

Partial versus full wrapping confinement systems for concrete columns

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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 Mander et al. analytical model was modified to predict the compression stress-strain behaviour of concrete column elements partially confined by strips of CFRP lay-up sheets. The main results of the experimental program are presented and analysed. The model performance is assessed using the experimental results.

1 INTRODUCTION

Structural elements such as beams, slabs, and columns may require strengthening during their service life period. The need for strengthening and rehabilitating of existing structures is, in general, caused by the following main reasons: increase of service load levels; material degradation; design/construction defects; new code requirements. Carbon and Glass fibre reinforcement polymer (CFRP, GFRP) sheets have been used as the reinforcing system on structural rehabilitation and strengthening. These materials are opportune alternatives to the use of conventional materials like concrete and steel in the strengthening practice, since they have high tensile strength, they are lightweight, which makes its installation costs low in comparison to conventional steel systems, and they have high resistance to corrosion. The full wrap of the concrete column with CFRP or GFRP sheets is a general practice to increase the load carrying capacity, the ductility, and the shear strength of this type of structural elements, Mirmiran and Shahawy (1997).

The present work aims to compare the confinement efficacy of full and partial wrapping of concrete elements under compression loads. For this purpose, series of cylinder concrete elements, confined by distinct arrangements of CFRP wet lay-up sheets, were tested under direct compression loading configuration up to its rupture. The experimental program was designed to evaluate the influence of the concrete strength class, the stiffness of the CFRP sheet, the number of strips, the width of the strip, and the number of layers per each strip.

The Mandel et al. analytical model was modified in order to predict the compression stress-strain re-

sponses of the concrete elements partially confined, Mander, Priestley and Park (1988).

2 CONFINEMENT ARRANGEMENTS

The confinement systems are composed by strips of CFRP sheet bonded to concrete and to subjacent layers by epoxy resin. Each specimen is designated by $WiSjLk$, where Wi is the strip width, Sj is the number of strips along the specimen and Lk is the number of CFRP layers per each strip.

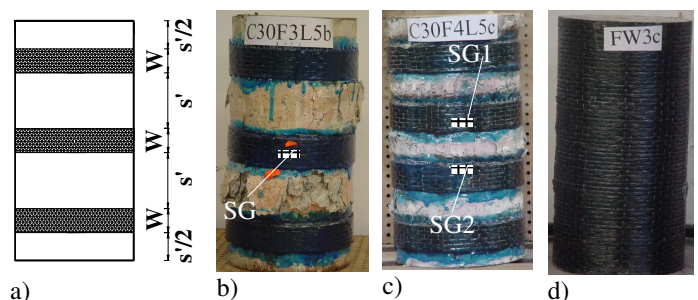


Figure 1 - Generic confinement system and photos of some adopted confinement systems.

Figure 1a) schematizes the partial confinement system, and Figure 1b) to Figure 1d) includes photos of some of the adopted confinement systems. A detailed description of the confinement arrangements and procedures are given elsewhere Ferreira and Barros (2003).

3 MATERIALS

To evaluate the influence of the concrete strength class and the stiffness of the CFRP sheet on the con-

finement efficacy provided by the distinct CFRP arrangements, a moderate and a low strength concretes and two CFRP sheets of distinct fiber content were used in the experimental program. From uniaxial compression tests carried out at 28 days with concrete cylinder specimens of 150 mm diameter and 300 mm height, average compression strength of 23 MPa and 16 MPa was obtained for the moderate and low strength concretes, respectively.

The CFRP sheets used has the trade name of Mbrace CF-130 (300 g/m² of fibers) and CF-120 (200 g/m² of fibers). According to the supplier, the Mbrace CF-130 and CF-120 sheets have a thickness of 0.167 mm and 0.117mm, respectively, and can attain 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, Mbrace (2003). To evaluate these properties, samples of CFRP were tested according to ISO recommendations (2003). The obtained results are presented in table 1.

