Improved Strength Model of FRP-Confined Concrete in Rectangular Columns

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***Abstract*—Fiber Reinforced Polymer (FRP) composite materials are widely used to wrap compression members for improving their strength and ductility. There are several models of FRP-confined concrete in rectangular columns proposed by some researchers or codes of different countries. In this paper, an improved strength model of FRP-confined concrete in rectangular columns was presented for retrofitting existing buildings. First, a database was established by collecting 188 specimens tested by other researchers. And then, based on the database, existing models of FRP-confined concrete in rectangular columns were reviewed and evaluated in terms of the sum of square errors between experimental results and theoretical predictions. Finally, an improved model was presented, which is more accurate than existing models.**

***Index Terms*—strength model, FRP, rectangular column**

I. Introduction

Retrofit technique using Fiber Reinforced Polymer (FRP) sheets has great advantages over conventional ones, for it features light weight, high strength, easy construction and little effects on building function. The behavior of FRP-confined concrete in circular columns has been extensively studied, and therefore researchers have turned their attention to FRP-confined concrete in rectangular columns. The ultimate strength and ductility of FRP-confined concrete increase significantly with the enhancement of the number of composite layers and the confinement level [1]. The confinement effect is directly related to the shape of the cross sections of columns and the most effective confinements are obtained for circular sections [2]. A smaller corner radius can significantly reduce the ultimate strength of the FRP laminate due to stress concentration around the corner area. The stress concentration factor increases when the corner radius decreases [3].

In this study, existing strength models of FRP-confined concrete in rectangular columns were reviewed and evaluated by data collected from literatures. And then improved model was proposed for more accurate estimation of the ultimate strength of the FRP-confined concrete in rectangular columns.

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II. Existing Strength Models of FRP-Confined Concrete in Columns

A. Uniform Expression of Strength Model

Only strength models of FRP-confined concrete in rectangular columns were introduced. These models were proposed by Mirmiran *et al*. (Mirmiran's model for short) [4], Lam and Teng (Lam's model for short) [5], Ilki *et al.* (Ilki's model for short) [6], Al-Salloum. (Al-Salloum's model for short) [7], GB50367(model of GB50367 for short) [8] and ACI 440 (model of ACI 440 for short) [9], respectively. Existing models can be uniformly expressed as follows

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

where the $f_{cc}^{'}$ and $f_{co}^{'}$ are compressive strengths of the confined and the unconfined concrete, respectively, k_1 is the confinement effectiveness coefficient, k_s is shape coefficient, and f_l is the lateral confining pressure. Lateral confining pressure, f_l, is given by

$$f_l = \frac{2E_{FRP} t\varepsilon}{D} \tag{2}$$

where E_{FRP} is the elastic modulus of FRP, t is the total thickness of FRP, ε is the hoop tensile strain in the FRP jacket at failure, and D is the diameter of an equivalent circular column. The values of k_1, k_s, f_l, ε, and D are different among these models.

B. Mirmiran's Model

The confinement effectiveness coefficient of Mirmiran's model, k_1, is given by

$$k_1 = 6.0 f_l^{-0.3} \tag{3}$$

shape coefficient k_s is defined as

$$k_s = \frac{2r}{D} \tag{4}$$

where r is the corner radius of the rectangular section. the diameter of an equivalent circular column, D, is

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taken as the side length of a square column or the longer side length of a rectangular column.
Equation (1) becomes

$$\frac{f'_{cc}}{f'_{co}} = 1 + 6.0\left(\frac{2r}{D}\right)\frac{f_l^{0.7}}{f'_{co}} \quad (5)$$

while determining the confinement pressure f_l, the ultimate rupture strain of wrapped FRP sheet is assumed to be equal to the ultimate strain of FRP $\varepsilon_{\mathrm{FRP}}$.

