Materials and Structures/Matériaux et Constructions, Vol. **35**, January-February 2002, pp 50-58

TECHNICAL REPORTS

Strength of short concrete columns confined with CFRP sheets

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Paper received: December 5, 2000; Paper accepted: May 2, 2001

ABSTRACT

The confinement of concrete columns provided by carbon fibre reinforced plastic (CFRP) sheets can be an efficient technique for their structural strengthening. The principal advantages of this technique are the high strength-to-weight ratio, good fatigue properties, non-corroding characteristics of the CFRP, and the facility of its application.

An experimental research program, that included tests on 54 short column specimens, was carried out to investigate the gain in strength and ductility of concrete columns externally confined by CFRP wrapping. The variables studied were the column cross section shape (circular, square and rectangular) and the amount of confinement expressed in the number of CFRP sheet layers applied to the models (one or two layers).

On the basis of the obtained results, equations were proposed to calculate the confined concrete strength and the ultimate confined concrete strain as a function of the confining lateral stress for each of the cross section geometry used, circular, square and rectangular. The estimations given by these equations and by those from formulas encountered in the literature were compared with the experimental ones and general conclusions were, finally, drawn.

RÉSUMÉ

Le confinement de colonnes de béton assuré par des feuilles de plastique renforcé par des fibres de carbone (CFRP) peut être une technique efficace pour leur comportement structural. Les principaux avantages de cette technique sont la haute relation résistance-poids, des bonnes propriétés de fatigue, les caractéristiques non-corrosives du CFRP, et la facilité de leur application.

Un programme expérimental comprenant des essais sur 54 colonnes courtes fut entrepris en vue de déterminer le gain de résistance et de ductilité de colonnes en béton confinées sur le plan externe en les recouvrant de feuilles de CFRP. Les variables étudiées étaient la forme de la section transversale (circulaire, carrée et rectangulaire), et la quantité de renforcement, mesurée par le nombre de feuilles de CFRP appliquées aux modèles (une ou deux couches).

En prenant comme base les résultats obtenus, des équations ont été proposées pour calculer la résistance du béton confiné et sa déformation spécifique ultime en fonction de la contrainte latérale de confinement, pour chaque forme de section transversale utilisée, circulaire, carrée et rectangulaire. Les estimations données par ces équations et celles données par des formules trouvées dans la littérature ont été comparées avec les résultats expérimentaux et des conclusions générales ont finalement été établies.

1. INTRODUCTION

External confinement has been successfully applied to concrete columns in order to increase their strength and ductility or to recover them from eventual deterioration originated from different sources.

In early constructions, concrete-filled steel tubes were used for some of the reasons mentioned above. The main disadvantages of this technique are the high cost for maintenance against corrosion, the low fire resistance and the heavy weight of the tubes.

As a result of the fast development of new materials, urged by the demand of more durable and resistant materials, fibre reinforced plastic composites (FRP) were introduced as replacement for the reinforcing steel. Carbon FRP has been used since the seventies in the space industry, where the requirement for lightweight, high-tensile strength, corrosion and high temperature resistance is essential.

Recently, in Brazil and many other countries, FRP composites (mainly carbon) have been used in strengthening slabs (of bridges and parking floors), beams (of bridges and buildings), columns (of bridges, buildings and piers), concrete walls, tunnels, silos and tanks.

Many research works are being developed, in different research centres, in order to study the behaviour of RC elements strengthened with FRP and to provide relevant data for designers.

With respect to concrete columns, several research works aimed to develop expressions to quantify the effects of confinement on their strength and ductility. As early as 1903, Considerè [1] developed a research program to study the behaviour of concrete columns reinforced with spirals. Most of the studies that followed were about concrete columns mainly confined with internal reinforcement, few confined with external steel tubes and, recently, limited number confined with external FRP.

This work presents the preliminary results of an experimental study on the behaviour of short concrete columns, with different cross sections (circular, square and rectangular), externally confined with CFRP sheets. The obtained experimental strengths and ultimate strains are here compared with the ones given by the equations proposed in this work and others available in the literature.

It is worth noting that a model for accurate prediction of the stress-strain curve of composite confined concrete is rather complex to obtain due to the number of variables that affect it. The factors that greatly influence this curve are the concrete characteristics (modulus of elasticity, strength and Poisson ratio), the modulus of elasticity and strength of the composite, the cross section geometry (circular, square or rectangular) and column cross section size. In the case of rectangular cross section the degree of rectangularity affect the stress-strain curve, while in both square and rectangular cross sections the curve is also influenced by the radius to which the corners of the section are rounded off, in order to avoid the breakage of the fibres.

As, for practical design, it is sufficient to know the compressive strength and ultimate strain of the confined concrete, this work focus only on the evaluation of their values and no attempts are made to obtain the complete stress-strain curve of the confined concrete.

2. BACKGROUND ON THE STRENGTH OF CONFINED CONCRETE

The analysis presented in this section is related to the Ultimate Limit State (ULS) of strength of confined concrete and hence is not applicable to the general state of stress (axial stresses lesser than the ultimate stress). The difference lies on the factors that affect each case.

In the general state of stress, as in all types of passive confinement, the confinement provided by composite wrapping at any stress level depends on the tendency of concrete to dilate at that level. This is generally affected by the compressive strength, Poisson ratio, modulus of elasticity and type of coarse aggregate of the concrete, the thickness, strength and modulus of elasticity of the confining material and the cross section geometry.

