The behaviour of GFRP reinforced concrete columns under monotonic and cyclic axial compression

Carlos Chastre Rodrigues
PhD Student, Universidade Nova de Lisboa, Portugal, c-chastre@mail.fct.unl.pt
Manuel Gonçalves da Silva
Full Professor, Universidade Nova de Lisboa, Portugal, mgs@mail.fct.unl.pt

ABSTRACT: Retrofitting reinforced concrete columns with FRP materials is a recent but established technique based on their high strength/weight ratio and on other relative advantages, including the fact that FRP external shells prevent or mitigate environmental degradation of the concrete and consequent corrosion of the steel reinforcement. These techniques require, nevertheless, further studies and this paper presents and discusses experimental results obtained in tests of RC columns jacketed with GFRP under monotonic and cyclic axial compression, topic especially relevant when interventions on seismic zones are required. In order to evaluate the effect of the loading type on strength and ductility, 27 circular columns with 750mm height and 150 mm diameter, either of plain concrete or of RC, were tested. Among these circular columns, 11 were confined with two plies of CFRP whereas six were confined with three plies of GFRP. Comparison of results with proposed empirical models is shown.

1 INTRODUCTION

Rehabilitation and strengthening of existing columns of reinforced concrete with FRP wraps has been growing rapidly, requiring further studies on the reliability of their use, both in terms of mechanical properties and in durability. Design expressions that fully explore the properties of the composites have to be based on experimental work and on modelling that respects failure modes, ductility gains, interfacial pressure and other important aspects. The present study adds some information on those topics and examines test data against recently proposed empirical formulations.

Concrete is a brittle material that deforms inelastically under compression, due to progressive loss of stiffness caused by voids and micro cracking. Under axisymetric stresses **(σ_x=σ_y)**, micro cracking is related to confinement and the following phases can be identified:
(i) Stiffening, when $d\sigma/d\varepsilon>0$;
(ii) Peak stressing, when $d\sigma/d\varepsilon$ reaches zero and damage accumulation leads to σ_{max};
(iii) Softening associated with $d\sigma/d\varepsilon<0$ and the formation of cracks and/or shear bands. Restraining lateral deformation, a higher strength capacity is obtained as well as higher ductility. Confinement may be provided by transversal reinforcement (stirrups) or external wraps of FRP or steel and the behaviour of the specimen differs for each case. In the latter solution, the elastic behaviour of FRP's contrasts with yielding of steel and has to be reflected on the modelling and on the estimate of interfacial pressure.

Many available data have been obtained for low values of the aspect ratio, λ=height/diameter, typically λ=2, raising some doubts on generalisation of those results. Besides well-known shortcomings of such scaling for compressive tests based on which failure modes are to be analysed, the relative stiffness of the outer composite shell vs. concrete appears over estimated. The aspect ratio for the tests reported in this note is λ=5, avoiding the above objection to frequently cited results (Harmon & Slaterry 1992, Mirmiran & Shahawy 1997, Samaan et al. 1998).

Earlier results on lateral confinement and on response to cyclic loading are briefly outlined below to frame adequately the results obtained at UNL. Models for confinement of RC columns by FRP shells still need improvement. In fact, core confinement provided by transverse reinforcement in RC columns has been extensively studied and quantified in Codes, although some procedures are still debated. It has been referred, for instance, that the response of cylinders subjected to equivalent levels of pressure depends on how that lateral pressure is transmitted and not on its magnitude alone (Samaan et al. 1998). Consequently, the stiffness of the FRP jackets is of great importance and has to be accounted for in the modelling (Sarkani et al. 1999), contrary to common practice. It also raises questions on applicability of Mander et al. (1988) model extension to FRP confinement. The balance of axial strain energy of confined concrete with hoop strain energy plus axial strain energy of the unconfined column, fails in the case of FRP wrapping, when lateral strain energy in concrete cannot be neglected.

This paper presents and discusses several experimental results of GFRP reinforced concrete columns under monotonic or cyclic axial compression in order to evaluate the effect of the monotonic and cyclic loading on strength and ductility.

2 TESTING SET-UP

Tests on 27 circular columns with 750mm height and 150 mm diameter either of plain concrete or of RC with 6ϕ6mm – S400 longitudinal steel, and ϕ3mm stirrups at spacing equal to 5, 10 or 15 cm were carried out. Among these circular columns, 11 were confined with 2 plies of CFRP (Rodrigues & Silva 2001) whereas 6 were confined with 3 plies of GFRP.

