Calculation of the compressive strength of concrete columns partially confined with CFRP

Marina L. Moretti, and Asad-ur-Rehman Khan

[1] National Technical University of Athens, Athens, Greece
[2] NED University of Engineering &Technology, Karachi, Pakistan

ABSTRACT: A series of concrete specimens partially confined by by carbon fiber reinforced polymers (CFRP) have been tested in the Laboratory of NED University of Engineering & Technology, in Karachi, Pakistan. The specimens examined had circular and square cross-sections and height between 300mm and 600mm. Unreinforced specimens, reinforced concrete specimens, as well as specimens strengthened with different layouts of CFRP confinement, aiming at the reduction of the FRP material used, have been tested. The aim of this work is to offer a methodology to predict the increase of the compressive strength of the specimens for the various layouts tested. EN code provisions, and models found in the literature are applied to reproduce the experimental results. A modified model is proposed that predicts more accurately the specimens's strength for the FRP layouts reported in this research.

1 INTRODUCTION

Application of fiber reinforced polymers (FRP) as a reinforcing method of concrete structural elements is a comparatively modern method which leads to the enhancement of the performance of the structural element, with little interference with the structure (referring to both the dynamic characteristics, and the practical application details). In order to investigate the potential of the application of FRPs to strengthen mainly plain concrete structures, an extensive experimental program has taken place in the Department of Civil Engineering, NED University of Engineering & Technology, in Karachi, Pakistan, Khan et al. (2010), (2012), (2013). Starting point for the experimental investigation was the observation of major distresses in RC structures located by the sea in Pakistan due to environmental attack, shortly after their construction. The experimental investigation included testing of short concrete elements with rectangular and circular cross-sections in uniaxial compression. Specimens with various layouts of wrapping with Carbon Fiber Reinforced Polymers (CFRP) were tested. The main idea was to examine different CFRP layouts with partial confinement in order to obtain similar characteristics of confinement, but with reduced material. Control specimens without reinforcement and with reinforcement were included in the experimental program. The results reported in this paper are the average of each typical case.

Scope of this paper is to offer a methodology to predict the increase of the compressive strength of the specimens for the various layouts tested. EN code provisions and analytical models found in the literature are applied to reproduce the experimental results. A modified model is proposed that predicts more accurately the specimens' strength for the FRP layouts reported in this research. The analytical predictions of the confined concrete compressive strength are compared to the ones measured in the tests.

2 CHARACTERISTICS OF THE SPECIMENS

The specimens tested were cylindrical with diameter 150 mm and height 300 mm, cylindrical with diameter 100 mm and height 600 mm, and finally specimens with rectangular cross-section of 107 mm and height 600 mm. In all three cases fully wrapped specimens and reinforced specimens without CFRP were constructed, serving as control specimens. Furthermore, specimens with strips of CFRP of width 25 mm and 50 mm (isolated and continuous strips), combined with or without the presence of wrap in the middle part extending at one third, half and two thirds of the specimens' height, were tested. The characteristics of the specimens and the compressive strength of the confined specimens, f_{cc}, may be seen in Tables 1, 2, and 3.

Table 1. Cylindrical specimens with 150 mm diameter and 300 mm height, Khan et al. (2010)

Reinforcement	f_{cc} (MPa)	Layout of CFRP
none	25.72	fully wrapped
none	18.82	100 mm-wide wrap in middle
none	36.31	25 mm-wide wrap @25 mm c/c spacing
none	28.73	25 mm-wide wrap @50 mm c/c spacing
none	25.05	25 mm-wide wrap @75 mm c/c spacing
none	40.22	25 mm wrap @25 mm c/c + 100 mm-wide wrap in middle
none	30.06	25 mm wrap @50 mm c/c + 100 mm-wide wrap in middle
none	23.65	25 mm wrap @75 mm c/c + 100 mm-wide wrap in middle
4∅10 +∅6@102	19.72	none
4∅10 +∅6@102	44.54	fully wrapped
4∅10 +∅6@102	26.89	100 mm-wide wrap in middle

Table 2. Cylindrical specimens with 100 mm diameter and 600 mm height, Khan et al. (2013)

Reinforcement	f_{cc} (MPa)	Layout of CFRP
none	23.18	none
none	54.78	fully wrapped
none	52.48	two third wrapped in the middle (400 mm)
none	40.89	half wrapped in the middle (300 mm)
none	24.33	one third wrapped in the middle (200 mm)
none	41.78	50 mm-wide wrap @100 mm c/c spacing
none	40.51	50 mm wrap @100 mm c/c continuous strip at angle of 30°
4∅10 +∅6@102	39.49	none

