International Journal of the Physical Sciences Vol. 5(15), pp. 2304-2309, 18 November, 2010
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2010 Academic Journals

Full Length Research Paper

Stress-strain model of PVC-FRP confined concrete column subjected to axial compression

Feng Yu[1]*and Ditao Niu[2]

[1]College of Civil Engineering, Anhui University of Technology, Ma'anshan, 243002, P. R. China.
[2]College of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, P. R. China.

Accepted 15 November, 2010

The design of PVC-FRP confined concrete members requires accurate evaluation of the performance enhancement due to the confinement provided by PVC-FRP tube. Based on the static equilibrium condition and the yield criteria of concrete and PVC-FRP tube, this paper presents a calculating model of the load-carrying capacity of PVC-FRP confined concrete column, the influences of the hoop spacing of FRP strips and equivalent confinement effect coefficient on load-carrying capacity were well considered. According to the ingression of experimental data, a calculating formula of the ultimate axial strain is also put forward. For this last case, a bilinear stress-strain model of PVC-FRP confined concrete column in axial and lateral directions is established. The comparison between experimental and numerical results indicates that the model provides satisfactory predictions of the stress-strain response of the columns.

Key words: PVC-FRP tube, stress-strain model, load-carrying capacity, axial compressive strain, concrete column.

INTRODUCTION

In recent years, fiber reinforced polymer has been widely used in civil engineering because of its high strength, good durability, light weight, convenient construction and so on. Engineering practice shows that FRP is adaptive to the development of modern structural engineering in long span, towering, heavy loading, high strength, light weight and the requirement of bearing atrocious environment. Therefore, it has been more and more widely used in bridge, civil buildings, oceanic engineering and underground structure (ACI Committee, 1996; Chambers, 1993; Mufti et al., 1992; Erki, 1995). There are two application modes of FRP, one is used in the reinforcement of existing buildings, and the other is directly used in newly built structure. Most research of FRP mainly focuses on the maintenance and reinforcement, results show that the load-carrying capacity and ductility of FRP reinforced concrete are obviously improved, and the service life and durability of concrete structure are prolonged (Wu et al., 2006; Kader et al., 2006; Abbasnia and Ziaadiny, 2010; Jumaat et al., 2010; Yung-Chih and Hsu, 2008; Jiang et al., 2007).

PVC-FRP confined concrete column is formed by pouring concrete into PVC-FRP tube (Feng and Ditao, 2009). In the proposed new structural system, the lateral confinement of concrete column is provided by PVC-FRP tube, and the confining stress applied by FRP strips may be uniformly transferred to concrete column through PVC tube. Before FRP strips exert confining action, the PVC tube has enough stiffness to resist the crack and deformation of core concrete. Moreover, the PVC tube can act as formwork, improve the construction speed, and protect the core concrete from the corrosion of atrocious environment.

In order to further study the performance of PVC-FRP confined concrete column, the determination of stress-strain model is the key issue to analyze the behavior of PVC-FRP confined concrete column. Scholars have done much research and proposed many stress-strain models for FRP confined concrete column (Yung-Chih and Hsu, 2008; Jiang et al., 2007; Feng and Ditao, 2009).

But these models are not suitable to predict the stress-strain relationship of PVC-FRP confined concrete column, because different confining mechanism exists between FRP and PVC-FRP tube.

To better study the mechanical behavior of PVC-FRP confined concrete column, based on the experimental

*Corresponding author. E-mail: yufeng2007@126.com.

study and theoretical analysis, this paper presents the formula for load-carrying capacity and ultimate axial strain of PVC-FRP confined concrete column, and then a bilinear stress-strain model is established. Comparison between the predicted stress-strain curves and test results are analyzed.

The confining action of PVC-FRP tube to concrete column

For reinforced concrete column, the confining stress of steel spirals to concrete keeps constant after steel spirals yielding. But for PVC-FRP confined concrete column, the confining action of PVC-FRP tube to concrete is different. In the beginning load stage, the confining action of PVC-FRP tube to concrete is still not activated due to the small lateral deformation of core concrete. In the vicinity of ultimate compressive strength of unconfined concrete, the confinement of PVC-FRP tube is activated and starts to be obviously enhanced. In the final stage, the confining action continuously increase with the increment of axial load, and the load-carrying capacity and axial deformation has been greatly improved before the failure of PVC-FRP tube.