In the ULS, the composite strength and the section geometry determine the confining stress. Hence, in the ULS the elastic characteristics of both concrete and the composite will have no influence on the strength of confined concrete. In fact, this is only true when the full development of the fibre strength occurs before any excessive damage to the core concrete takes place. On the contrary, if the core concrete suffers from extensive damage at the time of full development of composite strength, the confined concrete strength is lower than in the case of slightly damaged concrete core.

According to the modified Mohr-Coulomb failure criterion, the strength of concrete under a triaxial state of stress is given by:

$$f_{cc} = f_{co} + \frac{1+\text{sen}\phi}{1-\text{sen}\phi} f_l \qquad (1)$$

where f_{cc} is the strength of concrete in the triaxial state, f_{co} is its strength under uniaxial compression, ϕ is the angle of internal friction of concrete and f_l is the lesser lateral confining stress.

Admitting the widely accepted value for the angle of internal friction of concrete of 37°, the previous equation leads to:

$$f_{cc} = f_{co} + 4f_l$$

This failure criterion expresses the material strength under active lateral confining stresses, which means that all stresses are increased proportionally until failure or the material has no internal damage prior to the application of any stress. In the case of passive confinement, this criterion can be still applied if the due adjustments are made to it. The difference between active and passive confinement is the state at which the core concrete is encountered when the full lateral confining stress is applied. In passive confinement, the concrete core suffers from some extent of damage which means lower f_{co} and lower angle of internal friction of concrete core when Equation (1) is used to determine the confined strength.

Generally, it is too difficult to estimate the reduced uniaxial strength of the damaged concrete core and its angle of internal friction at the time of full development of lateral confining stress. Instead, it is admitted that the core concrete has the original undamaged uniaxial strength and the correction to Equation (1) is made adjusting (empirically) the coefficient (1+ sin ϕ)/(1- sin ϕ) to values less than 4.

In agreement with these equations, Richart *et al.* [10] suggested the following expression to estimate the strength of plain concrete cylinders subjected to either active confinement from lateral pressure or passive confinement provide by restraint to lateral deformation from spiral stirrups:

$$f_{cc} = f_{co} + k_l f_l \qquad (2)$$

The factor k_l in Equation (2) was defined by them as a confining coefficient and was obtained empirically. Their experimental results showed that the coefficient k_l decreases as the lateral confining pressure increases, tending to a constant value equal to 4.1.

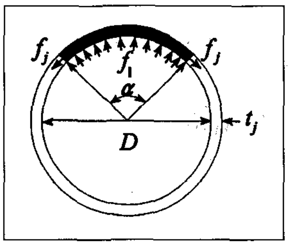

Fig. 1 – External confining action in column provided by composite.

In the case of circular cross-section column confined with FRP composite (see Fig. 1), the confining stress f_l, that is used in Equation (3) to obtain the confined concrete strength, can be obtained from the equilibrium of forces in the ULS in the plane of the column section:

$$f_l = \frac{2f_f t_f}{D} \tag{4}$$

where f_f is the tensile strength of the composite, t_f is its thickness and D is the confined concrete diameter.

Tests on circular and square columns wrapped with CFRP and GFRP (3, 5, 7, 8, 9, 11, 12, 14, 15, 16, 17), and with diameter or side length equal to 150 mm or 200 mm, showed that the concrete strength can be raised as high as three times its uniaxial strength.

Summary of some of the expressions, found in the literature, for estimating the confined concrete strength and the axial strain at failure are presented in Table 1.

Table 1 – Expressions for the strength of confined concrete and maximum axial deformation

Author	Type of confinement	Strength f_{cc}	Ultimate axial strain ε_{cc}
Fardis & Khalili (1981)	GFRP-encased concrete	$f_{co}\left[1+2.05\left(\frac{f_l}{f_{co}}\right)\right]$	$0.002\left[1+0.5\left(\frac{E_f\cdot t_f}{D\cdot f_{co}}\right)\right]$
Karbahari & Eckel (1993)	FRP-encased concrete	$f_{co}\left[1+2.1\left(\frac{f_l}{f_{co}}\right)^{0.87}\right]$	$0.002\left[1+5\left(\frac{2\cdot t_f\cdot f_f}{D\cdot f_{co}}\right)\right]$
Mirmiran & Shahawy (1997)*	GFRP-encased concrete	$f_{co}+4.269f_l^{0.587}$	
Miyauchi et al. (1997)**	CFRP-wrapped concrete	$f_{co}\left[1+3.5\left(\frac{f_l}{f_{co}}\right)\right]$	$0.002\left[1+10.6\left(\frac{2\cdot t_f\cdot f_f}{D\cdot f_{co}}\right)^{0.373}\right]$
Samaan et al. (1998)*	GFRP-encased concrete	$f_{co}+6.0f_l^{0.7}$	$\frac{f_{cc}-0.872f_{co}-0.371f_l-6.258}{245.61f_{co}^{0.2}+1.3456\frac{E_f t_f}{D}}$
Saafi et al. (1999)	CFRP and CFRP encased concrete	$f_{co}\left[1+2.2\left(\frac{f_l}{f_{co}}\right)^{0.84}\right]$	$\varepsilon_{co}\left[1+(537\varepsilon_f+2.6)\left(\frac{f_{cc}}{f_{co}}-1\right)\right]$
Toutanji (1999)	CFRP and GFRP wrapped concrete	$f_{co}\left[1+3.5\left(\frac{f_l}{f_{co}}\right)^{0.85}\right]$	$\varepsilon_{co}\left[1+(310.57\varepsilon_f+1.9)\left(\frac{f_{cc}}{f_{co}}-1\right)\right]$
Spoelstra & Monti (1999)	CFRP and GFRP wrapped and encased concrete	$f_{co}\left[0.2+3\left(\frac{f_l}{f_{co}}\right)^{0.5}\right]$	$\varepsilon_{co}\left(2+1.25\frac{E_c}{f_{co}}\varepsilon_f\sqrt{\frac{f_l}{f_{co}}}\right)$

