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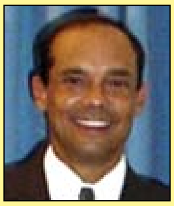
Design parameters for reinforced concrete columns strengthening with CFRP

Parâmetros de projeto para reforço de pilares de concreto armado com PRFC

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Abstract

This work deals with the behavior of reinforced concrete columns externally wrapped with carbon fiber composites. The technique of strengthening was experimentally evaluated analyzing eight reinforced concrete columns with distinct strengthening arrangements. The design parameters studied were the strengthening rate, the spacing between straps and the column cross section. Confinement models were considered based on experimental results. The increases of strength were analyzed based on the columns longitudinal strain.

Keywords: Strengthening; Confinement; Wrapping; Columns; Reinforced Concrete; Carbon Fibers.

Resumo

Este trabalho aborda o comportamento de pilares de concreto armado reforçados, por cintamento externo, com compósitos de fibras de carbono (PRFC). A técnica de reforço em questão foi avaliada pela análise experimental de oito pilares de concreto armado com distintos arranjos de reforço. Os parâmetros de projeto estudados foram a taxa de reforço, o espaçamento entre laços de cintamento e a seção transversal do pilar. Modelos para o confinamento do concreto foram avaliados com base nos resultados experimentais. Os incrementos de resistência foram analisados em função da deformação longitudinal dos pilares.

Palavras-chave: Reforço, confinamento, cintamento, pilares, concreto armado, fibras de carbono.

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1 Introduction

There are many techniques of repairing or strengthening in structural elements of reinforced concrete. Among these techniques the most used are the mortar, concrete or grout applied for the repair or enlargement of the structural element, and the utilization of complementary reinforcement (steel bars or metallic profiles) to the structural element.

In this paper, a technique of strengthening in structural elements was studied, with is based on the addition of reinforced polymers with fibers (FRP) to the structure. This technique starded around mid-twentieth century by RUBINSKY and RUBINSKY [2] and experienced a great development after the Kobe earthquake (Japan) in 1995.

Many researchers have studied concrete structures strengthening with FRP. The following works are cited, in the particular case of carbon fibers composites use in the strengthening of columns: SAADATMANESH et al [7] who have studied circular and rectangular columns reinforced with straps FRP; MIRMIRAN and SHAHAWY [5] and SAMAAN et al [8] that have discussed models for confined concrete with fiber composites and TOUTANJI [10] who has developed an experimental work with concrete cylinders wrapped with CFRP and has studied the concrete confinement with this type of composite.

In Brazil, some works about concrete columns strengthening with CFRP were achieved. CARRAZEDO [3] has analysed the concrete confinement mechanisms and their implication in the strengthening of wrapped columns with CFRP and SILVA [9] has studied the behavior of confined short columns with carbon and glass fibers composites.

In the present article, some parameters relevant for the project of this type of strengthening, as well as two models for confined concrete with FRP will be discussed and analysed, based on the experimental results obtained by RIGAZZO [6], who studied the behavior of circular and square reinforced concrete columns strengthened with CFRP.

2 Models for Concrete Confinement with FRP

In this item, two models for confined concrete with FRP are presented. These models were utilized in this work during the analysis of the experimental results.

2.1 Model of SAMAAN et al (8)

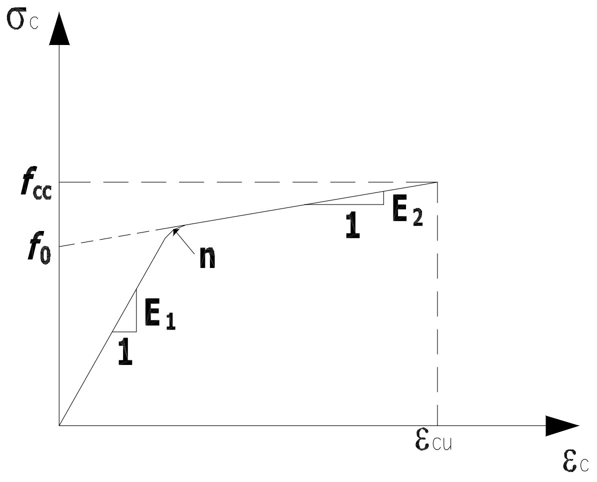
SAMAAN et al [8] have presented a model for confined concrete with fiber composites, based on a model upon a bi-linear stress-strain behavior (Figure 1). This model was developed for FRP tubes with concrete core; however, it was utilized to evaluate the behavior of the strengthened columns behavior with fiber carbon straps, theme of this work.

