Experimental Investigation of CFRP Reinforced Concrete Columns Under Uniaxial Cyclic Compression

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INTRODUCTION

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 FRP under axial cyclic compression, topic especially relevant when interventions on seismic zones are required. The studies of effects on the strength and ductility were conducted on 27 circular columns with 750mm-height and 150 mm diameter. Both CFRP and GFRP were utilised and spacing of stirrups was varied.

Many available data have been obtained for low values of the aspect ratio, λ=height/diameter, typically $\lambda=2$, and small diameters 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. This is a serious objection that the present study avoided, notwithstanding the fact that frequently cited results, e.g. [1, 2], were based on tests with $\lambda=2$. The aspect ratio for the tests reported in this note is $\lambda=5$.

Earlier results on lateral confinement and on response to cyclic loading are briefly outlined below to frame adequately the results obtained at UNL. 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 [3]. As a consequence, the stiffness of the FRP jackets is of great importance and has to be accounted for in the modelling [4], contrary to common practice. It also raises questions on applicability of Manders model [5] 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.

A short summary of main results available to consider effects of axial loading cycles is presented next, without any attempt at being exhaustive.

Early work on the response of unconfined concrete to cyclic loading was undertaken at Rice University in the late sixties by Demir Karsan and James Jirsa [6], followed by Blakeley and Park [7] in 1973. Fig. 1 reproduces results from [6] and shows that the slope of both

FRPRCS-5, Thomas Telford, London, 2001.

unloading and reloading branches decreases with increase of inelastic deformation, i.e. the material softens and the cylinder looses stiffness due to alternating load cycles. The envelope curve, below which lie all σ_i $-\varepsilon_i$ points corresponding to successive cycles, practically coincides with the curve for monotonic loading up to failure, except for large inelastic deformations.

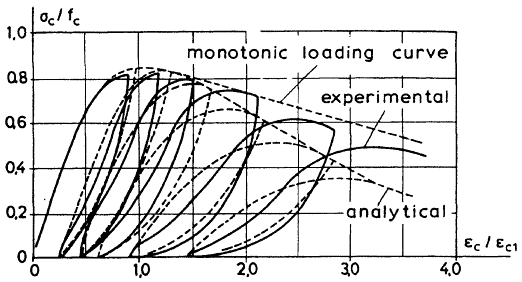

Fig 1. Stress-strain for unconfined, plain concrete cylinders [6].

Repeated loading and unloading do not influence the behaviour of concrete provided that σ_c does not exceed 50% of the dynamic strength in compression [5]. A decrease appears when σ_c exceeds approximately *85% of* $f_{c,dyn}$. Blakeley and Park [7] proposed a model that suggests for strains $\varepsilon_c \leq \varepsilon_{c1}$, unloading, as well as reloading, take place along a line parallel to the tangent at the origin of the curve (slope equal to E_{c0}) i.e., prior to reaching maximum stress, reloading takes place without energy dissipation nor stiffness deterioration. In the region of tensile stresses, loading and unloading also take place along straight lines with a slope E_{c0} until the tensile strength is attained. For strains $\varepsilon_c > \varepsilon_{c1}$ the model takes into account stiffness degradation by introducing a reduction factor F_c. The entire hysteretic mechanism is represented in Fig. 2.

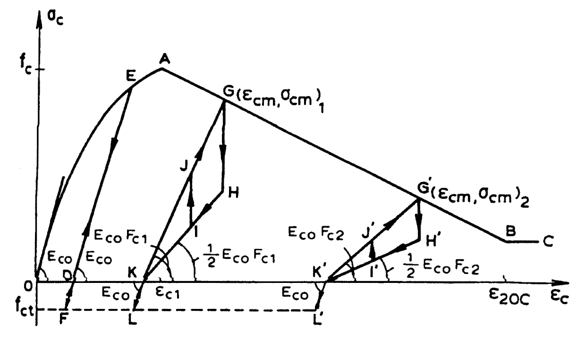

Fig. 2 . Idealised stress-strain curve for unconfined concrete [7].

These studies shed light on concrete behaviour and are of great interest, but columns are, in actuality, made of reinforced concrete with transverse reinforcement that provides some confinement, though not always sufficient. RC confined by hoops or spirals is subject to a combination of a principal compressive stress and a lateral confining pressure that enhances its performance and, thus, RC cylinders under axially symmetric load have to be studied for biaxial loading.