Concrete, tested in standard cubes, led to cylindrical strength f'_{c0}=37.7MPa. Glass fibers were acquired from TYFO and, from the manufacturer, the mechanical characteristics were E_j=27.6 GPa, f_j=552MPa, t_{ply}=1.27mm and ultimate strain of 2.0%.

Axial tests were conducted with a 5000kN press belonging to the National Laboratory of Civil Engineering, partner in the project. Three vertical displacement transducers were placed at mid-height and two pairs of two strain gauges were placed so as to measure vertical and circumferential deformation. In three of the specimen, additional twelve strain gauges were placed to evaluate eventual vertical variation of vertical strain. Monotonic and last cycle tests were displacement controlled at a velocity of 10 μm/s and continued beyond failure to record the stress-strain (f_c-ε) curves until a force of solely 50kN was attained. Cyclic tests were run at a rate of 0.2N/mm^2/s until beginning of last cycle when changed to displacement control. Figure 1 shows a column prior to test and after failure.

3 RESULTS

Table 1 presents discrete values of strength (f_c) from results of the experimental investigation of GFRP reinforced concrete columns under uniaxial cyclic compression. The value of axial strain in rupture (ε_{cc}) is also indicated.

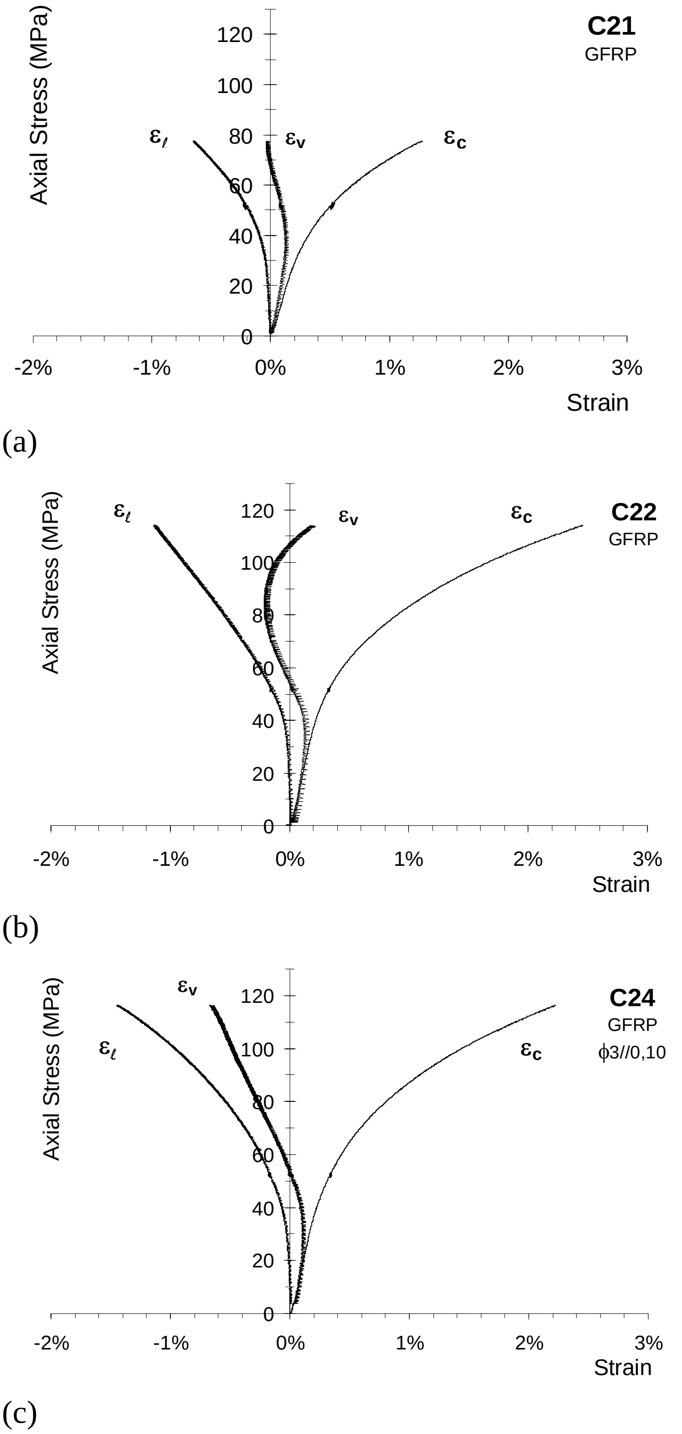
Figure 1 – Instrumented column of GFRP prior to test and after failure.

