CFRP-BASED CONFINEMENT STRATEGIES FOR RC COLUMNS-EXPERIMENTAL AND ANALYTICAL RESEARCH

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ABSTRACT

The present work aims to compare the confinement efficacy of full and partial wrapping of concrete elements under compression loads. The main results of the experimental program are presented and analysed. The Lam and Teng analytical model was applied to predict the compression stress-strain behaviour of concrete column elements partially confined by strips of CFRP lay-up sheets. The model performance is assessed using the experimental results.

1. INTRODUCTION

It is well recognized that both the strength and ductility of concrete compressive members can be greatly enhanced using transverse carbon fiber reinforced polymer (CFRP) wraps. These non-corrosive and lightweight wraps, which are easy of installing, can be used to rehabilitate damaged concrete columns, increase the load capacity of under strength members, and retrofit seismically inadequate bridges and buildings. Among many possible applications of CFRP materials, one of the most attractive is their use as confining systems for concrete columns, which may results in remarkable increase of strength and ductility. The current CFRP-based confinement strategy is wrapping the exposed area of the concrete column. Preliminary tests with concrete elements submitted to direct compressive loading have, however, revealed that partial wrapping (strips of CFRP sheets) is also a promising confinement technique, since significant increments on the load carrying capacity and energy absorption capacity were obtained using this type of discrete confinement Barros and Ferreira (2005), Ferreira and Barros (2004). Saadatmanesh (1994, 1996) found that the strength and

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ductility of bridge concrete columns can be significantly increased by wrapping FRP strips around the columns due to the concrete confinement and prevention of the buckling of longitudinal reinforcement bars.

To assess the efficacy of the partial wrapping technique, 108 prototypes of reinforced concrete (RC) columns were confined by distinct CFRP arrangements and tested under direct compression. The experimental program was designed to evaluate the influence of the concrete strength class, the stiffness of the wet lay-up CFRP sheet, the distance between strips, the width of the strip, and the number of layers per each strip. The present work describes the experimental program and analyses the main obtained results, especially those related to the load carrying capacity and deformation capacity of the tested RC elements, provided by the considered confinement arrangements.

The Lam and Teng (2003) analytical model was adopted to predict the compression stress-strain behaviour of the RC elements partially confined. Some of the parameters of this model were calibrated from the results obtained in the present experimental program.

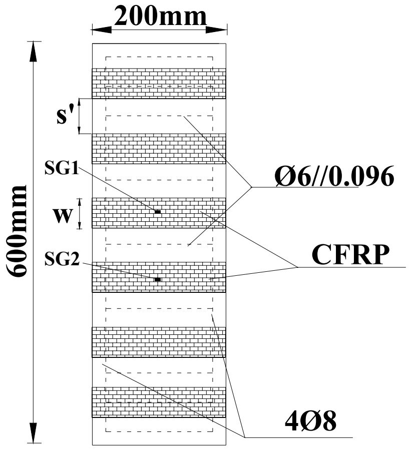
2. CONFINEMENT ARRANGEMENTS AND EXPERIMENTAL PROGRAM

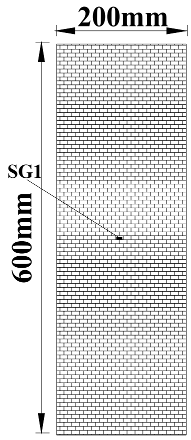
The experimental program deals with direct compression tests with reinforced concrete column elements of 600 mm length and 200 mm diameter. This program is composed by several groups of tests in order to evaluate the influence of the following parameters on the compressive strength and deformation capacity of RC elements submitted, predominantly, to compression loading: concrete strength class (two compressive strengths, 16MPa and 32MPa); stiffness of the confinement CFRP system (two CFRP sheets, one of 300 g/m^2 of fibers and the other of 200 g/m^2 of fibers); width (W) and spacing (s') of the CFRP strips; number of CFRP layers per strip (L); percentage of the longitudinal, ρ_{sl}, and transversal, ρ_{st}, steel reinforcement ratio. Due to lack of space, only the groups of tests C32S200Φ8 and C32S300Φ8, indicated in Table 1, are analyzed in the present paper. In this designation, C32 means specimens of a concrete of average compressive strength of 32 MPa, while S200 and S300 indicate the type of CFRP sheet, 200 g/m^2 and 300 g/m^2, respectively. Finally, Φ8 indicates the diameter, in mm, of the steel longitudinal bars.

One group was confined with a CFRP sheet of 300 g/m^2 of fibers, with the tradename of CF130 S&P 240, while the specimens of the other group were confined with a CFRP sheet of 200 g/m^2 of fibers, with the tradename of CF120 S&P 240.

