



Rounded corners columns strengthened with CFRP

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ABSTRACT. Experimental results for twelve concrete columns with rectangular cross sections under axial compression are presented and discussed. Nine columns were strengthened with one layer of Carbon Fiber Reinforced Polymer (CFRP) at their ends. The study aimed to evaluate the performance of strengthened columns with several rounded corners radii. The results showed that the rounded corner columns presented a better performance and ultimate resistance but still with brittle failures.

Keywords: reinforced concrete, structural strengthening, carbon fiber.

Pilares com cantos abaulados reforçados com CFRP

RESUMO. Foram apresentados e discutidos os resultados experimentais para 12 pilares de concreto à compressão axial, dos quais nove foram reforçados com material compósito de fibra de carbono (CFRP). Em todos os reforços foi utilizada uma faixa de tecido de fibra de carbono nas extremidades dos pilares. O principal objetivo do trabalho foi avaliar a influência da variação do raio de abaulamento dos cantos dos pilares no desempenho dos reforços. Os pilares sem os cantos abaulados apresentaram resistência significativamente inferiores àquelas obtidas com os cantos abaulados.

Palavras-chave: concreto armado, reforço estrutural, fibra de carbono.

Introduction

Early researches concerning strengthening performance of CFRP (Carbon Fiber Reinforced Polymer) were developed in Japan for nearly 25 years once the country is constantly facing (and still faces) earthquake problems. The Japanese researchers have usually reinforced the ends of columns with carbon fiber to stiffen the nodes of structures, reducing vibration in the structures and thus slowing down the soil liquefaction during earthquakes. Currently, the reinforcement is installed even in new structures to prevent collapse due to the aftershocks. The United States began using this type of reinforcement in aerospace projects, and later its use spread to the automotive industry, covering passenger and racing cars to protect drivers in case of collisions. The Brazilian market has started using of this technique just about ten years ago. One of the first applications was in the retrofitting of the Santa Tereza viaduct, a work by the government of the city of Belo Horizonte, and up to the present date only four companies distribute the CFRP structural systems in Brazil.

Confinement is one of the main goals of CFRP techniques to reinforced concrete columns subjected to axial and eccentric compression

loadings, which brings many benefits for their structural behavior. However, according to Wang et al. (2012), depending on the shape of the cross section, the efficiency of the strengthening may vary due to the distribution of the confining pressure. In the case of columns with circular section this distribution is uniform, and the more approximate is the section to a circular shape the more uniform will be the distribution of the confinement pressures and, consequently, greater will be the strengthening efficiency.

However, for square or rectangular cross sections, there is the concentration of stress at their corners which may cause the premature failure of the CFRP reinforcement, resulting in an inefficient system. Thus, this study aims to evaluate the influence of the radii for rounded corners of columns with square and rectangular cross section strengthened with CFRP in their behavior and failure loads.

Material and methods

According to Abbasnia et al. (2012) the external confinement of concrete columns increases its compressive strength and ductility and has been applied in order to their recovery or

to increase their bearing capacity. For this reason, systems with carbon fiber reinforcement have been widely used in the strengthening of concrete structures, and the confinement is one of the main techniques for concrete columns. Expressions to evaluate the strength of concrete elements of circular and square section (f_{cc}), confined with composite resin and fiber, can be found in ACI 440.2R-08 (ACI, 2008), and some are presented in Table 1.

Table 1. Equations to estimate strength of confined columns.

Cross section	f_{cc} (MPa)
Circular	$f_{co} \cdot (2.25 \cdot \sqrt{1 + 7.9 \cdot \frac{f_l}{f_{co}}} - 2 \cdot \frac{f_l}{f_{co}} - 1.25)$
Square or rectangular	$f_{co} \cdot (2.25 \cdot \sqrt{1 + 7.9 \cdot \frac{f_{le}}{f_{co}}} - 2 \cdot \frac{f_{le}}{f_{co}} - 1.25)$
	$k_2 = k_e; \frac{b_x}{b_y} \leq 1.5; b_x \text{ or } b_y \leq 900 \text{ mm}$

ACI (2008).

where:

f_{co} is the compressive strength of unconfined concrete;

f_l is the lateral stress of confinement for square and rectangular sections, determined by the equation 1.

$$f_l = \frac{f_f \cdot t_f (b_x + b_y)}{b_x \cdot b_y} \quad (1)$$

where:

t_f and f_f are the thickness and tensile strength of the confining material, respectively;

b_x and b_y are the cross section dimensions.

For the expression, which includes the effective lateral confinement stress (f_{le}), it must be adopted the equation 2.

$$f_{le} = k_2 \cdot f_l \text{ and } k_e = \left[1 - \left(\frac{(b_x - 2 \cdot r_c)^2 + (b_y - 2 \cdot r_c)^2}{3 \cdot A} \right) \right] \quad (2)$$

In this equation, r_c is the radius of the rounded corners and A is the cross-section area of confined concrete, as shown in Figure 1.

