AXIAL LOAD BEHAVIOR OF RECTANGULAR CONCRETE COLUMNS CONFINED WITH FRP COMPOSITES

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1 INTRODUCTION

Most of the available studies on the behavior of FRP confined concrete columns have concentrated on circular shaped columns, while relatively few studies have addressed rectangular columns [1]. This is partly because the rectangular section is not uniformly confined and the compressive pressure is unevenly distributed. The higher stress is usually found at the corners. Rounding of the column's corners is a common practice used to reduce the cutting effect on confining sheets. The corner radius is one important factor which will be addressed in this paper. Although, some models have focused on the behavior of rectangular columns, the effect of aspect ratio when the structure is loaded and the section size on the strength at the ultimate load are not well known. Most of the earlier studies concerning the axial strength behavior of rectangular columns were small size specimens with b=94, 108, 150, 152 mm, and h=108, 150 152, 188, 203mm [2]. It is unclear if the existing models can be used for predicting the behavior of large-scale columns.

This research mainly intended to study the behavior of large-scale rectangular columns (b= 250, 355mm and h=500, 355mm) externally confined with FRP wrapping. The effects of varying the aspect ratio (h/b), fiber thickness, corner radius are examined. The existing models are reviewed and evaluated to predict the experimental data. This study investigates the strength models of FRP confined concrete columns, the effect of increasing confining pressure and the effective circumferential FRP failure strain (ratio of circumferential FRP strain at ultimate load $\varepsilon_{c\ell u}$ over FRP failure strain ε_{fu}). A proposed model to predict the ultimate strength of small and large-scale concrete rectangular columns confined with FRP sheets was presented. The predicted strength values compared well with the experimental.

2 EXPERIMENTAL PROCEDURE

Three large-scale reinforced rectangular concrete columns k9, k10 and k11 were constructed and tested at Ghent University. The test parameters of the wrapped columns are shown in Table 1. The specimen dimensions and the wrapping configuration are shown in Fig.1. The type of FRP sheets and number of layers were used as indicated in Table 1. Corners of the square and rectangular columns were rounded with a radius of 30 mm or 15 mm. GFRP fabrics have been used to confine the specimens. This 'wet lay-up' FRP type was glued, impregnated and cured in-situ. The GFRP confinement system comprised of a quasi unidirectional fabric TU600/25 (600g/m^2 fibers in main direction and 25 g/m^2 in opposite direction) and PC 5800 epoxy.

The fabric had a width of 200 mm and a nominal thickness of 0.300 mm. For the columns, also internal steel reinforcement, type S500 deformed steel with diameter of 8 mm, was used (Fig. 1). The compressive strength f_{cm} at 28 days and the properties of the reinforcement are given in Tables 1 and 2, respectively.

Table 1 Test parameters of wrapped columns.

Spec.	Column shape [mm]	Age at test [days]	f_{cm} (28days) [N/mm^2]	FRP type	No. of layers	Width [mm]
K9	355x355/r30	29	39.1	TU600/25	2	200
K10	355x355/r15	28	37.7	TU600/25	2	200
K11	250x500/r30	29	37.7	TU600/25	2	200