* *units are in MPa,* ** *Equation for* ε_{cc} *is valid for* f_{co} *= 30 MPa*

Generally, for concrete columns confined with stirrups, the expression given to estimate the confined core concrete strength is:

$$f_{cc} = f_{co} + k_l k_e f_l \tag{3}$$

where $k_e f_l$ is the effective lateral confining pressure. For columns with circular cross-section and with distributed longitudinal reinforcement along their perimeters, the value of k_e is taken as 1.0 for closely spaced circular stirrups or spirals. In columns with square cross sections, due to non-uniformity of the lateral pressure in the plane of the section, even for high steel volumes and small spacing of lateral reinforcement, $k_e < 1.0$. In the case of rectangular sections the value of k_e is even lesser than the ones for square sections because the transversal stresses are different in the two orthogonal directions. Generally, the value of k_e is found to be dependent on the compressive strength of concrete, the volume and spacing of lateral reinforcement and the arrangement of longitudinal and lateral reinforcements.

3. EXPERIMENTAL PROGRAM

In order to evaluate the efficiency of the external confinement provided by CFRP sheets to increase the concrete strength and ductility, 54 concrete short columns were tested under axial compression. The specimens were mainly divided into three groups, 18 specimens each, by the cross section shape, circular, square and rectangular. Each group, in turn, was divided into three sub-groups, 6 specimen each, by the type of confinement: unconfined, confined with single wrapping and confined with double wrapping of CFRP sheets.

The circular columns were 150 mm in diameter, the square ones had 150 mm side length and the rectangular ones had 94 mm x 188 mm cross section. The cross sectional area of both the rectangular and circular columns was the same. All the specimens were 300 mm high in order to keep a minimum ratio of specimen height/short side length of the section equal to 2. The degree of rectangularity of the rectangular columns was equal to 2.

3.1 Materials

Two concrete mixes were made of two coarse aggregates with maximum size of 19 mm, both of the crushed stone type (gneiss in mix 1 and trachyte in mix 2). The proportion of both mixes, by mass, was of 1: 1.71: 2.84

Table 2 - Carbon fibre properties					
Fibre type	Mass per unit area (g/m²)	Tensile strength f_f (MPa)	Modulus of Elasticity E_f (GPa)	Nominal Thickness t_f(mm)	Ultimate strain ε_{fu} (%)
CF 130	300	3,550	235	0.165	1.5

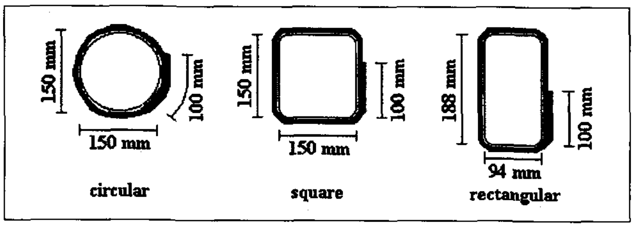

Fig. 2 – Cross section types and strengthening of tested columns.

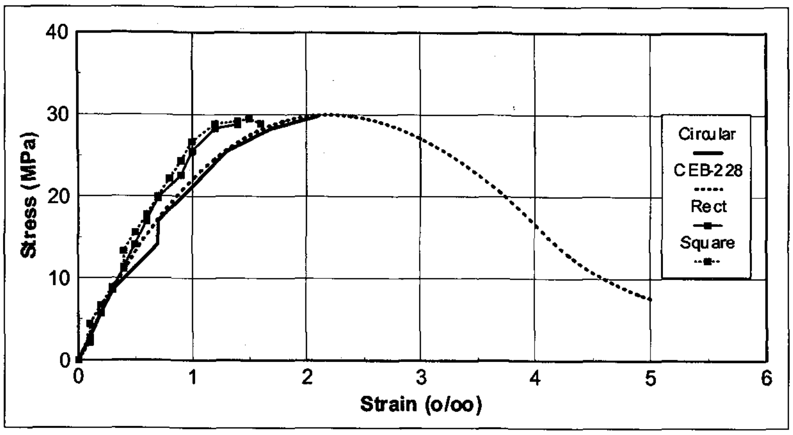

Fig. 3 – Comparison between the obtained stress-strain curves for unconfined columns and the one of CEB bulletin 228.

(cement: river sand: coarse aggregate), with water/ cement ratio = 0.63 and cement content equal to 329 kg/m^3. The slump of both mixes was around 100mm. The average compressive strengths of the concrete were approximately 25 MPa for mix 1 and 30 MPa for mix 2.