Biaxial cyclic loading tests are scarcer than uniaxial tests. An example are the studies of Buyukozturk and Tseng [9] who considered 127 x 127 x 25 mm flat concrete plates subjected to a constant horizontal strain (ε_h) and an alternating vertical strain (ε_v) and a σ_v–σ_h envelope for biaxial compression is shown in Fig. 3 for monotonic and cyclic tests.

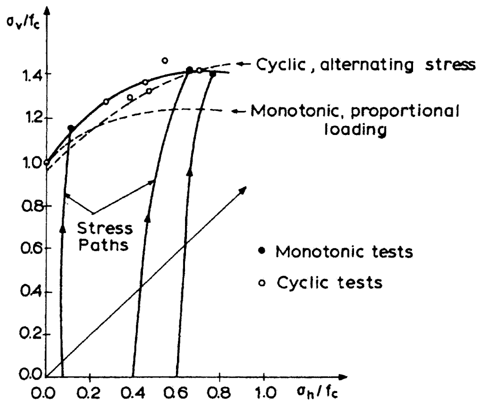

Fig. 3. Biaxial strength envelop for monotonic and cyclic loading [9].

Corresponding curves show performance similar to that of uniaxial loading, confirming progressive degradation of the material. This degradation is due both to microcracking in the out of plane direction, and to the inelastic behaviour of mortar. The envelope of the biaxial cyclic stress-strain curves is, initially, very close to that of the uniaxial curve for low strains, but rises above the uniaxial curve for higher strains. The biaxial strength envelope is practically the same for both monotonic and cyclic loading for the load histories studied. If non-proportional loading (variable σ_h/σ_v) is applied, strengths greater than those under proportional loading materialise.

It has, thus, been accepted that models for concrete subjected to uniaxial cyclic loading may be used for biaxial loading, provided an appropriate envelope curve is defined. An equivalent uniaxial curve for cyclic loading is proposed in the CEB Model Code and shown in Fig. 4.

There are few cyclic tests on reinforced concrete and it has long been assumed that its hysteretic behaviour is similar to that of unconfined concrete. Tests by Mander et al. [5] have confirmed that assumption. Fig. 6 reproduces results obtained for RC with steel spirals and introduces the possibility of monotonic loading curves below the envelope for static cyclic loading [10] a fact known for dynamic compressive loading.

Tests of specimen confined by FRP, subjected to axial cyclic loading, are yet scarcer. Some results are known for confined plain concrete, e.g. [11 to 13], whereas Fig. 7 shows experimental data and predicted response for concrete cylinder confined with 14 ply FRP and submitted to four loading-unloading cycles[12]. The reason for the paucity of publications on RC confined with FRP and subject to cyclic loading is the complexity of the problem, incorporating factors like the coexistence of concrete confined by stirrups and concrete cover, the influence of the transverse reinforcement and the stiffness of the outer shell.

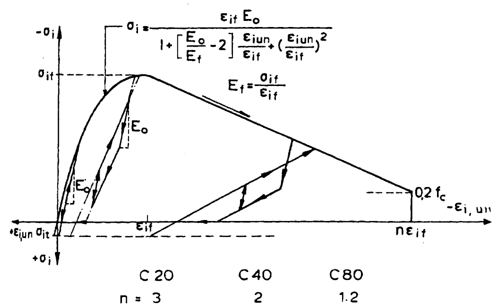

Figure 4. Equivalent uniaxial curve for cyclic loading [9].

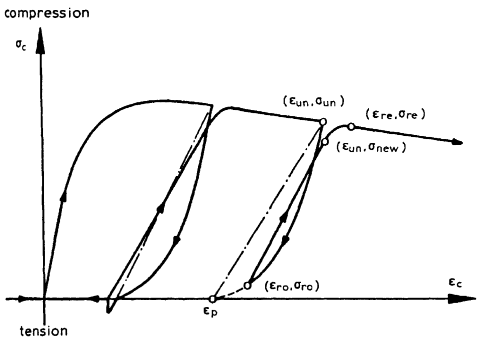

Fig. 5 : Stress-strain model for confined concrete subjected to cyclic loading [8].