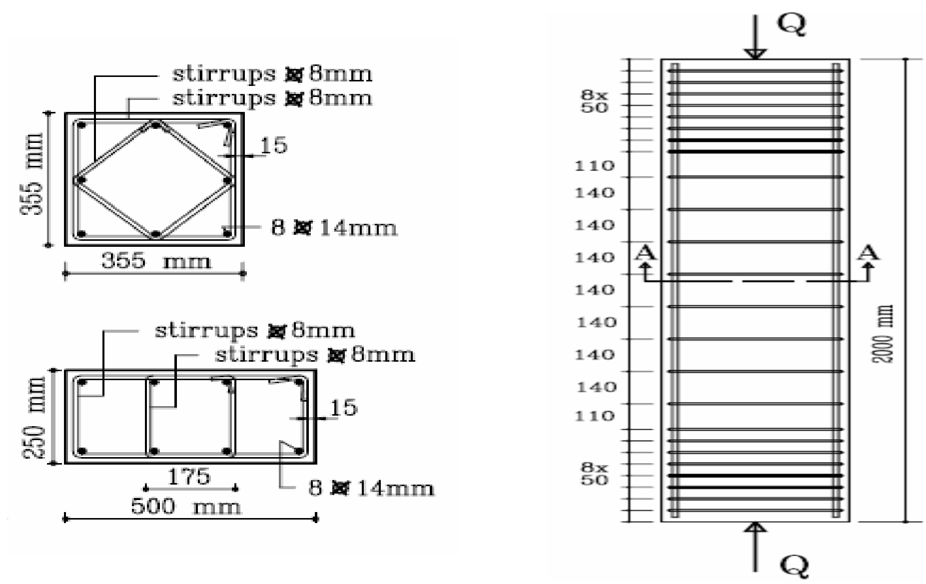

Fig. 1 Column dimensions and wrapping configuration.

Table 2 Mean tensile properties obtained by tensile testing.

Type	Nominal Dimensions [mm]	Yield strength [N/mm^2]	Tensile Strength [N/mm^2]	Ultimate strain [%]	E-modulus [N/mm^2]
Rebar S500	Ø 8	560	610	2.77	200000
TU600/25 -	200 x 0.300[1]	-	780	1.30	60000[2]
PC5800					

[1] Equivalent dry-fiber thickness [2] Tangent modulus at the origin

The test specimens were cast in the laboratory. Formwork was removed after 1 day and concrete curing occurred under a plastic foil during the first 7 days and under laboratory environment afterwards. After concrete columns were fully cured, FRP wrapping procedure was performed according to the procedure specified by the manufacturer. The epoxy was prepared by mixing 3 volumetric parts of component A with 1 part of component B. The FRP was applied minimum 7 and maximum 9 days before the loading test. Axial and circumferential deformations of the columns were measured both manually and electronically. Manual measurement comprised of dial gauges with a gauge length of 1 m and mechanical deformeters with a gauge length of 200 mm or 50 mm. For the electronic measurements, both strain stirrups (gauge length 200 mm or 80 mm) and strain gauges have been used.

3 TEST RESULTS FOR CONFINED COLUMNS

3.1 Behavior at Ultimate Load

Test results in terms of the maximum load $Q_{\max}$, axial stress $Q_{\max} / A_g$, strength increase, axial (ε_{c1} and ε_{cu}) and circumferential strains ($\varepsilon_{c\ell 1}$ and $\varepsilon_{c\ell u}$) at maximum and ultimate load and ratio of $\varepsilon_{c\ell 1}$ over the FRP failure strain ε_{fum} are given in Table 3. The listed strains are the mean values of the strain gauge measurements.

Table 3 Test results of compression tests on columns.

Specimen	$Q_{\max}$ [KN]	$Q_{\max}/A_g$ [N/mm^2]	Q/Q_{ref} [-]	ε_{c1} [mm/m]	ε_{cu} [mm/m]	$\varepsilon_{c\ell 1}$ [mm/m]	$\varepsilon_{c\ell u}$ [mm/m]	$\varepsilon_{c\ell u}/\varepsilon_{fum}$ [-]
K9 (sq./r30/G/#2/full)	5810[1]	46.1	1.24	5.1	5.1	2.1	2.1	0.16
K10 (sq./r15/G/#2/full)	5140	40.8	1.10	3.2	4.2	1.8	3.4	0.26
K11 (rect./r30/G/#2/full)	4990	39.9	1.07	1.8	1.9[2]	0.6	0.9[2]	0.07[2]

[1] The load suddenly increased to failure after activating the 2nd pump

[2] Failure of the FRP at the column end (strain measurements located in central zone)