The specimens of the two groups were manufactured with a concrete of average compressive strength of 32MPa, and were reinforced longitudinally and transversally with four steel bars of 8 mm diameter and steel hoops of 6 mm diameter at 96 mm, respectively. The groups dealing with a concrete of average compressive strength of 16 MPa were analyzed in another paper, Barros and Ferreira (2005). Each group is constituted by three test series, being distinguished by the width of the CFRP strip: 45 mm (W45), 60 mm (W60) and 600 mm (W600 – fully-wrapped). As Figure 1 shows, the partially-wrapped specimens are confined by six strips (W45S6 and W60S6). These three test series have two sub-series, one of three layers per strip (L3) and the other with five layers per strip (L5). Previous research revealed that, above five layers per strip, the benefits in terms of specimen load carrying capacity and energy absorption capacity are marginal Ferreira and Barros (2004).

Table1 – Experimental program





W [mm]	Designation	s' [mm]	W [mm]	Designation
45	W45S6L3	55	600	W600S1L3
	W45S6L5			
60	W60S6L3	40		W600S1L5
	W60S6L5			
Concrete of average compressive strength: 32 MPa				
Longitudinal bars: ϕ8				
Type of CFRP sheet	CF130 S&P 240 (300 gm/m^2)	Group of test series		C32S300ϕ8
	CF120 S&P 240 (200 gm/m^2)			C32S200ϕ8

W45S6 W60S6 W600S1

Figure 1 - Confinement arrangements

3. MATERIALS

From direct compression tests carried out at 28 days with three concrete cylinder specimens of 150 mm diameter and 300 mm height, average compression strength of 32 MPa was obtained.

The CFRP sheets used have the trade name of Mbrace CF-130 (300 g/m^2 of fibers) and CF-120 (200 g/m^2 of fibers). According to the supplier, CF-130 and CF-120 sheets have a thickness of 0.176 mm and 0.117mm, respectively, and have a tensile strength higher than 3700 MPa, and an elasticity modulus and an ultimate strain in the fibre direction of about 240 GPa and 15‰, respectively, (degussa 2003). To check to values of these properties, samples of CFRP were tested according to ISO recommendations (2003), see Barros and Ferreira (2005). The obtained results are presented in Table 2. The values determined experimentally for the thickness, included in Table 2, were used in the evaluation of the elasticity modulus and tensile strength of the CFRP sheets.

Table 2 – CFRP properties (average of five tests)

CFRP Sheets	Thickness (mm)	Tensile strength (MPa)	Ultimate strain (%)	Elasticity modulus (GPa)
CF120	0.113	3535	1.52	232
CF130	0.176	3070	1.33	230

4. TEST SETUP

Three displacement transducers were positioned at 120 degrees around the specimen and registered the displacements between the steel load plates of the equipment (see figure 2). This test setup avoids that the deformation of the test equipment is added to the values recorded by the LVDTs. Taking the values registered in these displacement transducers, the displacement at the specimen axis was determined for each scan reading (Ferreira and Barros 2004), and the corresponding strain was obtained dividing this displacement by the measured specimen's initial height. To decrease the restriction imposed by the machine load plates to the radial expansion of the specimen's extremities, a system of two sheets of teflon with oil between them was applied in-between the bottom plate of the test machine and the bottom specimen's extremity. The Teflon system was not applied in-between the top plate and the top specimen's extremity, since this plate was connected to a spherical steel hinge. Strains in the CFRP fiber direction were measured by strain gauges (SG1 and SG2) fixed on the specimen according to the arrangements indicated in the figures into Table 1. A detailed description of the test equipment and test procedures can be found elsewhere (Ferreira and Barros 2004).

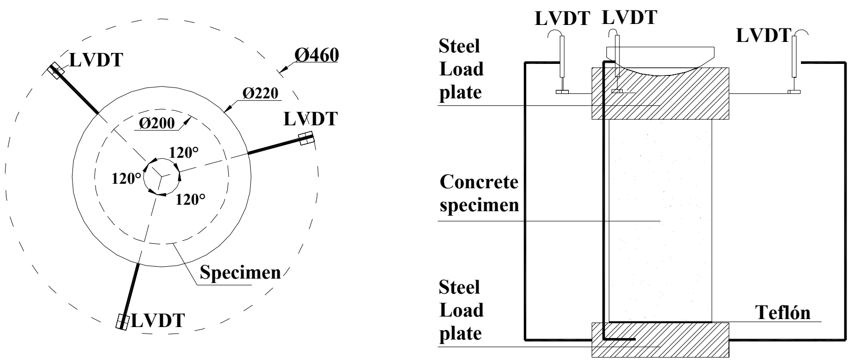


Figure 2 – Position of the LVDTs

5. EXPERIMENTAL RESULTS

Figures 3 and 4 show the relationships between concrete stress and both the concrete axial strain and the CFRP strain in the fiber direction for the groups of tests C32S200Φ8 and C32S300Φ8 confined with strips of 45 mm, 60 mm and 600 mm of width. Each curve represents the average response registered in the two specimens that compose each series. The concrete stress is the ratio between the applied load and the specimen cross section.

