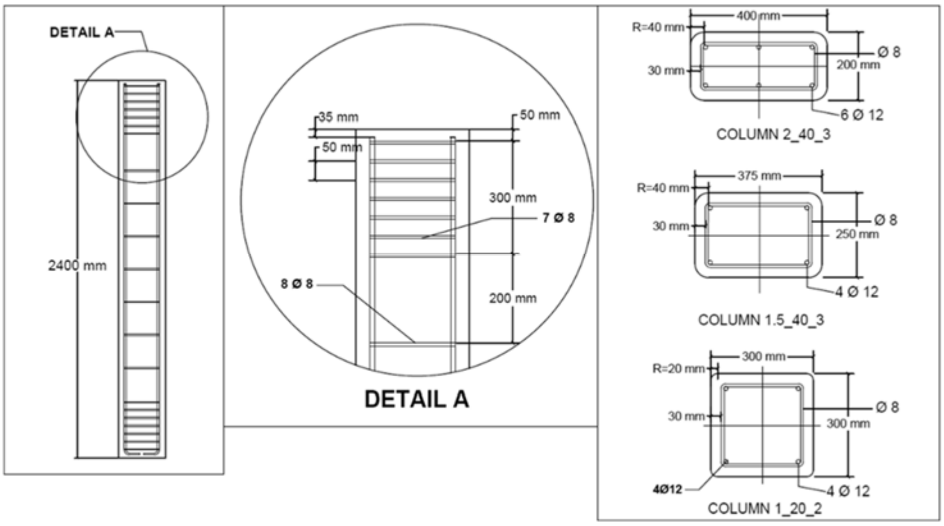


Figure 1 Reinforcement detailing and cross-section dimensions.

The tests presented in this paper are part of a more extensive experimental program whose variables are:

- The aspect ratio of the cross section or relationship between the sides of the concrete section (b/d). Square section specimens (b/d=1) and rectangular section ones (with b/d=1,5 and b/d=2) have been tested.

- The radius of curvature of the corners ($R_c$). Before applying the strengthening, the corners of the sample are rounded to obtain different radius of curvature. Two values of $R_c$ have been chosen: 20 and 40 mm.

- The amount of FRP reinforcement. Specimens have been strengthened with 2 and 3 layers of carbon FRP. The FRP material has a nominal fibre thickness of 0,129 mm.

Thereafter the specimens were named as follows: first the cross section aspect ratio (b/d) is indicated, followed by the radius of curvature of the corners $R_c$ in mm and finally the number of layers of the FRP strengthening.

### *2.2 Specimens preparation*

Concrete prismatic specimens were formed with a length of 2400 mm and three different types of section:

- Square section (300 x 300 $mm^2$).

- Rectangular section with aspect ratio of the cross section b/d=1,5 (250 x 375 $mm^2$).

- Rectangular section with aspect ratio of the cross section b/d=2 (200 x 400 $mm^2$).

To obtain the planned radius of curvature of the corners, it has been used wooden formwork with rounded corners. After concrete specimens hardened, the corners were reviewed and the irregular areas were repaired with mortar to assure the intended radius of curvature. Figure 2 shows the cast of the specimens, which is done vertically and the work of rounding the corners and subsequent strengthening.

Figure 2: Preparing the surface of the columns (2400 mm), round of corners and applying CFRP strengthening.

The value of the concrete compressive strength was obtained by testing at 28 days after casting cylindrical normalized specimens. The unconfined concrete strength ($f_{co}$) of the 4 tested columns is low (between 17,5 MPa and 20 MPa). Low strength concrete can frequently be found in rehabilitation works of older structures.

### *2.3 FRP strengthening*

The FRP material used for the strengthening is formed by unidirectional carbon fibre sheets with epoxy resin. The net fibre thickness is 0,129 mm for each reinforcement layer. Tensile testing of FRP flat coupons has been carried out according to ISO 527-4. It has obtained a mean value of tensile strength of 4161 N/$mm^2$ and a modulus of elasticity equal to 236918 N/$mm^2$ (both properties referred to the net section of fibre). The mean value of the ultimate strain was equal to 0,017.