The bi-linear behavior for confined concrete is defined by the following equation:

$$\sigma_c = \frac{(E_1 - E_2)\varepsilon_c}{\left[1 + \left(\frac{(E_1 - E_2)\varepsilon_c}{f_0}\right)^n\right]^{1/n}} + E_2\varepsilon_c \qquad (1)$$

Where ε_c and σ_c are the strain and the stress in the concrete, respectively; E_1 and E_2 are the first and the second slopes, respectively; f_0 is the plastic stress of reference in the intersection point of the second slopes with

Figure 1 – Bi-linear stress-strain diagram



stress axis and n is a curve shaped parameter that mainly controls the curvature in the transition zone.

The confined concrete strength (f_c) is given, in function of the non-confined concrete strength (f_c) by the following equation:

$$f_{cc} = f_c + 6{,}0 f_l^{0,7} \quad \text{(MPa)} \tag{2}$$

Where f_l is the lateral pressure deriving from the FRP composite, defined as:

$$f_l = \frac{2 f_f t_f}{D} \tag{3}$$

Where t_f is the tensile strength for the composite and t_f is its thickness. D is the column diameter.

2.2 Model of MIYAUCHI et al (4)

The authors have defined two expressions to evaluate the stress-strain behavior of the confined concrete with FRP. These expressions depend on the parameter ε_{tan} , defined as follows:

$$\varepsilon_{tan} = \varepsilon_{co} - \frac{\lambda \varepsilon_{co}^2}{2 f_c} \tag{4}$$

Thus the stress-strain behavior was divided in two intervals, which depend on ε_{tan} .

$$\sigma_c = f_c\left[2\frac{\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right] \text{ for } 0 \,[\, \varepsilon_c \,[\, \varepsilon_{tan} \tag{5}$$

$$\sigma_c = f_{cc} - \lambda(\varepsilon_{cc} - \varepsilon_c) \text{ for } \varepsilon_{tan} \,[\, \varepsilon_c \,[\, \varepsilon_{cc} \tag{6}$$

Where:

$$\lambda = \frac{1}{\varepsilon_{co}^2}\{-2 f_c(\varepsilon_{cc} - \varepsilon_{co}) + \sqrt{4 f_c\left(f_c \varepsilon_{cc}^2 - 2 f_c \varepsilon_{co} \varepsilon_{cc} + f_{cc} \varepsilon_{co}^2\right)} \tag{7}$$

For confined concrete strength, the authors have proposed the following expression, in which the coefficient of efficiency, k_e , is defined as 0,85.

$$\frac{f_{cc}}{f_c} = 1 + 4{,}1 k_e \left(\frac{2 f_f t_f}{f_c D}\right) \tag{8}$$

3 Experimental Program

Aiming to find out the behavior of reinforced concrete columns wrapped with CFRP, RIGAZZO [6] tested five columns of circular cross section (PCT, PC01S'0, PC02S'5, PC03S'10 and PC04S'0) and three columns with square cross section (PQT, PQ01S'0 and PQ02S'5). Table 1 and 2 summarize the characteristics of the analyzed columns.

The adopted diameter for the circular columns was 20cm and, for the purpose of maintaining the same area of the cross section, the adopted side for the square columns was 17,5cm. Besides, all the columns were made with 160cm-length, resulting in a non-reinforced column slenderness ratio, λ, of about 32.

For all these columns, the compression strength of the non-confined concrete was about 15.5MPa. In addition, all of them received identical longitudinal bars (8φ10mm) and transversal bars of φ 5mm, every 10cm. The yield stress found for the steel of the longitudinal bars was 539MPa, while a yield stress of 616MPa was obtained for the steel of the transversal bars.

Referring to the CFRP composite utilized in the tests, its average tensile strength was 3731MPa and the Young`s Modulus was 293GPa.

Each column was instrumented with six displacement transducer; four to estimate the longitudinal strain and two for measuring the horizontal displacement of the central region.

In order to estimate the longitudinal strain, the mechanical extensometers were placed in such a way that their needles touched the angle plates fixed near the ends of the columns, thus allowing to measure the displacement between these two points. Having the displacement and knowing the initial distance between the angles it was possible to determine the column longitudinal strain of the column (Figure 2).

