Ninth Canadian Conference on Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

BEHAVIOR OF FRP-WRAPPED CIRCULAR REINFORCED CONCRETE COLUMNS

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ABSTRACT

Reinforced concrete columns are usually reinforced with longitudinal reinforcement and at least a minimum amount of transverse steel reinforcement. Therefore, concrete columns that have to be retrofitted by fiber reinforced polymer (FRP) sheets due to lack of confinement, usually contain transverse steel reinforcement. This paper presents tests performed on small and large-scale circular FRP and FRP-steel confined concrete columns under concentric loading. The test program was chosen to study the effect of the unconfined concrete strength, the volumetric ratio, the type and the yield strength of the transverse steel reinforcement, the concrete cover, and the number of FRP layers on the behavior of concrete columns subjected to axial load. The results show that the increase in the confined concrete strength and strain is more pronounced in specimens with a normal strength concrete. The results obtained from tests of large-scale reinforced concrete columns show that the rupture of the FRP in specimens with higher volumetric transverse reinforcement ratio corresponds to larger axial compressive strength and strain. Moreover, the post-peak behavior of these specimens is also more ductile. It was also noticed that the behavior of the specimens with the same volumetric transverse reinforcement ratio is similar after the FRP rupture. This behavior is well predicted by the proposed model which is suitable not only for the axial behavior of circular concrete columns confined by transverse reinforcement or by FRP wraps but also by both transverse reinforcement and FRP wraps.

Introduction

A large number of experiments have been conducted in order to investigate the compressive behavior of concrete confined with FRP wraps or tubes (e.g., Fardis and Khalili 1982, Saafi et al. 1999, Xiao and Wu 2000, Lam and Teng 2004). The published test results show that the stress-strain behavior of the concrete well confined with FRP is characterized by two ascending parts with an increase of the ultimate concrete compressive strength and strain, which correspond to the FRP rupture strain. Most of the available test results are based on small-scale plain normal-strength concrete. Very few tests were performed in order to investigate the behavior of high strength concrete (HSC) columns confined by FRP (Harmon and Slattery 1992, Miyauchi et al. 1999, Mandal et al. 2005) or to investigate the behavior of reinforced concrete columns confined by both transverse steel reinforcement (TSR) and FRP (Demers and Neale 1999, Matthys et al. 2005, Carey and Harries 2005). Moreover, most of the available test results of reinforced concrete columns confined by FRP contain small volumetric transverse steel reinforcement

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ratio that do not influence the behavior of the FRP-confined column. The insufficient information regarding the behavior of FRP-steel confined concrete columns and the behavior of FRP-confined high strength concrete was noted in several studies (DE Lorenzis and Tepfers 2003, Teng and Lam 2004).

Structural concrete design codes require not only longitudinal but also a minimum amount of transverse reinforcement in concrete columns. Thus, the retrofitted concrete column is under two actions of confinement, the action due to the FRP and the action due to the steel ties. This paper presents tests performed on small and large-scale circular FRP and FRP-steel confined concrete columns under concentric loading. The tests were designed and performed in the civil engineering laboratories at the University of Sherbrooke. Moreover, an analytical confinement model is proposed for the axial behavior of circular concrete columns confined by transverse steel reinforcement and FRP wraps.

Experimental Program

Thirty-six FRP-wrapped concrete cylinders (152×300 mm) and 21 (16 wrapped and 6 unwrapped) large scale reinforced concrete columns (303×1200 mm) were tested under concentric loading. Fig. 1 shows details of the large scale test specimens. The experimental program was designed to examine the effect of the following variables on the behavior of concrete elements subjected to axial compression load: the unconfined concrete strength, $f_c^{'}$, the volumetric ratio, the type and the yield strength of the transverse steel reinforcement (f_{yh}), the concrete cover, and the number of FRP layers. Tables 1 and 2 provide the details of the concrete cylinders and the reinforced concrete columns. It should be noted that the volumetric transverse steel reinforcement ratio was chosen according to the ACI 318-05 Code (2005) and the CSA A23.3-94 Standard (1994).

