IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 3 Issue 6, June 2016
ISSN (Online) 2348 – 7968 | Impact Factor (2015) - 4.332
www.ijiset.com

Review paper of Analysis of FRP Confined Cylinders under Axial Compression

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ABSTRACT

FRP is used for strengthening of the structural member and also as a permanent formwork. Many researchers carried out tests for compression member and compare their test results with the available codal formulae. One of them also proposed mathematical model on the basis of their test results. This paper presents the formulae provided in 'ACI 440_2r.08' and Chinese code, and also equation proposed by 'Hamdy M. Mohamed and Radhouane Masmoudi' for the analysis of the FRP confined or FRP wrapped cylinders. The test results from the available literature are compared with these formulae.

Keywords: FRP, concrete, confinement, axial compression

1. INTRODUCTION

Fiber reinforced polymer (FRP) is a composite material made up of polymer matrix reinforced from fibers. FRPs are fabricated generally from glass, carbon, aramid and basalt. Paper, wood and asbestos fibres also preferred for certain requirements. FRPs are commonly used in the aerospace, automotive, marine, construction industries and ballistic armour in the form of wrapping or concrete filled Fiber reinforced polymer tubes (CFFT). Masmoudi used fibers as an internal reinforcement for beams, slabs and pavement whereas Demeres and Neale used as an external reinforcement for rehabilitation and strengthening of structures. Now a day, FRPs are preferred for increasing strength of concrete members because of its many advantages like protecting the concrete from aggressive environments, confinement of concrete.

Mirmiran and shahawy [6] introduced CFFTs in 1997. CFFT is a combination of FRP and concrete in an optimal manner. Filament winding process is generally used in CFFT. B. Zhang concluded from the tests, that lateral confinement of CFFT can increase significantly the strength as well as ductility of the concrete. Due to these advantages, CFFT can be used for construction exposed to severe outdoor environment such as bridge columns, piles etc. It can also reduce clear covr, confinement reinforcement and the longitudinal reinforcement. Many researchers conducted tests on the circular CFFT in filled with plane concrete or reinforced concrete column. They compared their results with ACI 440_2r.08. Togay Ozbakkaloglu has conducted tests on rectangular CFFT but results are not compared with code or mathematical model.

2. LITERATURE REVIEW

American Code Institute, ACI 440.2R-08 [1] is the "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures". This code has provided the empirical equation for the analysis of the FRP wrapped square, rectangular and circular columns. Maximum confining pressure due to the FRP jackets, can be obtained by the following equation,

$$f_l = \frac{f'_{cc} - f'_c}{3.3 k_a} \tag{1}$$

Where,

$$k_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \tag{2}$$

$$\frac{A_e}{A_c} = \frac{1 - \frac{\left[\left(\frac{b}{h}\right)(h-2r_c)^2 + \left(\frac{h}{b}\right)(b-2r_c)^2\right]}{3A_g} - \rho_g}{1-\rho_g} \tag{3}$$

The value of k_a is 1 for circular columns and calculate according to "Eq. (1)" for other shapes. f'_{cc} is confined concrete strength. f'_c is non-confined concrete strength. f_l is maximum confining pressure due to the FRP jacket can be obtained by formula

$$f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D} \tag{4}$$

where, n is number of FRP layers and t_f is thickness of FRP layer

Y. M. Hu [10] conducted tests on seven specimens under axial compression and studied its behaviour. Out of seven specimens, three were plane concrete, one was concrete filled steel tube and remaining were CFFTs with the varying thickness of the FRP layer. CFFTs were made up of GFRP with thickness ranges from 0.17mm to 0.68mm and its diameter-to-thickness ratio more than 100. Size of specimens was 152.5 X 305 mm. The analysis was made as per the ACI 440.2R-08 provisions for concrete filled FRP tubes. The confining stress is calculated by the following equations,