For columns strengthening, a primer and epoxy putty filler were firstly applied to their surfaces followed by a high solids epoxy resin to saturate the layers (one or two) of the CF sheets. Finally, a protective topcoat resin was applied. Table 2 gives the properties of the high tensile strength CF used in this work, according to MASTER BUILDERS TECHNOLOGIES.

3.2 Specimen preparation

Before strengthening, corners of the square and rectangular cross section columns were rounded off to a radius of about 10 mm (see Fig. 2), in order to prevent breakage of the CF sheets due to sharp bends, and the concrete surface of all columns was cleaned and completely dried.

Qualified personnel from the manufacturer then carried out the strengthening in 3 stages. In the first stage, a primer and epoxy putty filler were applied to the surfaces of the columns in order to let them even and free from defects and, then, the columns were left out for a complete day for curing. In the second following day, stage two was carried out by gluing the CF sheets, one or two layers, using surface coat epoxy resin. In the final stage a protective topcoat epoxy resin was applied.

In all strengthened columns, each layer had an overlap of about 100 mm to assure the development of full composite strength (Fig. 2). In the case of columns strengthened with 2 layers, the overlap positions, one for each of the CF layers, were opposite to one another. After strengthening, all columns had their ends, top and bottom, capped with sulphur to assure parallel surfaces and uniform load distribution.

Finally, in order to measure both longitudinal and lateral deformations of the columns during loading, strain gages were glued to their surfaces at mid height.

3.3 Test procedure and results

The specimens were placed in a 5000-kN test machine, one at a time, and subjected to increasingly compressive axial load, under a constant rate of 0.22 MPa/s, until their failure. At load intervals of 50 kN, the strain measurement was taken by means of a data-logger.

As the used test machine was not of the closed loop type, in the case of unconfined columns, measurements on the falling branch of the stress-strain curves were not possible. For this reason, the CEB bulletin 228 curve will be taken here as a reference for comparisons with confined concrete curves. The choice of the CEB bulletin 228 curve was based on the comparisons made in Fig. 3. In this figure, the obtained unconfined stress-strain curves (only ascending branches) are drawn together with the complete curve proposed by CEB bulletin 228. It can be observed the good match between that curve and the one obtained for the circular column. For square and rectangular columns, Fig. 3 shows some difference between the experimental curves and that of the CEB bulletin 228.

The obtained axial stress-longitudinal and lateral strain curves for some of the confined concrete columns are shown in Fig. 4 together with the unconfined stress-strain curve given by the CEB bulletin 228. In this figure, the individual curves are firstly identified by the direction of the strain, longitudinal (Long) or lateral (Lat), and secondly by the number of CFRP wraps provided, (w1) for one wrap, (w2) for two wraps and (wo) for none.

In Fig. 4 it can be clearly noticed that both the stress and strain at failure for the confined columns were higher than those for the unconfined ones and the highest values were obtained for confined circular columns with 2 CFRP sheet layers. Fig. 4 shows also how the