Table 3. Specimens with square cross-section of 107 mm and 600 mm height, Khan et al. (2012)

Reinforcement	f_{cc} (MPa)	Layout of CFRP
none	26.38	none
none	35.99	fully wrapped
none	34.76	two third wrapped in the middle (400 mm)
none	31.97	half wrapped in the middle (300 mm)
none	24.19	one third wrapped in the middle (200 mm)
none	37.56	50 mm-wide wrap @100 mm c/c spacing
none	27.60	50 mm wrap @100 mm c/c continuous strip at angle of 30°
4∅10 +∅6@102	30.92	none

One layer of CFRP wrap was used in all cases. The overlapping length of the fabric was 102 mm in general. The material properties of the carbon fibers used were: Ultimate tensile strength of 4,100 MPa, tensile modulus of elasticity E_f = 231,000 MPa, fabric thickness equal to t_f=0.117 mm and fiber density 1.78 gr/cm^3. All RC specimens had the same reinforcement consisting of four 10 mm-diameter longitudinal rebars, with 6 mm-diameter stirrups at distances 102 mm c/c (center to center of consecutive stirrups). Mild steel was used with yield strength f_y = 320 MPa and strain at yielding ε_{sy}=0.0015.

Cylindrical specimens 150×300 mm had cylindrical (unconfined) compressive concrete strength equal to 16.17 MPa and clear concrete cover 19 mm, while the specimens in the other two cases had cylindrical (unconfined) compressive concrete strength equal to 21 MPa and clear concrete cover 13 mm. Maximum aggregate size was 19 mm. The corner radius of the rectangular cross section was R_c=7 mm. More details about the specimens and the testing may be found in previous publications Khan et al. (2010), (2012), (2013).

3 ANALYTICAL PREDICTIONS FRO THE STRENGTH OF THE TEST DATA

3.1 General

Numerous stress-strain models have been proposed for FRP- and steel-confined concrete since the 1980's. Although much progress has been achieved towards understanding of the stress-strain behavior of FRP-confined circular elements, much work still has to be done for the case of rectangular columns, and still more when both FRP confinement and steel reinforcement are present (Kalogerakis et al, 2014 and Paparizos, 2015).

The models appropriate to predict the increased compressive strength of the specimens considered in this paper have to take into account the contribution of strips, as well as the contribution of the continuous part of wrap in the middle, when present. For the latter no such provision exists in the available models found in the literature, since it was a novelty introduced in the experimental researches considered. The contribution of FRP strips to increase the compressive strength due to confinement is generlly assumed to be analogous to the action of stirrups based on the approach proposed by Sheikh et al. (1980), and Mander et al. (1988).

3.2 Eurocodes

The enhancement of the strength of a reinforced concrete element subjected to compression and lateral compressive stresses σ_{lat} is calculated according to EN1992-1-1 as follows:

$$f_{ck,c} = f_{ck}\left(1+5\frac{\sigma_{lat}}{f_{ck}}\right) \quad \text{for} \quad \sigma_{lat} \le 0.05 f_{ck} \tag{1a}$$

$$f_{ck,c} = f_{ck}\left(1.125+2.5\frac{\sigma_{lat}}{f_{ck}}\right) \quad \text{for} \quad \sigma_{lat} > 0.05 f_{ck} \tag{1b}$$

The lateral confinement pressure σ_{lat} applied by continuous FRP sheet is calculated according to EN1998-3:

- For circular columns with diameter equal to D, and total thickness of FRP equal to t_f :

$$\sigma_{lat} = \frac{1}{2}\rho_f E_f \varepsilon_{ju}$$ where ε_{ju}, E_f : ultimate strain and elastic modulus of FRP (3)

$$\rho_f = \frac{4 \cdot t_f}{D}$$ where ρ_f is the volumetric ratio of the FRP (4)

- For rectangular cross-sections in which the corners have been rounded with a radius R_c to allow wrapping around them (where D is the larger section width):

$$\sigma_{lat} = k_s \frac{2E_f \varepsilon_{ju} t_f}{D} \quad \text{where} \quad k_s = 2\frac{R_c}{D} \tag{5}$$