In these figures, UPC represents the unconfined plain concrete specimens, URC_ϕ8 the unconfined reinforced (longitudinally and transversally) concrete specimens. In each graph, the CFRP confinement ratio is also included, where $\rho_f = A_f/A_{c,t}$, with $A_f = 2\times S\times W\times L\times t_f$ mm^2 being the cross sectional area of the confinement system (t_f is the thickness of the CFRP sheet), and $A_{c,t}$ is the area of specimen longitudinal cross section ($A_{c,t} = 200\times600$ mm^2). In general, the stress-strain relationship of the confined specimens is composed by two quasi-linear branches, connected by a nonlinear transition branch.

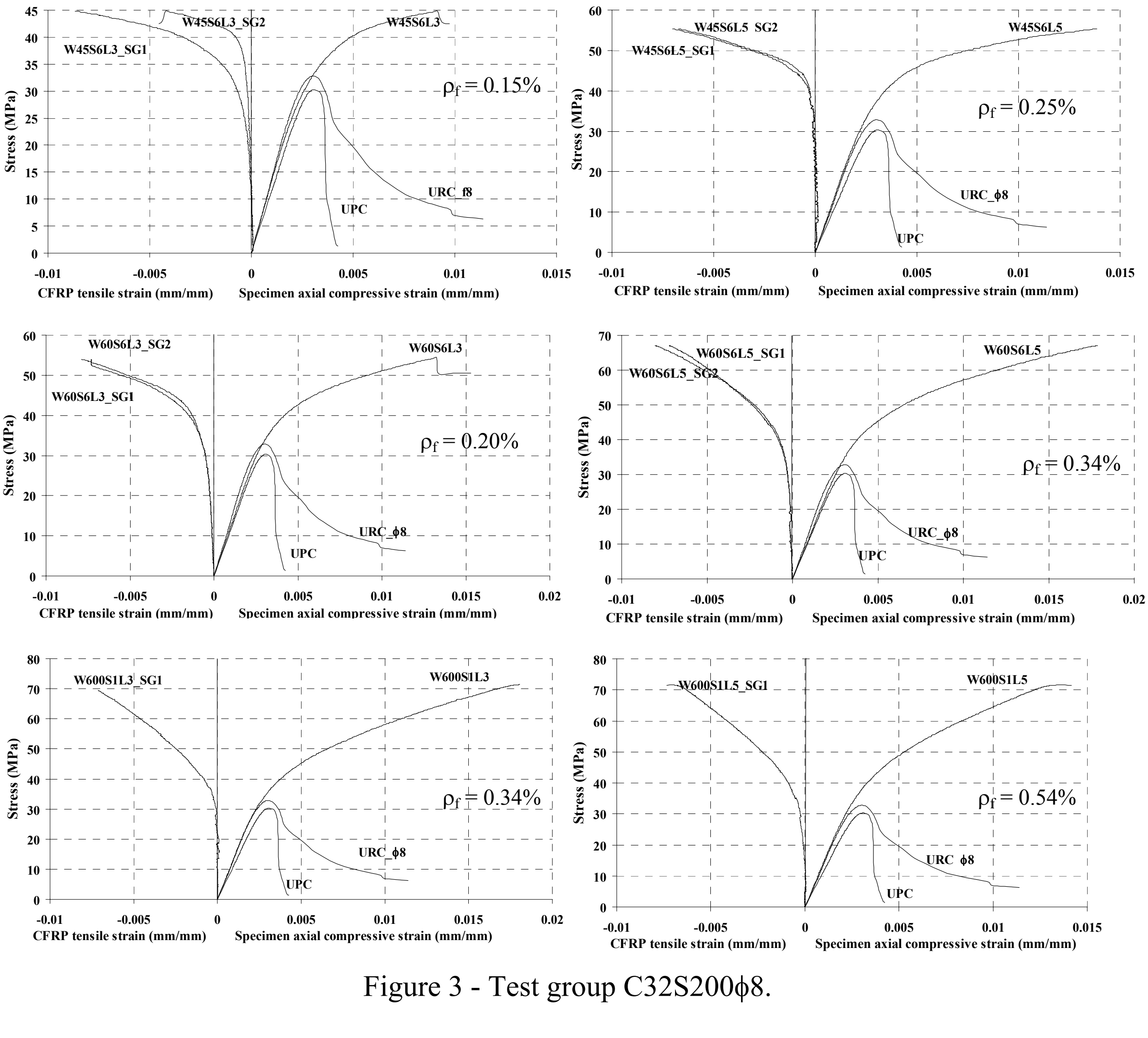


Figure 3 - Test group C32S200ϕ8.

