Advanced Composite Materials Wrapped Concrete: Stress-Strain Models

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Abstract: ***Buildings and bridges which collapsed in recent earthquakes highlighted the need for the retrofitting old infrastructure. The need arises because of the inadequate lateral strength and ductility of old structures which were primarily designed to transfer dead load and live loads. The availability of advanced composite materials and its innovative applications in civil engineering is relatively new. The interest in using composite material for confinement of new or existing concrete columns, has led to the attention of researchers and of the industry on its applications in civil engineering. For design of any member, along with the other properties, its stress-strain behaviour is of utmost importance. A detailed study of different stress-strain models is presented in this paper.***

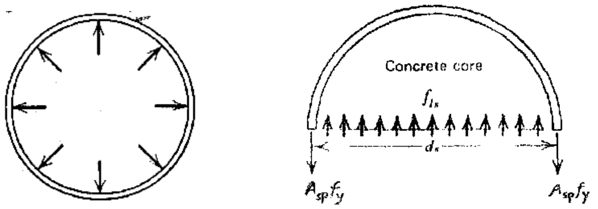
Keywords: Columns, Concrete, Confinement, Fibre reinforced polymers, Reinforcement.

1. Introduction

Confining the concrete increases the strength and the ductility. One of the methods of achieving improvement in strength and ductility is confining the concrete by composite material wraps. The need arises because of the inadequate lateral strength and ductility of old structures which were primarily designed to transfer dead load and live loads. The availability of advanced composite materials and its innovative applications in civil engineering is relatively new. The non-corrosive nature, light weight, high strength, high fatigue resistance, low thermal conductivity, bad conductor of electricity, non-magnetic nature, and ease installation gives added advantages over the conventional confining reinforcing material (i.e. steel). It has the advantage of using for the rehabilitation of corrosion damaged columns, to increases the load carrying capacity of weak members, and to provide additional strength and ductility for retrofitting of structures to improve seismic resistance capacity. This paper attempts to study the various stress-strain models taken from literature on composite confined concrete. For this a total of seven models on composites confined concrete have been selected and detailed discussion is presented.

2. Confinement of Concrete

Concrete can be confined by hoops and ties or spiral steel reinforcement. Confinement of concrete by steel pipes or plastic pipes has been reported in literature. The findings have confirmed that both strength and ductility of the concrete increases with an increase in confining pressures. Figure 1. (a) and (b) show the confinement provided by circular spirals, and confining pressure, respectively.



(a) Confinement by circular spirals (b) Confining pressure

Figure 1. Confinement and confining pressure

Richart *et al.*[1] were among the first to propose a confinement model for concrete. They developed an empirical formula to quantify the increase in the concrete compressive strength due to the application of a constant triaxial pressure. The authors proposed the following relation for stress enhancement of confined concrete:

$$f'_{cc} = f'_{co} + k_1 f_l \tag{1}$$

The strain at peak stress was predicted using:

$$\varepsilon_{cc} = \varepsilon_{co}\left(1 + k_2 \frac{f_l}{f'_{co}}\right) \tag{2}$$

3. Stress-Strain Models for Concrete with Composite Materials

This section describes in brief the confinement models developed for concrete confined with advanced composite materials.

A. Fardis and Khalili: The authors are believed to be the first applicators of composite materials for confinement of concrete. Compression tests were conducted on several 3 x 6 in. and 4 x 8 in. (75 x 150 and 100 x 200 mm) concrete cylinders, encased in four different types of composite materials. The results of the 3 x 6 in. cylinders strength wrapped with composite materials showed agreement with the failure envelopes of concrete under the action of axial stress f'_{cc} and lateral pressure f_l as suggested by Richart et al. (1928).:

$$\frac{f'_{cc}}{f'_{co}} = 1 + 4.1\frac{f_l}{f'_{co}} \tag{3}$$

$$f_l = \frac{2 f_{frp} n t_{frp}}{D} \tag{4}$$

i.e., the maximum confinement pressure that the composite material can zexert before rupturing in tension. Therefore, the model can be summarized as follows:

$$\frac{f'_{cc}}{f'_{co}} = 1 + 4.1\left(\frac{2 f_{frp} n t_{frp}}{f'_{co} D}\right) \tag{5}$$

Whereas the following proposals were made for the prediction of strain ε_{cc} at peak stress and axial stress-strain relationship:

$$\varepsilon_{cc} = \varepsilon_{co} + 0.001\left(\frac{E_{frp} n t_{frp}}{f'_{co} D}\right) \tag{6}$$

$$f_c = \frac{E_{co}\varepsilon_c}{1 + \varepsilon_c\left(\frac{E_{co}}{f'_{co}} - \frac{1}{\varepsilon_{cc}}\right)} \tag{7}$$