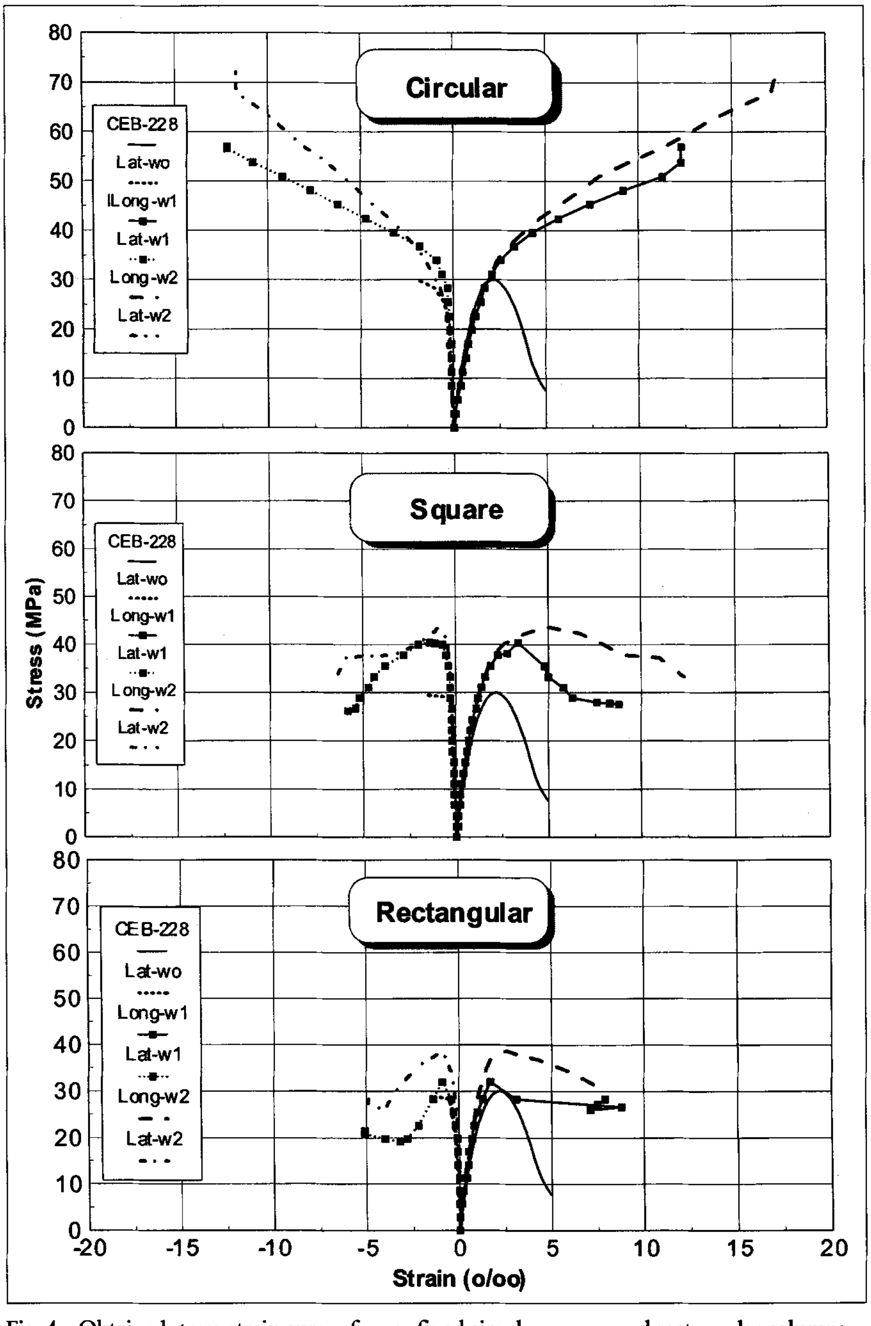

Fig. 4 – Obtained stress-strain curves for confined circular, square and rectangular columns.

Table 3 gives the compressive strength and ultimate axial strain for each of the tested columns with and without CFRP sheets (quoted values are average of three results). Also given in this table the relationships between the strengths of confined and unconfined concrete.

4. ANALYSIS OF THE OBTAINED RESULTS

From Table 3, it can be seen that the increase in strength varied according to the cross section shape and the amount of confinement provided by the CFRP (expressed in number of layers). For circular columns, the average increases in strength were in the order of 81% and 138% for columns with 1 layer and 2 layers, respectively, while the respective values for square columns were 27% and 51% and for rectangular ones were 10% and 37%.

It is clear from this table that the increase in strength provided by confinement is very sensitive to the cross section geometry and the amount of this increase drops sharply as the geometry deviates from the circular one.

Table 4 gives the estimated lateral confining pressure provided by the CFRP sheets according to Equation (4), with f_f = 3,550 MPa and t_f = 0.165 mm for one CFRP layer or 0.330 mm for two CFRP layers. As for the value of D, in the case of square columns it was considered the side length of the section while for the rectangular ones it was considered the long side length of the section, which gave the lesser confining stress value.

Also given in Table 4 the product of the parameters k_l and k_e as found from expression (3) for the tested columns of this work. To obtain their individual values for the different cases, first it was considered k_e = 1 for the circular columns, which led to k_l = 2.3 for mix 1 and k_l = 3.1 for mix 2. Admitting that the parameter k_l does only depend on the concrete used (strength and components), the values obtained for circular columns should be valid also for columns with other types of cross section made with the same concrete. Considering the known values of k_l, the values of k_e were deduced, and were on average equal to 0.33 for square columns confined with one or two layers, and equal to 0.16 and 0.30 for the rectangular ones confined with one layer and two layers, respectively.

ductility of the columns was affected by the increase of the degree of confinement.

For the columns with different cross section geometry (see Fig. 4), the effective confinement provided by the same number of CFRP sheets is maximum for the circular columns and minimum for the rectangular ones.

Fig. 5 illustrates the failure modes for circular, square and rectangular columns wrapped with CFRP sheets. For all confined columns with 1 layer, the CFRP sheets failed in tension at mid height of the column. For columns confined with 2 layers, generally, the failure initiated from one-fourth to midway of the height of columns, and occurred without warning. The breakage of the CFRP sheets in square and rectangular columns occurred at one of the columns corners, due to stress concentration in this region.

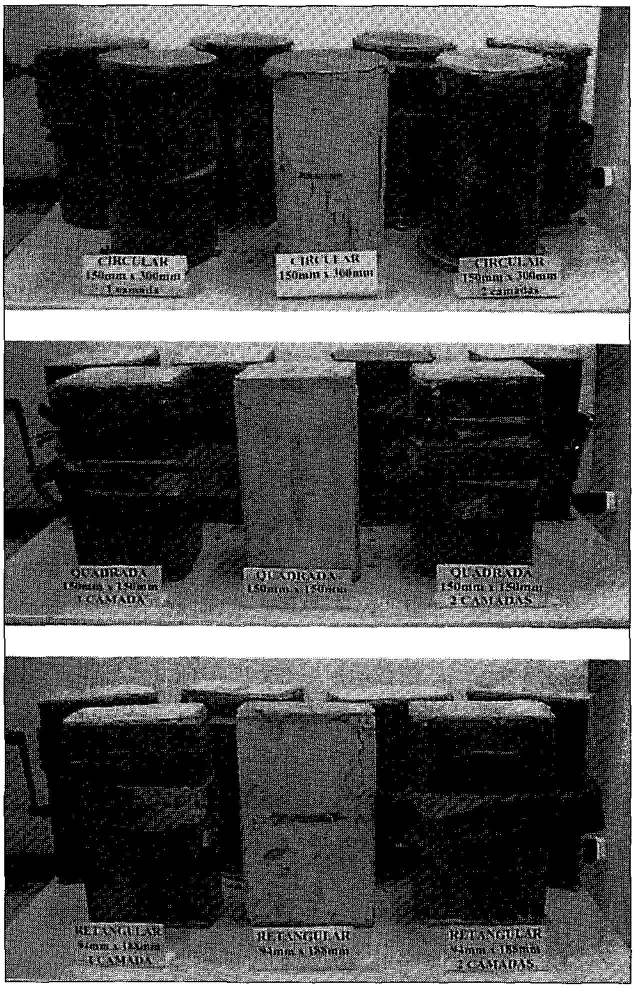

Fig. 5 – Typical failure modes for the tested columns.

