A NEW TECHNIQUE FOR THE CONFINEMENT OF RECTANGULAR CROSS SECTION REINFORCED CONCRETE COLUMNS

Worajak Janwaen[1], Joaquim Barros[2] and Inês Costa[3]

[1]ISISE, Department of Civil Engineering, University of Minho, Azurém 4800-058 Guimarães, Portugal
Email: tontrakarn.w@gmail.com
[2]ISISE, Department of Civil Engineering, University of Minho, Azurém 4800-058 Guimarães, Portugal
Email: barros@civil.uminho.pt
[3]CiviTest, Parque Industrial de Jesufrei, Rua da Indústria, n.º144, 4770-160 Vila Nova de Famalicão, Portugal
Email: inescosta@civitest.com

Keywords: Confinement, RC columns of rectangular cross section, CFRP, post-tensioned, experimental tests, advanced numerical simulations

Abstract
In this work a new technique aiming an efficient confinement of reinforced concrete (RC) columns of rectangular cross-section is presented. This technique is based on the concept of applying strips of carbon fiber reinforced polymer (CFRP) wet layup sheets with a certain pre-stress level. A mechanical system was developed for pre-stressing the CFRP strips. The experimental program was composed by the following four types of RC column elements, all of cross section aspect ratio (larger to smaller edge ratio) of 2.0: 1) reference column without any confinement; 2) RC column fully wrapped with CFRP; 3) RC column confined with strips of CFRP; 4) RC column confined according to the new proposed technique. The columns have a cross section of 120×240 mm^2, height of 700 mm, and corner radius of 25 mm. All columns were subjected to axial compressive loading until their failures. The experimental results showed that the new proposed technique provides a significant increase of the load carrying capacity compared to the conventional strengthening techniques and the reference columns. Based on the obtained experimental results, the new proposed technique remarkably increased the confinement effectiveness of the rectangular RC columns.

1. Introduction

In recent years, Fiber Reinforced Polymer (FRP) composites have been extensively used for the strengthening and rehabilitation of existing reinforced concrete (RC) structures. There are several reasons for using FRP composites, such as high stiffness, lightweight, non-corrosiveness in harsh environments, and the ease of application [1]. Externally bonded FRP composite jacketing is one of the most common applications of FRP composites for column strengthening as it can provide significant confinement effectiveness on RC columns, mainly those of circular cross-section. This technique allows the increase of axial load and deformation capacity, as well as its energy absorption performance [2].

From previous studies, it can be clearly noted that the confinement effectiveness depends on the lateral confining pressure applied to the concrete core. The confinement of FRP-strengthened columns with circular section is more efficient than in columns with non-circular section due to the uniform confining pressure assured by the former type of cross section [3]. However, most of the existing structural columns have a rectangular cross-sectional configuration. Relatively less experimental data exists on RC columns of rectangular cross section confined with FRP systems, and, hence, the availability of reliable models for the prediction of their response is limited. Mirmiran et al. [3] studied the confinement of concrete columns with FRP jackets and found that its effectiveness depends on several parameters such as concrete strength, type of fibers and resins, fiber volume and fiber orientation in the jacket, jacket thickness, shape of cross section, slenderness ratio of the column (i.e. length-to-diameter ratio) and the interface bond between the core and the jacket. Furthermore, it was found that the corner radius of FRP-confined prismatic concrete columns is an important parameter that influences the confinement effectiveness of FRP strengthening systems. This issue is attributed to the stress concentration level in the corner zones that can promote premature tensile rupture of the strengthening systems if the corner radius is less than a critical value [4-7]. Moreover, the size and aspect ratio of the cross section (largest edge to smallest edge ratio) are also related to the columns effective confinement provided by FRP systems. When this aspect ratio increases, the confinement effectiveness of the columns is significantly decreased [8-9]. However, to improve the efficiency of FRP confined columns, the use of hybrid strengthening techniques is an alternative option. Lei et al. [10] used a technique that converts a square column to a circular section by bonding pieces of segmental circular concrete covers, called the Circularization Hereafter technique, with a significant increase of the confinement effectiveness of the column. Rousakis and Tourtouras [11] proposed a strengthening technique of square reinforced concrete columns by using special mechanical devices combined with high extension polypropylene fiber ropes, PPFR. The results revealed that the stress-strain relationship of the strengthened columns was highly improved by the proposed technique, and that the strengthened RC columns showed higher load carrying capacity when compared to columns with conventional wrapping techniques.

