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Strengthening Reinforced Concrete Columns by Fiber Reinforced Polymer (FRP): A General Review

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Abstract: Study and analysis of different experimental researches for different columns external strengthening by using fiber reinforced polymer composites and review. The focus is on the experimental results as well as analytical and numerical research contributions in the review. Different columns were reviewed (rectangular, cylinders) and structural behavior of each type is discussed briefly, analysis and discuss the effects of various parameters such as shape of column section, thickness of FRP sheets, direction of fiber, etc. A new model has been proposed in this study for the compressive strength, ultimate axial strain and Validation of the proposed model based on the results of the seven studies and the results were close to the experimental results. At the end provide important observations contribute along with possible future directions of research.

Key words: Strengthening, Fiber Reinforced Polymer (FRP), compressive strength, axial strain, experimental, important observations

INTRODUCTION

Strengthening of concrete columns is one of the most important tasks in civil engineering as well as strengthening other elements and structures such as beams, bridges, municipal buildings, transportation systems and parking. We may go to strengthening because a change in structural building or removal of some load bearing structural elements or because it is damaged by external factors or when the column is sought to be used in a different manner from previously planned. Reinforced concrete columns as a major supporting element for any structure may, for numerous reasons, need strengthening. Conventional methods like concrete or steel jacketing were used for repair, strengthening or providing a lateral confinement for the RC columns (ChaiI *et al.*, 1991; Nanni *et al.*, 1993; Priestley *et al.*, 1994). Although, both methods are effective in increasing the structural capacity, they are labor consuming, mostly results in a substantial increase in the cross section of the strengthened column, high density, long time of installation, difficulty application. For these reasons and to replace outdated techniques, the innovative rehabilitation and strengthening methods for reinforced concrete structures, especially with composite materials, have taken a large portion of the research and application research in the field of repair and restoration of structural elements.

Lately emerged Fiber Reinforced Polymer (FRP) as a new material has been used in aerospace, marine and automobile industries and to be used in different structural elements for its mechanical properties such as high tensile strength, low density, high resistance for corrosion, low thermal coefficient, short time of installation, easy application and low cost for maintenance (Ferguson and Cowan, 1981). Moreover, it is considered as an alternative to steel in reinforced concrete structures because of the continuing decline in the cost of FRP. FRP sheets for strengthening and rehabilitation of elements concrete structures has attracted great attention (Nanni, 1993; Mufti *et al.*, 2002; Hollaway, 2003; Mufti, 2003). First applications for FRP were in the form of rebar. Then, FRP laminates were used for strengthening of concrete bridge girders by binding them to the tension face (Meier, 1992) as well as for rehabilitation of concrete columns (Saadatmanesh, 1994). FRP are available in the form of rods, grids, sheets and winding strands. Review of literature up to 1996 can be found in ACI Committee 440 (Anonymous, 1996). Another general review on class of materials including FRP used in civil construction was presented by Bakis *et al.* (2002). Some research by Parvin and Wang (2001a, b) on FRP-confined columns under eccentric loading which involved numerical and experimental analysis of FRP jacketed concrete columns, the effect of FRP jacket thickness and various eccentricities were investigated.

MATERIALS AND METHODS

Types and properties fiber reinforced polymer: There is more than one type of fiber reinforced polymer of Fiber Reinforced Polymers (FRP) including composites with

Table 1: The mechanical properties fiber reinforced polymer (Anonymous, 2003, 2011; ACI Committee 440, 2008)

Reinforcing mterials	Yield strength ksi (MPa)	Tensile strength ksi (MPa)	Elastic modulus ksi (MPa)	Strain at break percent L (mm)
Glass FRP	N/A	70-230 (480-1,600)	5,100-7,400 (35-51)	1.2-3.1
Basalt FRP	N/A	150-240 (1,035-1,650)	6,500-8,500 (45-59)	1.6-3.0
Aramid FRP	N/A	250-368 (1,720-2,540)	6,000-18,000 (41-125)	1.9-4.4
Carbon FRP	N/A	250-585 (1,720-3,690)	15,900-84,000 (120-580)	0.5-1.9

Aramid (AFRP), Basalt (BFRP), Carbon (CFRP) and Glass (GFRP) fibers, versus steel reinforcing should be understood prior to undertaking the design of structures using these reinforcements. The mechanical properties fiber reinforced polymer in Table 1 (Anonymous, 2003, 2011; ACI Committee 440, 2008).