Carbon fiber reinforced plastic (CFRP) sheets, with ply thickness of 0.381 mm, were used to provide the external confinement. The externally confined reinforced concrete columns and the plain concrete cylinders were wrapped with 2 and 4 and with 1, 2 and 3 CFRP layers, respectively. The mechanical properties of the FRP were obtained based on coupon tests (ASTM D 3039 1995) with an average results of 78 GPa, 1050 MPa and 0.0134 for the elastic modulus, E_f, the ultimate tensile strength, f_{fu}, and the ultimate tensile strain ε_{fu}, respectively. Complete details of the test specimens' instrumentation and the mechanical properties of the plain concrete and the steel bars are given in Eid et al. (2006).

Experimental Results

Typical appearance after testing of the concrete cylinders and the reinforced concrete columns is shown in Fig. 2. The axial load sustained by the concrete, P_c, was determined for each specimen by subtracting the load carried by the longitudinal bars from the total load. The stress-strain response of the specimens coincides with the ascending part of the curve P_c/A_c where, A_c is the total concrete cross-sectional area. After the FRP ruptures (or after the spalling of the concrete cover for the unwrapped specimens) the confined concrete cross-sectional area is defined only by the area between the centerline of the TSR and therefore the post FRP rupture part coincides with the curve of P_c/A_{cc} where, A_{cc} is the concrete core cross-sectional area. The transition between the two curves is estimated as a linear curve or as a smooth curve for the wrapped and the unwrapped specimens, respectively.

Effect of concrete compressive strength

Fig. 3 shows the 2-layers FRP-confined cylinders' relative concrete load P_c/P_{0c} ($P_{0c} = 0.85 f_c^{'} A_c$) versus the axial and the lateral strains for the N, M, H1, and H2 series. Average strength gains of P_c/P_{0c} = 2.11, 1.96, 1.42, and 1.27 and average strain gains of $\varepsilon_{cu}/\varepsilon_c^{'}$ = 9.06, 5.01, 3.50, and 2.32 were obtained for specimens N, M, H1, and H2 with 2 layers of FRP wrapping, respectively. The test results indicate that

Table 1. Details of plain concrete specimens (152×300mm).

Series	$f_c^{'}$ (MPa)	**FRP layers**	***t*** **(mm)**	$f_{lf}/f_c^{'}$ (1)	**No. of specimens**
N	32.1	1	0.381	0.16	3
		2	0.762	0.33	3
	33.6	3	1.143	0.47	3
M	48	1	0.381	0.11	3
		2	0.762	0.22	3
		3	1.143	0.33	3
H1	67.7	1	0.381	0.08	3
		2	0.762	0.15	3
	75.9	3	1.143	0.21	3
H2	107.7	1	0.381	0.05	3
		2	0.762	0.1	3
		3	1.143	0.15	3

(1) $f_{lf} = 2tE_f\varepsilon_{fu}/D$

Table 2. Details of test columns (length of 1200mm).

Specimen	$f_c^{'}$ **(MPa)**	***D***(2) **(mm)**	***c***(3) **(mm)**	**Transverse reinforcement**					**FRP**		
				ϕ_h **(mm)**	***s*** **(mm)**	f_{yh} **(MPa)**	ρ_s **(%)**	$f_{ls,e}/f_c^{'}$ (1)	**layers**	***t*** **(mm)**	$f_{lf}/f_c^{'}$ (1)
A5NP2C	29.4	303	25	9.5	150	602	0.72	0.04	2	0.762	0.18
A3NP2C	31.7				70		1.54	0.12			0.17
A1NP2C	31.7				45		2.42	0.21			0.17
C4NP0C	31.7	303	25	11.3	100	456	1.51	0.1	0	0	0
C4N1P0C	36.0							0.09			
C4NP2C	31.7							0.1	2	0.762	0.17
C4N1P2C	36.0							0.09			0.15
C4NP4C	31.7							0.1	4	1.524	0.33
B4NP2C	31.7	303	25					0.08	2	0.762	0.17
C4MP0C	50.8	303	25	11.3	100	456	1.51	0.06	0	0	0
C4MP2C									2	0.762	0.1
C2NP0C	31.7	303	25	11.3	65	456	2.33	0.17	0	0	0
C2N1P0C	36.0							0.15			
C2NP2C	31.7							0.17	2	0.762	0.17
C2N1P2C	36.0							0.15			0.15
C2N1P4C	36.0							0.15	4	1.524	0.29
C2N1P2N	36.0	253	0					0.15	2	0.762	0.18
C2MP0C	50.8	303	25	11.3	65	456	2.33	0.1	0	0	0
C2MP2C									2	0.762	0.1
C2MP4C									4	1.524	0.21
C2MP2N	50.8	253	0					0.1	2	0.762	0.12

(1) $f_{ls,e} = K_e A_{sh} f_{yh}/sD_c$; $f_{lf} = 2tE_f\varepsilon_{fu}/D$. (2) Column's diameter. (3) Concrete cover.