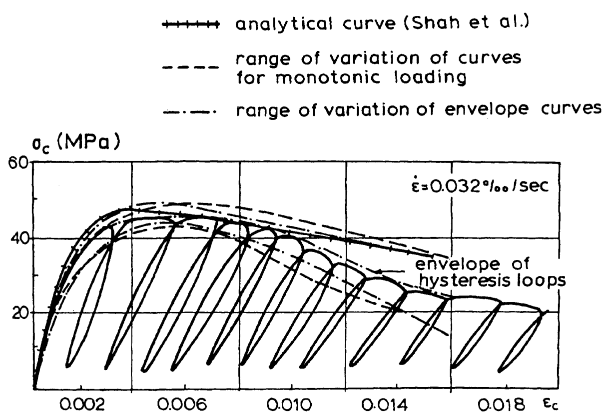

Fig. 6. Reinforced concrete confined by transverse reinforcement under cyclic axial load [10]

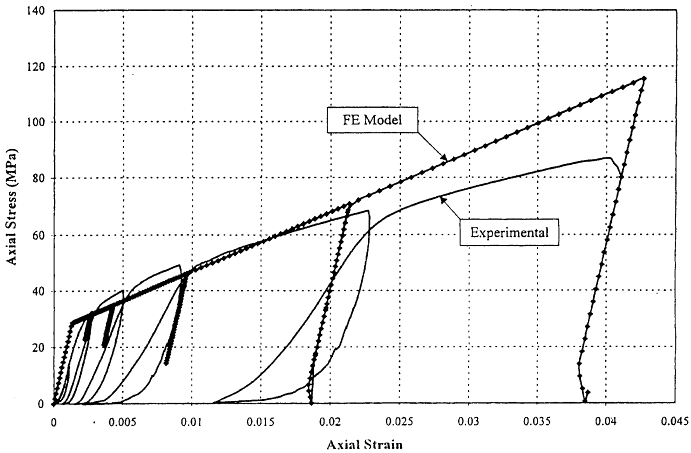

Fig. 7. Comparison of predicted and experimental cyclic response [12].

MATERIAL CHARACTERIZATION

Concrete, tested in standard cubes, led to cylindrical strength f_{cm}=37.7MPa. Epotherm resin was supplied together with Replark 30 carbon fibers and was tested, leading to E=1768 MPa, σ_{tu}=23.7 MPa, strain for maximum force 4.99% and ultimate strain 13.53%.

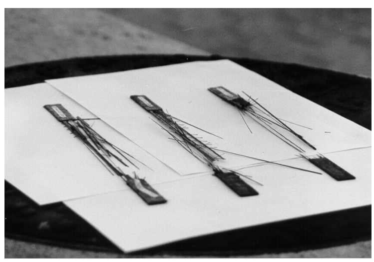

Fig. 9. Coupons of CFRP after tensile testing.

Carbon fibers were acquired from Mitsubishi Chemical Corporation and, from the manufacturer, the mechanical characteristics were E=230 GPa, σ_t= 3400MPa, t $_{ply}$=0.167mm. Lab tests revealed E=210 GPa, σ_{tu}= 3371MPa, strain for maximum force 2.8% and ultimate strain 3.0% for coupons with 2 plies of CFRP.

TESTING SET-UP

The 27 circular columns with 750mm height and 150 mm diameter are either of plain concrete or of RC with 6ϕ6mm – S400 longitudinal steel, and ϕ3mm stirrups at spacing s=5, 10 or 15cm. Part of these circular columns 11 were confined with 2 plies of CFRP.

Axial tests were conducted with a 5000kN press belonging to the National Laboratory of Civil Engineering, partner in the project. A HBM UPM 60 Data Logger and a Pentium were also used. Three vertical displacement transducers were placed at mid-height and two pairs of two strain gauges were placed so as to measure vertical and circumferencial 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 μ/s and continued beyond failure to record the σ-ε curves until a force of solely 50kN was attained. Cyclic tests were run at a velocity of 0,2N/mm2/s until beginning of last cycle when changed to displacement control. Fig. 10 shows a column prior to test and after failure.

Fig. 10 – Instrumented column prior to test and after failure [14].

RESULTS

Fig. 11 trough 15 display results obtained on tests. Fig. 11 shows fc-ε_z curves for unconfined specimens (C7, C8 and C9) and confined with CFRP (C10 and C11). All these concrete columns have 6ϕ6 for longitudinal reinforcement and ϕ3//0,10 for stirrups. As remarked elsewhere, following concrete failure, the CFRP 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.