C. Lam's Model

In Lam's model, k_1 is taken as 3.3, and k_s is given by

$$k_s = \left(\frac{b}{h}\right)^2 \frac{A_e}{A_c} \quad (6)$$

where b and h are width and length of the rectangular section, respectively. A_e / A_c is effective confinement area ratio

$$\frac{A_e}{A_c} = \frac{1 - \dfrac{\left(\frac{b}{h}\right)(h-2r)^2 + \left(\frac{h}{b}\right)(b-2r)^2}{3A_g} - \rho_s}{1-\rho_s} \quad (7)$$

where A_e and A_c are the effective confinement area and the total area of concrete, respectively. ρ_s is the cross sectional area ratio of the longitudinal steel reinforcement. A_g is the gross area of the column section with rounded corners, which can be evaluated by

$$A_g = bh - (4-\pi)r^2 \quad (8)$$

Therefore, Lam's model can be expressed as follows

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.3\left(\frac{b}{h}\right)^2 \frac{A_e}{A_c}\frac{f_l}{f'_{co}} \quad (9)$$

while determining the confinement pressure f_l, ε and D are taken as 0.85 $\varepsilon_{\mathrm{FRP}}$ and $\sqrt{h^2+b^2}$, respectively.

D. Ilki's Model

In Ilki's model, k_1 is taken as 2.54, and k_s is given by

$$k_s = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-\rho_s)} \quad (10)$$

while determining f_l, ε is taken as 0.85 $\varepsilon_{\mathrm{FRP}}$, and D is given by

$$D = \frac{2\left[bh - (4-\pi)r^2\right]}{b+h} \quad (11)$$

E. Al-Salloum's Model

In Al-Salloum's model, k_1 is taken as 3.14 and k_s is given by

$$k_s = \left(\frac{b}{D}\right)\left(1 - \frac{2}{3}\left[\frac{(1-2r/b)}{1-(4-\pi)(r/b)^2}\right]\right) \quad (12)$$

where D is given by

$$D = \sqrt{2b} - 2r\left(\sqrt{2}-1\right) \quad (13)$$

Therefore, Al-Salloum's model becomes

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.14\left(\frac{b}{D}\right)^2\left(1 - \frac{2}{3}\left[\frac{(1-2r/b)}{1-(4-\pi)(r/b)^2}\right]\right)\frac{f_l}{f'_{co}} \quad (14)$$

while determining the confinement pressure f_l, ε is taken as $\varepsilon_{\mathrm{FRP}}$.

F. Model of GB50367

In the model of GB50367-2006, k_1 is taken as 4.0 and k_s is given by

$$k_s = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3A_g(1-\rho_s)} \quad (15)$$

where ε is taken as 0.0035 and D is given by

$$D = \frac{2\left[bh - (4-\pi)r^2\right]}{b+h} \quad (16)$$

G. Model of ACI 440

The model of ACI 440 is similar to Lam's model, where k_s and D are the same as those of Lam's model. ε is taken as 0.55 $\varepsilon_{\mathrm{FRP}}$, and k_1 is given by