The FRP was applied by the hand lay-up technique or wrapping (Figure 2) which is the most common strengthening method. It consists on applying the unidirectional carbon fibre fabric and the resin to the specimen, forming the composite material on the concrete substrate when the resin is cured. All the fibres are oriented in a direction perpendicular to the axis of the pillar with a minimum overlap length of 200 mm. The specimens are reinforced along their full length with 2 and 3 layers of fibre, according to the test plan. Also at the ends of each specimen, two additional strip with 300 mm of width and two layers of fibres is applied in order to avoid local failures in the heads. With this strengthening scheme the failure will occur in the central zone.

### *2.4 Test set-up and instrumentation*

The specimens were instrumented in order to know their stress-strain behaviour. In all the specimens the axial and transversal strains were measured. Transversal strain was measured with eight electrical strain gauges glued onto the FRP jacket at half the height of the specimen: one strain gauge at the centre of each side and one at the central point of each rounded corner. four displacement sensors were used (over a measurement length of approximately 2300 mm).To measure the axial deformation four displacement sensors were used, over a measurement length of approximately 2300 mm, and also four strain gauges were placed at mid-height of the column (one gauge at the centre of each side in axial direction).

The specimens were tested with centered compression load in a 10000 kN capacity actuator (Figure 3). The data of the displacement sensors and the strain gauges, as well as the applied load, are recorded continuously during the test.

Figure 3: Test set-up and instrumentation.

## 3 EXPERIMENTAL RESULTS

The experimental results are summarized in Table 1, indicating for each test:

- The unconfined concrete strength $f_{co}$ obtained from cylindrical standard samples.

- The peak axial load $Q_{max}$.

- The confined concrete strength $f_{cc}$, or concrete stress at peak load. $f_{cc}$ is computed as the diference between the peak load ($Q_{max}$) and the load carried by the longitudinal steel reinforcement, divided by the net area of concrete.

- The rate of confined and unconfined concrete strength or strength enhancement ratio ($f_{cc}$ /$_{fco}$). It must be noted that the contribution of existing steel stirrups has been neglected in this preliminary analysis.

- The ultimate axial strain $\varepsilon_{cc}$, which is obtained by the mean value of the four side measurements.

- The ultimate transversal strain or FRP effective strain $\varepsilon_{f,eff}$. It is also obtained by the mean value of the four side measurements.

- The relationship between the FRP effective strain ($\varepsilon_{f,eff}$) and the ultimate strain of the fibre obtained by standard tensile tests of flat coupons ($\varepsilon_f$), in this case equal to 0,017. This rate is commonly called strain efficiency factor.

- The maximum transversal strain measured by any of the strain gauges located at the centre of the four faces ($\varepsilon_{fmax}$).

Tabla 1. Experimental results.

| Specimen | $f_{co}$ [MPa] | $Q_{max}$ [kN] | $f_{cc}$ [MPa] | $f_{cc}/f_{co}$ | $\varepsilon_{cc}$ | $\varepsilon_{f,eff}$ | $\varepsilon_{f,eff}/\varepsilon_f$ | $\varepsilon_{f,max}$ |
|---|---|---|---|---|---|---|---|---|
| Reference | 18,24 | 1660,43 | | | | | | |
| 1_20_2 | 19,85 | 2623,30 | 26,87 | 1,35 | 0,00889 | 0,00906 | 0,53 | 0,00799 |
| 1,5_40_3 | 17,44 | 3115,43 | 31,43 | 1,80 | 0,01350 | 0,00838 | 0,49 | 0,01642 |
| 2_40_3 | 20,09 | 2743,80 | 30,85 | 1,54 | 0,01386 | 0,00581 | 0,34 | 0,00628 |

The axial and lateral stress-strain curves obtained for the tested specimens are drawn in Figure 4.