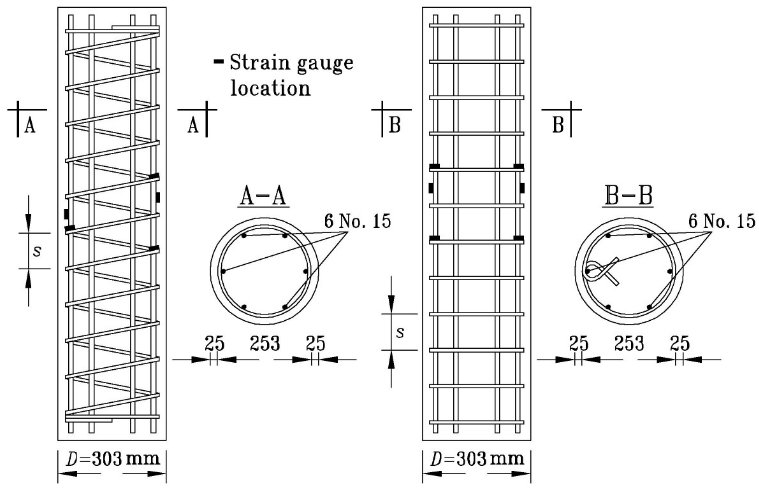

Figure 1. Reinforcing cage of the concrete columns 303×1200 mm.

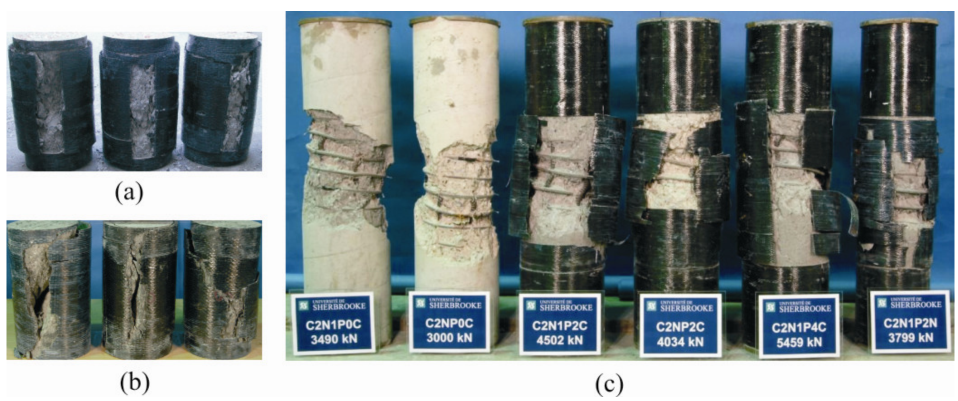

Figure 2. Appearance after testing of (a) normal (series N) and (b) high strength (series H2) FRP-confined cylinder specimens and of (c) FRP-steel confined normal strength concrete columns (N and N1 series with 65 mm spiral spacing).

the highest strength and strain gains are observed for specimens made with lower strength concrete. The axial stress-strain behavior of the confined high strength concrete cylinders (H2 series and the low confined specimens of H1 series) is characterized by ascending and descending branches, as opposed to the axial behavior of the confined normal and moderate strength concrete which is characterized by a bilinear curve.

Effect of transverse steel reinforcement - TSR

The influence of the transverse steel reinforcement (TSR) on the behavior of the FRP-confined concrete is illustrated in Fig. 4. The figure shows the unconfined and the confined stress-strain response of normal (Fig. 4a) and moderate (Fig. 4b) strength concrete under three types of passive confinement: TSR confinement, FRP confinement, and both TSR and FRP confinement. It can be seen in the figure that for the same effective lateral FRP pressure, f_{lf}/f'_c ($f_{lf} = 2tE_f\varepsilon_{fu}/D$), the specimens with the lateral reinforcement (internal confinement) have higher ultimate strengths and strains. It is also shown that the behavior of the TSR-FRP confined concrete columns is superior than the specimens with one confining material and when the FRP ruptures the stress-strain curve is close to the curve of the TSR confined specimen (note that for specimen C4NP4C only the load after the rupture of the FRP was recorded). Fig. 5 shows that increasing the volumetric TSR ratio for a column with the same FRP confinement results in an increase in the ultimate strength and strain and in an enhancement of the post-peak behavior for both normal and moderate strength concrete.

