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.

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.

<table>
<thead>
<tr>
<th>Cross section</th>
<th>$f_{cc}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>$f_{co} \cdot (2.25 - 1 + 7.9 \cdot \frac{f_{l}}{f_{co}} - 2 \cdot \frac{f_{l}}{f_{co}} - 1.25)$</td>
</tr>
<tr>
<td>Square or rectangular</td>
<td>$f_{co} \cdot (2.25 - 1 + 7.9 \cdot \frac{f_{le}}{f_{co}} - 2 \cdot \frac{f_{le}}{f_{co}} - 1.25)$</td>
</tr>
</tbody>
</table>

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.

$$f_{l} = \frac{f_{f} \cdot t_{f} (b_{x} + b_{y})}{b_{x} \cdot b_{y}}$$  \hspace{1cm} (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.

$$f_{le} = k_{e} \cdot f_{l} \quad \text{and} \quad k_{e} = 1 - \left[ \frac{(b_{x} - 2 \cdot r \cdot c)^{2} + (b_{y} - 2 \cdot r \cdot c)^{2}}{3 \cdot A} \right]$$  \hspace{1cm} (2)

In this equation, $r$ 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.](image)

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.
Columns strengthened with CFRP

Table 2. Characteristics of short columns.

<table>
<thead>
<tr>
<th>Column</th>
<th>Section</th>
<th>Ratio (mm)</th>
<th>Area (mm²)</th>
<th>Type of CFRP reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQR</td>
<td>Square</td>
<td>100</td>
<td>1,000</td>
<td>Without CFRP</td>
</tr>
<tr>
<td>PQA - 01</td>
<td>Square</td>
<td>50</td>
<td>7,854</td>
<td>Two ribbons at the ends</td>
</tr>
<tr>
<td>PQA - 02</td>
<td>Square</td>
<td>55</td>
<td>8,887</td>
<td></td>
</tr>
<tr>
<td>PQA - 03</td>
<td>Square</td>
<td>60</td>
<td>9,509</td>
<td></td>
</tr>
<tr>
<td>PRR - 01</td>
<td>Rectangular</td>
<td>120</td>
<td>12,000</td>
<td>Without CFRP</td>
</tr>
<tr>
<td>PRA - 01</td>
<td>Rectangular</td>
<td>50</td>
<td>9,854</td>
<td>Two ribbons at the ends</td>
</tr>
<tr>
<td>PRA - 02</td>
<td>Rectangular</td>
<td>55</td>
<td>10,946</td>
<td></td>
</tr>
<tr>
<td>PRA - 03</td>
<td>Rectangular</td>
<td>60</td>
<td>11,509</td>
<td></td>
</tr>
<tr>
<td>PRA - 04</td>
<td>Rectangular</td>
<td>50</td>
<td>12,854</td>
<td></td>
</tr>
<tr>
<td>PRA - 05</td>
<td>Rectangular</td>
<td>55</td>
<td>13,987</td>
<td></td>
</tr>
<tr>
<td>PRA - 06</td>
<td>Rectangular</td>
<td>60</td>
<td>14,509</td>
<td></td>
</tr>
</tbody>
</table>

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

Figure 3. Rounding radius of columns corners.

The concrete used in the columns was mixed in situ using Portland cement CPII – 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.

<table>
<thead>
<tr>
<th>CP</th>
<th>f_c (MPa)</th>
<th>E_f (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>46.4</td>
<td>37.3</td>
</tr>
<tr>
<td>02</td>
<td>47.1</td>
<td>36.2</td>
</tr>
<tr>
<td>03</td>
<td>49.3</td>
<td>37.1</td>
</tr>
<tr>
<td>Mean</td>
<td>47.3</td>
<td>36.9</td>
</tr>
</tbody>
</table>

It was used the MFC-130 system to strengthen the columns, which is distributed in Brazil by Rogertec. 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.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Primer</th>
<th>Structuring epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>12 MPa</td>
<td>57 MPa</td>
</tr>
<tr>
<td>Tensile strain</td>
<td>1 x 3 %</td>
<td>2.40 %</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>687 MPa</td>
<td>2,998 MPa</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>26 MPa</td>
<td>131 MPa</td>
</tr>
<tr>
<td>Flexural modulus</td>
<td>570 MPa</td>
<td>3,684 MPa</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>20 MPa</td>
<td>81 MPa</td>
</tr>
<tr>
<td>Compressive modulus</td>
<td>615 MPa</td>
<td>2,360 MPa</td>
</tr>
</tbody>
</table>

Table 5. Properties of carbon fiber.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber density</td>
<td>1.82 g cm⁻³</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>3.58 x 10⁶ MPa</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>2.35 x 10⁵ MPa</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.165 mm</td>
</tr>
<tr>
<td>Density/weight/ proportion field</td>
<td>300 g m⁻³</td>
</tr>
<tr>
<td>Useful stretching</td>
<td>1.50 %</td>
</tr>
<tr>
<td>Width</td>
<td>500 mm</td>
</tr>
</tbody>
</table>
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 (Fu) 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 $F_u/F_{cc}$, being $F_{cc}$ 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.

<table>
<thead>
<tr>
<th>Column</th>
<th>$F_u$ (kN)</th>
<th>Gain (%)</th>
<th>Column</th>
<th>$F_u$ (kN)</th>
<th>Gain (%)</th>
<th>Column</th>
<th>$F_u$ (kN)</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQR - 01</td>
<td>396</td>
<td>-</td>
<td>PRR - 02</td>
<td>496</td>
<td>-</td>
<td>PRA - 06</td>
<td>580</td>
<td>-</td>
</tr>
<tr>
<td>PQA - 01</td>
<td>472</td>
<td>49.4</td>
<td>PQA - 02</td>
<td>475</td>
<td>18.7</td>
<td>PRA - 05</td>
<td>415</td>
<td>-</td>
</tr>
<tr>
<td>PQA - 03</td>
<td>457</td>
<td>44.6</td>
<td>PRA - 03</td>
<td>518</td>
<td>8.4</td>
<td>PRA - 06</td>
<td>496</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 7. Relationship between failure and estimated loads.

<table>
<thead>
<tr>
<th>Column</th>
<th>$F_{cc}$ (kN)</th>
<th>$F_u/F_{cc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQR</td>
<td>300</td>
<td>0.67</td>
</tr>
<tr>
<td>PQA - 01</td>
<td>596</td>
<td>0.60</td>
</tr>
<tr>
<td>PQA - 02</td>
<td>436</td>
<td>0.65</td>
</tr>
<tr>
<td>PQA - 03</td>
<td>461</td>
<td>0.75</td>
</tr>
<tr>
<td>PRR - 01</td>
<td>360</td>
<td>0.84</td>
</tr>
<tr>
<td>PRR - 02</td>
<td>467</td>
<td>0.92</td>
</tr>
<tr>
<td>PRA - 01</td>
<td>520</td>
<td>0.60</td>
</tr>
<tr>
<td>PRA - 02</td>
<td>546</td>
<td>0.72</td>
</tr>
<tr>
<td>PRA - 03</td>
<td>450</td>
<td>0.70</td>
</tr>
<tr>
<td>PRA - 04</td>
<td>571</td>
<td>0.77</td>
</tr>
<tr>
<td>PRA - 05</td>
<td>624</td>
<td>0.50</td>
</tr>
<tr>
<td>PRA - 06</td>
<td>656</td>
<td>0.57</td>
</tr>
</tbody>
</table>

### 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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### References


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