Table 1 – Geometric characteristics of the columns

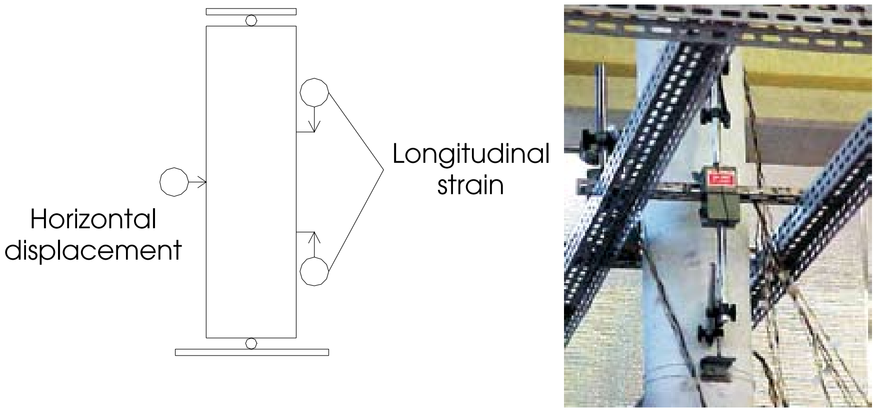
Section	D or Side (cm)	Area (cm²)	L (cm)	λ
Circular	20	314. 2	160	32
Square	17.5	306. 3	160	31.6

Table 2 – Columns reinforcement arrangements

Column	Number of CFRP composite layers	Spacing between straps (S' in cm)
PCT	–	–
PC01S'0	1	0 (*)
PC02S'5	2	5
PC03S'10	3	10
PC04S'0	4	0
PQT	–	–
PQ01S'0	1	0
PQ02S'5	2	5

(*) indicates that the entire column was wrapped with CFRP

Figure 2 – Displacement Transducers



For the PCT, PC01S'0, PC02S'5, PC04S'0, PQT, PQ01S'0 and PQ02S'5 columns, the instrumentation of the cages followed the scheme of Figure 3, in which the letter "L" represents the extensometers bonded on the longitudinal reinforcement and the letter "T" represents the extensometers bonded on the transversal bar surface.

For the PC03S'10 columns, the instrumentation of the cages followed the scheme represented in Figure 4.

In the case of carbon fibers, extensometers were bonded on the jacket or on the CFRP straps at the same position of the extensometers bonded on the stirrups.

The tests were performed at an equipment with load capacity of 5000kN; the loading application followed a load increase of 50kN for non-reinforced columns and 100kN for the reinforced ones.

Figure 3 – Instrumentation of the cages

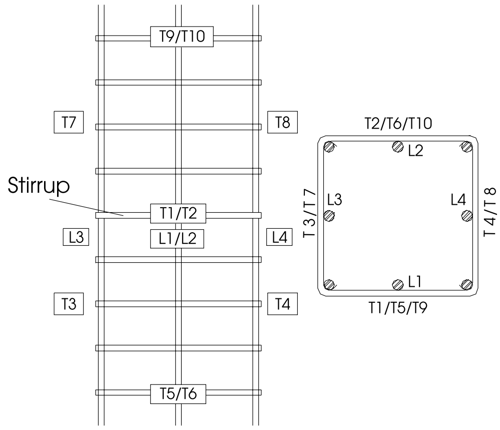
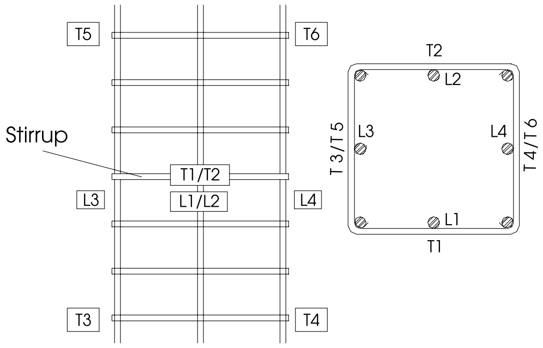


Figura 4 – Instrumentação das armaduras PC03S'10



4 Results and Discussions

In this section, results and conclusions obtained through RIGAZZO experimental work are presented [6]: the load capacity increase of the reinforced columns with CFRP, the confined concrete models presented in item 2 and some of the design parameters that influenced the design for this type of strengthening with CFRP.

4.1 Load capacity increase

Table 3 presents an experimental load, that corresponds to columns longitudinal strain of 0.2%, value normally taken as the last limit for the concrete in simple compression column, and the experimental load obtained at the tested columns collapse.