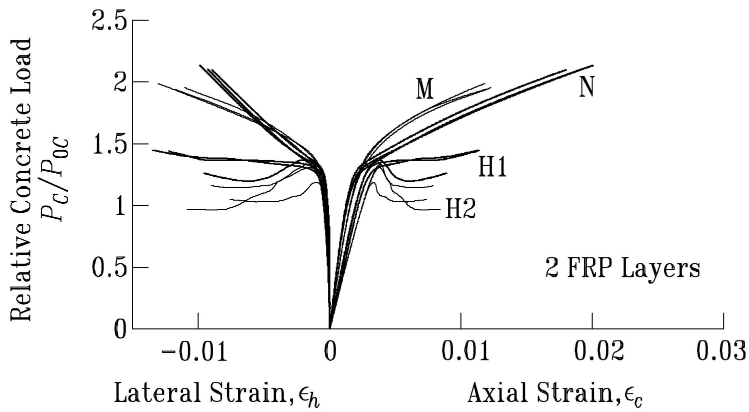

Figure 3. Experimental stress-strain curves for different strength concrete.

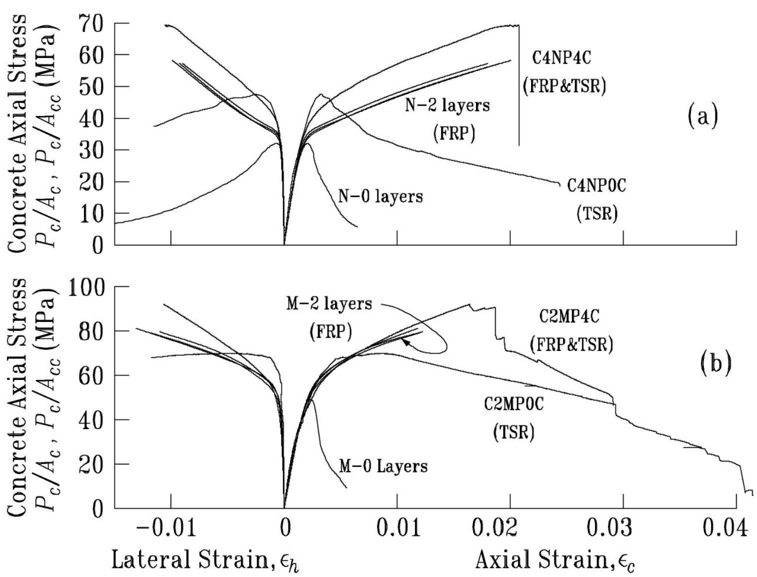

Figure 4. Experimental stress-strain curves for unconfined and confined concrete specimens confined by only transverse steel reinforcement (TSR), by only FRP, and by both TSR and FRP.

Effect of number of FRP layers

The test results show that increasing the number of FRP layers results in an increase in the axial compressive ultimate strength and strain of the FRP-wrapped reinforced concrete columns. The results also show that the influence of the FRP confinement is less efficient for higher concrete strength. According to the test results the higher the number of FRP layers the higher the ratio $\xi = \varepsilon_{\text{fu,a}}/\varepsilon_{\text{fu}}$ where, $\varepsilon_{\text{fu,a}}$ is the actual FRP rupture strain. Several researchers have suggested that this ratio is mainly affected by the curvature of the FRP and the nonuniform deformation of the cracked concrete (De Lorenzis and Tepfers 2003, Lam and Teng 2004, Matthys et al. 2005). The influence of the nonuniform deformation of cracked concrete on $\varepsilon_{fu,a}/\varepsilon_{fu}$ is affected by the number of the FRP layers, the elastic modulus of the FRP and the cross-section size of the column. The test results of this research show that the average ratio $\varepsilon_{fu,a}/\varepsilon_{fu}$ for the concrete cylinders (D=152 mm) and for the concrete columns (D=303 mm) is 73% and 61%, respectively. Thus, the larger the cross-section size of the column the smaller the ratio $\varepsilon_{fu,a}/\varepsilon_{fu}$.