In the present work a new hybrid CFRP-based strengthening technique for RC columns is proposed. This technique is based on the concept of applying strips of carbon fiber reinforced polymer (CFRP) wet layup sheets with a certain pre-stress level by means of a mechanical device. The research entirely focuses on CFRP-confined rectangular RC columns. This exploratory experimental program is detailed, and the relevant results are presented and discussed.

2. Experimental Program

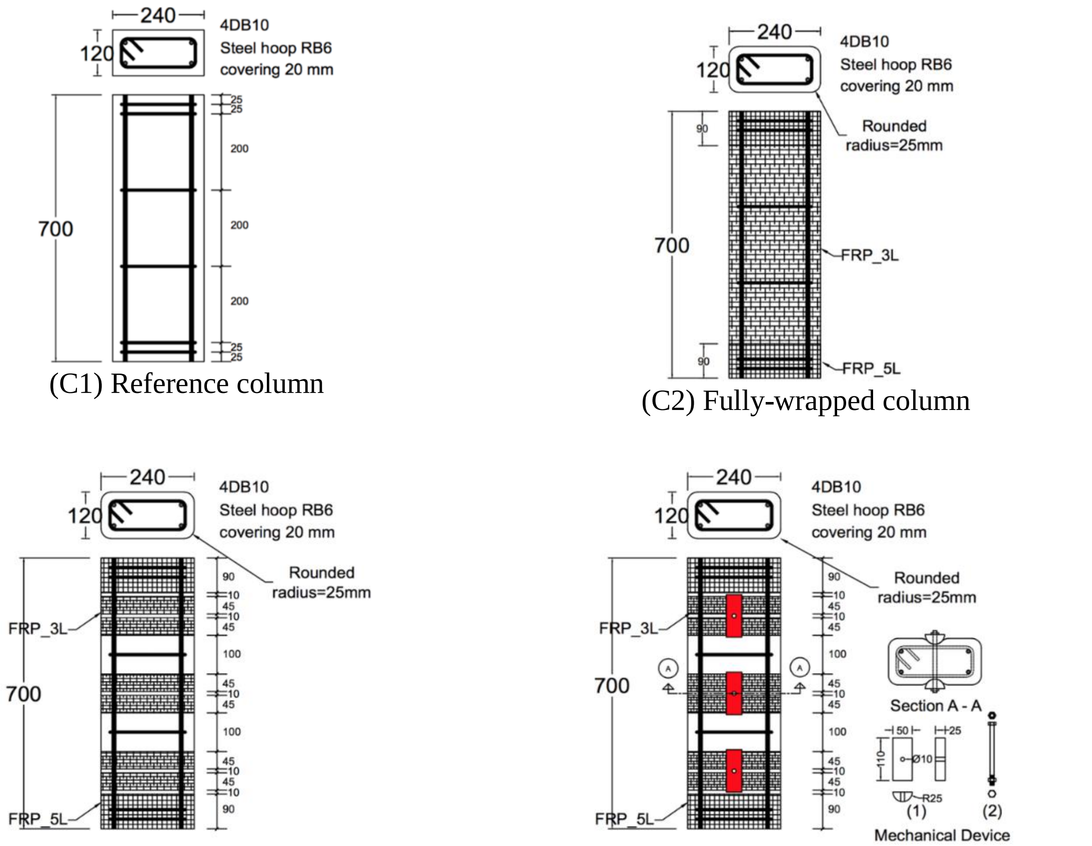
2.1. Specimen design

All specimens in this study have a cross section of 120×240 mm^2, height of 700 mm, and corner radius of 25 mm. The experimental program was composed by the following four types of columns: (1) Conventional RC column (Reference column); (2) Fully-wrapped column; (3) Partially-wrapped column; (4) Column strengthened according to the new technique. The strengthened columns were confined using three layers of CFRP sheets. To prevent failure due to high stress concentration in the extremity parts of the columns in contact with the test equipment, additional strips were installed using five layers of CFRP sheet. For strengthening according to the new technique, a mechanical device was used to apply a certain pre-stress level on the CFRP strips. The mechanical device consists of two parts: (1) a haft round (D-shaped) steel bar (with a diameter of 50mm) with one through hole to insert a threaded bolt that transmits the pre-stress and (2) a threaded bolt with washer and nut on the opposite extremity. The details of the columns are represented in Figures 1 and 2.