In case wrapping is applied through strips with clear spacing between strips, s_f , the confining pressure $\sigma_{lat}^{'}$ applied by the FRP strips is calculated by multiplying the lateral pressure σ_{lat} with the reduction factor k_g as follows:

$$\sigma_{lat}^{'} = k_g \cdot \sigma_{lat} \quad \text{where} \quad k_g = \left(1-\frac{s_f}{2D}\right)^2 \tag{6}$$

In presence of steel stirrups only the effective lateral confining stress σ_{lat} is given in EN1998-3:

$$\sigma_{lat} = \alpha \cdot \rho_{sx} \cdot f_{yw} \tag{7}$$

where α is the confinement effectiveness factor, calculated according to EN1998-1, as shown in equation (8), and $\rho_{sx} = A_{sx}/(b_w s_h)$ = ratio of transverse steel parallel to the direction x of loading (s_h = stirrup spacing).

$$\alpha = \left(1-\frac{s_h}{2b_o}\right)\left(1-\frac{s_h}{2h_o}\right)\left(1-\frac{\Sigma b_i^2}{6b_o h_o}\right) \tag{8}$$

where b_o, h_o are the dimensions of confined core measured from the centerline of the stirrups, and b_i is the spacing of longitudinal bars laterally restrained by a corner stirrup or a cross-tie.

The analytical predictions of the Eurocodes compared to the experimental data for the specimens shown on Tables 1 to 3 are depicted in Figure 1. Neither the specimens in which a continuous sheet of FRP was placed in the central part of the specimen, nor the specimens confined spirally by a strip inclined compared to the direction of the cross sections are displayed, since the contribution of these layouts are not included in the Eurocode provisions. The square of the Pearson Product-Moment Correlation Coefficient (r^2) between the analytical and the experimental data is also indicated on Figure 1.

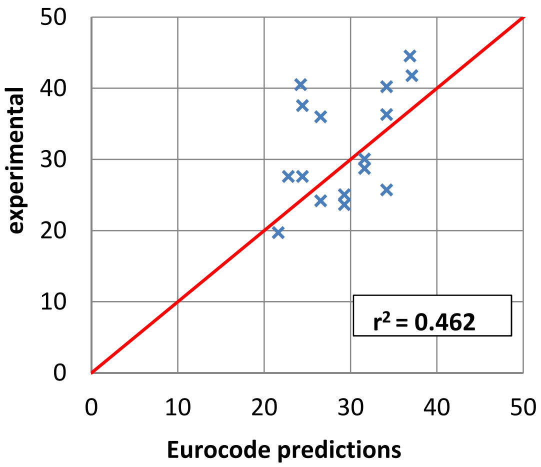

Figure 1. Analytical predictions according to Eurocodes compared to the experimental data.

3.3 *Implementation of selected analytical models*

The models that will be applied were selected among others available in the literature because they were found to reproduce well the behaviour of RC elements subjected to compression, according to experimental reslults from the literature (Paparizos, 2015). A practical (owing to the easy application) empirical model evaluated against a number of test data was proposed by Roussakis et al. (2008). More detailed models that were formulated to take into account the confining effect of both FRP sheets and steel stirrups were proposed by Wang et al. (2007), and by Pellegrino et al. (2010). It is noted that the model of Wang et al. (2007) does not include provisions for FRP strips. The model of Pellegrino et al. (2010) is based on the recommendations of the Italian Research Council (CNR), 2004, and takes into account the contribution of fibers spirally installed at an angle a with respect to the member cross- by multiplying the lateral effective confining pressure with the coefficient K_α :

$$K_\alpha = \frac{1}{1+\tan^2\alpha} \tag{9}$$

The predictions of the three models against the respective experimental results are depicted in Figures 2 to 4. The correlation coefficient RSQ is indicated in each case. Only those specimens are included with FRP layouts explicitly described in each analytical model.

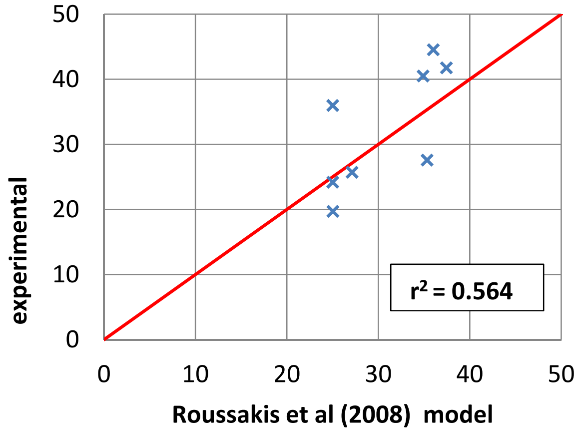

Figure 2. Analytical predictions according to the model of Roussakis et a. (2008).