Based on the analysis of experimental data, the load-carrying capacity and axial strain of PVC-FRP confined concrete column are mainly related to the equivalent confinement effect coefficient ξ_{ef}, which can be defined as:

$$\xi_{\mathrm{ef}} = \frac{A_{\mathrm{f}} f_{\mathrm{f}}}{A_{\mathrm{c}} f_{\mathrm{co}}^{'}} k_{\mathrm{g}} \tag{1}$$

Where f_{f} is the ultimate tensile strength of CFRP, A_{f} is the cross section area of CFRP, A_{c} is the cross section area of concrete, $f_{\mathrm{co}}^{'}$ is the ultimate compressive strength of unconfined concrete, k_{g} is the confining influence coefficient of CFRP strips, the expression of k_{g} is:

$$k_{\mathrm{g}} = \frac{s_{\mathrm{f}}}{s^{'}} \tag{2}$$

Where s_{f} is the width of CFRP strips, $s^{'}$ is the hoop spacing of CFRP strips, and $s^{'} \geq s_{\mathrm{f}}$.

The load-carrying capacity and ultimate axial strain

The load-carrying capacity

Based on the analysis of experimental data, the load-carrying capacity of PVC-FRP confined concrete column is mainly related to the hoop spacing of FRP strips and equivalent confinement effect coefficient. PVC-FRP tube can be equivalent to bidirectional composites tube according to the elastic theory. The compressive strength of unidirectional CFRP may be approximate to zero, so the compressive strength of PVC-FRP tube is the compressive strength of PVC tube $f_{\mathrm{p}}^{'}$. Compared with the tensile strength of CFRP, the tensile strength of PVC tube is very small and can be neglected, so the lateral tensile strength of PVC-FRP tube is the tensile strength of CFRP f_{f}.

Yu (Feng, 2007). Proposed the formula of the unified load-carrying capacity for confined concrete column can be shown by the following expression:

$$N = A_{\mathrm{c}} f_{\mathrm{co}}^{'} \left[1 + \xi \frac{\left(k - \frac{X}{Y}\right)^2 + 3\left(\frac{X}{Y}\right)^2}{\sqrt{3\left(k - \frac{X}{Y}\right)^2 + 9\left(\frac{X}{Y}\right)^2}} \right] \tag{3}$$

For PVC-FRP confined concrete column, in the formula (3), $X = f_{\mathrm{p}}^{'}$, $Y = f_{\mathrm{f}}$. X/Y is the ratio of the compressive strength of PVC tube to the tensile strength of CFRP, the value of X/Y is about 0.02. k is the lateral confinement coefficient, the value of k is 2.26 proposed by Yu (Feng and Ditao, 2007). The effects of the hoop spacing of CFRP strips and the width of CFRP strips on the load-carrying capacity are also considered, then the confining influence coefficient of CFRP strips k_{g} is introduced. The load-carrying capacity of PVC-FRP confined concrete column can be expressed as

$$N_{\mathrm{a}} = A_{\mathrm{c}} f_{\mathrm{co}}^{'} (1 + 1.31\xi_{\mathrm{ef}}) \tag{4}$$

Formula (4) is verified by experimental data in this paper. Experimental results N_{ae} and the calculating value N_{ac} of load-carrying capacity are respectively listed in Table 1. From Table 1, we can conclude that the effect of hoop spacing of FRP strips on the load-carrying capacity and axial compressive strain are obvious. Lateral confinement by PVC-FRP tube causes the development of a triaxial stress field within the confined concrete. The axial compressive strength and strain gradually decrease with the increase of hoop spacing of FRP strips. The average value of $N_{\mathrm{ae}} / N_{\mathrm{ac}}$ is 1.02, the mean square deviation is 0.002. It is obvious that the proposed formula of load-carrying capacity has high calculating precision. Ultimate axial strain is an important index of ductility for PVC-FRP confined concrete column. To present the expression of

Table 1. Comparison between experimental results and calculating value.