In Fig. 6 the normalised confined compressive strength-normalised confining lateral pressure plots for the test results of this work are shown, together with their respective linear regressions, while Fig. 7 gives this relationship for circular specimens from this work and from others (3, 5, 7, 8, 9, 11, 12, 14, 15, 16, 17) confined with either glass or carbon fibre. From these figures, it can be seen that the normalised confined compressive strength, approximately, increase linearly with the increase in normalised confining lateral pressure for all types of section geometry. There is also a great distinction between the tendency of the results obtained for circular columns and those for square and rectangular ones.

Fig. 8 shows the relationship between the normalised ultimate strain and the quantity $(f_l/f_{co}).\ (f_{co}/E_f)$ for the tests of this work and for others (3, 5, 7, 8, 9, 11, 12, 14, 15, 16, 17). This figure includes results of columns confined with both carbon fibre and glass fibre sheets. The choice of the upper mentioned two terms, (f_l/f_{co}) and (f_{co}/E_f), was based on previous regression analyses of the test results which were made with each term individually and showed the dependency of the axial strain on both.

The equations deduced from the regression analysis, for the strength and the deformation were as follows:

a) For circular columns

The equations for the confined concrete strength are

$$\frac{f_{cc}}{f_{co}} = 1 + 2.0\frac{f_l}{f_{co}} \quad \text{for average values} \qquad (5a)$$

Table 3 – Compressive strength and ultimate strains values for the tested concrete columns

column	Without CFRP		With CRFP									
			1 layer					2 layers				
	f_{co} MPa	ε_{co} o/oo	f_{cc} MPa	ε_{cc} o/oo	f_{cc}/f_{co}	$\varepsilon_{cc}/\varepsilon_{co}$	f_l/f_{co}	f_{cc} MPa	ε_{cc} o/oo	f_{cc}/f_{co}	$\varepsilon_{cc}/\varepsilon_{co}$	f_l/f_{co}
C1-25	25.6	-	43.9	-	1.71	-	0.31	59.6	-	2.33	-	0.61
C2-30	29.8	2.1	57.0	12.3	1.91	5.86	0.26	72.1	17.4	2.42	8.29	0.52
S1-25	23.7	-	27.4	-	1.16	-	0.33	36.5	-	1.54	-	0.66
S2-30	29.5	1.6	40.4	8.8	1.37	5.50	0.27	43.7	12.3	1.48	7.69	0.53
R1-25	23.7	-	25.8	-	1.09	-	0.26	33.2	-	1.40	-	0.53
R2-30	28.8	1.4	32.0	7.9	1.11	5.64	0.22	38.7	7.5	1.34	5.36	0.43

Table 4 – Values of lateral confining pressure and product $k_l\, k_e$ for tested columns

Cross section shape/batch		CRFP			
		1 layer		2 layers	
		f_l (MPa)	$k_l k_e$	f_l (MPa)	$k_l k_e$
Circular	C1-25	7.8	2.3	15.6	2.2
	C2-30		3.5		2.7
Square	S1-25	7.8	0.5	15.6	0.8
	S2-30		1.4		0.9
Rectangular	R1-25	6.2	0.3	12.5	0.8
	R2-30		0.5		0.8

$$\left(\frac{f_{cc}}{f_{co}}\right)_k = 1 + 1.25\frac{f_l}{f_{co}} \quad \text{for characteristic values} \qquad (5b)$$

where the characteristic equation was determined by the 95% confidence limit for the tests from this work and others, while the equation for the ultimate concrete strain is:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 632\left(\frac{f_l}{f_{co}} \cdot \frac{f_{cc}}{E_f}\right)^{0.5} \qquad (6)$$

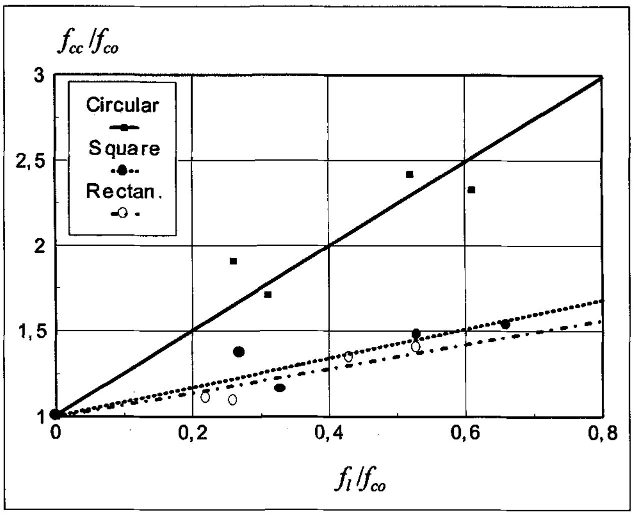

Fig. 6 – Normalised confined compressive strength-normalised confining lateral pressure relationship for the test results of this work.