Q_{max}: maximum load; Q_{ref}: maximum load of unwrapped column; A_g: gross cross-sectional area; ε_{c1}: axial concrete strain at maximum load; ε_{cu}: ultimate concrete strain at the extreme compression fiber; $\varepsilon_{c\ell 1}$: circumferential concrete strain at maximum load; $\varepsilon_{c\ell u}$: circumferential ultimate concrete strain; ε_{fum}: ultimate FRP strain

The confined concrete columns failed by fracture of the FRP reinforcement just beside one or more of the rounded corners (Fig. 2). The failure occurred partly in the central zone of the columns. For these columns at ultimate load, when confinement action was no longer provided due to FRP fracture, the internal steel started buckling and the crushed concrete fell down between the fractured FRP. Hence, this indicates that the concrete core is significantly damaged (but yet confined) even before reaching ultimate load. The strength gain was 1.24 for K9, 1.1 for K10, and 1.07 for K11. The stress-strain curves are showed in Fig. 3.

Fig. 2 Confined concrete columns failed by fracture of the FRP after testing.

3.2 Behavior at Ultimate Strain

The ratio $\varepsilon_{c\ell u}/\varepsilon_{fum}$ (circumferential ultimate strain/ultimate strain of FRP) was 0.16%, 0.26% and 0.07% for columns K9, K10 and K11 respectively as shown in Table 3. According to the experimental results [4], the ratio $\varepsilon_{c\ell u}/\varepsilon_{fum}$ for fully wrapped circular columns was between 0.55 and 0.62, which is much higher than the value for rectangular columns in this paper. This may indicate that secondary effects near failure, such as stress concentration in the FRP due to non-homogeneous strength characteristics and deformations of the damaged concrete are more prevalent. This may lead to a non-uniform strength and strain distribution with higher value located at the four corners. It should be noted that the ultimate tensile failure strain ε_{fum} reported by the manufacturer was much higher than the value obtained in this study, which is about 1.3 %.

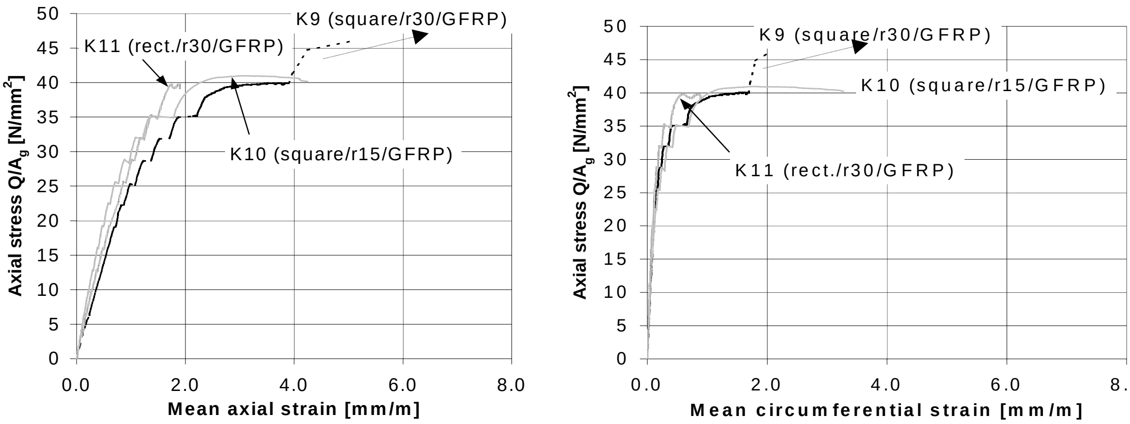

Fig. 3 Stress-strain behavior of non-circular columns.