$$\sigma_{r,frp} = \frac{E_{frp} t_{frp} \varepsilon_{frp}}{(R+t_s)} \quad (5)$$

$$\sigma_{r,steel} = \frac{\sigma_{\theta,steel} t_s}{R} \quad (6)$$

Where, $\sigma_{r,frp}$ is confining pressure , E_{frp} is elastic modulus in the hoop direction and t_{frp} is thickness of the FRP wrapping, ε_{frp} is hoop strain of the FRP wrap, R is radius of the concrete core, $\sigma_{r,steel}$ is confining pressure provided by the steel tube; and $\sigma_{\theta,steel}$ and t_s is hoop stress and thickness of the steel tube, respectively. From the test results, they concluded that the FRP wrapping is effective to increase the load-carrying capacity and improves the ductility also. All specimens failed by the lateral expansion of the concrete. The local buckling of concrete filled steel tubes can either be much delayed or completely suppressed by the FRP wrapping, and the strength of the concrete can be significantly enhanced with the additional confinement from the FRP wrap. From the graph of axial stress-strain behaviour they concluded that in the first stage, the concrete is similar to unconfined concrete, in the second stage confining pressure increases and in the third stage confinement provided by the FRP wrap dominates.

T. Yu [7] conducted tests on 24 cylinders of glass and carbon fiber tubes having diameter 152.5mm and height 305mm under axial compression. Cylinders are filled with self compacting concrete (SCC). The cylinders were casted from three grades of concrete and different layers of FRP. The results were compared with the stress–strain model given by Jiang and Teng. From test results, they concluded that the behaviour of FRP-confined SCC is similar to that of FRP-confined normal concrete (NC). But for the same axial strain, the lateral confining pressure in the SCC is larger than the NC.

B. Zhang [2] tested the CFFTs of high grade concrete and studied their behaviour under the cyclic load. From the test results, they concluded that the rupture of fibers started from the outermost ply and progressed towards inner side which was different from the failure of concrete confined with an FRP wrapping. The cyclic axial stress-strain behaviour of concrete is similar to that of concrete confined with an FRP wrapping.

T. Yu [8] had given the recommendation for circular CFFTs under axial compression, bending and combined bending and axial compression as per Chinese technical code. Variable confinement model is specified in the Code for the stress-strain behaviour of the confined concrete, taking into consideration the effect of the strain on confinement ratio. They have also mentioned the method of analysis for evaluating the mechanical properties and the ultimate strength of the FRP tube and testing approach for the design of CFFTs in the paper as per the code provisions. The empirical equation for stress calculation under concentric axial compression is given below.

$$\sigma_{cc} = E_1 \varepsilon_{cc} - \frac{(E_1 - E_2)^2}{4 f_c} \varepsilon_{cc}^2 \qquad 0 \leq \varepsilon_{cc} \leq \varepsilon_t \quad (7)$$

$$\sigma_{cc} = f_c + E_2 \varepsilon_{cc} \quad (8)$$

$$\varepsilon_t = \frac{2 f_c}{(E_1 - E_2)} \quad (9)$$

$$E_2 = \frac{f_{cc} - f_c}{\varepsilon_{cc,u}} \quad (10)$$

where, σ_{cc} is axial stress and ε_{cc} is axial strain; E1 is elastic modulus of unconfined concrete; E2 is slope of the linear second portion; ε_t is strain at which the parabolic first portion meets the linear second portion; f_{cc} is design compressive strength of confined concrete; $\varepsilon_{cc,u}$ is design ultimate axial strain of confined concrete and should not exceed the design ultimate axial strain (i.e., compressive coupon tests of FRP). f_{cc} and $\varepsilon_{cc,u}$ are by the equation,

$$f_{cc} = f_c + 3.5 \frac{E_{\theta t,eff} t_{frp}}{r} \left(1 - \frac{6.5}{\beta_j}\right) \varepsilon_{ru} \quad (11)$$

Where, β_j is confinement stiffness parameter and is given by,

$$\beta_j = \frac{E_{\theta t,eff} t_{frp}}{f_{c,k} r} > 6.5 \quad (12)$$

Also $\varepsilon_{cc,u}$ is given by the formula,

$$\varepsilon_{cc,u} = 0.003 + 0.6{\beta_j}^{0.8}\varepsilon_{ru}^{1.45} \quad (13)$$