Table 1. Results of Uniaxial Compression Tests

Specimen number	Stirrups	GFRP	Load Type	f'_{c0} (MPa)	f'_{cc} (MPa)	ε_{cc} (%)
C1	-	-	Monotonic	23.1	-	0.20
C2	-	-	Monotonic	24.4	-	-
C3	-	-	Monotonic	32.2	-	0.20
C21	-	3 layers	Monotonic	-	77.6	1.28
C22	-	3 layers	Monotonic	-	114.2	2.46
C23	-	3 layers	Cyclic	-	115.7	3.13
C27	-	3 layers	Cyclic	-	112.4	2.21
C7	ϕ3 // 0.10	-	Monotonic	-	26.4	0.20
C8	ϕ3 // 0.10	-	Monotonic	-	30.4	0.20
C9	ϕ3 // 0.10	-	Monotonic	-	24.9	0.20
C24	ϕ3 // 0.10	3 layers	Monotonic	-	116.3	2.23
C25	ϕ3 // 0.10	3 layers	Cyclic	-	91.3	1.66

Figure 2 trough 5 display results of stress (f_c), axial strain (ε_c), lateral strain (ε_ℓ), volumetric strain (ε_V) and dilation rate (μ) obtained on tests. Figure 2 shows $f_c - \varepsilon_c$, $f_c - \varepsilon_\ell$ and $f_c - \varepsilon_V$ curves for confined concrete with GFRP (C21; C22). Column C24 has 6ϕ6 for longitudinal reinforcement and ϕ3//0,10 for stirrups.

As described for CFRP (Rodrigues & Silva 2001), following concrete failure, the GFRP jacket holds the column and provides stiffness that allows an increase of the strength and still higher increase of ultimate strain. The monotonic curve can be approximated by a bilinear curve, as seen. The volumetric strain, $\varepsilon_v = 2\varepsilon_\ell + \varepsilon_c$, can be correlated to the failure and post-failure of the concrete, with volume decreasing for f_c near f'_{c0} in the present case.



(a)

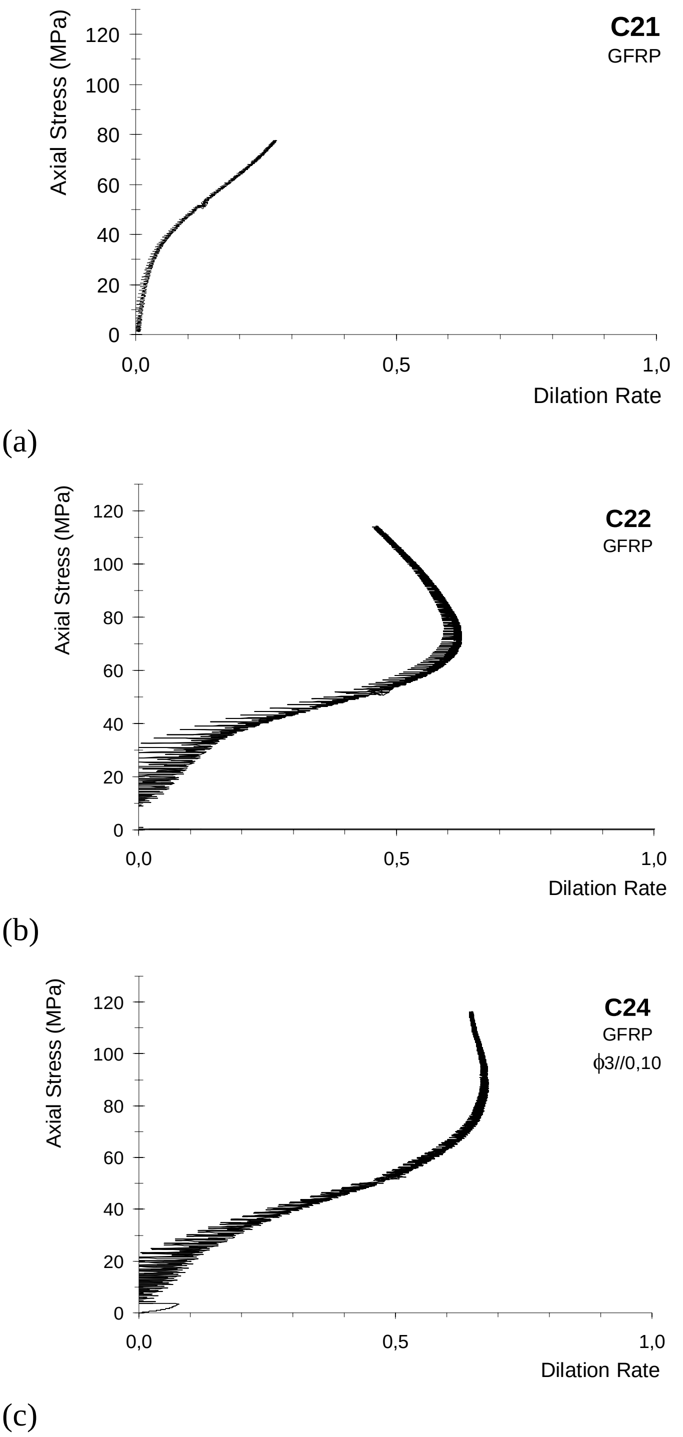
(b)