B. Karbhari and Gao: The proposed model was based on composite analysis and resulted in the following equations for stress and strain at ultimate.

$$f'_{cc} = f'_{co} + 3.1 f'_{co}\upsilon_c \frac{2t_{frp}}{d}\frac{E_{frp}}{E_c} + \frac{2 f_{frp} t_{frp}}{d} \tag{8}$$

$$\varepsilon_{cc} = 1 - \frac{1.004\left[1 - \frac{f'_{co}}{E_{ff}} - 4.1 f'_{co}\upsilon_c\left(\frac{2t_{frp}}{d}\right)\left(\frac{E_{frp}}{\mathrm{E}_c E_{eff}}\right)\right]}{\left(1 + \varepsilon_{frp,rup}\right)^2} \tag{9}$$

C. Samaan, M., Mirmiran, A., and Shahawy, M.: The authors adopted and calibrated the four-parameter stress-strain relationship suggested by Richard and Abbott (1975) to model the bilinear response of composite material confined concrete:

$$f_c = \frac{(E_c - E_2)\varepsilon_c}{\left\{1 + \left[\frac{(E_c - E_2)\varepsilon_c}{f_o}\right]^n\right\}^{\frac{1}{n}}} + E_2\varepsilon_c \tag{10}$$

where E_c and E_2 are the first and second slope, respectively; f_o is the reference plastic stress at the second slope with the stress axis; and $n*$ is a curve-shaped parameter that mainly controls the curvature in the transition zone. $n*$ is taken equal to 1.5 and f_o is correlated to the unconfined concrete strength. The maximum confining pressure provided by the composite material is given as:

$$f_o = 0.872^{0.2} + 0.371 f_l + 6.258 \tag{11}$$

the peak stress and strain are evaluated as follows:

$$f'_{cc} = f_{co} + 6.0 f_l^{0.7} \tag{12}$$

$$\varepsilon_{cc} = \frac{f'_{cc} - f'_o}{E_2} \tag{13}$$

D. Miyauchi, K., Inoue, S., Kuroda, T., and Kobayashi, A.: The researchers proposed the following equation to estimate the strengthening effect of the composite material confinement:

$$\frac{f'_{cc}}{f'_{co}} = 1 + 4.1 k_e\left(\frac{2 f_{frp} n t_{frp}}{f'_{co}}\right) \tag{14}$$

for the computation of ε_{cc} two empirical equations were suggested:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 10.6\left(\frac{f_l}{f'_{co}}\right)^{0.373} \quad \text{for } f'_{co} = 30 \text{ MPa} \tag{15}$$

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 10.5\left(\frac{f_l}{f'_{co}}\right)^{0.525} \quad \text{for } f'_{co} = 50 \text{ MPa} \tag{16}$$

which were calibrated using the experimental values of ε_{co}.

The complete stress-strain relationship of the confined concrete was proposed based on the observed behaviour as consisting of a parabolic branch modeled by the same equation of the unconfined concrete, followed by a straight line tangent to the parabola at the intersection point:

$$f_c = f'_{co}\left[2\left(\frac{\varepsilon_c}{\varepsilon_{co}}\right) - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right] \quad \text{for } (0 \le \varepsilon_c \le \varepsilon_t) \tag{17}$$

$$f_c = f'_{cu} - \lambda(\varepsilon_{cu} - \varepsilon_c) \quad \text{for } (\varepsilon_t \le \varepsilon_c \le \varepsilon_{cu}) \tag{18}$$

where:

$$\varepsilon_t = \varepsilon_{co} - \frac{\lambda\varepsilon^2{}_{co}}{2 f'_{co}} \tag{19}$$

and:

$$\lambda = \frac{\left\{-2 f'_{co}(\varepsilon_{cu} - \varepsilon_{co}) + \left[4 f'_{co}\left(f'_{co}\varepsilon^2{}_{cu} - 2 f'_{co}\varepsilon_{co}\varepsilon_{cu} + f'_{cu}\varepsilon^2{}_{co}\right)\right]^{0.5}\right\}}{\varepsilon^2{}_{co}} \tag{20}$$

E. Toutanji: Model provided by the author is a stress-strain curve characterized by two different regions. In the first region, the behaviour of the confined cylinder does not appreciably differ from that of the unconfined concrete, due to the limited lateral expansion taking place. For this stage, the author suggests an equation:

$$f_c = \frac{A \cdot \varepsilon_c}{1 + B\varepsilon_c + C\varepsilon_c{}^2} \tag{21}$$

in which the three parameters A, B, C are related to the slope of the first region, the slope of the second region at the intersection point between the two regions and axial stress and strain at the intersection point. Such point is suggested at that corresponding to a lateral strain equal to 0.002.