Tables 3 and 4 include de main indicators of the efficacy provided by the applied confinement arrangements. In these tables, $f_{co,UPC}$ and $f_{co,\phi8}$ are the compressive strength of UPC and URC_ϕ8 specimens, respectively, $\varepsilon_{co,UPC}$ and $\varepsilon_{co,\phi8}$ are the specimen axial strain at

$f_{co,UPC}$ and $f_{co,\phi8}$, respectively, f_{cc} is the maximum compression stress of the confined specimens, ε_{cc} is the confined-specimen axial strain at f_{cc}, ε_{fmax} is the maximum tensile strain in the CFRP fiber's direction and ε_{fu} is the CFRP failure strain indicated in Table 2. Each value of Tables 3 and 4 is the average of the values obtained in the two specimens of each series.

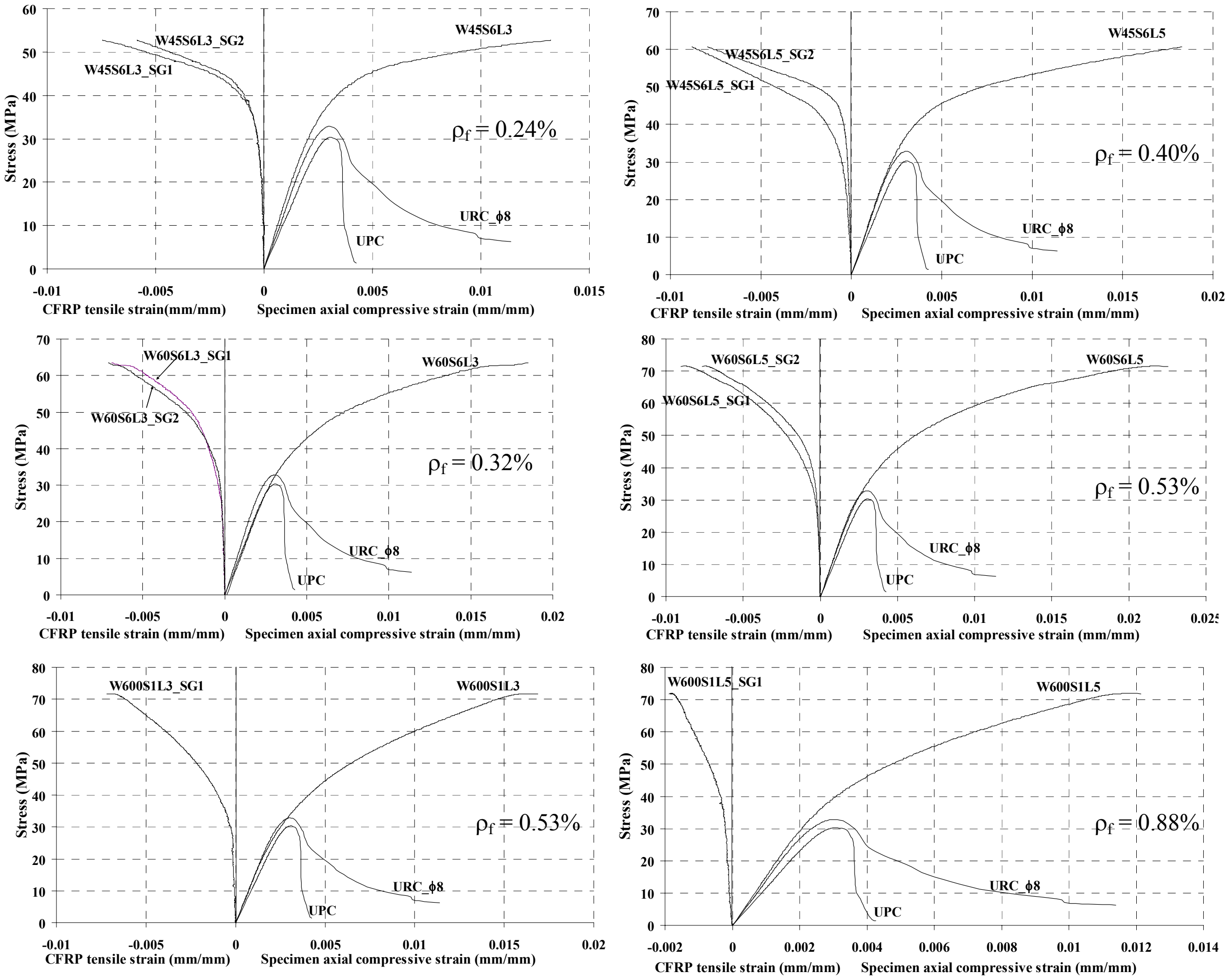


Figure 4 - Test group C32S300ϕ8.