(c)

Figure 2 – Stress-Strain response (f_c vs. ε_c, ε_ℓ, ε_V) for plain (C21,C22) & RC (C24) jacketed columns. Monotonic loading.

Observed Behaviour of columns of plain concrete can be divided in phases. Firstly, increasing axial strain causes decrease of volume and lateral expansion at low rate. Then concrete fails, volume reverses change and the jacket enters its main function of confinement, with dilation rate increasing almost linearly with stress. Finally, total load capacity is exhausted and the column fails through rupture of the jacket.

Reinforced concrete shows a different behaviour near failure with ε_V decreasing continuously, whereas $|\varepsilon_V|$ reaches a maximum at failure for plain concrete.



(a)

(b)

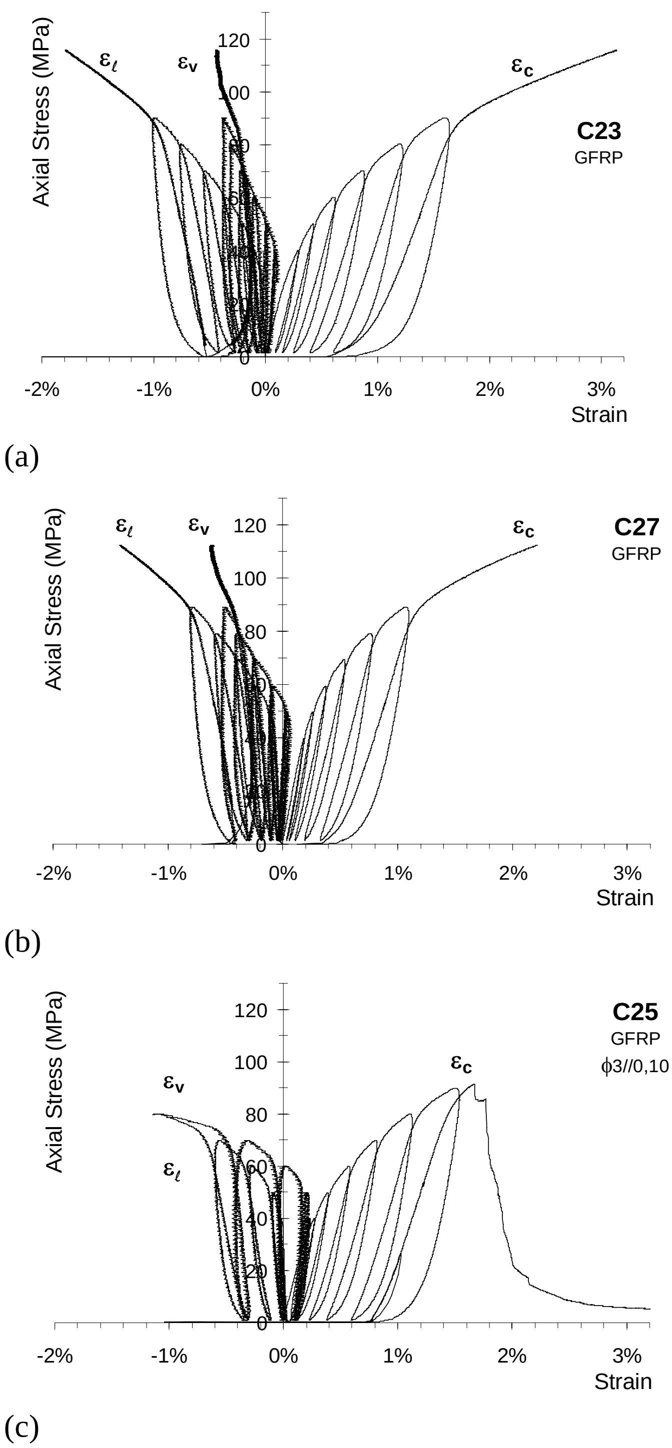
(c)