Number of specimen	f_{f} **(MPa)**	$f_{\mathrm{co}}^{'}$ **(MPa)**	t **(mm)**	N_{ae} **(kN)**	N_{ac} **(kN)**	$N_{\mathrm{ae}} / N_{\mathrm{ac}}$	$\varepsilon_{\mathrm{cc}}^{'\mathrm{e}}$	$\varepsilon_{\mathrm{cc}}^{'\mathrm{c}}$	$\varepsilon_{\mathrm{cc}}^{'\mathrm{e}} / \varepsilon_{\mathrm{cc}}^{'\mathrm{c}}$
A-Cs20-1	3612	28.5	0.33	1812.4	1872.24	0.97	0.0162	0.0175	1.08
A-Cs20-2				1756.8	1872.24	0.94	0.0182	0.0175	0.96
A-Cs30-1				1464.2	1546.5	0.95	0.0158	0.0154	0.97
A-Cs30-2				1552	1546.5	1.00	0.0159	0.0154	0.97
A-Cs40-1				1406.7	1383.6	1.02	0.0144	0.0143	0.99
A-Cs40-2				1368.8	1383.6	0.99	0.0149	0.0143	0.96
A-Cs50-1				1272.6	1285.1	0.99	0.0136	0.0137	1.01
A-Cs50-2				1279.5	1285.1	1.00	0.0134	0.0137	1.02
A-Cs60-1				1261.1	1220	1.03	0.0132	0.0132	1.00
A-Cs60-2				1327.2	1220	1.09	0.0126	0.0132	1.05

The ultimate axial strain.

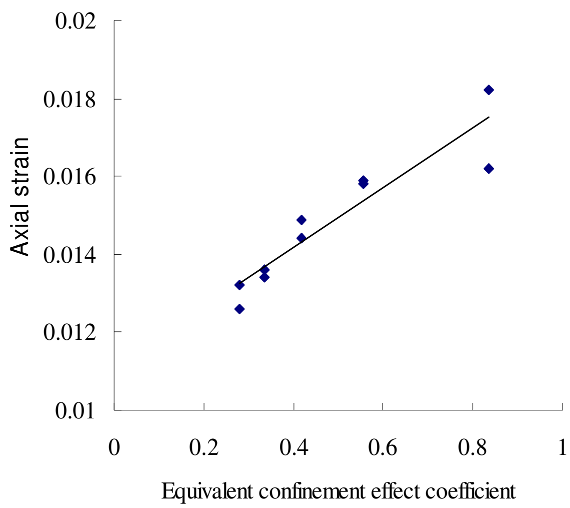

Figure 1. The relationship between $\varepsilon_{\mathrm{cc}}^{'}$ and ξ_{ef}.

ultimate axial strain, the experimental results were analyzed and regressed (shown in Figure 1), and then the formula of ultimate axial strain of PVC-FRP confined concrete column is proposed, the expression of $\varepsilon_{\mathrm{cc}}^{'}$ is that

$$\varepsilon_{\mathrm{cc}}^{'} = 0.0111 + 0.0077\xi_{\mathrm{ef}} \tag{5}$$

The related coefficient of the regressed formula of ultimate axial strain is 0.935. Comparison between experimental results $\varepsilon_{\mathrm{cc}}^{'\mathrm{e}}$ and calculating value $\varepsilon_{\mathrm{cc}}^{'\mathrm{c}}$ of ultimate axial strain are also listed in Table 1, the average value of $\varepsilon_{\mathrm{cc}}^{'\mathrm{e}} / \varepsilon_{\mathrm{cc}}^{'\mathrm{c}}$ is 1.002, the mean square deviation is 0.002. It is obvious that the calculated values of the formula for axial strain agree well with experimental results.

The stress-strain model of PVC-FRP confined concrete column

Based on the analysis of experimental data and the features of the stress-strain response of PVC-FRP confined concrete column, the curves between axial stress σ_{c} and axial strain ε_{c} may be divided into two segments (Figure 2).

In the first segment, the stress-strain curves of PVC-FRP confined concrete column are similar to that of unconfined concrete. The slope of parabola at $\varepsilon_c = 0$ is equal to the elastic modulus of unconfined concrete E_c, and the curve is influenced by the presence of PVC-FRP tube in some degree. The first parabola segment may be expressed by the following formula.

$$\sigma_{\mathrm{c}} = E_{\mathrm{c}}\varepsilon_{\mathrm{c}} - \frac{(E_{\mathrm{c}} - E_2)^2}{4 f_{\mathrm{o}}}\varepsilon_{\mathrm{c}}^2 \qquad 0 \le \varepsilon_{\mathrm{c}} \le \varepsilon_1 \tag{6}$$

ε_{c}

Where E_{c} is elastic modulus of concrete, $E_{\mathrm{c}} = 4773\sqrt{f_{\mathrm{co}}^{'}}$; E_2 is the slope of linear strengthening segment, ε_{t} is the intersection strain between the first segment and the linear strengthening segment, E_2 and ξ can be respectively calculated by the formula (7) and (8).