The load carrying capacity of the test equipment was attained in the W600S1L5 series of C32S200Φ8 group and in the W60S6L5, W600S1L3 and W600S1L5 series of C32S300Φ8 group, without the occurrence of the rupture of the specimens. Since the load carrying capacity of equipment can be doubled if the tests are carried out in a non-closed loop control, the specimens of these series were again tested, up to its failure, and the attained f_{cc} values are indicated in Tables 3 and 4, in square brackets. The relationship between the normalized strength of the confined specimens (f_{cc}/f_{co}) and ρ_f, represented in Figure 5, shows a linear increasing trend between these two parameters. In this figure, the f_{cc} corresponds to the compressive strength at the failure of the specimens. Figure 6 shows that $\varepsilon_{cc}/\varepsilon_{co}$ has also a linear increase trend with the increase of ρ_f. Since in the manually controlled tests the strains were not measured, this figure only includes the results obtained in the specimens that failed when the tests were carried out under closed loop control.

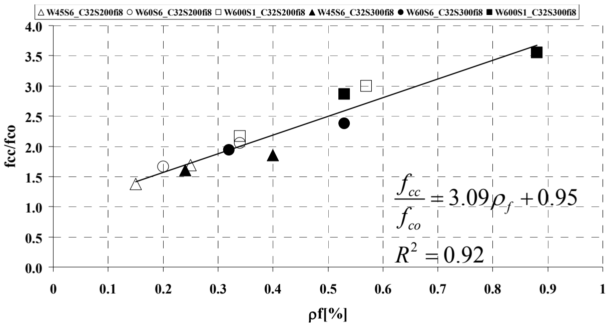


Figure 5 - $f_{cc}/f_{co,\phi 8}$ versus ρ_f for all the specimens

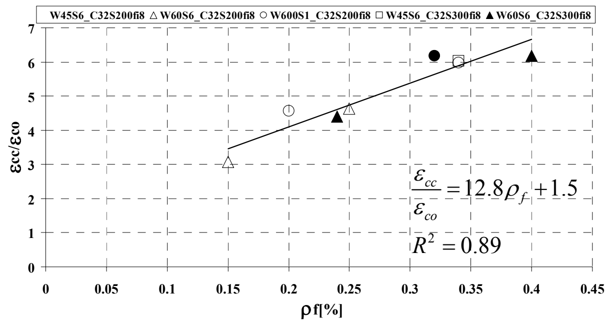


Figure 6 - $\varepsilon_{cc}/\varepsilon_{co,\phi 8}$ versus ρ_f

In series of equal ρ_f, such is the case of series W60S6L5 and W600S1L3, the confinement was a little bit more effective in the specimens fully wrapped, but the time consumed in the confinement procedures was higher and the failure modes were more violent. The last column of Tables 3 and 4 shows that, at the failure of the specimens, which always occurred by the CFRP tensile rupture, the maximum tensile strain in the direction of the fibers, ε_{fmax}, varied from 27% up to 85% of the CFRP ultimate tensile strain, ε_{fu}. These values are just for specimens that have failed up to the load carrying capacity of the equipment working in closed-loop control. As Lam and Teng, (2003) have already reported, the variation of the strain field in CFRP depends considerably on the distribution of the damage in the concrete specimen. Taking this into account and considering that only one or two strain gauges were applied, per specimen, for recording the CFRP strain variation, it is not surprising that a tendency was not determined for the $\varepsilon_{fmax}/\varepsilon_{fu}$ ratio. A high scatter was registered on the maximum strain values in the CFRP, since the recorded values only represent the areas where the strain gauges are placed, and are too dependent on specimen failure mode configuration.

Table 3 - Main indicators of the efficacy of the confinement systems in the C32S200ϕ8 test group.