3.3 Effective FRP Strain Coefficient

According to the obtained test results, the effective FRP failure strain (circumferential failure strain $\varepsilon_{c\ell u}$) when confined member is reaching the ultimate state is lower than the ultimate FRP tensile strain ε_{fum}. The ratio of the circumferential failure strain $\varepsilon_{c\ell u}$ to ultimate FRP tensile strain ε_{fum} is referred to as the effective FRP strain coefficient $\beta = \varepsilon_{c\ell u} / \varepsilon_{fum}$. β is lower than 1, as shown in Table 3. Thus, for rectangular and square columns, the maximum lateral confinement pressure f_{lu} is given as [3]:

$$f_{lux} = k_{confx} \varepsilon_{fum} = k_{confx} \times \frac{\varepsilon_{clu}}{\beta} = k'_{confx} \times \varepsilon_{clu} \tag{1}$$

where $k_{confx} = \rho_{fx} k_e E_f$ and $k'_{confx} = k_{confx} / \beta$

$$f_{luy} = k_{confy} \varepsilon_{fum} = k_{confy} \times \frac{\varepsilon_{clu}}{\beta} = k'_{confy} \times \varepsilon_{clu} \tag{2}$$

where $k_{confy} = \rho_{fy} k_e E_f$ and $k'_{confy} = k_{confy} / \beta$

where, f_{lux} and f_{luy} are lateral confinement pressure on x and y directions respectively. E_f is elastic modulus of FRP. The ratio ρ represents the quantities of transverse confining reinforcement in the x and y directions (see Fig. 4). k_e is the confinement effectiveness coefficient. k_{conf} is the confining stiffness and is given by:

$$k_{conf} = \frac{2 t_j E_{frp}}{D} \varepsilon_j \tag{3}$$

where

$$\varepsilon_j = \beta f_{frp} \quad \text{and} \quad D = \frac{2bd}{(b+d)} \tag{4}$$

The relationship of parameter β and k_{conf} for the experimental data in this study and others [2] is shown in Fig.5. For the purpose of obtaining a simple design equation for the lateral confinement pressure, the value β is set to be equal to 0.43.

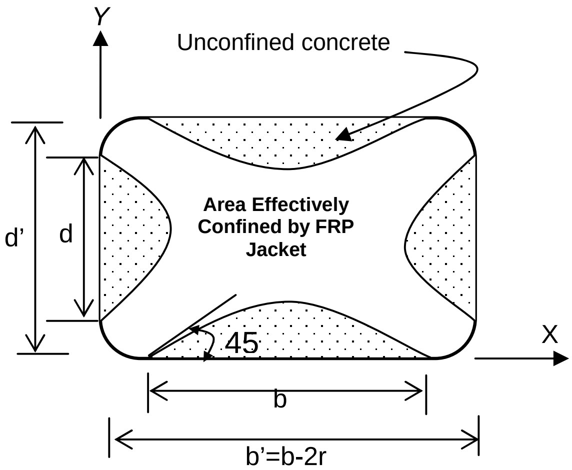

Fig. 4 Effectively confined region of rectangular column due to arching action.

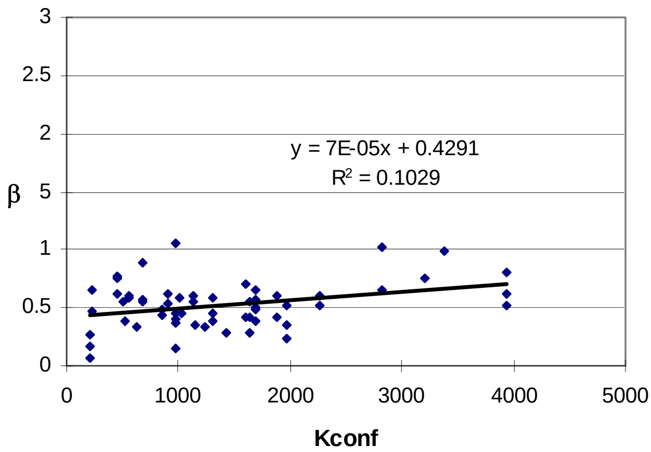

Fig. 5 Effective FRP failure strain coefficient.