It is possible to note in Table 3 that for a shortening of 0.2%, most of the reinforced columns with CFRP does not present a significant increase of the load capacity. On the other hand, it is possible to realize that, before the collapse, the reinforced columns reach a longitudinal strain much higher than 0.2%. This means that to consider an ultimate shortening in about 0.2% for the confined concrete with CFRP can be conservative. Likewise, it is not possible, in terms of design, to adopt strain from 0.8 to 1.0%. So, for an adequate design for this type of strengthening, it is necessary to adopt a longitudinal strain limit, not so conservative, but that could also be in the values of behavior for a real structure.

Admitting, for example, a longitudinal strain of 0.3%, acceptable value in terms of design, one might conclude that the columns load capacity increases, described in Table 4, through which it is possible to realize the need of taking into account the longitudinal strain to evaluate adequately the load capacity increase produced by the strengthening and also to design reinforced concrete columns with FRP.

Table 3 – Experimental and strain loads

Column	Ultimate limit state for the non-confined concrete ($E_l = 2^0/_{00}$)	Collapse of the column	Strain in the Collapse ($^0/_{00}$)	Mode of Reinforced Columns Collapse
Name	Load (kN)	Load (kN)	--	--
PCT	739,7	809,7	3,4	--
PC01S'0	847,4 (+14,6%)	1294,9 (+59,9%)	9,5	Composite rupture
PC02S'5	786,3 (+6,3%)	1291,4 (+59,5%)	12,2	Composite rupture
PC03S'10	743,8 (+0,55%)	1065,7 (+31,6%)	11,9	Concrete rupture between CFRP straps
PC04S'0	854,6 (+15,5%)	1672,5 (+106,6%)	14,4	Composite rupture
PQT	722,3	786,3	3,1	--
PQ01S'0	743,8 (+3,0%)	1000,0 (+27,2%)	14,6	Composite rupture
PQ02S'5	723,5 (0,17%)	900,0 (+14,5)	8,5	Concrete rupture between CFRP straps

Table 4 – Experimental load for longitudinal strain of 0.3%

Columns	Experimental Load for strain of 0.3% (kN)
PCT	801,9
PC01S'0	928,5 (+15,8%)
PC02S'5	925,2 (+14,4%)
PC03S'10	840,8 (+4,9%)
PC04S'0	955,7 (+19,2%)
PQT	786,3
PQ01S'0	847,4 (+5,7%)
PQ02S'5	796.5 (+1,3%)

4.2 *Analysis of models for confined concrete with FRP*

Table 5 presents a comparison between the strength and the longitudinal strain of the confined concrete obtained experimentally in the collapse of the column PC01S'0 (Figure 5)and the strength and the strain obtained, for the same column, through the confinement analytic models.

Model of SAAMAN et al[8] has provided strength of 7.3% higher than the one determined experimentally, and a longitudinal strain almost twice as higher than the experimental one. This model was developed empirically for FRP tubes with concrete core, in which the composite presents a much higher thickness than the one in the composite used over the column strengthening in question. This might have contributed for the errors in the previsions of the model.

Model of MYIAUCHI et al [4] presented a nearer result for the strength of the confined concrete, making an error of 4.5%. However, the presented error for the longitudinal strain was very evident.

Figure 5 – Detail of rupture - PC01S'0

Table 5 – Comparison between the experimental and theoretical results – Collapse PC01S'0

Results	f_{cc} (MPa)	$\frac{f_{cc}}{f_{cc,exp}}$	e_{cc} ($^0/_{00}$)	$\frac{e_{cc}}{e_{cc,exp}}$
Experimental	31,71	--	9,5	--
SAAMAN et al	34,03	1,073	18,2	1,916
MIYAUCHI et al	33,15	1,045	16,2	1,705

Table 6 – Experimental and theoretical results – Strain 0.2% – Pc01S'0

Results	f_{cc} (MPa)	$\frac{f_{cc}}{f_{cc,exp}}$
Experimental	19,12	--
SAAMAN et al	16,78	0,878
MIYAUCHI et al	15,05	0,787

In Table 6, a new comparison between the experimental data and the data provided by the analytical models is done, considering now a longitudinal strain of 0.2%. This new comparison tends to evaluate the models in the prevision of the confined concrete strength for the longitudinal strain, acceptable in a design with this type of strengthening.

The new results show that the two models provided satisfactory results for the strength of compression estimated for a longitudinal strain of 0.2%. Moreover, it was pointed out that the previsions given by these two models were in favor of the security in this new situation.