Repair and rehabilitation of columns: The structural strengthening when inadequate design, damage due to seismic activities, poor quality construction, to meet current design requirement, repair of old structures, degradation problems which may arise from environmental exposure and other natural hazards. Therefore, the structural strengthening has received much attention over in the recent period in the all world. The experimental and analytical research have demonstrated that the use of FRP for strengthening and structural repair is less costly, more effective and requires less effort and time than the traditional means. FRP composites were first used as strengthening materials for reinforced concrete columns and walls against earthquake forces in addition strengthening of beams, bridge girders, beam-column joints, used in bridge decks and in cable stayed bridges (Saadatmanesh, 1994; Fardis and Khalili, 1982).

The parameters affecting performance of columns which strengthened by FRP: The parameters affecting the performance of confined column's systems including concrete strength, shape of column section (depth-width) ratio (Ilki *et al*., 2004; Hamad *et al*., 2004; Li and Park, 2004), longitudinal steel , stirrups, corrosion of steel, type of fiber, direction of fiber (Sadeghian *et al*., 2010), thickness of FRP sheets (Ilki and Kumbasar, 2002), slenderness ratio (Mirmiran *et al*., 2001), deformability of the concrete, stiffness of the jacket in the lateral direction (Chaallal and Shahawy, 2000), concrete dilation ratio (Pessiki *et al*., 2001), geometric and loading imperfection (Mukherjee *et al*., 2004), number of cycles per unloading and reloading (Abbasnia and Holakoo, 2012), heating and cooling cycles (El-Hacha *et al*., 2010; Karbhari, 2001; Homan and Sheikh, 2010; Karbhari and Eckel, 1994; Fanggi and Hadi, 2011), etc. and in this study. We will analysis and discuss the some most important parameters that affects the performance of confined columns using (FRP).

Shape of column section: The shape of column section affecting confined strength of column. The most effective confinement is obtained when the shape of the column is circular or oval more than section which contain angles such as square, rectangle etc. (Rochette and Labossiere, 2000; Mirmiran *et al*., 1998; Teng and Lam, 2002), rectangular or square sections have high confining pressure at their corners but little pressure on their flat sides, therefore the cross-section is not effectively resulting in a lower the strength (Demers *et al*., 1996). In order to increase the effectiveness of confinement for rectangular and square columns, the cross section column can be modified into the elliptical section, that is, the corners have to be close to the oval shape or rounded shape to prevent premature failure but radius is limited because of internal longitudinal reinforcement (Rochette and Labossiere, 2000). Shear strength of RC columns strengthened with FRP was studied by Ye *et al*. (2002) who finally concluded that shear strength of RC column can be effectively increased through external strengthening by using FRP sheets.

Fiber orientations: Fiber orientations is a parameter affecting moment-curvature behavior when fiber orientations of 0°, 90° with respect to an axis perpendicular to the column axis shown that longitudinal layers improved the bending stiffness and moment capacity of the specimens but when fiber orientations of +45°, -45° with respect to an axis perpendicular to the column axis curvature capacities are not generally improved (Sadeghian *et al*., 2010). The moment-curvature behavior of the specimen fiber orientation is a little different because it almost shows an elastoplastic behavior. In this case, not only the bending stiffness and moment capacity are enhanced but also, the curvature capacity is improved.

This special effect of angle orientation when fiber orientations (+45°, -45°) has been significantly observed in axial compressive tests of Carbon Fiber Reinforced Polymer (CFRP) confined concrete cylinders and axial tensile tests of (CFRP) coupons by the writers (Sadeghian *et al*., 2009, 2010). The ductility improvement is produced by the plastic shear behavior of resin in FRP with diagonal fibers. In the case of Specimen were fiber orientations (+45°, -45°) because of the rectangular section and eccentric loading, the improvement of the angle orientation on ductility has been limited.