$$k_1 = 3.3\psi_f \quad (17)$$

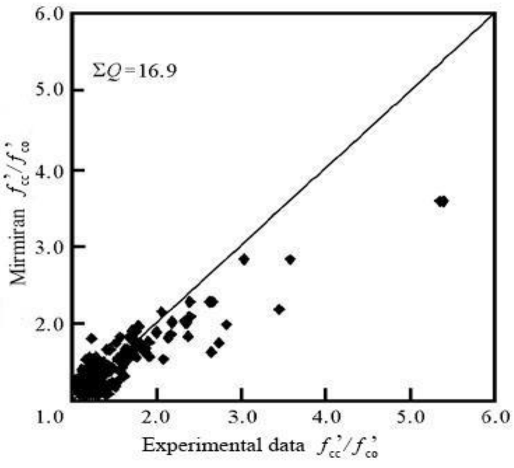

Figure 1. Performance of Mirmiran's model

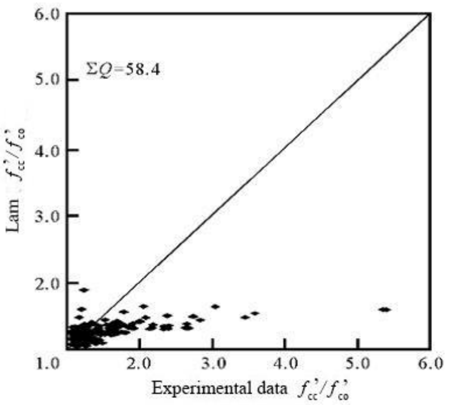

Figure 2. Performance of Lam’s model

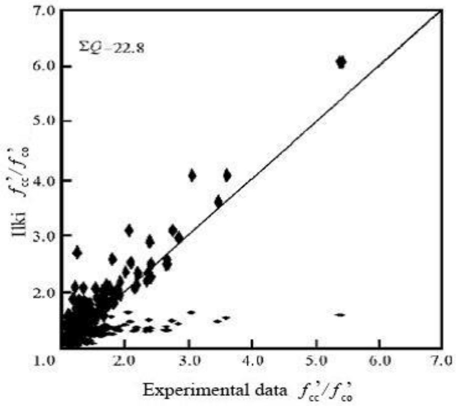

Figure 3. Performance of Ilki’s model

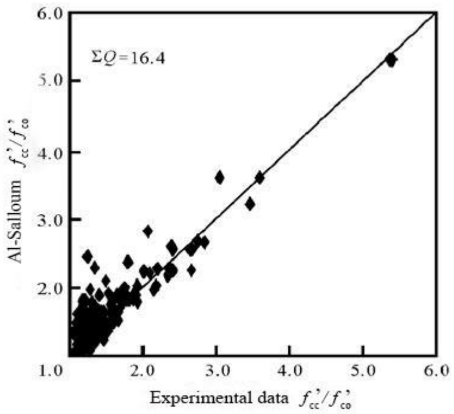

Figure 4. Performance of Al-Salloum’s model

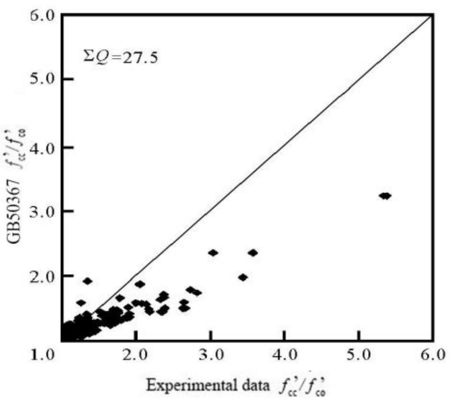

Figure 5. Performance of model of GB50367

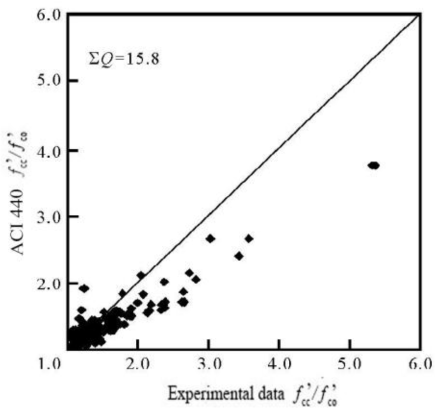

Figure 6. Performance of model of ACI 440

where ψ_{f} is coefficient of reduction. ψ_{f} can be taken as 0.95.

III. Performance of Existing Models

In this study, 188 specimens tested by other researchers were used for evaluating the performance of existing models. These specimens were carefully selected from literatures. In order to specially study FRP-confined plain concrete columns, all specimens selected were made of plain concrete. The principal fibers of all specimens were oriented perpendicular to the column axis, therefore the FRP jacket only provided hoop confinement.