$$E_2 = \frac{f_{\mathrm{cc}}^{'} - f_{\mathrm{o}}}{\varepsilon_{\mathrm{cc}}^{'}} \tag{7}$$

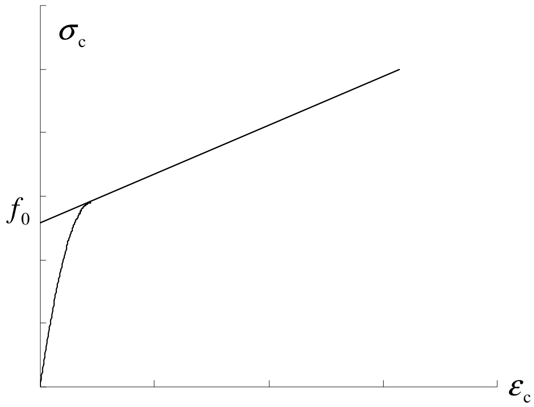

Figure 2. Typical stress-strain curves.

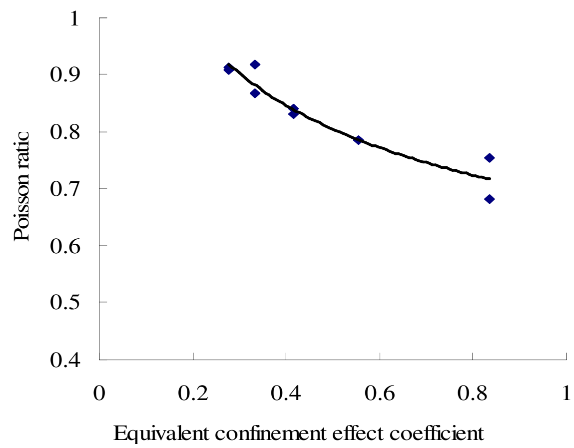

Figure 4. The relationship between υ and ξ_{ef} .

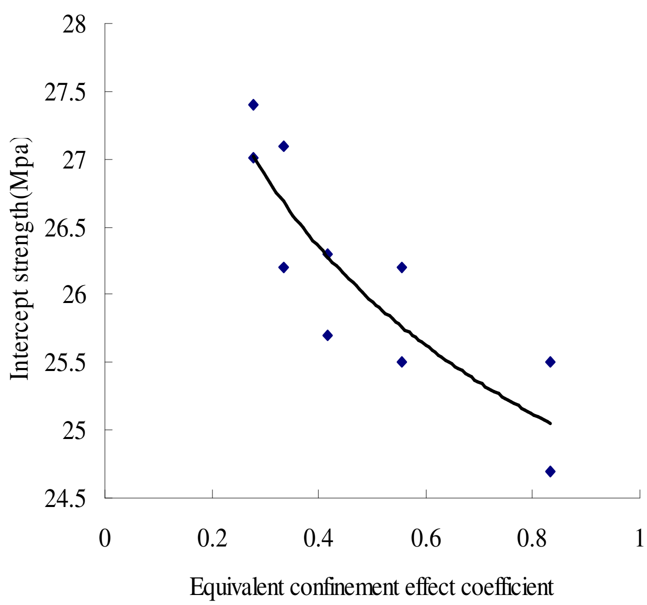

Figure 3. The relationship between f_0 and ξ_{ef} .

$$\varepsilon_t = \frac{2f_o}{(E_c - E_2)} \tag{8}$$

Where f_o is the intercept of linear strengthening segment, Figure 3 shows the regression of experimental data in this paper, the expression of f_o is shown below.

$$f_o = 24.734 \, (\xi_{ef})^{-0.0692} \tag{9}$$

The second segment is the stress strengthening segment of PVC-FRP confined concrete column, the confining stress of PVC-FRP tube to concrete keeps increasing with the increment of axial load, the stress-strain curve can be approximate to a linear section, the expression of the linear section is

$$\sigma_c = f_o + E_2 \varepsilon_c \tag{10}$$

The stress and strain corresponding to the end point of the linear section are respectively the compressive strength f_{cc}' and ultimate axial strain ε_{cc}' of PVC-FRP confined concrete column, which can be respectively calculated by formula (4) and (5).