Table 1 – CFRP properties (average of five tests)

CFRP Sheets	Tensile strength (MPa)	Ultimate strain (%)	Elasticity modulus (GPa)
CF-120 (S&P) 240	2219	1.05	211
CF-130 (S&P) 240	3894	1.55	251

4 TEST SETUP

Three displacement transducers were positioned at 120 degrees around the specimen and registered the displacements between the loading steel plates of the equipment. This test setup avoids that the deformation of the test equipment are being added to the values read by the LVDTs. Taking the values recorded in these transducers, the displacement at the specimen axis was determined for each scan reading, and the corresponding strain was obtained dividing this displacement by the measured specimen's height. To decrease the confinement effect on the specimen introduced by the machine load platens, a teflon system was applied in-between the platens of the testing rig and the specimen extremities. Strains in the fibre direction of the CFRP strips were measured by strain gauges (SG) placed at half width of the strip, accordingly to the arrangement represented in Figure 1. A detailed description of the test equipment and test procedures can be found in Ferreira and Barros (2003).

5 EXPERIMENTAL RESULTS

Figure 2 to Figure 5 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 C23S300, C23S200, C16S200 and C16S300 confined with strips of 45 mm, 60 mm and 300 mm of width. In the designation attributed to the four groups of tests, C16 and C23 means specimens constituted by a concrete average compression strength of 16 and 23 MPa, respectively, while S200 and S300 indicates the type of CFRP sheet, 200 g/m² and 300 g/m², respectively. Each curve represents the average response registered in the three specimens that compose each series. The concrete stress is the ratio between the applied load and the specimen cross section.

From the analysis of the results of group C23S300 it is verified that it is not effective to apply a number of layers higher than 5, since the specimen load carrying capacity and its energy absorption capacity are not significantly increased. Therefore, in the remaining groups of tests, the number of layers was 3 and 5.