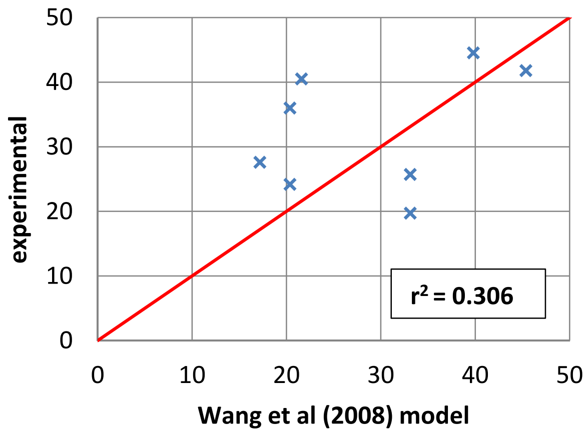

Figure 3. Analytical predictions according to the model of Wang et al. (2007).

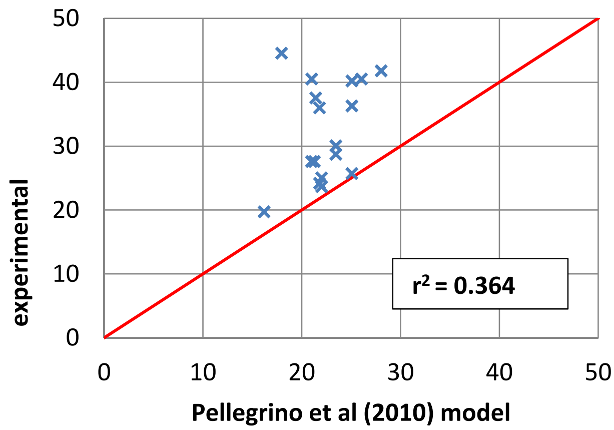

Figure 4. Analytical predictions according to the model of Pellegrino et al. (2010).

3.4 Proposed analytical model

In order to estimate the enhancement of the compressive strength of the specimens considered with the layouts tested and reported in this work, a model is proposed essentially based on the Eurocode provisions presented in 3.2. The enhancement of the compressive strength is calculated from equations (1a) or (1b), depending on the value of the lateral compressive pressure σ_{lat} due to the FRP layout and also to the steel stirrups, when present. The lateral stress σ_{lat} is expressed as shown in equation (10). The influence of the different confinement effectiveness factors are taken into account by a single factor, K_f, expressed in equation (11).

$$\sigma_{lat} = 0.5 K_f \rho_f E_f \varepsilon_f^{eff} \tag{10}$$

$$K_f = K_h K_v K_\alpha K_L \tag{11}$$

where $\varepsilon_f^{eff} = 0.8 \cdot \varepsilon_{fu}$ is the effective hoop FRP strain, assumed as 80% of the ultimate FRP strain, ε_{fu}, according to Lam et al (2003), K_h and K_v are the confinement effectiveness factors parallel to the cross-section, and along the height of the element, respectively, K_α is a factor taking into account the inclination of the strips, as in equation (9), and K_L is applied when a continuous sheet extends along a certain length L' of the element's total length, L, assumed to be: $K_L = L'/L$ for $L'/L \geq 0.50$, and $K_L = 0.50L'/L$ for $0.33 \leq L'/L < 0.50$. For circular cross-sections it is $K_h = 1$, both for FRP and for stirrups. For rectangular cross-section $K_h = (1 - \Sigma b_i^2 / 6 b_o h_o)$ (8). For the confining effect of the FRP in the rectangular cross-section of the tests, it is $b_o = h_o = 107mm$, and $b_i = b_o - 2R_c = 107 - 2 \times 7 = 93mm$. In case of stirrups, the concrete core is measured from the centerlines of the stirrups.