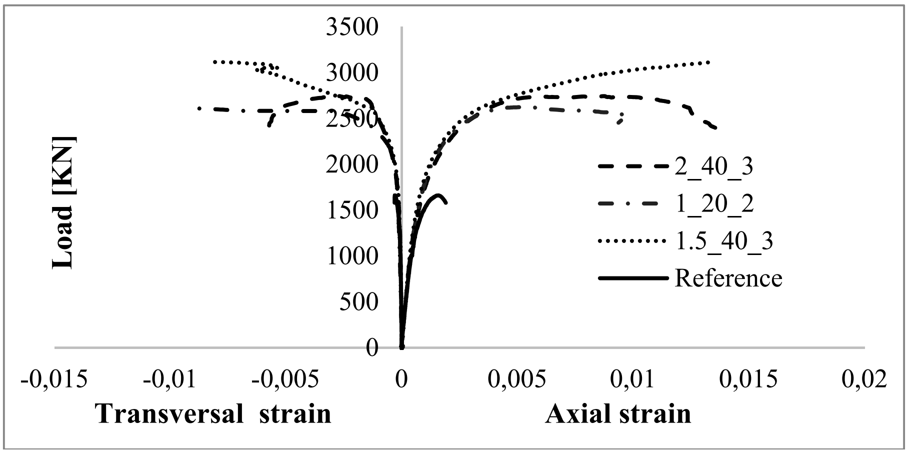


Figure 4: Experimental load-strain curves for square and rectangular specimens.

The testing campaign is more extensive; however, in the results obtained so far, it can already be seen that the FRP wrapping significantly increase the load bearing capacity of the columns.

The stress-strain response is approximately bilinear. For specimen 1_20_2 (square section with $R_c$= 20 mm, strengthened with 2 FRP layer) the second branch is almost horizontal. It should be noted that the square column has been reinforced with two CFRP layers while the rectangular columns have been reinforced with three layers. When comparing rectangular specimens 1.5_40_3 and 2_40_3 (both with $R_c$=40 mm and wrapped with 3 layers), it can be observed that the effectiveness of confinement decreases as the cross-section aspect ratio b/d increases. For specimen 1.5_40_3 the strength enhancement ratio is greater, and the typical stress-strain behaviour with ascending second branch is observed.

In all the cases the ultimate axial deformation increases notably reaching values between 0.89 % and 1.39%.

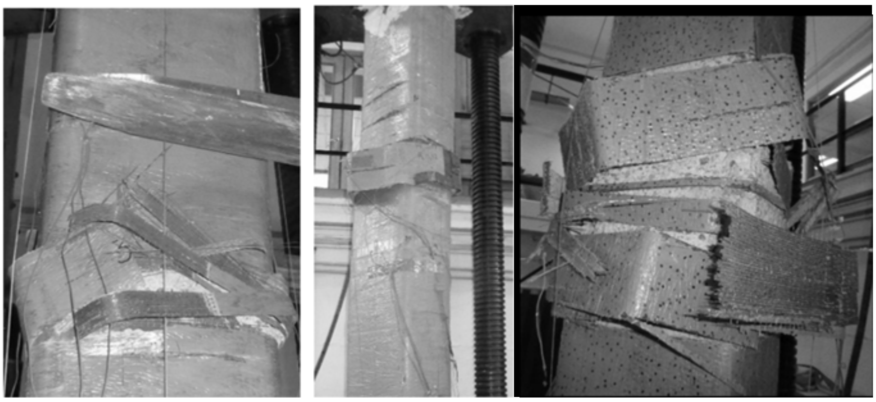

Figure 5: Failure of specimens.

The main cause of failure was the jacket rupture, usually near a corner (Figure 5). The failure occurred suddenly, although preceded by some warning signals such as noise, probably due to the rupture of some FRP fibres, followed by an explosive failure which occurs with rupture of the FRP jacket in the central area in which the concrete is completely disintegrated.

The FRP hoop rupture strain, or effective ultimate strain $\varepsilon_{f,eff}$, is lower than the ultimate tensile strain from tensile coupon tests. Table 1 gives the strain efficiency factor $\varepsilon_{f,eff}/\varepsilon_f$ in the columns tested, which decreases with increasing aspect ratio ranging from 0,34 for b/d=2 to 0,53 for b/d=1.

The value of the maximum deformation $\varepsilon_{f,max}$ measured by one of the strain gauges located in the center of the faces is also given in the table; in the case of column 1.5_40_3 it reaches a value of 0,016, close to the maximum deformation from tensile coupon tests (0,017).

The strain readings of the gauges installed on the corners are generally smaller than those at mid of side face, as shown in Figure 6.