According to Silva (2011), the stress distribution throughout the elliptical cross section of confined, contrary to circular section, is not uniform and the confinement efficiency is low when compared with columns of circular cross section. Therefore, the confinement stress used in predicting the maximum

axial stress should be replaced by an effective confining pressure. This estimation uses an effective area of confined concrete corresponding to 60% of the gross amount of cross section for square columns, which can also be used for rectangular columns.

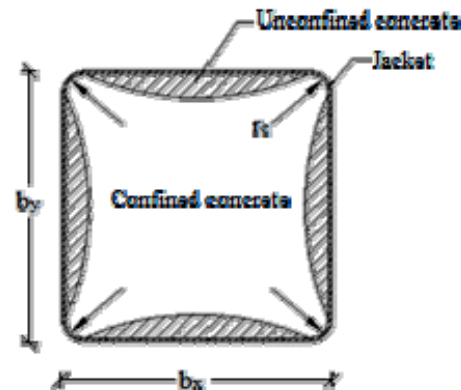


Figure 1. Square or rectangular concrete area effectively confined.

Fonte: Marwan et al. (2007).

The experimental program comprised twelve (12) models of columns of reduced scale ($h = 500$ mm), under axial compression at the Laboratory of Civil Engineering of the Federal University of Pará, in which nine (9) columns were strengthened with composite material of carbon fiber (CFRP). A 160 mm wide ribbon of CFRP was applied on the ends of all columns. Among the columns with 100 mm x 100 mm of square cross section one was used as reference and the others presented rounded corners and CFRP. For the columns with rectangular cross-section of 120 mm x 100 mm and 150 mm x 100 mm, two were used as reference and six presented rounded corners and CFRP.

The variation in the curvature radius of corners in both the rectangular and square columns was: $r = 50$ mm, 55 mm and 60 mm. More details of the columns are shown in Figure 2 and presented in Table 2. The Figure 3 shows the details for the radius of curvature.

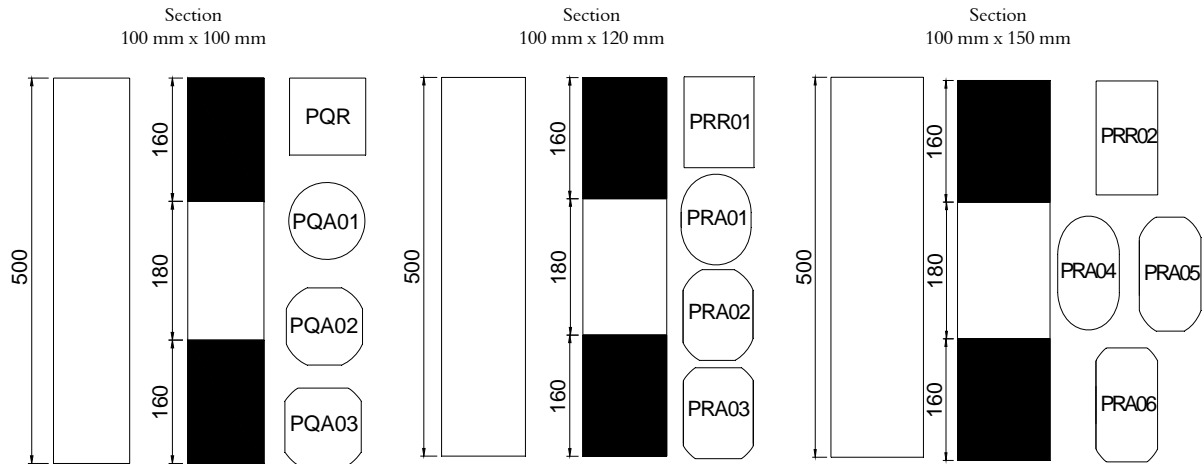


Figure 2. Cross section and side view of short columns.

Table 2. Characteristics of short columns.

Column	Section	Ratio (mm)	Area (mm ²)	Type of CFRP reinforcement
PQR	Square	-	1,000	Without CFRP
PQA - 01	Square	50	7,854	Two ribbons at the ends
PQA - 02	Square	55	8,887	
PQA - 03	Square	60	9,509	
PRR - 01	Rectangular	-	12,000	Without CFRP
PRR - 02	Rectangular	-	15,000	
PRA - 01	Rectangular	50	9,854	Two ribbons at the ends
PRA - 02	Rectangular	55	10,946	
PRA - 03	Rectangular	60	11,509	
PRA - 04	Rectangular	50	12,854	
PRA - 05	Rectangular	55	13,887	
PRA - 06	Rectangular	60	14,509	

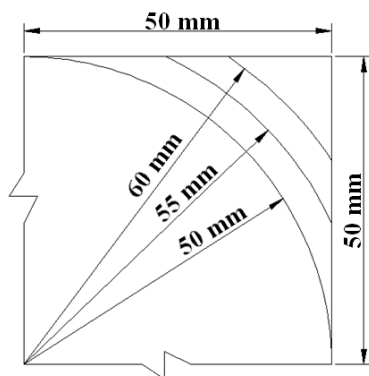


Figure 3. Rounding radius of columns corners.