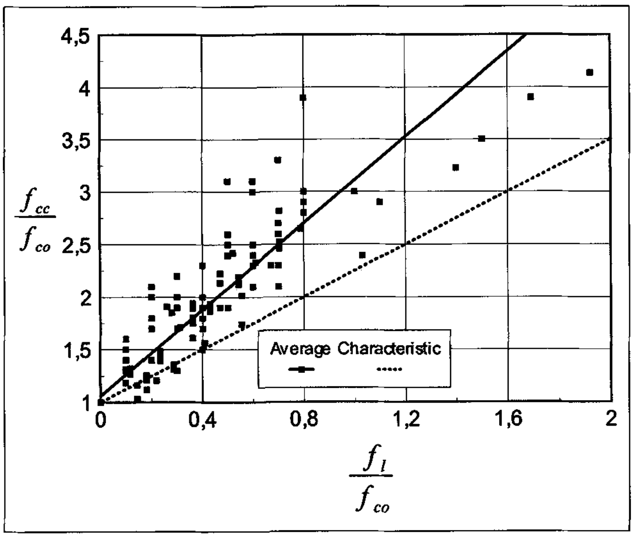

Fig. 7 – Normalised confined compressive strength-normalised confining lateral pressure for circular columns.

b) For square columns

For the few test results of this work, the equation for the average confined concrete strength is:

$$\frac{f_{cc}}{f_{co}} = 1 + 0.85\frac{f_l}{f_{co}} \tag{7}$$

and the equation for the ultimate concrete strain is:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 13.5\frac{f_l}{f_{co}} \tag{8}$$

c) For rectangular columns

The equation for the average confined concrete strength is:

$$\frac{f_{cc}}{f_{co}} = 1 + 0.7\frac{f_l}{f_{co}} \tag{9}$$

and the equation for the ultimate concrete strain is:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 12.4\frac{f_l}{f_{co}} \tag{10}$$

As the number of test results for columns with square and rectangular cross sections is very limited, equations for the characteristic confined concrete strength are not proposed for these cases.

5. COMPARISONS BETWEEN THE DIFFERENT EQUATIONS

With respect to the confined concrete strength, as the equations reviewed (refer to Table 1) were deduced from tests on circular columns, the comparisons made in Table 5, with the results of this work only, shows clearly that their validity is restricted to such cases. The best results were obtained from the equation given by Mirmiran & Shahaby [7] with an average of $f_{cc,cal}/f_{cc,exp}$ = 1.10 and a standard deviation of 0.25 for all columns irrespective of the section geometry. The disadvantage of this equation is its

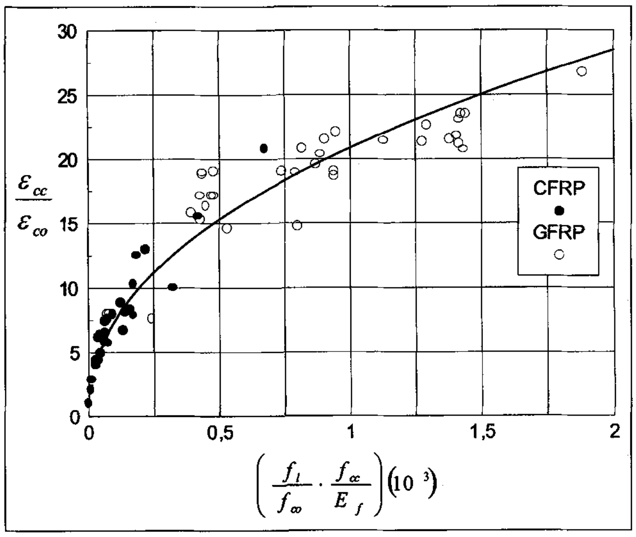

Fig. 8 – Normalised ultimate strain-$(f_l/f_{co})\cdot(f_{co}/E_f)$ curves for tests of circular columns available in the literature.

dimensional form. Except for the equations given by Toutanji [15] and Miyauchi *et al.* [8] that did not give generally good results, the rest of the equations gave good results for circular columns and extremely bad ones for columns with square and rectangular cross sections.

Table 6 summarises a comparison made between the different equations, the non-dimensional ones in Table 1 and the equation proposed in this work (Equation (5a)) for circular columns, and 80 test results collected from different sources [3, 5, 7-9, 11, 12, 14-17], including the ones from this work. This table shows that both the proposed Equation (5a) and the equation suggested by Saafi *et al.* [12] gave good results, with average $f_{cc,cal}/f_{cc,exp}$ = 0.98 and standard deviation equal to 0.12. The only difference between these two equations is that the proposed one is a linear equation while the other, suggested by Saafi *et al.* [12], is not. The equations given by Toutanji [15] and Miyauchi *et al.* [8] continued to give

Table 5 - Comparisons between calculated and experimental values of the confined concrete strength and maximum axial strain with $\alpha = f_{cc,cal} / f_{cc,exp}$ and $\beta = \varepsilon_{cc,cal} / \varepsilon_{cc,exp}$