2.2. Materials properties

2.2.1. Concrete

Local Portland cement, river sand, and coarse aggregate were used (maximum size of the aggregate was 25 mm) for producing the concrete of the columns that presented an average compressive strength of 18 MPa in cylinder tests.



(C1) Reference column

(C2) Fully-wrapped column

(C3) Partially-wrapped column

(C4) Column strengthened according to the new technique

Figure 1. Types of columns (dimensions in mm)

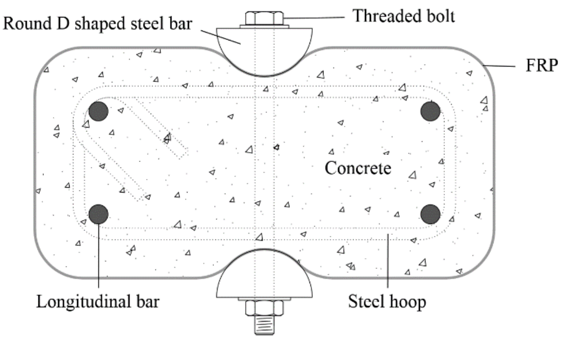


Figure 2. The schematic representation of the new proposed technique

2.2.2 Reinforcement

Two size of steel reinforcement bars were used in this study. Ribbed bars with 6 mm and 10 mm were used as steel hoops and longitudinal bars, respectively. The nominal yield stress of the reinforcement was 400 MPa.

2.2.3 CFRP sheet

A high tensile strength carbon fiber fabric, S&P C-sheet 240 was used for wrapping the columns. Two-component S&P epoxy resin 55 was also used to impregnate the CFRP sheets. The details of CFRP material properties are shown in Table 1.

Table 1. Mechanical Properties of CFRP

Properties	S&P C-sheet 240
Design tensile strength (MPa)	3750
Tensile Modulus (GPa)	240
Elongation at rupture (%)	1.75
Density (g/cm^3)	1.77
CFRP thickness (mm/ply)	0.113

2.3. Specimen preparation

2.3.1 CFRP wrapping

For wrapping the columns, the procedure recommended by ACI 440-2R-08 was followed. The concrete surface was prepared by lightly sanding to smoothen the surface, using water to remove dust and dirt from the surface, and the columns were then left to dry. Voids on the surface of columns were filled using cement paste. A two-component epoxy resin was used to bond the CFRP sheets on the surface of the columns. Before placing the CFRP sheets, a thin layer of resin was applied on the surface of the columns. After that, the first layer of the CFRP sheet was placed on the surface of the columns. A plastic roller was used to remove the excess resin between the fiber layers and any air voids. For wrapping the subsequent layers, the epoxy resin was applied again on top of the previous layer, and then the layer of CFRP sheet was placed. On each layer, the CFRP sheets were overlapped 50 mm. After the last layer of CFRP was applied, a final coat of epoxy was applied, and the plastic roller was used again to ensure that all air voids were removed. Finally, the wrapped columns were left to dry at the laboratory for approximately 1 week before testing.

2.3.2 Applying the pre-stress of CFRP strips (proposed technique)

Before applying the CFRP strips, a frictionless layer was applied on the concrete column to reduce friction between the surface of the concrete and the CFRP strips. After, the CFRP strips were bonded in the overlapping zone (approximately 50 mm of bond length) at the shorter side of the column and left to dry for approximately 1 week. For the application of pre-stress in the CFRP strips (approximately 20% of the ultimate strain of the CFRP sheet), the previously presented mechanical system was used. To install the device, firstly, the threaded bolt is inserted through a hole previously drilled on the column. Then, the D-shaped steel bars are installed on both sides of the column. Lastly, the head bolt is gradually screwed with a dynamometric wrench. In each turn, the D-shaped steel bars push the CFRP strips into the grooved section, and the intended pre-stress is induced in the CFRP strips. The torque from the wrench and the strain of the CFRP strips were registered up to the target strain of the CFRP strips. This approach produces a more uniform pre-stress distribution on the column perimeter since smaller friction forces are generated due to the presence of the frictionless layer between the surface of the concrete and the CFRP strips.