The relationship between axial stress σ_{cl} and lateral strain ε_l of PVC-FRP confined concrete column is that

$$\sigma_{cl} = E_{cl}\varepsilon_l - \frac{(E_{cl} - E_{2l})^2}{4f_o}\varepsilon_l^{\,2} \qquad 0 \le \varepsilon_l \le \varepsilon_{tl} \tag{11}$$

$$\sigma_{cl} = f_o + E_2\varepsilon_l \quad \varepsilon_{tl} \le \varepsilon_l \le \varepsilon_{cl} \tag{12}$$

Where $E_{cl} = E_c / \upsilon_c$, υ_c is the Poisson's ratio of concrete, υ_c=0.2; ε_{tl} is the intersection between the first segment and the linear strengthening segment, the expression of ε_{tl} can be shown by the following formula.

$$\varepsilon_{tl} = \frac{2f_o}{(E_{cl} - E_{21})} \tag{13}$$

Where E_{21} is the slope of linear strengthening segment, $E_{21} = E_2 / \upsilon$, we can get the expression of υ shown below by ingression of experimental data in this paper (Figure 4).

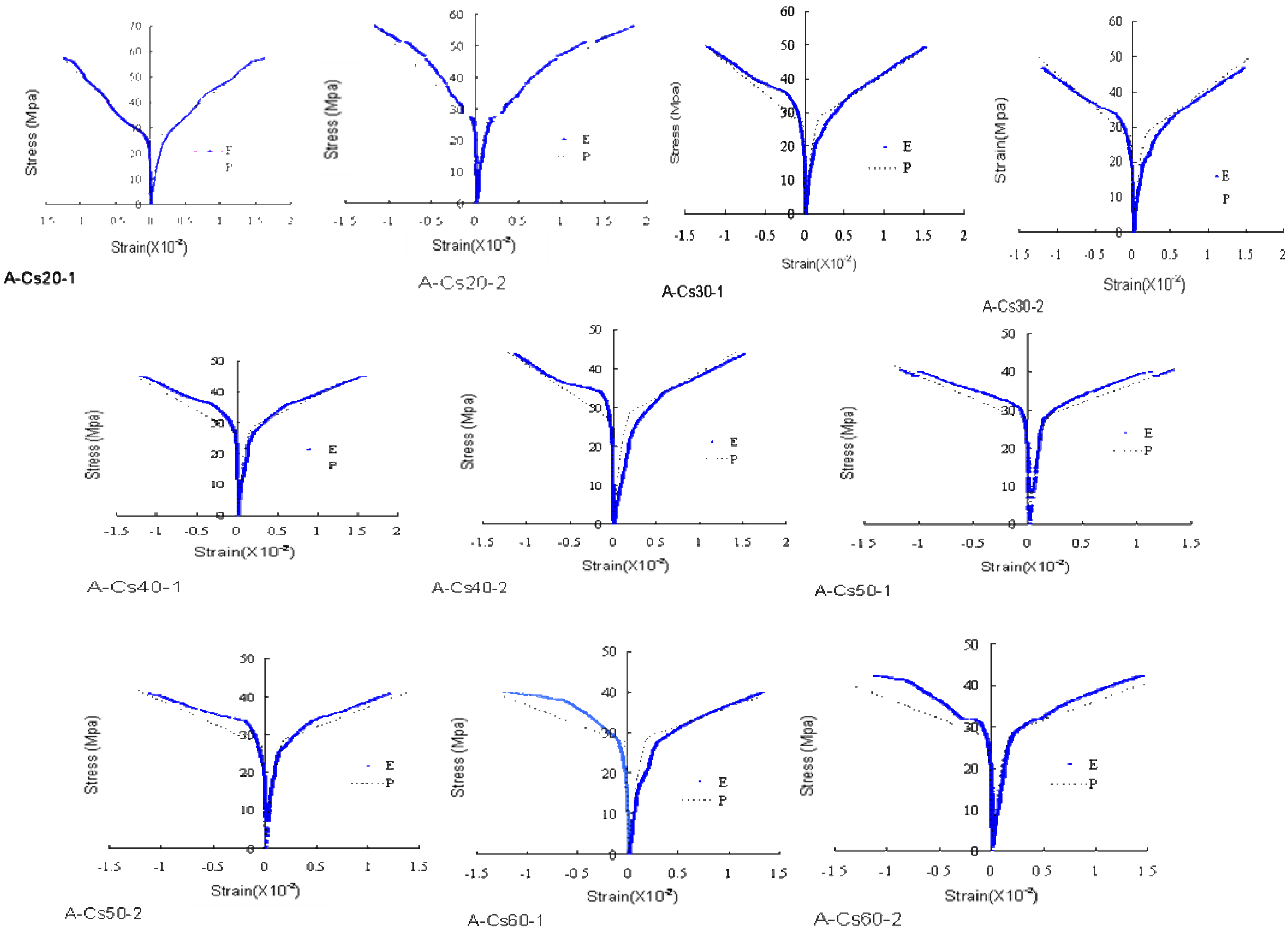

Figure 5. Comparison between experimental and numerical results.