The index of evaluating performance of existing models is taken as the sum of square errors between experimental results and theoretical predictions, that is

$$\sum Q=\sum\left[Exp.\left(f_{cc}^{'}/f_{co}^{'}\right)-Theor.\left(f_{cc}^{'}/f_{co}^{'}\right)\right]^2 \tag{18}$$

Obviously, the smaller $\sum Q$ is, the better theoretical model is. Evaluation results are shown in Fig. 1-Fig. 6. The performance of the model of ACI 440 is best, whose $\sum Q$ is 15.8.

IV. Improved Model

Based on the strength model of circular column[10], the improved model is given by

$$\frac{f_{\mathrm{cc}}^{'}}{f_{\mathrm{co}}^{'}}=\begin{cases}1+k_1k_{\mathrm{s}}\left(\rho_{\mathrm{K}}-0.01\right)\rho_{\varepsilon} & \rho_{\mathrm{K}}\geq 0.01\\ 1 & \rho_{\mathrm{K}}\geq 0.01\end{cases} \tag{19}$$

where ρ_{K} and ρ_{ε} are the confinement stiffness ratio and the strain ratio, respectively. The mathematical expressions of these two ratios are as follows

$$\rho_{\mathrm{K}}=\frac{2E_{\mathrm{FRP}}t}{\left(f_{\mathrm{co}}^{'}/\varepsilon_{\mathrm{co}}\right)D} \tag{20}$$

$$\rho_{\varepsilon}=\frac{\varepsilon}{\varepsilon_{\mathrm{co}}} \tag{21}$$

where ε is taken as $0.85\varepsilon_{FRP}$, and D is given by (11). ε_{co} is axial strain of unconfined concrete corresponding to peak stress, which is taken as 0.002. k_s is given by

$$k_s = \left(\frac{b}{h}\right)^{1.7} \frac{1 - \dfrac{\left(\frac{b}{h}\right)(h-2r)^2 + \left(\frac{h}{b}\right)(b-2r)^2}{3A_g} - \rho_s}{1-\rho_s} \quad (22)$$

In order to make $\sum Q$ as small as possible, k_1 is determined by trial calculation in the range of 2 to 7. When k_1 is equal to 4.6, is minimum (as shown in Fig. 7).

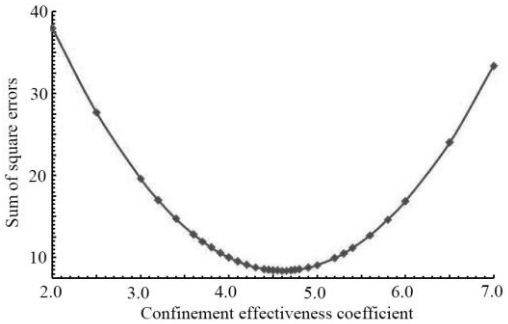

Figure 7. Trial calculation of confinement effectiveness coefficient k_1

The improved model was evaluated in terms of the index of the sum of square errors. The performance of the improved model is shown in Fig. 8. It can be found that the improved model match experimental data well.

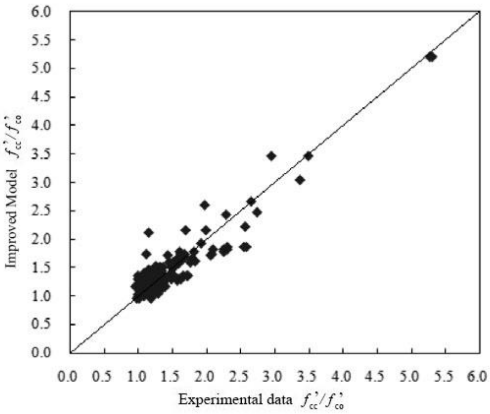

Figure 8. Performance of improved model

V. Conclusion

In this paper, existing theoretical models of FRP-confined concrete in rectangular columns have been reviewed and evaluated using 188 specimens selected from literatures. An improved model has been presented and shown to provide satisfactory predictions of test results, which can serves as a reference for retrofitting rectangular concrete columns with FRP composite jackets. Further work, including theoretical and experimental study, is required to verify the applicability of the model over a wider range of specimens since the specimens used to improved model are limited.

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