Effect of concrete cover

The test results show that the ultimate axial stress and strain developed in the confined concrete core are higher for columns without concrete cover. The lateral pressure acting on the concrete cover due to the FRP is smaller than the lateral pressure acting on the concrete core due to the TSR and the FRP. Thus, the stress-strain behavior of concrete column confined by both TSR and FRP is improved when there is no concrete cover.

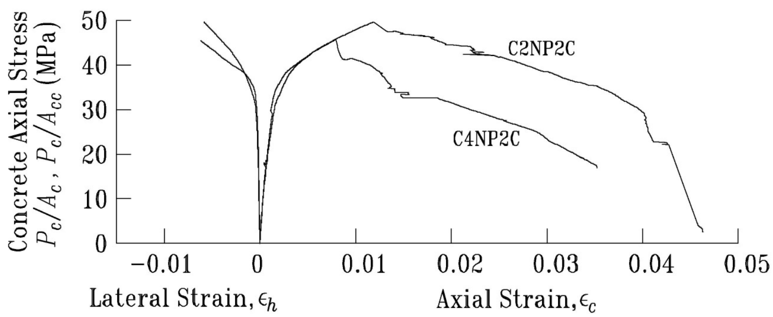

Figure 5. Effect of volumetric TSR ratio on the behavior of the FRP-wrapped reinforced concrete columns.

Analytical stress-strain model

Several models have been proposed to predict the compressive axial behaviour of steel-confined concrete columns (e.g., Sheikh and Uzumeri 1982, Mander et al. 1988, Cusson and Paultre 1995, Légeron and Paultre 2003) and of FRP-confined concrete columns (e.g., Saafi et al. 1999, Spoelstra and Monti 1999, Lam and Teng 2003). However, these models cannot be applied for concrete columns confined with both transverse steel reinforcement and FRP wraps. The proposed model which is based on the Légeron and Paultre (2003) steel-confined concrete model, can be used also for columns confined either by only lateral steel or by only FRP composite (See Fig. 6). The pre-peak branch of the proposed model is based on a relationship originally proposed by Sargin (1971):

$$f_c = \frac{a\varepsilon_c}{1 + b\varepsilon_c + z\varepsilon_c^2} \qquad \varepsilon_c \le \varepsilon'_{cc} \tag{1}$$

where:

$$a = E_c ; \qquad b = \frac{E_c}{f'_{cc}} - \frac{2}{\varepsilon'_{cc}} + \frac{E_c E_{cu} \varepsilon'_{cc}}{f'^{\,2}_{cc}} ; \qquad z = \frac{1}{\varepsilon'^{\,2}_{cc}} - \frac{E_c E_{cu}}{f'^{\,2}_{cc}} \tag{2}$$

E_c is the concrete's modulus of elasticity, and f'_{cc} and ε'_{cc} are the confined concrete peak stress and its corresponding strain, respectively. The expressions of these variables are function of the effective lateral pressure at peak stress, f_{le} (Légeron and Paultre 2003):

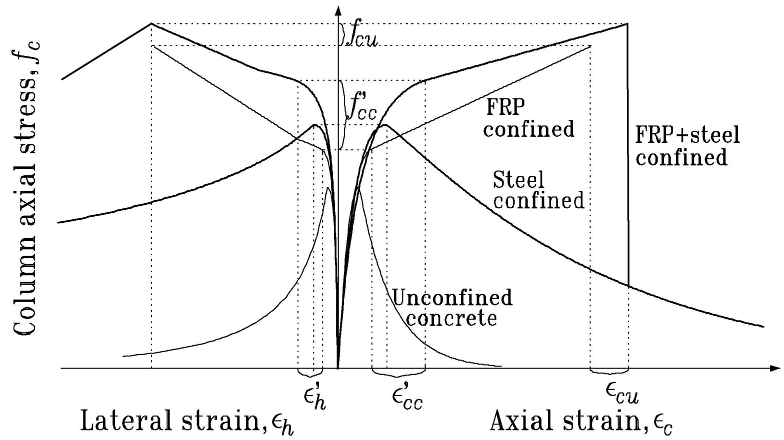

Figure 6. Proposed stress strain curve for FRP-steel confined concrete.