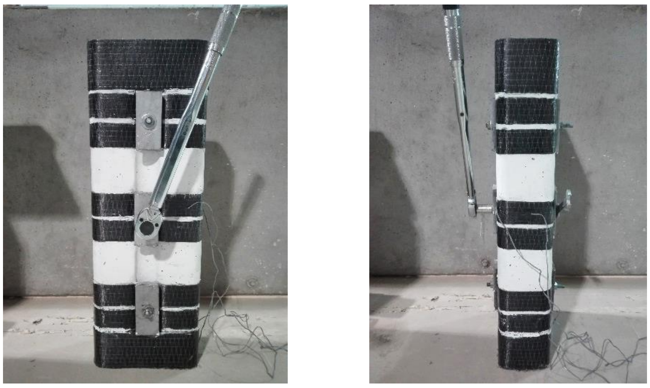


Figure 3. Representation of the pre-stress application on the CFRP strips

2.4. Testing Instrumentation

All columns were capped with polyester paste on the bottom and top surface of the columns to ensure uniform axial load transference. Additionally, a frictionless layer was applied at both ends of the columns, between the surface of the concrete and the testing machine basis to further reduce the friction. All of the strengthened columns were monitored with two strain gauges at mid-height, installed on the CFRP. One strain gauge was installed at the shorter side while the other was placed at the longer side of the column's cross section. Two linear voltage displacement transducers (LVDTs) were installed to record the axial deformation of the columns. The distance between the lower and upper fixing points was equal one-third of the height of the columns. The columns were subjected to pure axial compression with a loading machine of 2000 kN capacity. The representation of the instrumentation of the specimens is shown in Figure 4.

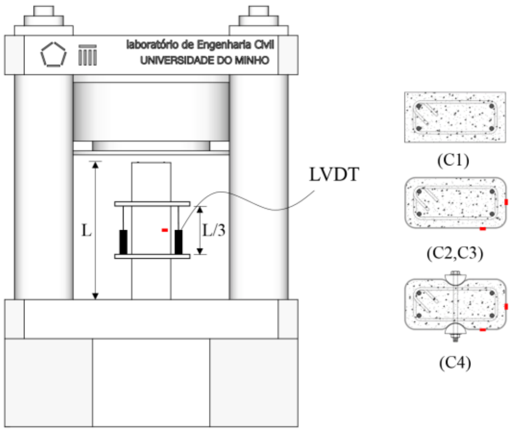


Figure 4. Strain gauges positions (red mark) and the test setup

3. Experimental results and discussion

3.1. Overall behavior

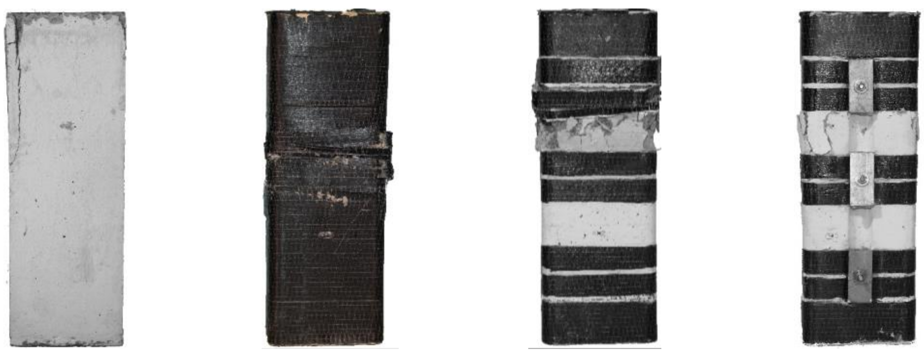
The ultimate load carrying capacity of the elements, obtained from the experimental tests is summarized in Table 2. The column strengthened according to the new technique exhibited a higher load carrying capacity than any of the other columns, despite the reduction of its cross section. It is clear that the new strengthening technique significantly increased the load carrying capacity compared to the conventional strengthening techniques.