4 EXISTING MODELS

In this study the following models were evaluated: Lam and Teng [2], ICBO [4], ACI Committee 440 [5], Hantouch [6], Mirmiran et al. [7], Campione and Miraglia [8], Chaallal et al. [9], Youssef [10], Cusson and Paultre [11], Razvi and Saatacioglu [12], Frangou et al. [13],wang and Restrepol [14], Harajli et al. [15] and Restrepol and DeVino [16]. Most of these previous studies were based on small-scale columns with the short sides being from 94 to 152 mm and the long side being from 108 to 203mm [2]. For practical applications, the mechanical behavior of large-scale concrete columns should be further investigated.

4.1 Stress-Strain Behavior Models

The stress-strain models of Lam & Teng, Chaallal et al., Youssef and Harajli et al. were evaluated based on the stress-strain experimental data obtained in this study. The experimental stress-strain curves and the predicted curves by the models are shown in Fig. 6.

Lam & Teng's model and Harajli et al.'s model predict the experimental stress-strain curves well. One obvious flaw in Chaallal et al's stress-strain model is that it assumes a tri-linear stress-strain curve and oversimplifies the stress-strain behavior. Youssef's model did not predict the stress-strain curves for these columns very well after the transition point (when axial strain is more than 0.002 mm/mm). It predicts a descending curve for the last region of the stress-strain response. This is not in agreement with the experimental data, which revealed ascending last region for the stress-strain curves for most specimens tested in this study and by others. This model has the tendency to significantly overestimate the ultimate axial strain.