$$\frac{f'_{cc}}{f'_c} = 1 + 2.4(f_{le}/f'_c)^{0.7} \; ; \quad \frac{\varepsilon'_{cc}}{\varepsilon'_c} = 1 + 35(f_{le}/f'_c)^{1.2} \tag{3}$$

where f'_c and ε'_c are the unconfined concrete strength and its corresponding strain, respectively. The effective lateral pressure, f_{le}, is derived by a superposition of the steel and the FRP confinement actions:

$$f_{le} = K_e f_{ls} + f_{lf} \tag{4}$$

where K_e is a coefficient introduced by Sheikh and Uzumeri (1982) and Mander et al. (1988), which reflects the effectiveness of the lateral steel in confining the concrete. The lateral pressures at peak concrete stress due to the action of the transverse reinforcement, f_{ls}, and due to the action of the FRP, f_{lf}, are derived based on force equilibrium of the half cross-section:

$$f_{lf} = \frac{2\,t\,E_f \varepsilon_{fc}}{D} \; ; \quad f_{ls} = \frac{A_{sh} f_{hc}}{s D_c} \tag{5}$$

where t is the thickness of the FRP, E_f is the elastic modulus of the FRP, ε_{fc} is the strain in the FRP at peak concrete stress, D is the column full diameter, D_c is the concrete core diameter, s is the steel tie spacing, f_{hc} is the stress in the lateral steel at peak concrete stress and A_{sh} is the total cross-section area of the transverse reinforcement.

The Légeron and Paultre (2003) stress-strain model can not be used for columns confined by FRP composite, mainly because the post-peak branch of the stress-strain relationship is defined by an exponential descending expression. In order to make the proposed model suitable for concrete columns confined by FRP or by FRP and steel, the descending nature of the post-peak branch is modified by adding a linear part to the exponential expression:

$$f_c = \begin{cases} f'_{cc} \exp\left[k_1(\varepsilon_c - \varepsilon'_{cc})^{k_2}\right] + E_{cu}(\varepsilon_c - \varepsilon'_{cc}) \quad , & \varepsilon_{cu} \geq \varepsilon_c > \varepsilon'_{cc} \\ f'_{cc,s} \exp\left[k_{1,s}(\varepsilon_c - \varepsilon'_{cc,s})^{k_{2,s}}\right] \quad , & \varepsilon_c > \varepsilon_{cu} \end{cases} \tag{6}$$

where k_1 and k_2 are parameters controlling the shape of the post-peak branch (Légeron and Paultre 2003) and E_{cu} is the slope of the curve after the peak:

$$E_{cu} = \frac{f_{cu} - f'_{cc}}{\varepsilon_{cu} - \varepsilon'_{cc}} \leq \frac{f_{cu} - f'_c}{\varepsilon_{cu}} \quad (\text{and } E_{cu} \geq 0) \tag{7}$$

Based on the test results which are presented in this paper and also on published test results, it was found that the expressions proposed by Lam and Teng (2003) for the ultimate concrete strength, f_{cu}, and strain, ε_{cu}, of FRP-confined normal strength concrete columns can be used for FRP and FRP-steel confined normal and high strength concrete with a minor modification of the ultimate strain expression:

$$\frac{f_{cu}}{f'_c} = 1 + 3.3\left(K_e \frac{A_{sh} f_{yh}}{s D_c f'_c} + \frac{2 t E_f \varepsilon_{fu}}{D f'_c} \cdot \xi\right) \geq \frac{f'_{cc}}{f'_c} \tag{8}$$

$$\frac{\varepsilon_{cu}}{\varepsilon'_c} = 1.56 + 12\left(k_e \frac{A_{sh} f_{yh}}{s D_c f'_c} + \frac{2 t E_f \varepsilon_{fu}}{D f'_c} \cdot \xi\right)\left(\frac{\varepsilon_{fu}}{\varepsilon'_c} \xi\right)^{0.45} \tag{9}$$

where ξ is the efficiency factor = $\varepsilon_{fu,a}/\varepsilon_{fu}$, ε_{fu} is the ultimate FRP tensile strain which is based on flat coupon tests and f_{yh} is the yield stress of the lateral steel. It should be noted also that the values of $f'_{cc,s}$, $\varepsilon'_{cc,s}$, $k_{1,s}$ and $k_{2,s}$ are derived using the same expressions of f'_{cc}, ε'_{cc}, k_1 and k_2, respectively, for concrete confined by only steel ties. The total stress-strain behavior of the confined concrete columns is derived by combining the axial behavior of the concrete core, which is confined by the dual action of steel ties and composite wrapping with the axial behavior of the concrete cover, which is confined only by the composite wrapping. Complete details of the proposed model are given in Eid and Paultre (2006).