The concrete used in the columns was mixed *in situ* using Portland cement CII – Z 32. The fine and the coarse aggregates were washed river sand and rolled pebble with diameter up to 9.5 mm, typical in northern Brazil. After 35 days of molding, tests of axial compression were performed, and also determined the modulus of elasticity in accordance with NBR 5739 (ABNT, 2007) and NBR 8522 (ABNT, 2003), respectively, with results presented in the Table 3.

Table 3. Compressive strength and modulus of elasticity of concrete.

CP	f_c (MPa)	E_{cc} (GPa)
01	46.4	37.3
02	47.1	36.2
03	49.3	37.1
Mean	47.3	36.9

It was used the MFC-130 system to strengthen the columns, which is distributed in Brazil by Rogerotec. The fabric is consisted of unidirectional carbon fibers oriented in longitudinal direction. This fabric is commercially supplied in rolls with 500 mm wide and mass equal to 225 g m⁻². The structural reinforcement system MFC-130 is constituted by three main components: epoxy primer, epoxy structural adhesive and blanket of carbon fiber. The Tables 4 and 5 present the main properties for the system components used in the strengthening, according to the information provided by the manufacturer and passed on by the distributor.

Table 4. Properties of primer and structuring epoxy.

Properties	Primer	Structuring epoxy
Tensile strength	12 MPa	57 MPa
Tensile strain	1 a 3 %	2.40 %
Tensile modulus	687 MPa	2,998 MPa
Flexural strength	26 MPa	131 MPa
Flexural modulus	570 MPa	3,684 MPa
Compressive strength	20 MPa	81 MPa
Compressive modulus	619 MPa	2,560 MPa

Table 5. Properties of carbon fiber.

Properties	Fiber
Fiber density	1.82 g cm ⁻³
Tensile strength	3.55 x 10 ³ MPa
Tensile modulus	2.35 x 10 ⁵ MPa
Thickness	0.165 mm
Density/weight/ proportion field	300 g m ⁻²
Useful stretching	1.50 %
Width	500 mm

After 36 days of their respective moldings, the columns were tested for the axial compression on a brand AMSLER servo-controlled hydraulic machine with a capacity of 2000 kN, as shown in the Figure 4. The columns had their ends smoothed using a grinder

for the removal of any lump, which leads to high stress concentrations and consequently the premature rupture of concrete during the tests. Then a pre-load was applied on each column to accommodate the test system, with load steps of 10 kN.



Figure 4. Short columns ready to test.

The CFRP strengthening was conducted following the manufacturer's recommendations, once this strengthening system comes with execution instructions. The surfaces of columns were cleaned to remove dust (air jet), grease and other materials which could affect the CFRP adherence and performance. The anchorage length for the carbon fiber corresponded to one and a half times the perimeter of the cross section for all columns. The Figure 5 shows all steps adopted to strengthen the short columns.

Results and discussion

The values obtained from the axial compression tests on the columns (F_u) are presented in the Table 6. As expected, for the square cross section column, with rounding radius of 50 mm, the gain in strength and ductility was significant, since the gross area for this column is significantly smaller than for the

reference column. These columns, with rounding radii of 50 mm showed the best results in comparison with those of rounding radii of 55 and 60 mm.

The column of rounding radius of 55 mm was inefficient in comparison with the reference columns for both the square and rectangular column. Probably the small gain in strength for the rectangular cross section columns with rounded corners minimized the influence of the 55 mm radius due to the difficulty in propagating the confinement stress in elliptical sections or similar, as mentioned by Silva (2011).

The Table 7 presents the estimated failure forces with regards to recommendations of the ACI 440.2R-08 (ACI, 2008). The results were compared using the ratio F_u/F_{ec} , being F_{ec} the ultimate force estimated by the American code. The Figure 6 shows the appearance of columns after tests.



Figure 5. Step-by-step process to strengthen the short columns.

Table 6. Failure modes and loads of columns.

Column	F_u (kN)	Gain (%)	Column	F_u (kN)	Gain (%)	Column	F_u (kN)	Gain (%)
PQR	316	-	PRR - 01	478	-	PRR - 02	496	-
PQA - 01	472	49.4	PRA - 01	564	18.0	PRA - 04	580	16.9
PQA - 02	375	18.7	PRA - 02	402	-	PRA - 05	415	-
PQA - 03	457	44.6	PRA - 03	518	8.4	PRA - 06	496	-

Table 7. Relationship between failure and estimated loads.

Column	F_u (kN)	F_u/F_{est}
PQR	300	0.67
PQA - 01	596	0.60
PQA - 02	436	0.65
PQA - 03	461	0.75
PRR - 01	360	0.84
PRR - 02	467	0.92
PRA - 01	520	0.60
PRA - 02	546	0.72
PRA - 03	450	0.70
PRA - 04	571	0.77
PRA - 05	624	0.50
PRA - 06	656	0.57

**Figure 6.** View of columns after tests.

Conclusion

The strengthened columns of rounded corners with radius of 50 mm showed the best performance in comparison with the reference columns, since this radius causes the maximum decrease of the gross cross section. The results corroborate other results from the literature and indicate that the CFRP strengthening for the circular cross section columns is more efficient than for the square and rectangular cross section columns, and clearly demonstrate that the final strength decreases as the ratio long to short sides of columns increases.

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