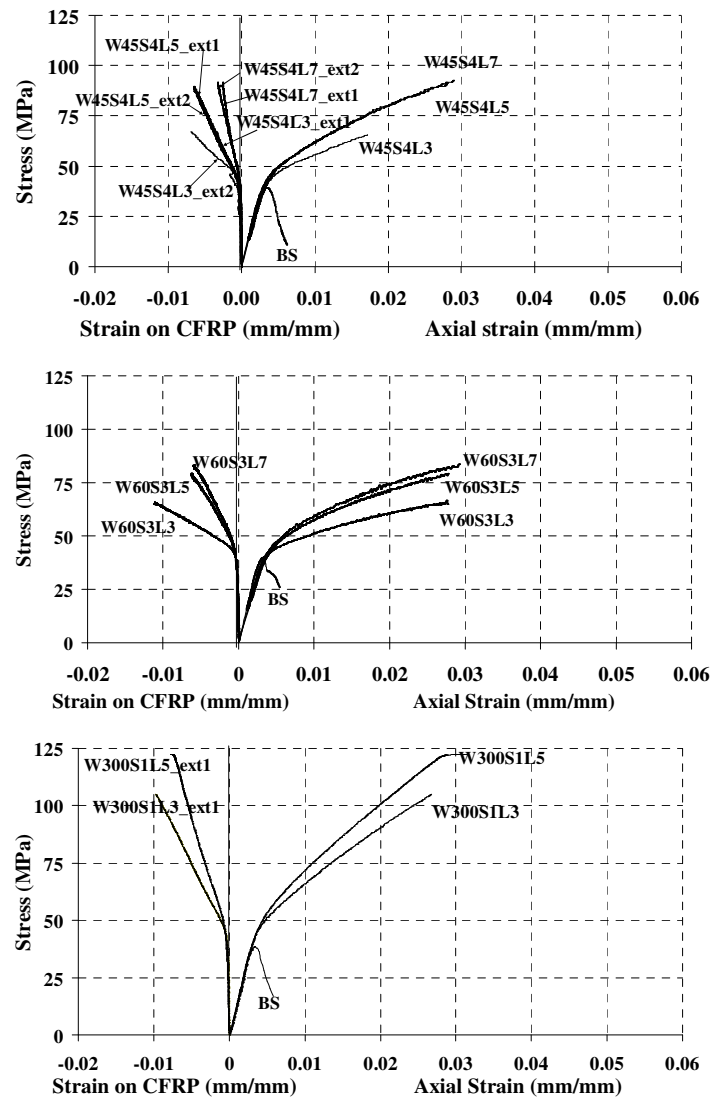


Figure 2 – Test group C23S300

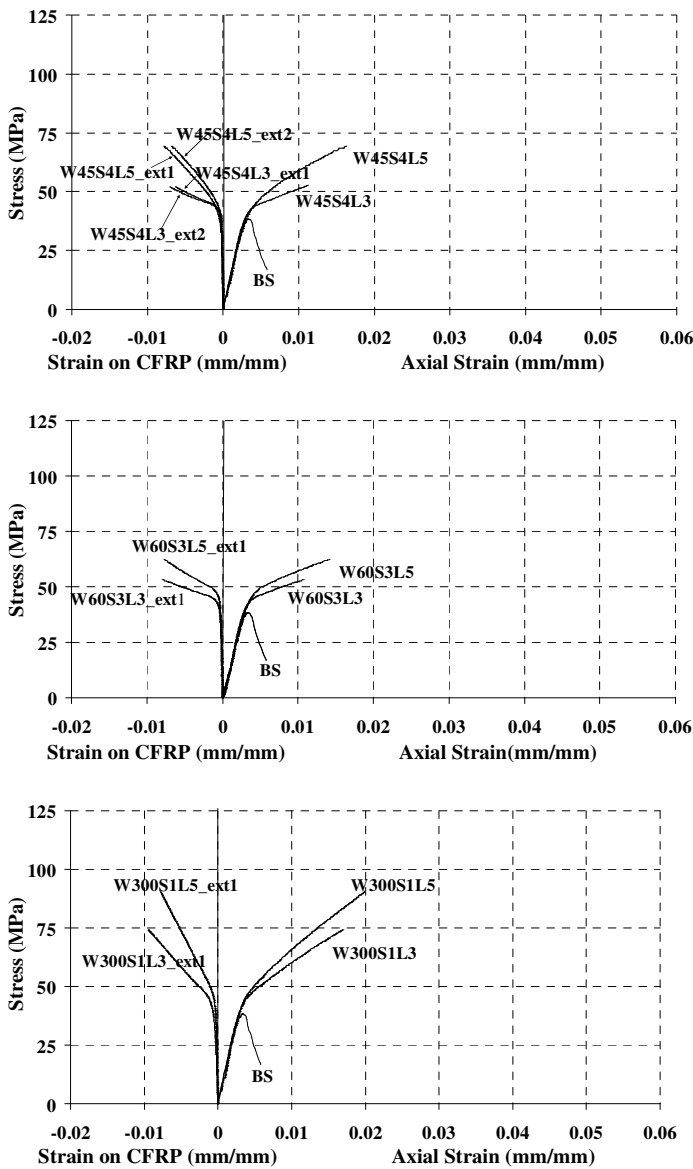


Figure 3 – Test group C23S200

The obtained curves show that the specimen load carrying capacity increases significantly when CFRP confinement ratio (ρ_f) is augmented. The stress-strain relationship up to the compression strength of the plain concrete (PC) specimens is practically unaffected by the presence of the CFRP. In general, the $\sigma_c - \epsilon_c$ relationship of the confined specimens is composed by two quasi-linear branches. The stress corresponding to the transition point between these two branches is higher than the compression strength of the corresponding PC specimens. This effect is more pronounced in the groups of C23 concrete. The stiffness of the second branch (inclination) is higher in the group C16S300 (lower strength concrete confined by the stiffer CFRP sheet).