Cross section/ batch	Author (1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
	α	β	α	β	α	β	α	β	α	β	α	β	α	β	α	β
Columns with 1 CFRP sheet layer																
C1-25	0.95	-	1.02	-	0.91	-	1.21	-	1.16	-	1.06	-	1.32	-	1.08	-
C2-30	0.80	0.87	0.87	0.37	0.77	-	1.00	1.21	0.97	2.14	0.90	1.74	1.11	-	0.91	1.89
S1-25	1.45	-	1.55	-	1.39	-	1.86	-	1.79	-	1.61	-	2.04	-	1.66	-
S2-30	1.13	1.23	1.21	0.52	1.08	-	1.41	1.69	1.36	0.75	1.26	1.13	1.56	-	1.27	2.68
R1-25	1.41	-	1.52	-	1.40	-	1.76	-	1.76	-	1.58	-	1.95	-	1.60	-
R2-30	1.30	1.16	1.40	0.53	1.29	-	1.58	1.77	1.58	-	1.45	0.56	1.76	-	1.43	3.08
Columns with 2 CFRP sheet layers																
C1-25	0.97	-	1.02	-	0.79	-	1.35	-	1.12	-	1.05	-	1.42	-	1.09	-
C2-30	0.86	1.11	0.91	0.41	0.71	-	1.17	1.07	0.98	1.66	0.94	1.85	1.25	-	0.98	1.52
S1-25	1.53	-	1.60	-	1.24	-	2.15	-	1.78	-	1.65	-	2.24	-	1.71	-
S2-30	1.41	1.59	1.49	0.59	1.16	-	1.93	1.52	1.62	0.41	1.54	1.00	2.05	-	1.61	2.18
R1-25	1.48	-	1.57	-	1.28	-	2.03	-	1.77	-	1.63	-	2.16	-	1.70	-
R2-30	1.40	2.17	1.50	0.84	1.23	-	1.87	2.33	1.65	3.47	1.56	1.24	2.02	-	1.62	3.35
average	1.22	1.36	1.31	0.54	1.10	-	1.61	1.60	1.46	1.69	1.35	1.25	1.74	-	1.39	2.45
Std.Dev	0.27	0.46	0.28	0.17	0.25	-	0.38	0.45	0.32	1.21	0.29	0.48	0.39	-	0.30	0.71

(1) Fardis & Khalili (1981), (2) Karbhari et al. (1993), (3) Mirmiran & Shahawy (1997), (4) Miyauchi et al. (1997), (5) Samaan & Mirmiran (1998), (6) Saafi et al. (1999), (7) Toutanji (1999), (8) Spoelstra & Monti (1999).

Table 6 - Comparisons between calculated and experimental values of the confined concrete strength of circular columns (for 80 test results from this work and from others)

	Author						
	Proposed	(1)	(2)	(3)	(4)	(5)	(6)
	$f_{cc,cal} / f_{cc,exp}$						
Average	0.98	0.91	0.95	1.20	0.98	1.26	0.92
Std.Dev.	0.12	0.12	0.12	0.20	0.12	0.19	0.27

(1) Fardis & Khalili (1981), (2) Karbhari et al. (1993), (3) Miyauchi et al. (1997), (4) Saafi et al. (1999), (5) Toutanji (1999), (6) Spoelstra & Monti (1999).

bad results when compared with the others.

As it can be seen from Table 5, none of the suggested equations in Table 1 for the ultimate deformation of confined concrete gave good estimate when compared with the test results of this work. For circular columns, where there is a reasonable number of tests results, the equations proposed in this work, extracted from the regression analysis, gave good results for both columns confined with GFRP and CFRP. The obtained average and standard deviation for the value of the ratio $(\varepsilon_{cc} / \varepsilon_{c0})_{exp} / (\varepsilon_{cc} / \varepsilon_{co})_{cal}$ were 1.02 and 0.16 for columns confined with GFRP and were 1.01 and 0.16 for columns confined with CFRP.

6. CONCLUDING REMARKS

This work investigated the behaviour of confined short column models with different cross section geometry and degree of confinement. The obtained results showed that the efficiency of the confinement is very sensitive to the column cross section geometry (circular, square and rectangular) and the confining stress expressed in the number of the CFRP sheet layers applied.

On the basis of the obtained results, equations were proposed, for the confined concrete strength and the ultimate confined concrete strain as a function of the confining lateral stress, for each of the cross section geometry used: circular, square and rectangular. The estimations given by these equations and by formulas found in the literature were compared with the experimental ones from this work and from others.

From the comparisons made in this work it is clear that proposed equations to estimate the confined concrete strength should be associated with the cross section shape and their validity is limited to that geometry. The ultimate deformation at failure is found to be dependent on the lateral confinement, the confined concrete strength and the modulus of elasticity of the FRP used for confinement.

LIST OF SYMBOLS

D diameter of a circular column
E_f modulus of elasticity of CFRP
E_l lateral modulus of elasticity of CFRP in confined specimens
f_{co} compressive strength of unconfined concrete
f_{cc} compressive strength of confined concrete
f_f tensile strength of the carbon fibres
f_l lateral confining stress
k coefficient
t_f thickness of CFRP
α, β coefficients
ε_{co} uniaxial concrete stıain at peak stress f_{co}
ε_{cc} ultimate confined concrete strain
ε_{fu} ultimate CFRP strain

ACKNOWLEDGEMENT

The authors would like to thank Mr. Alexandre Duarte, chairman of TEPREM Structural Repair Co., for the donation of the strengthening materials (MBrace™) and for the provided technical support, and the Brazilian Government Research Agencies CAPES and CNPq for financing this project.

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