Figure 3 – Dilation ($\varepsilon_\ell/\varepsilon_c$) curves for plain (C21, C22) and RC (C24) jacketed columns. Monotonic loading.

Figure 4 shows curves $f_c-\varepsilon_c$, $f_c-\varepsilon_\ell$ and $f_c-\varepsilon_V$ for confined plain concrete columns with GFRP (C23; C27) or RC (Strϕ3//0.10) under cyclic loads.

Specimen C25 experienced strain gauges failure and ε_ℓ not recorded in the upper range. Comparison of figures 2 and 4 indicates that the envelopes for cyclic loads follow trends approaching the monotonic curves.

Dilation curves shown in figures 3 and 5 require further study and more data for interpretation.



(a)

(b)

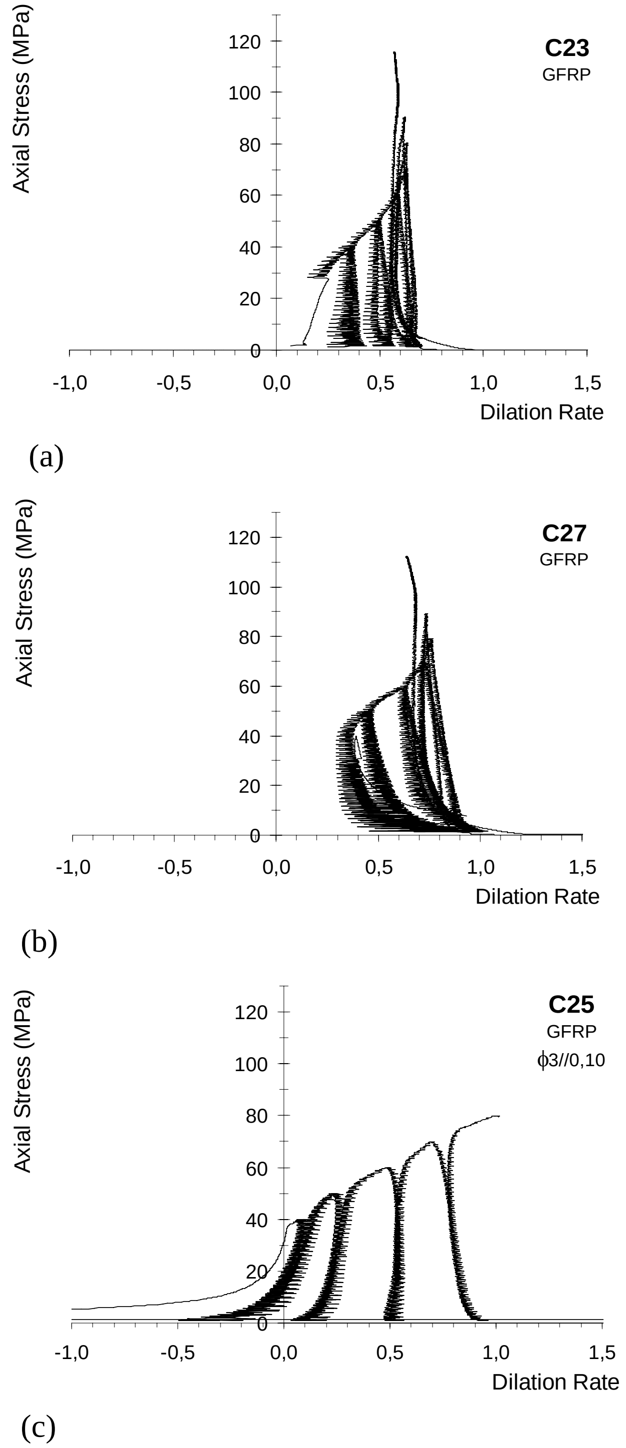
(c)