Table 2. Summary of experimental results for all columns

Column Type	Maximum Load (KN)	Effective cross-section (mm^2)	Maximum stress (MPa)	% of stress increase
Reference column (C1)	578	28800.0	20.07	-
Fully-wrapped column (C2)	789	28263.5	27.91	39.06
Partially-wrapped column (C3)	751	28263.5	26.58	32.44
New technique column (C4)	866	27192.3	31.84	58.64

3.2. Failure modes

The typical failures of the columns consisted of one or both of the two following types: (1) crushing-splitting of concrete; and (2) rupture of CFRP layers. In the reference column (C1), failure was observed just after the maximum vertical loading force has been attained, and consisted on a gradual axial splitting. The cracks initiated from the top section of the column and spread downwards, approximately parallel to the direction of the applied force (Fig. 5a). Regarding the fully-wrapped column (C2), the failure of the column was caused by the CFRP rupture (Fig. 5b). The failure occurred suddenly, accompanied by an explosive sound at the moment of CFRP rupture. The rupture of the CFRP layers occurred near the corner of the column due to the high stress concentration, as expected. Moreover, it could be seen that the failure was accompanied by concrete crushing at mid-height of the column. For the partially-wrapped column (C3), the column gradually failed due to concrete crushing at the unwrapped zones, followed by CFRP rupture. Cracks in this column were visible between the CFRP strips (Figure 5c). Again, the rupture of the CFRP strips was accompanied by an explosive sound, which also occurred near the corner of the column, as expectable. For the column strengthened with the new technique (C4), the failure of the column took place rapidly and nosily, due to the rupture of CFRP strips at the middle of the section, which was in contact with the mechanical device. However, small cracks could be observed in the concrete surface before the CFRP rupture. After that, the column gradually failed by concrete crushing until the test was finished (Fig. 5d). All of the failures described can be observed in Figure 5.



(a) C1 (b) C2 (c) C3 (d) C4

Figure 5. The failure modes of the columns at final testing stage

3.3. Stress-strain response

The axial stress-strain relationship for each tested column is shown in Figure 6. The axial strain was calculated from the displacement readings of the loading machine divided by the total length of the columns (700 mm). All strengthened columns showed an increase in term of the load capacity, due to the confinement provided by the CFRP systems. The results showed that the maximum stress was 31.84, 27.91, 26.58 and 20.07 MPa in the column strengthened according to the proposed technique, the fully-wrapping, the partially-wrapping and in the reference column, respectively. For the fully-wrapped and partially-wrapped columns, a stress transition point (f_{ct}) could be observed on their stress-strain curves. After this point, a stress drop was evidenced. However, the stress of the fully-wrapped column started increasing again due to the mobilization of the confinement pressure. On the partially-wrapped column, a plateau formation is visible on its stress-strain curve after the temporary stress drop. For the column strengthened according to the proposed technique, the stress transition point could not be observed on the stress-strain curve. The load carrying capacity dropped suddenly just after the maximum load has been attained, due to the rupture of the CFRP portion in the contact with the mechanical device. However, at both serviceability and ultimate limit states, the column strengthened according to the new strengthening technique had a higher strength capacity compared to the other columns due to the effectiveness of the pre-stress level of the CFRP strips.

The axial stress versus the strain on the CFRP for the strengthened columns is presented in Figure 7. The CFRP strain was measured by the strain gauges at the positions presented in the figure. The results showed that the ultimate CFRP strain was 0.0030, 0.0017 and 0.0012 for the fully-wrapped, partially-wrapped and the column strengthened according to the new technique, respectively.