The values of f_{cc}/f_{co} , $\epsilon_{cc}/\epsilon_{co}$ and U_{cc}/U_{co} ratios (see Figure 6) for the tested series are indicated in Table 2 to 4. The concept of f_{cc} , f_{co} , ϵ_{cc} , ϵ_{co} , U_{cc} and U_{co} is schematically represented this Figure. Note that U_{co} and U_{cc} are the energy dissipated in the softening phase of the unconfined and confined specimen, re-

spectively. The values of these ratios indicate that the effectiveness of a confinement system, in terms of increasing the specimen load carrying capacity, deformability and energy absorption capacity, increases when the concrete compressive strength decreases and when the stiffness of the CFRP sheet increases.

In series of equal ρ_f , such is the case of series W45S4 and W60S3, the confinement was more effective in the W45S4 series since the free space between the CFRP strips is smaller in this series, which means that more volume of concrete is effectively confined.

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.

In the series W300S1L5 of test group C23S300, the maximum capacity of the machine was achieved without the occurrence of the rupture of the specimens of this series.

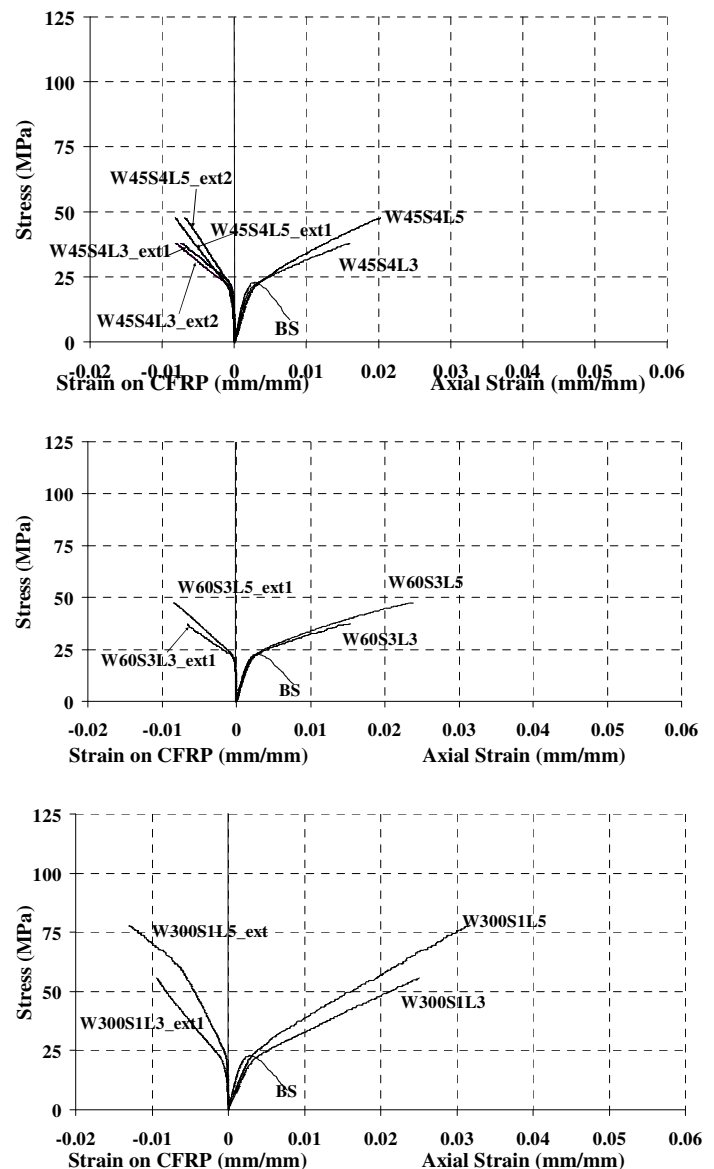


Figure 4 – Test group C16S200

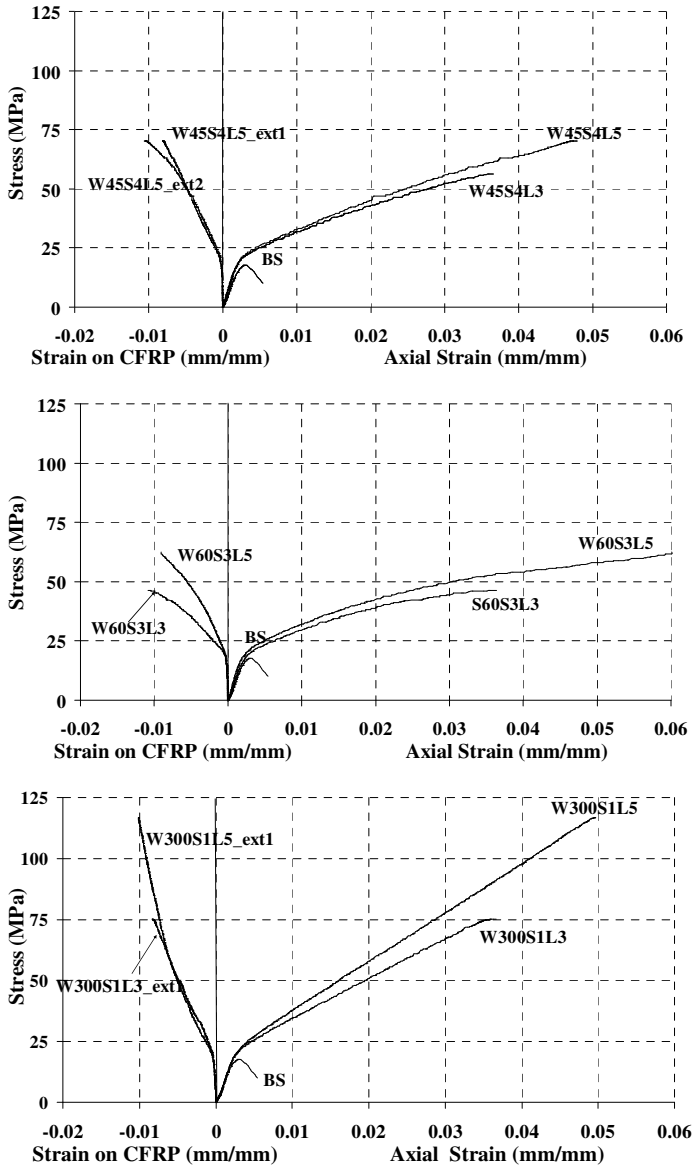


Figure 5 – Test group C16S300.

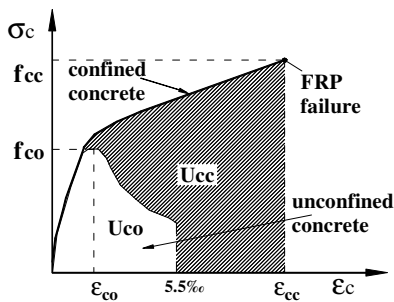


Figure 6 – Stress-strain diagram for the evaluation of ΔU_{cc} .

Table 2 - f_{cc}/f_{co} values for the group of tested series (see also Figure 6)

Series	Group			
	C16S200	C16S300	C23S200	C23S300
W45S4L3	1.66	3.17	1.37	1.84
W45S4L5	2.09	3.96	1.81	2.33
W60S3L3	1.64	2.62	1.38	1.65
W60S3L5	2.08	3.51	1.60	1.98
W300S1L3	2.44	4.23	1.93	2.76
W300S1L5	3.41	6.58	2.36	3.22

Table 3 - $\epsilon_{cc}/\epsilon_{co}$ values for the group of tested series (see also Figure 6)