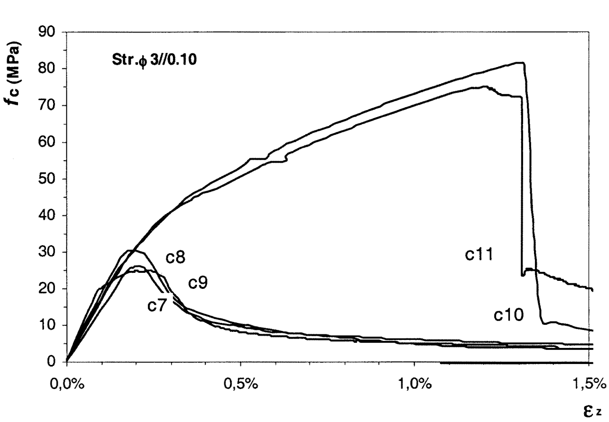

Fig. 11 – Curves fc-ε_z for specimens C7, C8, C9, C10 and C11.

Fig. 12 shows curves fc-ε_z for monotonic load (C10) and cyclic load (C12) in RC (Strϕ3//0.10) columns confined with CFRP. Monotonic loading curve is below the envelope for static cyclic loading, but practically coincident with the curve for monotonic loading near to failure. This proximity will be shown to depend on the density of transverse reinforcement.

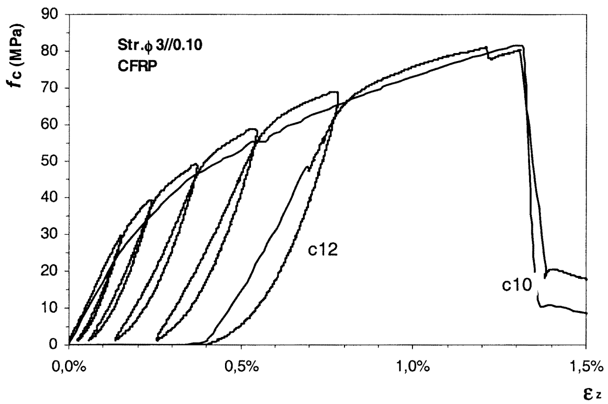

Fig. 12 – Curves fc-ε_z for monotonic loading (C10) and cyclic loading (C12).

Fig. 13 shows curves fc-ε_r or ε_z for cyclic loading (C12) in RC columns (ϕ3//0.10) confined with CFRP. The curves, for ε_z greater than approximately 0.2%, show an increase of the ratio $| \varepsilon_r / \varepsilon_z |$ that is often referred as an increase of the Poisson's ratio, after concrete failure.

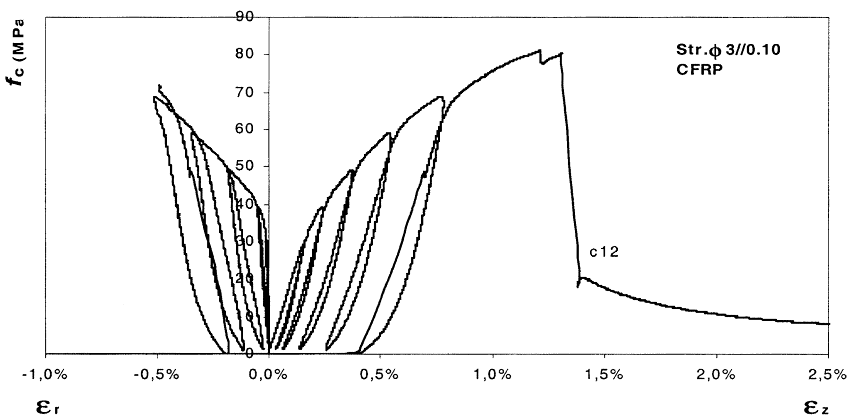

Fig. 13 – Curves fc-ε_r or ε_z for cyclic load (C12).

Fig. 14 shows curves for different stirrup spacing (5, 10, 15 cm). All these concrete columns have 6ϕ6 for longitudinal reinforcement and stirrups of ϕ3//0,15 (C13, C14, C15 and C16), stirrups of ϕ3//0,10 (C7, C8, C9, C10 and C11) and stirrups of ϕ3//0,05 (C17, C18, C19 and C20). The preliminary results suggest that the importance of jacketing is greater when stirrups spacing increases. It is also pointed out that, in this case, the monotonic loading curves are below the envelope for static cyclic loading.