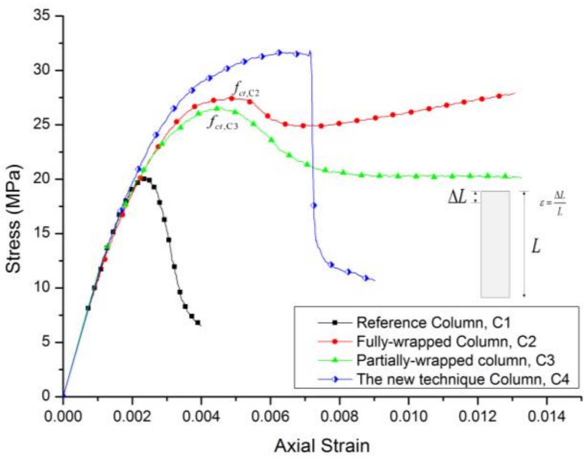


Figure 6. Axial stress versus strain of the columns

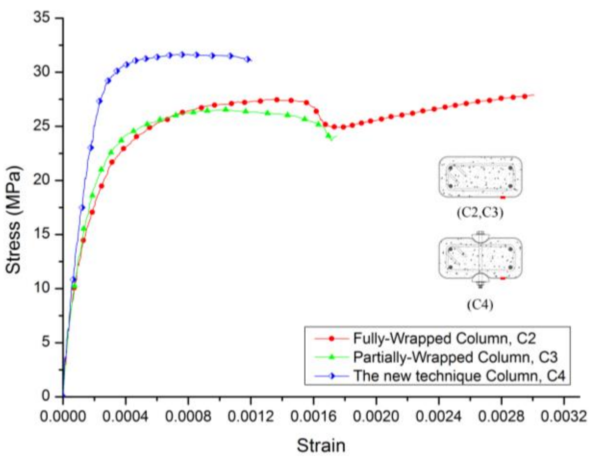


Figure 7. Axial stress versus CFRP strain on the strengthened columns

4. Conclusions

In this work a new technique for the confinement of rectangular reinforced concrete (RC) columns is presented. Four types of columns were tested: 1) a reference column; 2) a fully-wrapped column; 3) a partially wrapped column; 4) a column strengthened according to the proposed technique. The results can be summarized as follows:

- The confinement provided by the new proposed technique significantly enhances the performance of rectangular reinforced concrete columns;
- The new strengthening technique provided a significant increase of the load carrying capacity at both serviceability and ultimate limit states compared to the conventional strengthening techniques.

Currently, an extensive experimental program is being carried out to investigate the confinement effectiveness of higher cross section aspect ratios and to provide a representative experimental database for RC columns of rectangular cross-sections.

Acknowledgments

Authors would like to thank Casais Engineering and Construction Company for providing steel reinforcements, formworks and concrete. Also gratefully acknowledge the technician from laboratory of structures, Department of Civil Engineering, University of Minho and staff from CiviTest Company for their great helpfulness.

References

[1] ACI 440. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. Technical committee document 440.2R-08, *American Concrete Institute, Committee 440*, 2008.
[2] N. Nistico, F. Pallini, T. Rousakis, Y.F. Wu and A. Karabinis. Peak strength and ultimate strain prediction for FRP confined square and circular concrete sections. *Composites: Part B*, 67:543-554, 2014.
[3] A. Mirmiran, M. Shahawy, M. Samaan, H.E. Echary, J.C. Mastrapa and O. Pico. Effect of column parameters on FRP confined concrete. *Journal of Composites for Construction*, Vol. 2(4):175-185, 1998.
[4] X. Yang, J. Wei, A. Nanni and L.R. Dharani. Shape effect on the performance of carbon fiber reinforced polymer wraps. *Journal of Composites for Construction*, 8(5):444-451, 2004.
[5] Y.A. Al-Salloum. Influence of edge sharpness on the strength of square concrete columns confined with FRP composite laminates. *Composites: Part B*, 38:640-650, 2007.
[6] L.M. Wang and Y.F. Wu. Effect of corner radius on the performance of CFRP confined-square concrete columns: Test. *Engineering Structures*, 30:493-505, 2008.
[7] R. Abbasnia, R. Ahmadi and H. Ziaadiny. Effect of confinement level, aspect ratio and concrete strength on the cyclic stress-strain behavior of FRP confined concrete prisms. *Composites: Part B*, 43:825-831, 2012.
[8] C. Cole and A. Belarbi. Confinement characteristics of rectangular FRP-jacketed RC columns. *The Fifth international symposium on Fiber Reinforced Polymer for Reinforced Concrete Structures, Cambridge, UK*, 823-832, 2001.
[9] Y.F. Wu and Y.Y Wei. Effect of cross-sectional aspect ratio on the strength of CFRP-confined rectangular concrete columns. *Engineering Structures*, 32:32-45, 2010.
[10] X. Lei, T.M. Pham and M.N. Hadi. Behaviour of CFRP wrapped square RC columns under eccentric loading. *Australasian Structural Engineering Conference*, 01-08, 2012.
[11] T.C. Rousakis and I.S. Tourtouras. RC columns of square section – Passive and active confinement with composite ropes. *Composites: Part B*, 58:537-581, 2014.