Where ε_{ru} equivalent design ultimate hoop strain of the FRP Tube and is given by the formula

$$\varepsilon_{ru} = \frac{\sigma_{frp}\theta_u}{E_{\theta t,eff}} \quad (14)$$

Hamdy M. Mohamed [5] conducted tests on 23 CFFTs filled with plane concrete and reinforced concrete the under axial compression and compared their results with the codes ACI 440.2R-08, CSA-S6-06, and CSA-S806-02. From their test results, they concluded that the codes of FRP wrapped columns can be used for the FRP tubes with modification suggested by them. The modified model is as given below.

$$f'_{cc} = f'_c\left[0.7 + 2.7\left(\frac{f_{lfrp}}{f'_c}\right)^{0.7}\right] \quad (15)$$

Where, f'_{cc} is the confined compressive strength of the concrete column, f'_c is the unconfined compressive strength of the concrete. And f_{lfrp} is the lateral pressure and is given by the following equation,

$$f_{lfrp} = \frac{2E_{frp}nt_{frp}\varepsilon_{fe}}{D} \quad (16)$$

$\varepsilon_{fe} = k_\varepsilon \varepsilon_{fu}$ and $k_\varepsilon = 0.55$ (17)

Where, ε_{fe} is effective strain level in the FRP at failure. The minimum lateral pressure is limited to be not less than 0.08 times f'_c.

Togay Ozbakkaloglu [9] carried tests and studied square and rectangular concrete filled fiber reinforced polymer tube (CFFTs) behaviour under concentric compression. They have shown experimentally, the effect of corner radius of column, thickness of FRP tube on the strength of the column. They concluded that, columns ductility and compressive strength can be increase substantially with the FRP tube. Also the corner radius of rectangular or square columns has significant effect on the effectiveness of confinement. Confinement provided by the FRP increases with the increase in the corner radius. They also showed that the FRP tube thickness has significant influence on the ultimate strain of confined concrete and ultimate strain of confinement increases with the increase in the tube thickness. The axial compressive behaviour of square columns is superior to that of rectangular columns having similar confinement.

In this paper, authors compared the available test results with the theoretical analysis made by different models mentioned in the literature. The results are tabulated in Table 1.

Table -1: Compared the Available Test Results with the Theoretical Analysis

Paper and Author name	***Specimen***	***Experimental Results***	***Results by ACI 440-2r.08***	***Results by Mohamed***	***Results by Chinese codal provisions***
Self compacting concrete, T. Yu, J. G. Teng GFFT 152.5X305mm	30G1 -1	31	34.63	36.25	23.70
	30G1 -2	3.7	34.63	36.25	23.70
	30G3 -1	44.6	43.59	41.17	40.12
	30G3 -2	44.9	43.59	41.17	40.12
	47G3 – 1	53.6	60.59	55.97	38.21
	47G3 – 2	48.9	60.59	55.97	38.21
	47G6 – 1	81.8	93.38	61.12	116.42
	47G6 – 2	85.5	93.38	61.12	116.42
Square tube, Ozbakkaloglu, CFFT 200*200*600	R10L3	24.7	30.67	69.71	90.58
	R20L3	25.9	30.67	69.71	90.58
	R40L3	33.8	30.67	69.71	90.58
	R10L5	26.9	35.43	122.05	235.46
	R20L5	35	35.43	122.05	235.46
	R40L5	47.2	35.43	122.05	235.46
Self compacting concrete Self compacting concrete, T. Yu, J. G. Teng CFFT	30c1	42.8	35.31	31.45	31.83
	30c2	61.8	51.25	48.58	52.67
	47c2	74.3	68.25	64.46	60.98
	47c3	87	94.82	88.58	96.47
	105c1	116	110.31	88.72	87.66

152.5X305mm	105c3	121	152.82	144.37	110.00
	105c6	196	296.28	260.53	286.04

3. CONCLUSIONS

1. The analytical and test results show that the values from the test results are closer to the values calculated from ACI code for circular as well as rectangular column with up-to three layers, but it overestimates the predictions for layers more than three.
2. The predictions from the Chinese code are closer to the test results for circular but it overestimates the strength of the square column.
3. The theoretical results from Mohamed model are very close to the test results for the circular columns but it overestimates the strength of the square columns.

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