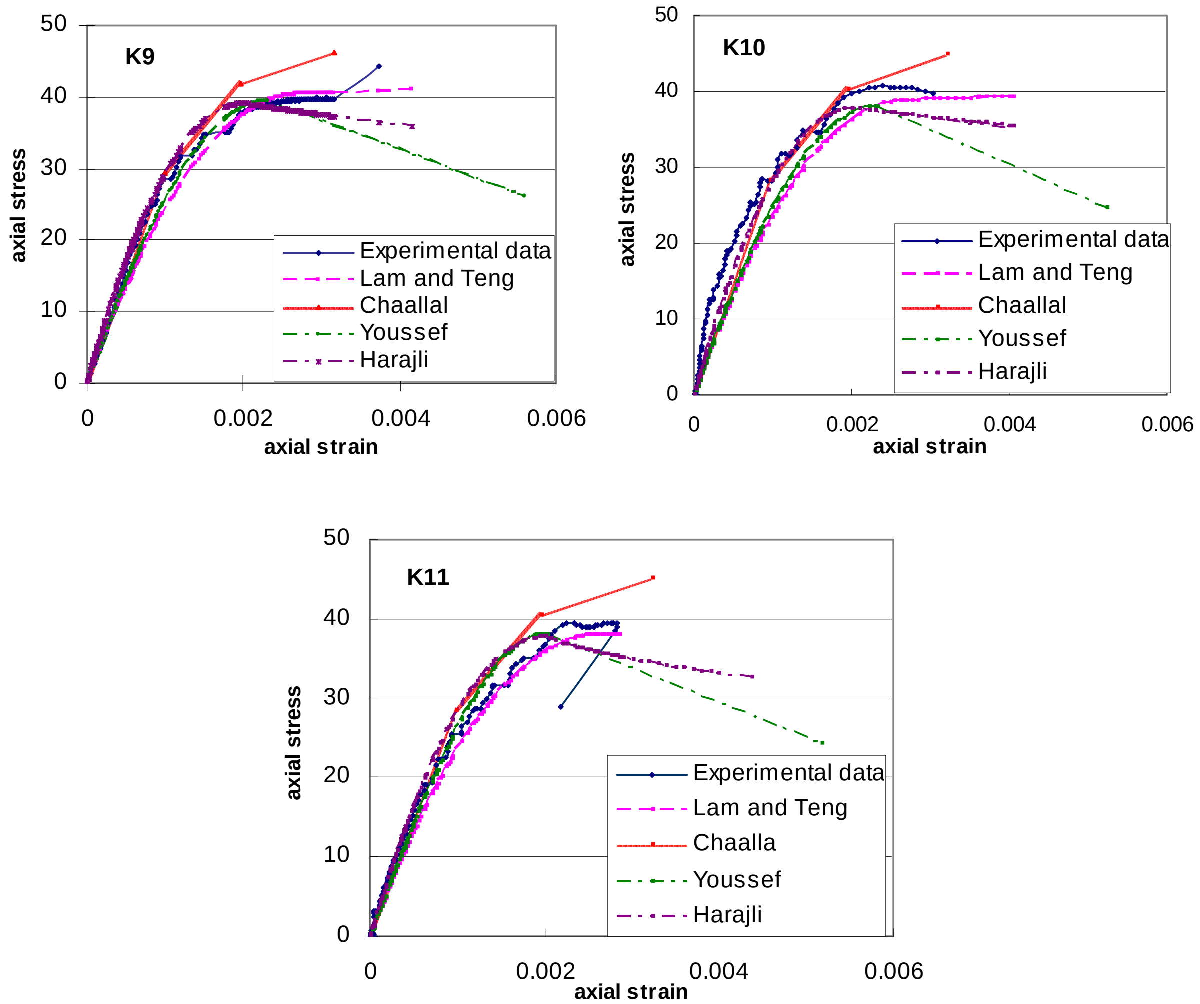

Fig. 6 Evaluation of the stress-strain models against 3 tested column specimens.

5 PROPOSED MODEL

The stress-strain response of a rectangular FRP-confined concrete column is dependent on several parameters. One such these parameters is the aspect ratio (b/d) of the concrete core. Experimental data has indicated that the overall increase in the column's strength is reduced when the aspect ratio is increased. Square columns experienced the highest strength increases. Also, an increase in the corner-rounding radius usually corresponds with a higher strength gain. The effective confinement strength ratio (f'_{cc}/f'_{co}) for K9 is higher than that of K10. In addition, the behavior of an axially loaded FRP-confined concrete column is also dependent on the mechanical properties of the confining material. The shape of specimens is another factor which may affect the ultimate failure strain of FRP wrapping. The effects of these parameters were determined through regression analysis, taking advantage of the experimental data currently available. The proposed stress-strain model provides equations for the most crucial points on the curve.

5.1 Newly Proposed Compressive Strength Model

Based on the linear equation previously proposed by Richart et al. [17] for uniformly confined concrete, the proposed model employs a similar approach with several modifications accounting for the effect of aspect ratio, corner radius and effective confinement. The compressive strength of a rectangular FRP-confined concrete column is predicted by the following equation:

$$\frac{f_{cc}^{'}}{f_{co}^{'}} = 1 + k_1 k_2 k_3 \frac{f_l^{'}}{f_{co}^{'}} \tag{5}$$

where the coefficients k_2 and k_3 account for the effect of varying the corner radius and aspect ratio respectively. The following power functions were assumed to be the solution for these coefficients:

$$k_2 = \left[\frac{2r}{D}\right]^{\alpha} \text{ and } k_3 = \left[\frac{d}{b}\right]^{\beta} \tag{6}$$