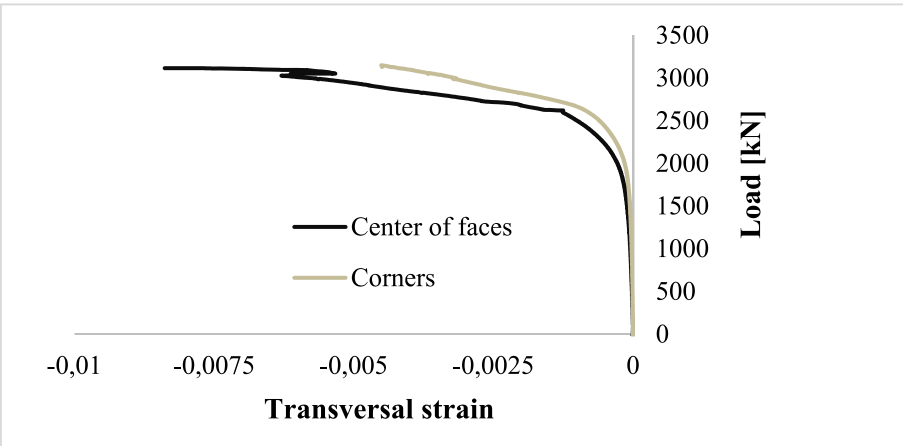


Figure 6: Hoop strain measurements in specimen 1,5_40_3.

## 4 COMPARISON OF EXPERIMENTAL RESULTS WITH THE RECOMMENDATIONS OF THE DESIGN GUIDES

The results of confined concrete strength $f_{cc}$ of the columns tested are compared with the values obtained through the design recommendations proposed in ACI-440.2R-17 (2017), Concrete Society TR55 (2012) and CNR-DT 200 R1/2013. (2013). Results are shown in table 2.

Tabla 2. Comparison of the confined concrete strength $f_{cc}$.

| Specimen | $f_{co}$ [MPa] | $f_{cc}$ [MPa] Test. | $f_{cc}$ [MPa] ACI-440.2R-17 | $f_{cc}$ [MPa] Concrete Society TR55 2012 | $f_{cc}$ [MPa] CNR-DT 200 R1/2013 |
|---|---|---|---|---|---|
| 1_20_2 | 19,85 | 26,87 | 24,19 | 23,08 | 24,48 |
| 1,5_40_3 | 17,44 | 31,43 | 20,93 | 24,55 | 22,47 |
| 2_40_3 | 20,09 | 30,85 | 22,15 | 27,83 | 23,91 |

In the case of the square column 1_20_2 it is observed in table 2 that the calculation of $f_{cc}$ with the recommendations of the guides is similar to the result obtained in the tests. However, for rectangular sections, it is observed that the confined strength obtained in the test is significantly higher, and there are significant differences between the predicted values by the guidelines. Further research is needed in order to obtain a shape factor and an accurate estimation of the FRP effective strain for rectangular columns.

All regulations appear to be conservative with respect to a side ratio greater than 1,5, however it is noted that for column 2_40_3 the confined concrete strength, $f_{cc}$, yields a value 53% greater than $f_{co}$. Regarding this observation, it should be considered that columns in this study have been cast with low strength concrete (around 20 MPa), and confinement efficiency strongly depends on the unconfined concrete strength.

## 5 CONCLUSIONS.

In this work, the results of a part of the axial compression tests of a study have been presented. They are 4 columns of non-circular section on a large scale (3 with FRP and one control column without external reinforcement).

The results obtained allow us to draw the following conclusions:

- FRP confinement can improve the load bearing capacity of rectangular reinforced concrete columns with rounded corners.
- In the case of low strength concrete, the confinement can significantly improve not only the ductility but also the strength of rectangular section columns.
- The failure usually occurs suddenly and explosively by tensile rupture of the jacket fibres to a strain value much lower than that obtained by tensile testing of FRP coupons.
- The coefficient of efficiency ($\varepsilon_{f,eff}/\varepsilon_f$) from tests are between 0,34 and 0,53 with an average value of 0,45. The results obtained so far in this experimental program show that $\varepsilon_{f,eff}/\varepsilon_f$ decreases with increasing aspect ratio although more tests are needed to confirm this finding. The approach by the Concrete Society TR55 2012, that propose a smaller coefficient for rectangular sections seems a valuable contribution, but further research is needed.

The above conclusions should be considered within the scope of the studied parameters, and with the limitations derived from the small number of tests carried out so far. The presented work is part of a more extensive test program.

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