In second region, in which the composite material is fully activated and the behaviour is strongly influenced by the stiffness of the confining system, the stress-strain is modeled as follows:

$$\sigma_c = f'_{co}\left[1 + 3.5\left(\frac{2E_{frp} t_{frp}\varepsilon_h}{d f'_{co}}\right)^{0.85}\right] \tag{22}$$

σ_c is the axial stress as a function of the lateral strain, and:

$$\varepsilon_c = \varepsilon_{co}\left[1 + (310.57\varepsilon_h + 1.9)\left(\frac{\sigma_c}{f'_{co}} - 1\right)\right]$$

$$(0.002 \le \varepsilon_h \le \varepsilon_{frp.rup}) \tag{23}$$

ε_c is the axial strain as a function of the lateral strain. Assuming that failure occurs by composite material rupture the expressions of the peak stress and strain (coinciding with ultimate stress and strain) follow immediately from (22) and (23) by setting the lateral strain equal to the ultimate composite material strain and given by:

$$\sigma_c = f'_{co}\left[1 + 3.5\left(\frac{2E_{frp} t_{frp}\varepsilon_h}{d f'_{co}}\right)^{0.85}\right] \tag{24}$$

$$\varepsilon_c = \varepsilon_{co}\left[1 + (310.57\varepsilon_h + 1.9)\left(\frac{\sigma_c}{f'_{co}} - 1\right)\right] \tag{25}$$

F. Saafi, M., Toutanji, H. A., and Li, Z.: The proposed model is identical to that by Toutanji, with the only exception

Paper ID: SR201208175333 DOI: 10.21275/SR201208175333

that regression analysis was conducted on experimental results obtained by composite material encased rather than wrapped cylinders. Different values of the coefficients were found and the discrepancy was attributed to the bond between composite material sheets and concrete being stronger as compared to that of composite material tubes. The expressions of ultimate stress and strain are as follows:

$$\sigma_c = f'_{co}\left[1+2.2\left(\frac{f_l}{f'_{co}}\right)^{0.84}\right] \quad (26)$$

$$\varepsilon_c = \varepsilon_{co}\left[1+\left(537\frac{f_{fu}}{E_f}2.6\right)\left(\frac{\sigma_c}{f'_{co}}-1\right)\right] \quad (27)$$

G. Xiao, Y., and Wu, H.: The authors proposed a bilinear axial stress-strain relationship for confined concrete, with the first region expressed by:

$$\sigma_c = E_c\varepsilon_c + \frac{2E_l{\nu_c}^2}{1+\frac{E_l}{E_{co}}\left(1-\nu_c-2{\nu_c}^2\right)}\varepsilon_c \quad (28)$$

where ν_c is the initial Poisson's ratio of the concrete, and the second region expressed by:

$$\sigma_c = 1.1 f'_{co} + kf_r \quad (29)$$

$$\varepsilon_c = \frac{\varepsilon'_{ro}-\varepsilon_c}{\upsilon'_c} \quad (30)$$

$$k_1 = 4.1 - 0.75\left(\frac{f'co^2}{C_j}\right) \quad (31)$$

$$C_j = \frac{2t_{frp}}{d}E_{frp} \quad (32)$$

$$f_r = -C_j\varepsilon_h \quad (33)$$

The peak stress and strain result as follows:

$$\frac{f'_{cc}}{f'_{co}} = 1.1 + k\frac{fl}{f'_{co}} \quad (34)$$

$$\varepsilon_c = \frac{\varepsilon'_{ro}-\varepsilon_c}{\upsilon'_c} \quad (35)$$

$$\varepsilon' ro = -0.0005 \quad (36)$$

$$\upsilon'_c = 7\left(\frac{f'^2co}{C_j}\right)^{0.8} \quad (37)$$

The previous expressions were calibrated empirically on experimental results by the authors on composite material-wrapped specimens. The recorded composite material hoop strains corresponding to failure ranged from about 50% to 80% of the rupture strains obtained for tensile coupons. However, calibration was based on the measured lateral strains and therefore such equations do not incorporate the premature tensile failure of composite material.

4. Conclusion

On the basis of the present study it can be concluded that the available composite materials stress-strain models are useful in predicting the confined concrete strength. They are also capable of predicting the ultimate strain of composite material confined concrete. However to have better level of confidence in predicting the stress-strain and ultimate strength and strain of composite material confined concrete more work is required.

Further research is required in this direction to find the most suitable model which can be used to predict stress-strain behaviour, and ultimate strength and strain of composite material confined concrete which can lead to development of Indian Code for applications of composite materials for concrete structures.

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Paper ID: SR201208175333 DOI: 10.21275/SR201208175333