4.3 Cross section geometry influence

The ACI-440 [1] recommends a decrease of 50% in the confined concrete strength for a square column compared to an equivalent circular one.

Aiming to evaluate the validity of this recommendation, RIGAZZO [6] tested circular and square columns with the same area of the cross section and the same strengthening characteristics. The tests showed that the confinement efficiency with FRP in square columns is much lower tham the one verified for the equivalent circular columns (Figure 6).

Table 7 – Comparison between the confined concrete strength for circular and square columns

PQ01S'0	PC01S'0	f_{cc} square column/ f_{cc} circular column
f_{cc} (MPa)	f_{cc} (MPa)	
19,26	31,71	0,61
PQ02S'5	**PC02S'5**	fcc square column/ f_{cc} circular column
f_{cc} (MPa)	f_{cc} (MPa)	
14,98	30,93	0,48

Figure 6 – Rupture of the concrete between the straps

Table 7 offers a comparison between the confined concrete strength obtained for the square columns and their respective equivalent circular ones.

Through the results presented on the table, it is possible to assert that for the columns tested in this research, the recommendation of ACI 440 [1] was confirmed. However, it is worth to point out the need of a higher number of experimental analyses to guarantee the recommendation adequacy of ACI 440 [1].

4.4 Influence of using CFRP straps

Some authors have suggested a coefficient of confinement efficiency to evaluate the influence of the spacing between the wrapping straps on the efficiency of the strengthening with FRP.

This coefficient is given by the ratio between the concrete core area effectively confined and the concrete liquid area, and it is applied on the pressure of the lateral confinement.

This approach was utilized in the analysis of the results for the reinforced columns with FRP straps tested by RIGAZZO [6]. The results showed that for spacing values smaller than 1/4 of diameter or column side the coefficient of efficiency utilization is adequate. However, for higher values of spacing, the efficiency of the strengthening is seriously affected and the use of the coefficient of efficiency does not represent the experimental results properly (Figure 7).

Anyway, it is necessary to have other experimental works to prove if the relations S'/D and S'/L can be an adequate parameter to limit the spacing between straps to values that do not compromise the efficiency of the strengthening with CFRP. It is necessary to verify, for example, what happens with these relations for other non-confined concrete strengths.

Figure 7 – Strap rupture – PC02S'5

4.5 Influence of the Strengthening Rate

Once the column diameter and the CFR composite strength are known, it is possible to adopt a lateral pressure of confinement and determine the composite thickness needed to that lateral pressure.

So, a good parameter to evaluate the strengthening rate with FRP is the relation f_l / f_c, that according to some researchers ranges from 0.1 to 0.6.

Below the inferior limit of 0.1, the efficiency of the confinement would be inappreciable and above the superior limit of 0.6, it would occur material wastefulness, once it could not increase the strenght of the concrete, even though using a higher strengthening rate.

The achieved analysis for the PC04S'0 column aims at the adequacy of the superior limit of 0.6.

Referring to the inferior limit, some analyses are needed to verify the adequacy of 0.1 value.

For the column PC03S'10, the lateral pressure of confinement calculated through the experimental results is 1.66 MPa, which represents a relation f_l / f_c of about 0.11.Considering that for this column there was not an increase of strength due to the concrete confinement for the strain of 0.2%, it is recommendable to work with a higher inferior limit.

For the column PC02S'5, for instance, the strength of the confined concrete for a strain of 0.2% was 10.1%, higher than the one obtained for the reference column. The experimental relation, f_l / f_c, for the column PC02S'5 is about 0.3. So, it is possible to state that an inferior limit of this order of magnitude is convenient.

5 Conclusion

This article allows the following conclusions:

- **Load Capacity Increase:** for an adequate evaluation of the load capacity increase of reinforced columns with FRP it is necessary to take into account the column longitudinal strain. This occurs because in the situation of a collapse of these structural elements, the longitudinal strains reach unacceptable values for a real structure.
- **Cross section form:** the results indicated an adequacy of the recommendation of the ACI-440 [1], and it estimates that the strength of the confined concrete in square columns is 50% smaller than the strength for equivalent circular columns.
- **Strengthening with FRP straps:** the results showed clearly the need of more studies about this issue. It is important to point out that, depending on the adopted spacing, the efficiency of the confinement can be totally implicated.
- **Confined concrete models with FRP:** we cannot choose a model that represents properly all the cases, although the models from SAMMAN et al [8] and MIYAUCHI et al models [4] have been showed adequate in many situations.

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