Appropriate values for α and β were determined to be 0.10 and 0.12 respectively through regression analysis after a close examination of the experimental data of the 104 columns [18]. The first value for k_1 was taken as 4.0, which was originally suggested by Richart et al. for uniformly confined concrete [17]. The lateral effective confining pressure provided by the FRP wrapping for rectangular sections $f_l^{'}$ is determined by the following equation:

$$f_l^{'} = k_e f_l \tag{7}$$

The coefficient k_e accounts for the effectively confined area ratio associated with arching action of rectangular FRP-confined concrete is found by the following equation [5]:

$$k_e = \frac{1 - \left(\left(b - 2R_c\right)^2 + (h - 2R_c)^2 / 3A_g\right) - \rho_{sc}}{1 - \rho_{sc}} \tag{8}$$

A_g is the gross sectional area of the concrete and ρ_{sc} is the area of the steel over the gross sectional area of the concrete. The maximum confining pressure provided by the FRP of an equivalent uniformly confined column (f_l) is determined by the following equation derived by the equilibrium of forces on a free-body:

$$f_l = \frac{2\varepsilon_{frp}\varepsilon_j t_j}{D} \tag{9}$$

The term ε_j represents the lateral strain in the FRP wrapping recorded at the point of rupture. This strain is usually lower than the ultimate strain recorded for a flat FRP coupon (ε_{frp}). $\varepsilon_j = 0.43\varepsilon_{frp}$ has been used in this study. The diameter of an equivalent circular column is determined by the following equation [5]:

$$D = \frac{2bh}{b + h} \tag{10}$$

5.2 Performance of Proposed Compressive Strength Model

The theoretical predictions of the proposed compressive strength (f_{cc}) were compared with a compilation of experimental results currently available. The predictions of the proposed compressive strength model showed good correlation with the experimental data for a total of 59 points as shown in Fig. 7. Points located within relatively close proximity to the equilibrium line $y = x$ predicted the trend of points very well.

A comparison between the different models for predicting the compressive strength values of the 3 large scale columns are shown in Table 4. Most models predict within 13%of the experimental values as shown in Table 4.

Table 4 Strength comparison between the analytical models and the experimental data.

Model	K9 % Difference	K10 % Difference	K11 % Difference
ACI 440 [5]	-11.4	-7.2	1.0
Hantouch [6]	13.4	17.7	12.6
Lam and Teng [2]	-9.2	-2.8	-3.7
Mirmiran and Shahawy [7]	-9.1	-4.2	-4.8
Campione and Miraglia [8]	-7.6	-2.9	-
Challal [9]	2.2	11.2	13.6
Youssef [10]	-12.7	-5.8	-3.8
Cusson and Paultre [11]	-5.7	0.8	2.4
Razvi and Saatacioglu [12]	-6.1	0.3	1.9
Richart et al. [17]	-9.5	-3.0	-1.4
Wang and Restrepol [14]	-7.0	-0.7	0.8
ICBO [4]	-10.6	-3.5	-
Frangou et al. [13]	-9.4	-2.0	-0.5
Restrepol and DeVino [16]	-6.0	0.025.	0.5
The proposed model	-2.9	0.9	2.8

5.3 Axial Stress-Strain Behavior

Axial stress-strain behavior of rectangular column with FRP wrapping is defined by three different regions in this study. Crucial points are shown in Fig. 8. The first region is linear part. That corresponds to the axial load which is lower than the axial ultimate load for unconfined equivalent column. In this region, the FRP wrapping doesn't provide lateral pressure because expansion of column is minimal. The stress-strain response mainly depends on the axial stress-strain behavior of unconfined column rather than the effect of FRP wrapping properties. The second region is the transition part which starts from the point when the first crack on column can be seen and the confinement stress start to be activated. The starting point is also defined by the strength of unconfined column. That means the axial stress-strain curve comes into the transition region after the axial stress of confined column is equal to ultimate stress of the equivalent unconfined column. During this region, a noticeably high axial and circumferential strain increase can be observed accompanying with smaller stress increase. The stress-strain response shows a smooth curve in this region. After FRP confinement is completely built up, the axial stress-strain response comes into the third region. The third region represents a period at which the FRP wrapping is fully active. The end of the third region corresponds to the point of column's failure. It should be noted that, even this region is assumed as an ascending straight line, the trend of stress-strain curve in this region is not exactly clear. Both of increasing and decreasing trends were reported in prior studies.