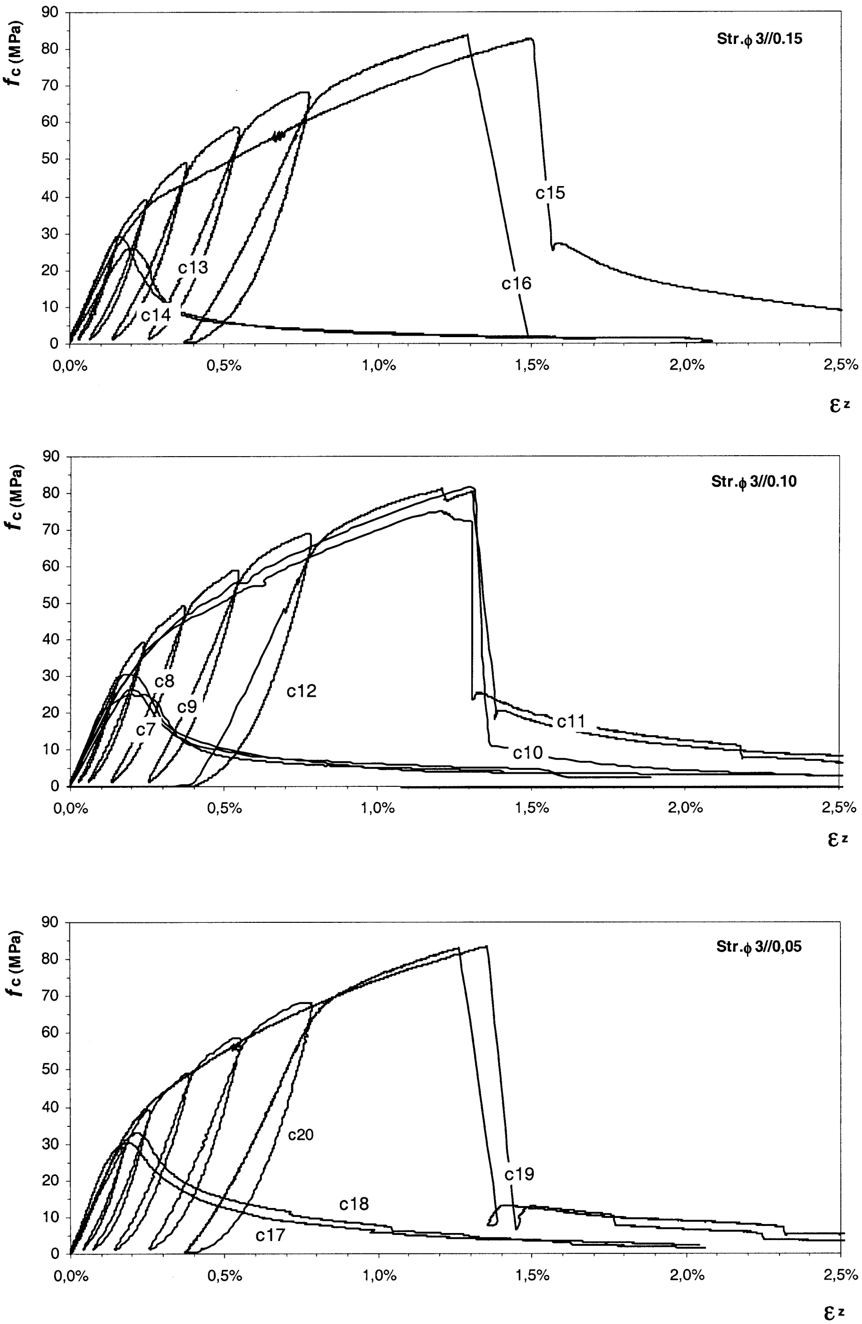

Fig. 14. Curves for different stirrup spacing (5, 10, 15 cm)

In Fig. 15 the volumetric response of CFRP confined RC (C12) under uniaxial cyclic compression can be observed. The volumetric strain, $\varepsilon v = 2\varepsilon_r + \varepsilon_z$, can be correlated to the failure and post-failure of the column. First cycle, up to 30 MPa, does not damage significantly the concrete. However, third cycle, up to 50 MPa shows volume increase, a fact successively more evident until failure of the RC column.