Figure 4 – Stress-Strain response (f_c vs. ε_c, ε_ℓ, ε_V) for plain (C23, C27) and RC (C25) jacketed columns. Cyclic loading.

4 COMPARISON WITH EMPIRICAL MODELS

Several procedures have been proposed to estimate the strength and the ultimate strain of concrete confined with FRP, under axial loading (Karbhari et al. 1997, Mirmiran & Shahawy 1997, Samaan et al. 1998, Spoelstra & Monti 1999).

Expressions submitted by Samaan et al. (1998) and Spoelstra & Monti (1999) provide also the stress-strain curves and are selected for application hereafter.



(a)

(b)

(c)

Figure 5 – Dilation ($\varepsilon_\ell/\varepsilon_c$) curves for plain (C23, C27) and RC (C25) jacketed columns. Cyclic loading.

a) Samaan et al. (1998)

The bilinear relationship advanced by Samaan et al. (1998) is displayed in figure 6 based on (1):

$$f_c = \frac{(E_1 - E_2)\varepsilon_c}{\left[1+\left(\frac{(E_1 - E_2)\varepsilon_c}{f_0}\right)^{1.5}\right]^{1/1.5}} + E_2\varepsilon_c \qquad (1)$$

Initially, the jacket acts passively and the slope ($\partial f_c / \partial \varepsilon$) corresponds solely to the vertical response of concrete and is given by:

$$E_1 = 3950\sqrt{f_{c0}} \quad [\text{MPa}] \tag{2}$$

For f_c near the maximum stress of unconfined concrete, f'_{c0}, the effective modulus (E_j) and the thickness (t_j) of the FRP also play a role, as indicated by:

$$E_2 = 245.61 f_{c0}^{\ 0.2} + 1.3456 \frac{E_j \times t_j}{D} \quad [\text{MPa}] \tag{3}$$

The strenght of the confined concrete relates to f'_{c0} through the equation:

$$f'_{cc} = f_{c0} + 6.0 f_l^{0.7} \tag{4}$$

that derives from s modification of the linear expression proposed by Richart et al. (1929).

Analogously, an estimate of the ultimate strain can also be found:

$$\varepsilon_{cc} = \frac{f'_{cc} - f_0}{E_2} \tag{5}$$

where:

$$f_0 = 0.872 f_{c0} + 0.371 f_l + 6.258 \quad [\text{MPa}] \tag{6}$$

b) Spoelstra & Monti (1999)

The model suggested by Spoelstra & Monti (1999) is based on Popovics (1973) formula:

$$f_c = \frac{f'_{cc} x r}{r - 1 + x} \tag{7}$$

where:

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}}; \quad r = \frac{E_c}{(E_c - E_{\sec})}; \quad E_{\sec} = \frac{f'_{cc}}{\varepsilon_{cc}} \tag{8-a,b,c}$$

$$\varepsilon_{cc} = \varepsilon_{c0}\left(1 + 5\left(\frac{f'_{cc}}{f'_{c0}} - 1\right)\right) \tag{9}$$

Strain ε_{c0}, corresponding to the maximum compressive stress of unconfined concrete f_{c0}, is taken as 2‰. The elasticity modulus at the origin is:

$$E_c = 5000\sqrt{f'_{c0}} \ [\text{MPa}]. \tag{10}$$

Maximum stress f'_{cc} for confined concrete, based on Mander et al. (1988) modified by Karbhari et al. (1997) is given by:

$$f'_{cc} = f'_{c0}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f_l}{f'_{c0}}} - 2\frac{f_l}{f'_{c0}}\right) \tag{11}$$

where f_l is the confinement pressure due to the FRP jacket and given by static equilibrium:

$$f_l = \frac{2 f_{FRP} \cdot t}{D} \tag{12}$$

Mander et al. (1988) model [4] is applicable to concrete confined by steel, except in the early stages when steel is still in the elastic range. Spoelstra & Monti (1999) adapted formula due to Pantazopoulou & Mills (1995) to take into consideration the elastic behaviour of FRP through the entire range of strain:

$$\varepsilon_\ell(\varepsilon_c, f_\ell) = \frac{E_c \varepsilon_c - f_c(\varepsilon_c, f_\ell)}{2\beta f_c(\varepsilon_c, f_\ell)} \tag{13}$$

the relationship of f_c and ε_ℓ with the current strain ε_c and confining pressure f_ℓ is given by the authors. The constant β is a property of concrete:

$$\beta = \frac{E_c}{|f_{co}|} - \frac{1}{|\varepsilon_{co}|} \tag{14}$$

Once ε_ℓ is computed from Equation (11), the strain ε_j in the confining jacket can be found, as well as stress $f_j = E_j \varepsilon_j$. The updated value of f_ℓ can be used for a new estimate of ε_ℓ through Equation (13), the iterations continuous until f_ℓ converges. The procedure is repeated for each ε_c, until the complete stress-strain curve is covered (Spoelstra & Monti 1999).

The response of an FRP-wrapped RC specimen obtained with Spoelstra & Monti (1999) model can be seen in Figure 6, along with a comparison with Samaan et al. (1998) model. Figure 7 shows curves $f_c - \varepsilon_c$, $f_c - \varepsilon_\ell$ and $f_c - \varepsilon_V$ for Spoelstra & Monti (1999) model compared with experimental results (C24) and compared with $f_c - \varepsilon_c$ curve of Samaan et al. (1998) model. Figure 8 shows dilation curves of GFRP confined concrete obtained with Spoelstra & Monti (1999) model compared with experimental results (C24).

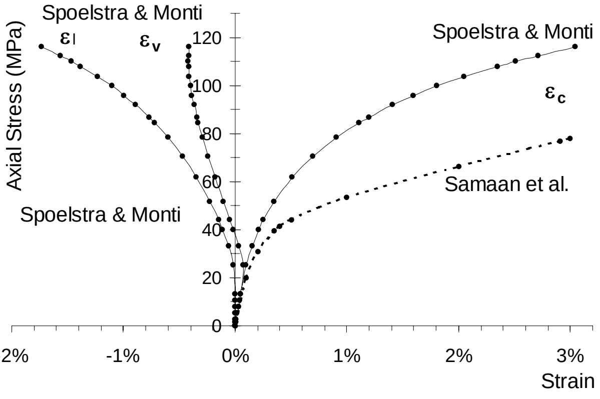


Figure 6 – Empirical Stress-Strain responses of GFRP confined concrete (Spoelstra & Monti 1999, Samaan et al. 1998) models.

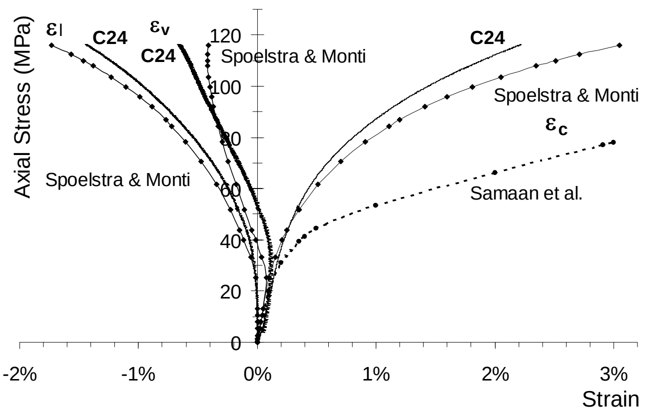


Figure 7 – Empirical Stress-Strain models compared with experimental results (C24).

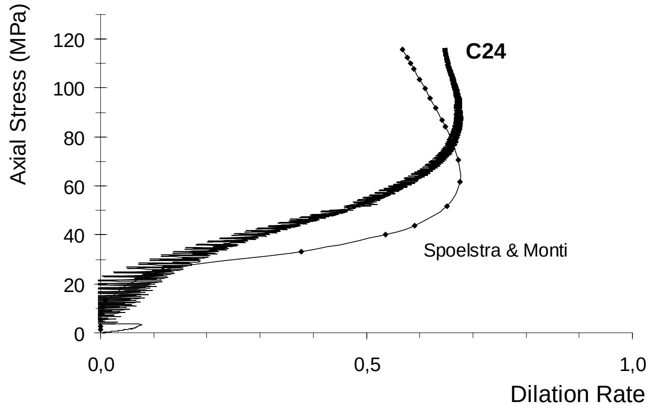


Figure 8 – Dilation curves of GFRP confined concrete obtained with Spoelstra & Monti (1999) model compared with experimental results (C24).