Specimen designation	S	L	ρ_f[%]	f_{cc} (MPa)	ε_{cc} (μm/m)	f_{cc}/f_{co}, ϕ8	$\varepsilon_{cc}/\varepsilon_{co}$	ε_{fmax} (μm/m)	$\varepsilon_{fmax}/\varepsilon_{fu}$
Uncon. Plain Concrete (UPC)				30.31 ($f_{co,UPC}$)	0.0031 ($\varepsilon_{co,UPC}$)	-	-	-	-
Uncon. ϕ10 Reinf. Concrete				32.80 ($f_{co,\phi 8}$)	0.0030 ($\varepsilon_{co,\phi 8}$)	-	-	-	-
W45S6L3	6	3	0.15	44.80	0.0092	1.37	3.07	0.00867 (SG1) 0.00422 (SG2)	0.56 (SG1) 0.27 (SG2)
W45S6L5	6	5	0.25	55.36	0.0139	1.69	4.63	0.00702 (SG1) 0.00672 (SG2)	0.45 (SG1) 0.43 (SG2)
W60S6L3	6	3	0.20	54.37	0.0137	1.66	4.57	0.00731 (SG1) 0.00822 (SG2)	0.47 (SG1) 0.53 (SG2)
W60S6L5	6	5	0.34	67.09	0.0179	2.05	5.97	0.00721 (SG1) 0.00804 (SG2)	0.47 (SG1) 0.52 (SG2)
W600S1L3	1	3	0.34	71.37	0.0181	2.17	6.03	0.0131 (SG1)	0.85 (SG1)
W600S1L5	1	5	0.57	71.51 [98.36]	0.014	2.18 [3.0]	4.67	0.00735 (SG1)	0.47 (SG1)

Table 4 - Main indicators of the efficacy of the confinement systems in the C32S300ϕ8 test group.

Specimen designation	**S**	**L**	ρ_f**[%]**	f_{cc} **(MPa)**	ε_{cc} **(μm/m)**	$f_{cc}/f_{co,\phi 8}$	$\varepsilon_{cc}/\varepsilon_{co}$	ε_{fmax} **(μm/m)**	$\varepsilon_{fmax}/\varepsilon_{fu}$
Uncon. Plain Concrete (UPC)				30.31 ($f_{co,UPC}$)	0.0031 ($\varepsilon_{co,UPC}$)	-	-	-	-
Uncon. ϕ10 Reinf. Concrete				32.80 ($f_{co,\phi 8}$)	0.0030 ($\varepsilon_{co,\phi 8}$)	-	-	-	-
W45S6L3	6	3	0.24	52.76	0.0132	1.60	4.40	0.00743 (SG1)	0.47 (SG1)
								0.00585 (SG2)	0.38 (SG2)
W45S6L5		5	0.40	60.70	0.0185	1.85	6.17	0.00883 (SG1)	0.57 (SG1)
								0.00796 (SG2)	0.51 (SG2)
W60S6L3	6	3	0.32	63.50	0.0185	1.94	6.17	0.00689 (SG3)	0.44 (SG1)
								0.00711 (SG4)	0.46 (SG2)
W60S6L5		5	0.53	71.52 [77.98]	0.0225	2.18 [2.38]	7.50	0.00902 (SG1)	0.58 (SG1)
								0.00764 (SG2)	0.49 (SG2)
W600S1L3	1	3	0.53	71.56 [93.59]	0.0168	2.18 [2.86]	5.60	0.00718 (SG1)	0.46 (SG1)
W600S1L5		5	0.88	71.88 [116.22]	0.0121	2.19 [3.55]	4.03	0.00188 (SG1)	0.12 (SG1)

6. ANALITICAL MODEL

To simulate the behavior of concrete specimens fully wrapped with CFRP sheets, submitted to direct compression loading, several analytical models have been proposed Saaman et. al. (1998), Toutanji (1999), Xiao and Wu (2000), Untiveros (2002), Lam and Teng (2003). To simulate the behavior of the partially confined concrete specimens tested in the present work, the model developed by Lam and Teng (2003) was adopted. According to this model, the stress in the confined concrete (σ_c) is determined by the following expressions (see Figure 7):

$$\sigma_c = E_c\varepsilon_c - \frac{(E_c - E_2)^2}{4f_0}\varepsilon_c^2 \text{ for } 0 \le \varepsilon_c \le \varepsilon_t \tag{1}$$

$$\sigma_c = f_0 + E_2\varepsilon_c \text{ for } \varepsilon_t \le \varepsilon_c \le \varepsilon_{cc} \tag{2}$$

where f_o was assumed equal to f_{co}, ε_t is the strain at the transition between the domain of these two equations,

$$\varepsilon_t = \frac{2f_0}{(E_c - E_2)} \tag{3}$$

with E_2 being the slope of the equation (2):