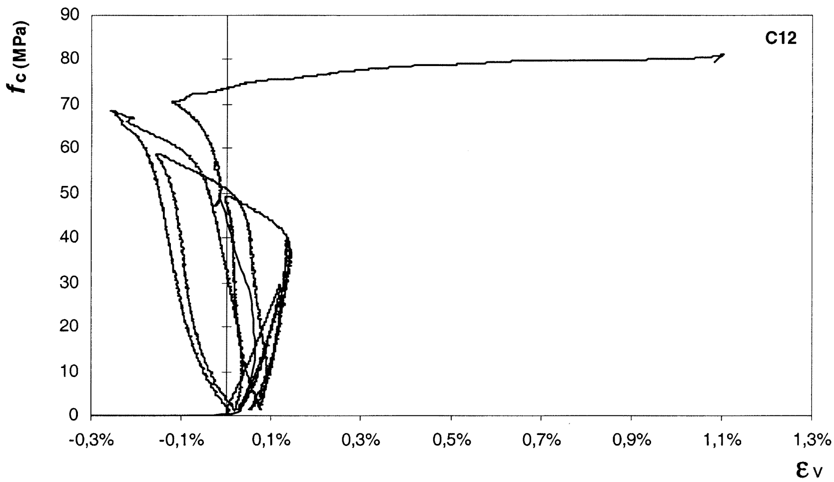

Fig. 15. Volumetric response of CFRP confined RC under uniaxial cyclic compression.

Table 1 presents discrete values of strength for several strains and different confinements, from results of the experimental investigation of CFRP reinforced concrete columns under uniaxial cyclic compression. The value of axial strain in rupture is also indicated.

Table 1. Discrete values of Strength for Several Strains and Different Confinements

	fc	CFRP; Str ϕ3//0.05m			CFRP; Str ϕ3//0.10m				CFRP; Str ϕ3//0.15m		
	εz	Monot.	Cyclic	%	Monot.		Cyclic	%	Monot.	Cyclic	%
	Model	C19	C20		C10	C11	C12		C15	C16	
ε_z	0,20%	35,0	33,0	94,3%	31,1	31,3	35,9	115,2%	32,0	34,7	108,4%
	0,35%	46,8	47,3	101,0%	45,0	43,9	48,1	108,2%	42,4	47,5	112,0%
	0,50%	54,9	56,9	103,7%	53,1	50,6	57,4	110,6%	48,7	56,6	116,3%
	0,75%	65,9	68,2	103,6%	64,4	61,3	68,3	108,7%	59,7	68,2	114,1%
	1,00%	74,3	76,7	103,2%	73,8	69,9	75,7	105,4%	68,9	75,7	110,0%
	1,25%	81,0	82,6	101,9%	80,3	72,9	78,7	102,7%	76,7	82,6	107,7%
$\varepsilon_{rupture}$	1,25%					*72,9*					
	1,26%		*82,9*								
	1,29%				*81,5*					*83,7*	
	1,31%						*80,3*				
	1,36%	*83,3*									
	1,48%								*82,5*		

Table 1 shows again the relation between stirrups spacing and the possibility of monotonic loading curves below the envelope for static cyclic loading. For example for axial strain ε_z at 1,25% it is observed an increment of the strength rate (cyclic/monotonic loading) with the increment of the stirrups spacing of the order of 1.9% to 2.7% to 7.7%.

FINAL REMARKS

A short summary of main results available to consider effects of axial loading cycles is presented in this paper. Results of the experimental investigation of CFRP reinforced concrete columns under uniaxial cyclic compression is also presented. The preliminary results suggest the possibility of monotonic loading curves staying below the envelope for static cyclic loading.

It is observed that the preliminary character of the results advises against presenting conclusions based on the evolution of the dilation rate $|\partial \varepsilon_r / \partial \varepsilon_z|$ with axial strain, as well as the volumetric strains. However those parameters relate to dilatancy of concrete as a granular material near failure and play a major role on the interpretation of the material behaviour as shown, correlating stress levels with dilatancy and failure. It is also shown the greater importance of lateral confinement for columns with weak transverse reinforcement.

ACKNOWLEDGMENTS

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