$$\upsilon = 0.6882(\xi_{ef})^{-0.2257} \tag{14}$$

The stress-strain model is verified by experimental data, Figure 5 shows the comparison between the predicted stress-strain curves and test results. It is obvious that the stress-strain model of PVC-FRP confined concrete column can well predict the results of this paper.

CONCLUSIONS

1. The load-carrying capacity and ductility of PVC-FRP confined concrete column can be obviously improved by the confinement of PVC-FRP tube to concrete. The mechanical behavior of PVC-FRP confined concrete column is different from that of reinforced concrete or concrete filled steel tube, so it is not proper to apply the existing stress-strain model of reinforced concrete or concrete filled steel tube to directly predict the stress-strain relationship of PVC-FRP confined concrete column.
2. The behavior of PVC-FRP confined concrete column is mainly related to equivalent confinement effect coefficient, the hoop spacing of CFRP strips and the width of CFRP strips. This paper takes ξ_{ef} as main parameter, and the formula of load-carrying capacity and ultimate axial strain are proposed. The proposed formula agrees well with test data.
3. Based on the characteristic of PVC-FRP confined concrete column, taking ξ_{ef} as main parameter, a bilinear stress-strain model is established. The model is not only simple, but also has higher calculating precision, the predicted stress-strain curves compare favorably with the results of this paper.

ACKNOWLEDGEMENTS

The work presented in this paper is sponsored by National Natural Science Foundation of China (50538060, 51008001) and the natural science foundation of Anhui Province (KJ2010A046). The authors are grateful for their financial support.

REFERENCES

Abbasnia R, Ziaadiny H (2010). Behavior of concrete prisms confined with FRP composites under axial cyclic compression, J. Eng. Struct., 32(3): 648-655.
ACI (1996). State-of-the-Art-Report on Fiber Reinforced Plastic for Concrete Structures [C]. American Concrete Institute, Detroit, Michigan Committee, p. 440.
Chambers RE (1993). Plastics Composites for 21st Century Construction[C]. New York: Am. Soc. Civil Eng., 2: 3.
Erki MA (1995). New Materials in Construction [C]. Progress in Struct. Eng. Mat., 1(2): 123-125.
Feng Y, Ditao N (2007). Analysis on Load-carrying capacity of FRP Confined Concrete Column subjected to axial Compression, J. Concrete, 3: 14-16.
Feng Y, Ditao N (2009). Stress-strain model of FRP-confined circular column subjected to axial compression, J. Harbin Institute Technol., 41(10): 214-216.
Feng Y (2007). Experimental Study and Theoretical Analysis on Mechanical Behavior of PVC-FRP Confined Concrete Column [D]. A Dissertation of Xi'an University of Architecture and Technology for the Degree of Doctor of Eng., 31(10): 2247–2256.
Jiang T, Teng JG (2007). Analysis-oriented stress–strain models for FRP–confined concrete. Eng. Struct. J., 29(11): 2968-2986.
Jumaat MZ, Rahman MM, Alam MA (2010). Flexural strengthening of RC continuous T beam using CFRP laminate: A review. Int. J. Phys. Sci., 5(6): 619-625.
Kader L, El-Salakawy E, Brahim B (2006). Creep and durability of sand-coated glass FRP bars in concrete elements under freeze/thaw cycling and sustained loads. Cement Conc. Comp., 28(10): 869-878.
Mufti AA, Erki MA, Jaeger LG (1992). Advanced Composite Materials in Bridges and Structures in Japan Tokyo: the Canadian Soc. Civil Eng., pp. 201-204.
Wu G, Lü ZT, Wu ZS (2006). Strength and ductility of concrete cylinders confined with FRP composites. Constr. Build. Mat., 20(3): 134-148.
Yung-Chih W, Hsu K (2008). Design of FRP-wrapped reinforced concrete columns for enhancing axial load carrying capacity, J. Comp. Struct., 82(1): 132-139.