$$E_2 = \frac{f_{cc} - f_0}{\varepsilon_{cc}} \tag{4}$$

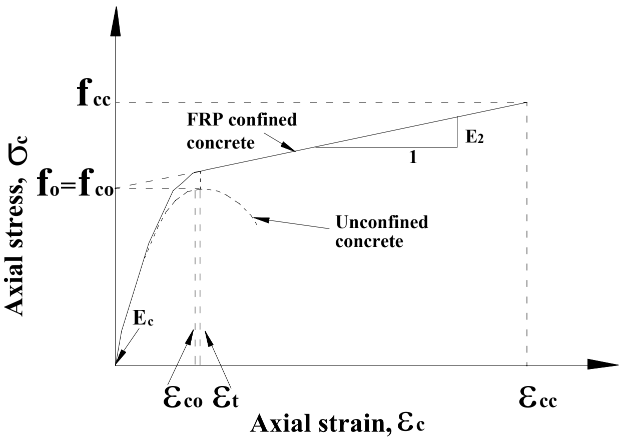


Figure 7 – Proposed stress-strain Lam and Tend model for FRP confined concrete.

To simulate the behavior of the specimens partially confined, the $f_{cc}/f_{co,\phi 8}$-ρ_f and $\varepsilon_{cc}/\varepsilon_{co,\phi 8}$-$\rho_f$ relationships registered experimentally were used (see Figures 5 and 6):

$$\frac{f_{cc}}{f_{co}} = 3.09\rho_f + 0.95 \quad \text{for} \quad 0.15 \le \rho_f \le 0.88 \tag{5}$$

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 12.8\rho_f + 1.5 \quad \text{for} \quad 0.15 \le \rho_f \le 0.34 \tag{6}$$

Using the $E_c = 14166$ MPa obtained from the stress-strain curves of the URC_ϕ8 specimens, the analytical and experimental stress-strain axial relationships (σ_c-ε_c) of the series of specimens partially confined are compared in Figure 8. For the series confined with CFRP sheets of 200 g/m^2 of fibers, the analytical model predicted the experimental stress-strain response with high accuracy, mainly the compressive strength. However, for the series confined with CFRP sheets of 300 g/m^2 of fibers, the analytical model shows a tendency of predicting a load carrying capacity higher than the one registered experimentally. Furthermore, in the $\varepsilon_t \le \varepsilon_c \le \varepsilon_{cc}$ strain field the experimental σ_c-ε_c relationship was not as linear as estimated by the analytical model, which indicates that the plastic deformation of the steel bars has influence in the σ_c-ε_c shape.