Series	Group			
	C16S200	C16S300	C23S200	C23S300
W45S4L3	5.07	12.21	3.14	7.24
W45S4L5	7.20	16.00	4.55	8.45
W60S3L3	5.46	12.15	3.21	8.32
W60S3L5	8.48	20.08	4.22	8.36
W300S1L3	8.92	12.26	5.02	7.45
W300S1L5	11.24	16.54	5.89	8.77

Table 4 - U_{cc}/U_{co} values for the group of tested series (see also Figure 6)

Series	Group			
	C16S200	C16S300	C23S200	C23S300
W45S4L3	3.15	35.42	3.84	10.46
W45S4L5	7.35	47.64	7.58	21.90
W60S3L3	3.27	31.05	3.95	15.98
W60S3L5	12.67	43.18	7.58	18.40
W300S1L3	11.57	43.65	7.70	14.25
W300S1L5	13.81	64.99	8.56	31.11

6 MODIFIED MANDER ET AL. MODEL

To evaluate the behaviour of full wrapped concrete specimens with CFRP sheets several analytical models have been proposed, Saaman, Mirmiran and Shahawy (1998), Toutanji (1999), Xiao and Wu (2000), Untiveros (2002), Lam and Teng (2003). Most of these models are based on stress-strain equations defined for modelling the confinement provided by steel jackets, Untiveros (2002). To simulate the partial confinement systems of the present work, the model developed by Mander et al. (1988) seems to be the most appropriate. The Mander et al. model will be modified to take into account that the confinement is now provided by strips of CFRP sheet that has a tensile behaviour distinct of the steel hoops considered in the Mander et al. original model.

According to the Mander et al. model, the stress in the confined concrete (f_c) is determined by the following expression:

$$f_c = \frac{f_{cc} x r}{r - 1 + x^r} \quad (1)$$

where

$$f_{cc} = \left[-1.254 + 2.254 \sqrt{1 + \frac{7.94 f_l}{f_{co}}} - 2 \frac{f_l}{f_{co}} \right] \quad (2)$$

$$x = \frac{\epsilon_c}{\epsilon_{cc}}; \epsilon_{cc} = \epsilon_{co} \left[1 + 5 \left(\frac{f_{cc}}{f_{co}} - 1 \right) \right] \quad (3)$$

$$r = \frac{E_c}{E_c - E_{sec}}; E_{sec} = \frac{f_{cc}}{\epsilon_{cc}} \quad (4)$$

$$f_l = \frac{1}{2} k_e \rho_f f_f; k_e = \left(1 - 0.5 \frac{s'}{d_s} \right)^2; \rho_f = \frac{4A_f}{d_s(W + s')}; \quad (5)$$

$$f_f = E_f \epsilon_{f,ef}$$

In eq. (2), f_{cc} is the maximum stress of the confined concrete, f_{co} is the maximum stress of the corresponding unconfined concrete and f_l is the confinement pressure exerted by the CFRP, see Figure 7 and Figure 8. In eq. (3), ϵ_c is the concrete axial strain, and ϵ_{cc} is the axial strain correspondent to f_{cc} . In eq. (4), E_c is the concrete Young's modulus that, according to Mander et al., can be determined by $E_c=15(f_{co})^{(1/2)}$. However, since in the present work the strain was obtained from the displacements measured between the machine load platens, the E_c values are smaller to those values determined from Mander et al. equation. Therefore, E_c was considered as being the initial slope of the $\sigma_c - \epsilon_c$ relationship recorded in the tests. In eq (5) f_l is maximum pressure applied by the CFRP, k_e is a coefficient that depends on the confinement's configuration, s' is the distance between strips (see Figure 1), d_s is the diameter of the specimen (150 mm), ρ_f is the CFRP confinement ratio, A_f is the CFRP cross section area per unit of volume of concrete (in the present confinement system, $A_f=W \times e \times L$, see Figure 1, where e is the thickness of the CFRP sheet), f_f is the maximum stress in the CFRP and E_f is the elasticity module of the CFRP. In the original Mander et al. model, f_f is the yield stress of the steel hoops. For the CFRP discrete confinement proposed in the present work, f_f represents the effective stress installed in the CFRP strips. This effective stress is obtained from the concept of effective strain, $\epsilon_{f,ef}$, which was determined from backfitting analysis, using the stress-axial strain curves registered in the experimental program. Since the strain in the CFRP is not uniform in the perimeter of the strip, $\epsilon_{f,ef}$ was determined multiplying the maximum recorded strain, $\epsilon_{f,max}$, by an effective coefficient, k_c , resulting $f_f = E_f k_c \epsilon_{f,max}$. The k_c values were determined in order to approximate with the minimum error the analytical and the experimental $f_c - \epsilon_c$ relationships. For the specimens confined with three layers per strip $k_c=0.6$, while in specimens with five layers $k_c=0.4$, which means that k_c decreases with the increase of the stiffness of the confinement system.