Fig. 7 compares between the analytical and the experimental stress-strain curves of FRP and FRP-steel confined normal and high-strength concrete columns. Moreover, Fig. 8 shows comparison between the proposed model and published experimental results of FRP and FRP-steel confined normal strength concrete columns (Demers and Neale 1999, Lam and Teng 2004). These figures show good agreement between the predicted and the measured stress-strain curves.

Conclusions

This paper presents experimental results obtained from small and large-scale circular FRP and FRP-steel confined concrete columns tested under concentric loading. The test results show that the increase in the confined concrete strength and strain is more pronounced in specimens with a normal strength concrete. It is shown also that the rupture of the FRP in the specimens with higher volumetric transverse reinforcement ratio corresponds to larger axial compressive strength and strain and that the post-peak behavior of these specimens is more ductile. Furthermore, the behavior of the specimens with the same volumetric transverse reinforcement ratio is similar after the FRP rupture. This behavior is well predicted by the proposed model which is suitable for predicting the axial behavior of circular concrete columns confined by transverse reinforcement, by FRP wraps and by both transverse reinforcement and FRP wraps. The overall behavior of the proposed model is in good agreement with the test results.

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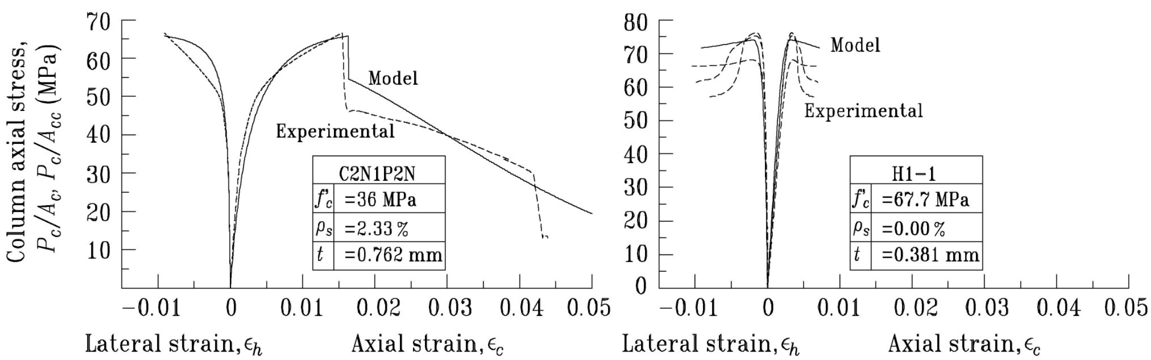

Figure 7. Experimental and analytical stress-strain behavior of FRP and FRP-steel confined concrete columns.

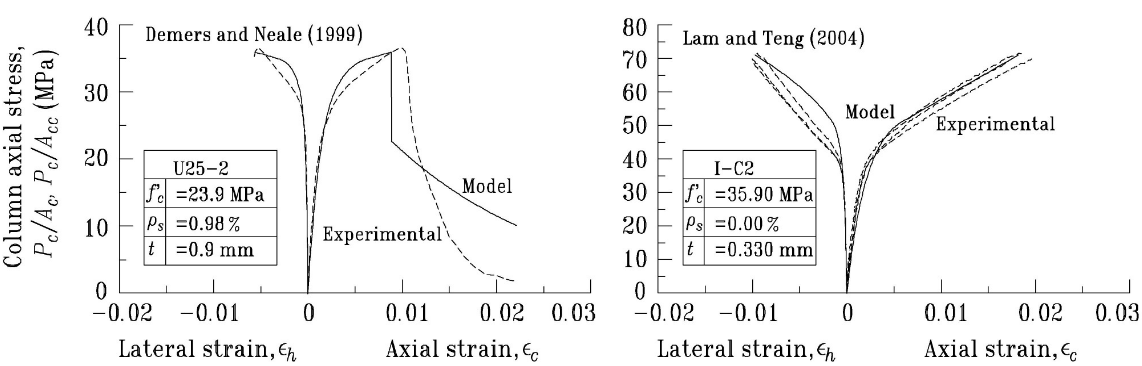

Figure 8. Comparison between the proposed model and published test results.