The Spoelstra & Monti (1999) curves show a fairly good agreement with experimental results.

5 FINAL REMARKS

The study provides interesting results on GFRP reinforced cylindrical columns, obtained for specimen with adequate aspect ratio (height/diameter). Both columns of plain concrete and of RC, wrapped with GFRP jackets, were tested under axial load until complete failure. Load was applied both monotonically and in cycles and the changes of volumetric expansions, lateral and axial strain with axial stress were recorded. Results show:

a) Relatively good agreement of results with empirical formulas proposed by Spoelstra & Monti (1999). Results are less accurate for model proposed by Samaan et al. (1998).
b) Behaviour of columns of plain concrete can be divided in phases. Firstly, increasing axial strain causes decrease of volume and lateral expansion at low rate. Then concrete fails, volume reverses change and the jacket enters its main function of confinement, with dilation rate increasing almost linearly with stress. Finally, total load capacity is exhausted and the column fails through rupture of the jacket.
c) Reinforced concrete shows a different behaviour near failure with ε_v decreasing continuously, whereas $|\varepsilon_v|$ reaches a maximum at failure for plain concrete.

Studies continue seeking the improvement of modelling and the generation of results applicable to design.

6 ACKNOWLEDGMENTS

Support for this study was provided by the Portuguese Foundation for Science and Technology under PRAXIS XXI Project nº CEG 3/3.1/2572-95. The writers are grateful to Mr. Rui Neves and Mr. Bernardino from LNEC and Mr. Gaspar from UNL for their help with the experiments.

REFERENCES

Harmon, T.G. and Slaterry, K.T. (1992); “Advanced composite confinement of concrete”, Proc. Advanced Composite Mat. In Bridges & Struct., CSCE, pp292-302.

Karbhari, Vistasp, M., Gao, Yanqiang (1997); “Composite Jacketed Concrete Under Uniaxial Compression – Verification of Simple Design Equations”. *Journal of Materials in Civil Engineering*, Vol. 9, nº 4, Nov., Paper nº 13873.

Mander, J.B., Priestley, M.J.N. and Park R. (1988); “Theoretical stress-strain model for confined concrete”, *Journal of Structural Engineering*, ASCE, 114 (8), pp.1804-1826.

Mirmiran, A. and Shahawy, M.(1997); “Behaviour of Concrete Columns Confined by Fiber Composites”, *Journal of Structural Engineering*, vol.123, No. 5, May, pp. 583-590.

Pantazopoulou, S. J. and Mills, R. H. (1995), “Microstructural aspects of the mechanical response of plain concrete”, *ACI Materials Journal*, 92-M62, November-December, 605-616.

Popovics, S. (1973), “Numerical approach to the complete stress-strain relation for concrete”, *Cement and Concrete Research*, 3(5), 583-599.

Richart, F. E., Brandtzaeg, A. and Brown, R. L. (1929), “*The failure of plain and spirally reinforced concrete in compression*”, Engineering Experiment Station Bulletin, 190, University of Illinois, Urbana, USA, April.

Rodrigues, C. C.; Silva, M. G. (2001); “Experimental investigation of CFRP reinforced concrete columns under uniaxial cyclic compression”; In *Proceedings of the 5th International Conference on FRP for Reinforced Concrete Structures*; Cambridge, UK.

Samaan, M., Mirmiran, A. and Shahawy, M.(1998); “Model of Concrete Confined by Fiber Composites”, *Journal of Structural Engineering*, vol.124, No. 9, September, pp. 1025-1031.

Sarkani, S. et al., (1999); “Strengthening RC Structures Using FRP”, Proc. Structural Faults + Repair, 8th. Intl. Conf., London, 13 -15 July, UK.

Spoelstra, M. R. and Monti, G., (1999), “FRP-confined concrete model”. *Journal of Composite for Construction*, ASCE, **3**(3), 143-150.