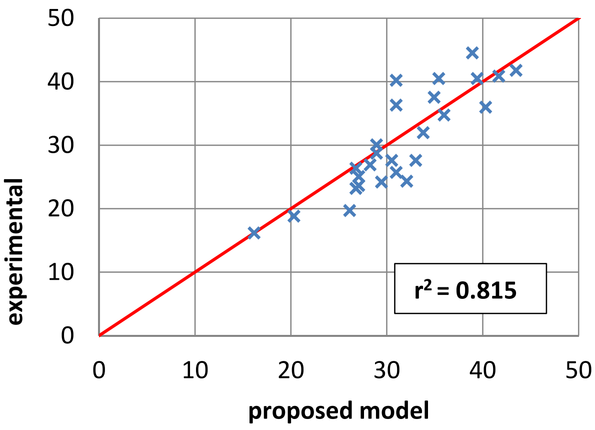

Figure 5. Analytical predictions according to the proposed model.

For full FRP wrapping $K_v = 1$. For confinement with stirrups or FRP strips it is $K_v = (1 - s_f / 2D)^2$ for circular and $K_v = (1 - s_f / 2b_o)(1 - s_f / 2h_o)$ for rectangular cross-sections, where s_f is the clear distance between the FRP strips, or the distance between stirrups, D is the diameter of a circular cross-section (FRP) or the diameter of the concrete core (stirrups), and b_o, h_o are the dimensions of confined core.

Furthermore, for elements with dimension of cross-section 100 mm and 107 mm, the concrete strength due to confinement was increased by a factor 1.5 (=150/100) to account for the size effect phenomena. The contribution of longitudinal reinforcement, when present, to compressive strength is calculated by assuming yielding of the rebars, without size effect.

4 CONCLUSIONS

The design model proposed in this work predicts well the increase of the compressive strength of the specimens considered with the different FRP layouts tested. The use of FRP strips, instead of continuous FRP wrapping, may be an option when the cost of the FRP material is crucial in selecting the appropriate design method for strengthening a sub-standard structure.

5 REFERENCES

EN 1992-1-1, 2004, Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings, *European Committee for Standardization, CEN.*

EN 1998-1, 2004, Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings, *European Committee for Standardization, CEN*.

EN 1998-3, 2005, Eurocode 8: Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings, *European Committee for Standardization, CEN.*

Kalogerakis, M, and Moretti ML, 2014, Behavior of concrete confined by glass and carbon fibers. *Proceedings of Conference CESARE'14, Amman, Jordan.*

Khan, AR, and Zafar MS, 2010, Compressive strength of concrete cylinders confined with CFRP wraps, *Proceedings of CICE 2010, The 5th International Conference on FRP Composites in Civil Engineering*, September 27-29, Beijing, China: 630-633.

Khan, AR, and S. Fareed, 2012, Confinement of short concrete columns with CFRP wraps subjected to concentric and eccentric loading, *Proceedings of International Conference on Concrete Repair, Rehabilitation and Retrofitting III,* Alexander et al. (eds), Taylor & Francis Group, London.

Khan, AR, and S. Fareed, 2013, Behaviour of concentrically and eccentrically loaded short concrete columns confined with CFRP wraps, *SMAR 2013 Second Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures*, September 9-11, Istanbul, Turkey.

Lam, L, and Teng JG, 2003, Design-oriented stress-strain model for FRP-confined concrete. *Construction Building Materials,*17: 471-489 .

Mander, JB, Priestley, MJN, and R. Park, 1988, Theoretical stress-strain model for confined concrete. *Journal of Structural Engineer*, 114(8): 1804-1826.

National Research Council (NCR), 2004, Guide for the design and construction of externally bonded FRP systems for strengthening existing structures: Materials, RC and PC structures, masonry structures. *Advisory Committee on technical recommendations for construction*, Rome.

Paparizos, I., 2015, Confinement of substandard RC columns wrapped with CFRP. *Undergraduate Thesis*, Dept. of Civil Engineering, University of Thessaly, (in Greek).

Pellegrino, C., and C. Modena, 2010, Analytical model for FRP confinement on concrete columns with and without internal steel confinement. *Journal of Composites for Construction*, 14(6): 693-705.

Roussakis, TC, and Karabinis, AI, 2008, Substandard reinforced concrete members subjected to compression: FRP confining effects. *Materials and Structures*, 41: 1595-1611.

Sheikh, SA, and Uzumeri, SM, 1980, Strength and ductility of tied concrete columns. *Journal of Structural Division*, 106(5): 1079-1102.

Wang, Y-C, and K. Hsu, 2007, Design of FRP-wrapped reinforced concrete columns for enhancing axial load carrying capacity. *Composite Structures*, 82: 132-139.