The stress-strain models by Lam and Teng, Chaallal, Youssef and Harajli et al., used to predict the behavior of large-scale rectangular columns shown earlier in Fig. 6. Lam and Teng's and Chaallal's models predicted accurately the maximum stress point and the corresponding axial strain. Chaallal's model overestimates the maximum axial stress. Youssef's overestimates the maximum axial strain and poorly predict the last part of the curve: the descending portion.

Generally, Lam and Teng's model showed superiority when predicting axial stress-strain behavior of large-scale FRP confined rectangular concrete column. The stress-strain model compared well with that of experimental.

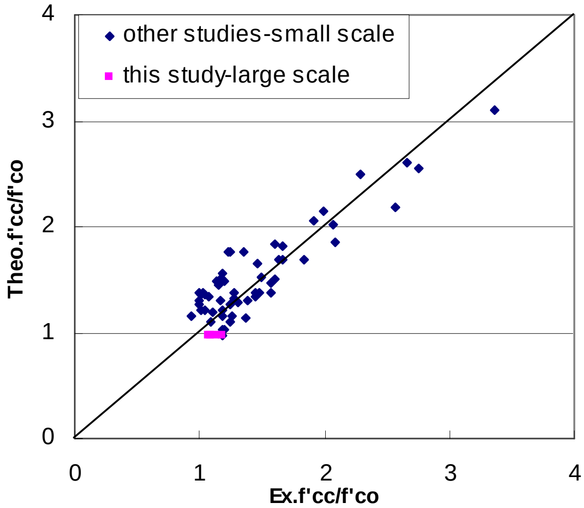

Fig. 7 Performance of the proposed model.

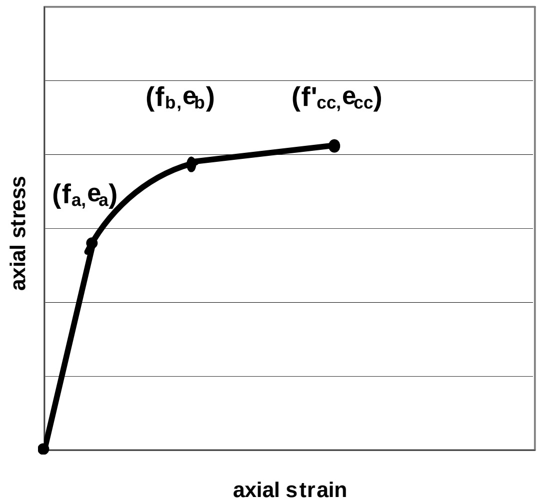

Fig. 8 The proposed stress-strain model.

6 CONCLUSIONS

Existing ultimate axial stress and stress-strain models are reviewed and applied to three large-scale rectangular columns. A simple design-oriented model for predicting the ultimate axial stress has been presented and shown to offer satisfactory predictions of ultimate stress for both small-scale and large-scale rectangular columns. The following conclusions were drawn from this study:

- Higher aspect ratio usually results in a reduction in the confinement pressure. Also, the compressive strength of a confined column increases as the corner radius increases.
- The proposed ultimate stress model is based on a new expression in which three different coefficients were introduced: the effective confinement coefficient, the aspect ratio coefficient and the corner radius coefficient. The proposed model predicts the ultimate stress for both small-scale and large-scale specimens rectangular columns confined with FRP composites reasonably well.
- Comparing the different existing confinement models, Lam and Teng's model seems to predict the entire stress-strain behavior for large-scaled rectangular quite accurately.
- The available test results focusing on the large scale rectangular columns are rare due to the difficult experimental procedure. For getting more accurate axial stress-strain behavior for rectangular column, more tests on actual field size columns should be conducted.

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