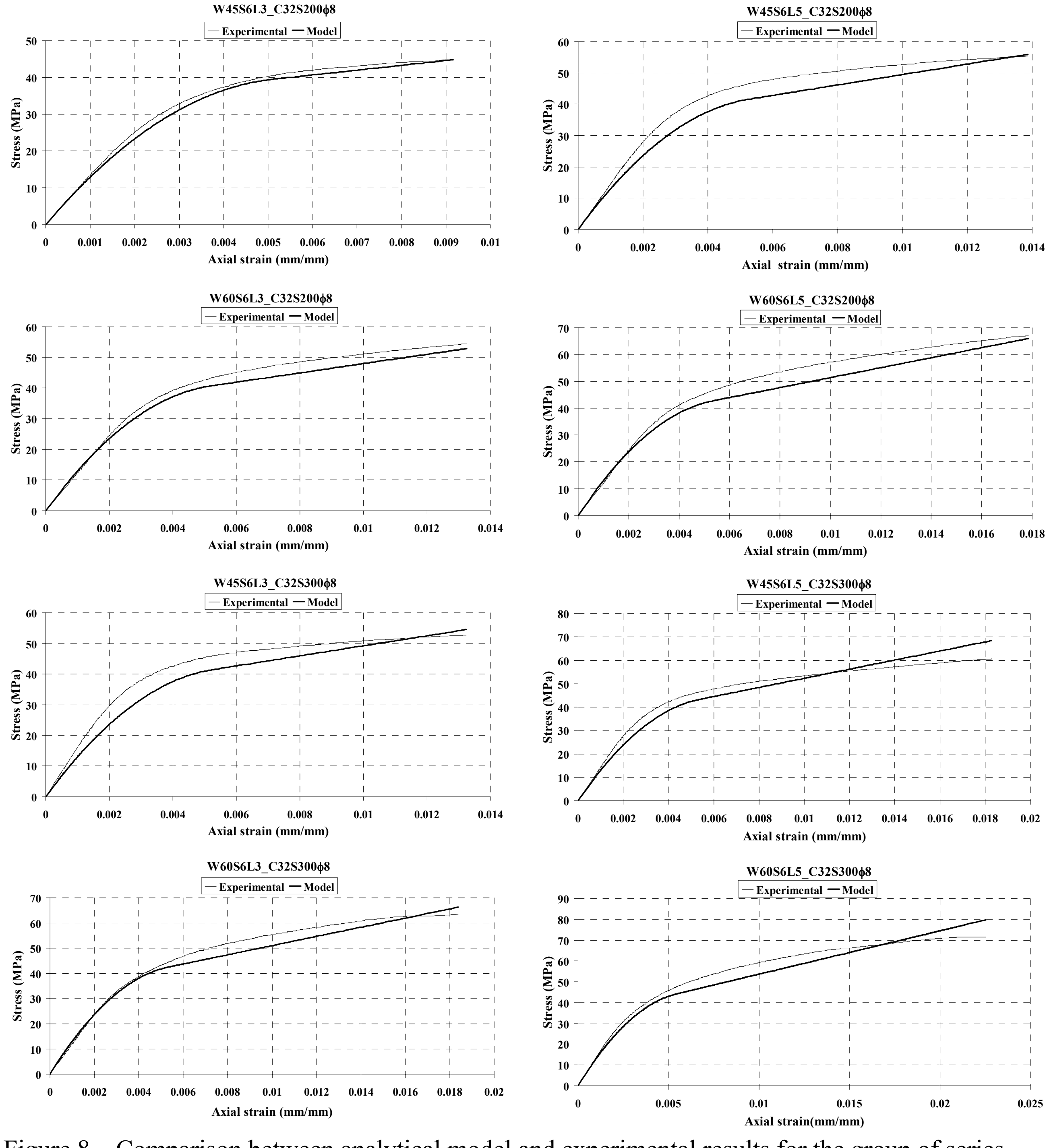


Figure 8 – Comparison between analytical model and experimental results for the group of series C32S200ϕ8 and C32S300ϕ8.

7. CONCLUSIONS

The present work dealt with an experimental and an analytical research involving the use of carbon fiber reinforced polymer (CFRP) wet lay-up sheets to increase the load carrying capacity and the deformation ability of reinforced concrete (RC) elements submitted to direct compression loading. The experimental program was conceived to evidence the influence of full and partial wrapping confinement arrangements in the compression behavior of this type of elements. In the partial wrapping systems, the distance and width of the CFRP strips and the thickness of the CFRP were also parameters considered in the experimental program. The RC elements had 200 mm diameter and 600 mm length, were manufactured by concrete of average compressive strength of 32 MPa, were reinforced longitudinally by four steel bars of 8 mm diameter and were confined by steel hoops of 6 mm diameter, spaced at 96 mm.

The experimental results showed that, the load carrying capacity of CFRP-confined elements has a linear increasing tendency with the increase of the CFRP confinement ratio, ρ_f. The normalized maximum compressive strength (f_{cc}/f_{co}, where f_{co} is the compressive strength of unconfined elements) varied from 1.37 for ρ_f=0.15% up to 3.55 for ρ_f=0.88%. A linear increasing trend was also observed for the $\varepsilon_{cc}/\varepsilon_{co}$-$\rho_f$ relationship, having $\varepsilon_{cc}/\varepsilon_{co}$ ranged from 3.0 for ρ_f=0.15% up to 7.5 for ρ_f=0.53%. For the specimens that, when failed, the strains in the fiber direction of the CFRP were registered, the maximum strain varied from 27% up to 58% of the CFRP ultimate tensile strain. For the specimens of equal ρ_f, the load carrying capacity of partially confined specimens was a little bit lower than the one of the fully confined specimens. However, partial confinement arrangements were easier and faster to apply than full confinement arrangements.

From the experimental results, two equations were derived, one to evaluate f_{cc}/f_{co} and the other to determine $\varepsilon_{cc}/\varepsilon_{co}$, both in function of the confinement ratio, ρ_f. These two equations, plus the initial concrete Young's Modulus, provide the basic data of an analytical model used to predict the stress-strain diagrams registered in the partially confined specimens. The accuracy of the simulation was reasonable, but it can be improved if a nonlinear equation was assumed for the phase when plastic deformation occurs in the longitudinal steel bars and/or in the transversal steel hoops. For the sake of simplicity, in the present model a linear relationship was assumed for the f_{cc}/f_{co}-ρ_f and $\varepsilon_{cc}/\varepsilon_{co}$-$\rho_f$. However, the increase ratio of f_{cc}/f_{co} and $\varepsilon_{cc}/\varepsilon_{co}$ should decrease with the increase of ρ_f. When more data are available, more accurate f_{cc}/f_{co}-ρ_f and $\varepsilon_{cc}/\varepsilon_{co}$-$\rho_f$ functions can be determined, which will improve the performance of the used analytical model.

8. ACKNOWLEDGMENTS

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