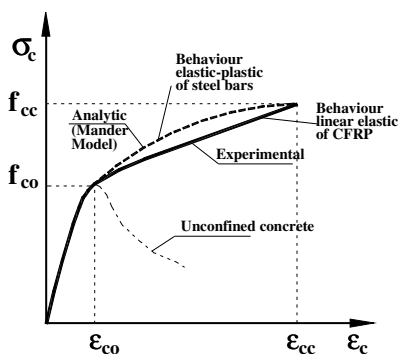


Figure 7 – Stress-strain diagram for the confined concrete.

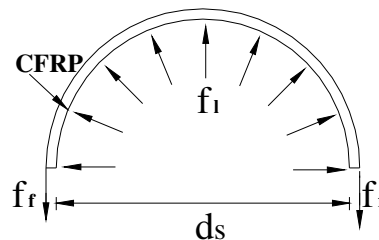


Figure 8 - Scheme of confinement action.

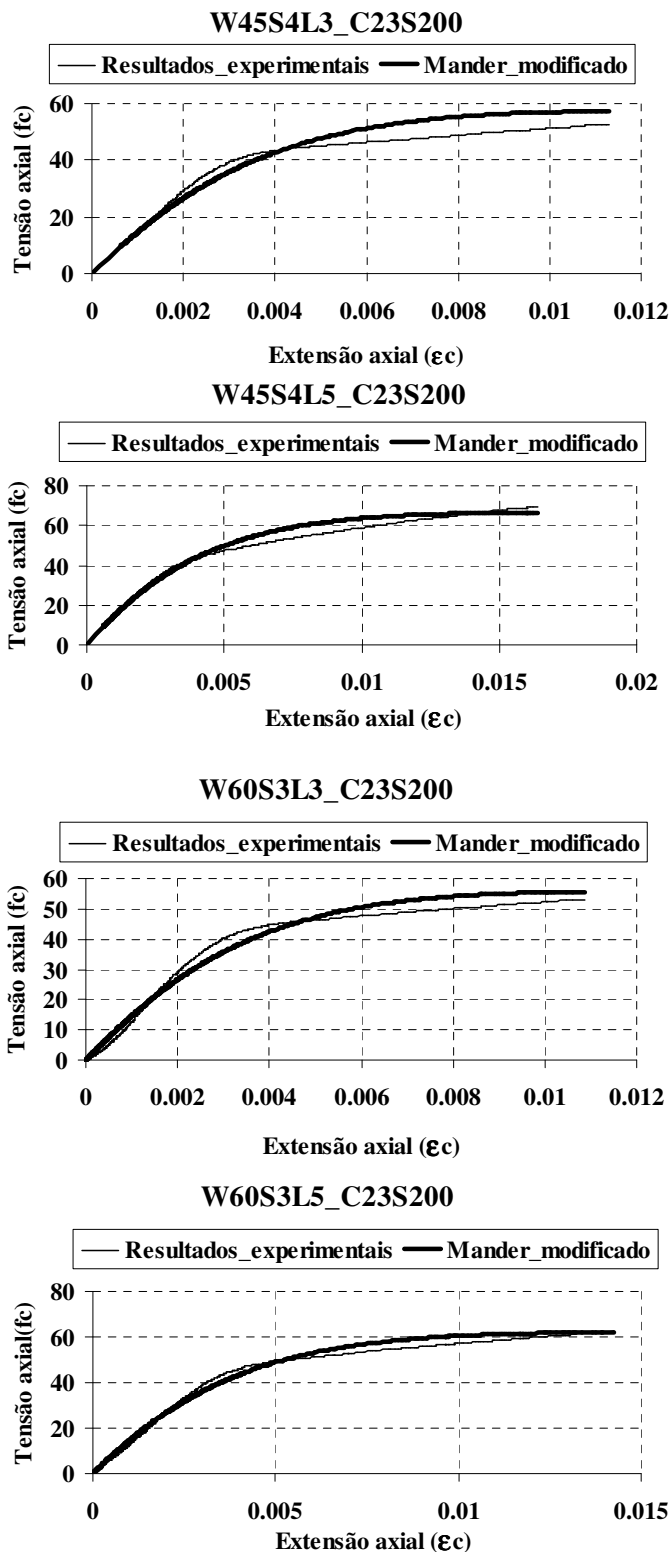


Figure 9 – Curves axial stress versus axial strain.

The $f_c - \varepsilon_c$ relationship of the series W45S4 and W60S3 for the group C23S200 was predicted by this modified Mander et al. model. Using the $E_f = 210 \text{ GPa}$ obtained in the tensile tests (see Table 1), it was determined the analytical $f_c - \varepsilon_c$ curves that are compared with the corresponding experimental ones, in Figure 9. The analytical curves fit quite well the experimental $f_c - \varepsilon_c$ relations. In the remaining series a level of accuracy similar to the one of C23S200 group was obtained. The larger deviations occur for strain levels above ε_{co} (see also Figure 7). Since the Mander et al. model was developed to simulate the confinement provided by steel hoops, the shape of the branch after ε_{co} has a nonlinear profile. This nonlinear shape is not so pronounced in the experimental $f_c - \varepsilon_c$ relations because the confinement is provided by CFRP materials that has linear-elastic behaviour up to failure.

7 CONCLUSIONS

In the present work, the behaviour under direct compression of concrete specimens confined by discrete and continuous CFRP systems is analysed. The discrete confinement system is composed by strips of CFRP wet lay-up sheets while the continuous confinement system corresponds to full wrapping the concrete specimen.

The influence of the strip's width, the number of strips along the specimen, the number of CFRP layers per strip, the concrete strength class and the stiffness of the CFRP sheet, was analyzed.

The specimen load carrying capacity has increased with the CFRP confinement ratio, ρ_f . In series of equal ρ_f , the most effective confinement system was the one of lower distance between strips of CFRP, since it corresponds to the confinement configuration where the wrapping material is distributed more uniformly along the length of the specimen. Amongst the groups of series of tests, the most effective was the one of specimens manufactured by the lower concrete strength and confined by the highest stiff CFRP sheet (C16S300). For this series the ratio between the ultimate load of confined specimens and the compression strength of its corresponding unconfined specimens have varied between 2.62 (series W60S3L3) and 6.58 (W300S1L5). In comparison to the full wrapping confinement system, the partial confinement arrangements are easier and faster to apply, and consume few CFRP and epoxy adhesive materials.

The analytical model developed by Mander et al. to simulate the stress-strain relationship of concrete specimens confined with steel hoops was modified

in order to take into account that the confinement systems are now made by CFRP material that has linear-elastic behaviour up to its failure. The modified Mander's analytical model has predicted with good accuracy the experimental responses.

8 ACKNOWLEDGMENTS

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