Lateral strengthen method of the column incidentally more efficient than longitudinal strengthen method by using strips on the faces of the column (Waryosh *et al*., 2012).

Strength concrete: According to a study to Touhari and Mitiche-Kettab (2016) it could be noted that, the Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) confinement on low strength concrete specimens produced higher results in terms of strength and strain than that those of normal and high strength concrete. For example, the CFRP low strength confined concrete cylinders where the one layer reinforcement specimen revealed an increase of 69% and 416% in terms of compressive strength and axial strain over the reference specimen. The normal strength concrete cylinders similarly confined, the specimen exhibited an increase of 40% in compressive strength and 280% in axial strain. However, in high strength concrete cylinders, the specimen exhibited an increase of 31% in compressive strength and 237% in axial strain for one layer of GFRP, the gain in terms of strength of Low Strength Concrete(LSC), Normal Strength Concrete (NSC) and High Strength Concrete (HSC) was 41, 35 and 19%, respectively. The gain in terms of ductility of LSC, NSC and HSC is about 519, 390 and 315%, respectively.

It can be seen that, the axial strength and strain enhancement ratios of FRP confined concrete cylinders decrease as the strength of unconfined concrete increases. In other words, higher concrete compressive strength reduces the effect of confinement for the same number of FRP layers. This might be because the more is the strength of concrete. Consequently, concrete with higher compressive strength exhibits lower lateral expansion under compression compared to concrete with lower compressive strength (Scholefield, 2003).

Number of cycles per unloading and reloading: According to Abbasnia and Holakoo (2012) comparison between ultimate strength for 18 cylindrical specimens of FRP-confined under single cycle at prescribed displacement and monotonic loading. Revealed that the amount of ultimate strength due to cyclic loading is greater than that of monotonic loading. While comparison between ultimate strength for specimens under single cycle at prescribed displacement and three cycle at prescribed displacement loading revealed that the amount of ultimate strength due to 3 cycle at prescribed displacement loading is less than that of single cycle at prescribed displacement loading in all specimens except one specimens. This means that increase number of cycles per unloading has significant effect on the ultimate strength. According to Karsan and Jirsa (1969), number of cycles per unloading and reloading have a cumulative effect on the plastic strain and stress deterioration.

Number of layers of FRP: The number of layers of FRP materials is one of the major parameters having a significant on the behaviour of specimens. According to Li and Hadi (2003) the test results proved that the benefit of confinement could be enhanced by increasing the stiffness of external confinement by applying multiple layers. However, the influence of the number of layers of FRP on the specimens under eccentric loading is not so pronounced as that of the specimens under concentric loading. Also in another search by Touhari and Mitiche-Kettab (2016) the difference in strength between CFRP confined cylindrical specimens and GFRP ones increases more and more with the increase in the number of layers of FRP. As estimated, the enhancement in strength and strain of FRP confined concrete cylinders is not proportional to the number of FRP layers, especially when high number of FRP layers strengthening is used.

Type of FRP material: According to Touhari and Mitiche-Kettab (2016) the results of the tested showed Carbone Fiber Reinforced Polymer (CFRP) jacketing attains higher strength and strain than that of Glass Fiber Reinforced Polymer (GFRP) confined specimens, significant the effect of the mechanical properties of FRP materials on the the strength and strains enhancement ratios. Also, in another search to Li and Hadi (2003) the results of the tested showed carbon fibres had a significantly better E-glass effect fibres on the normal strength concrete cylinders subjected to axial loading. Finally show that the ultimate compressive strengths are significantly influenced by the type of FRP material.

Heating and cooling cycles: El-Hacha *et al*. (2010), Kabhari *et al*. (2001), Homan and Sheikh (2010), Karbhari and Eckel (1994) and Nistico *et al*. (2014) investigated the behaviour of plain concrete cylinders wrapped with FRP sheets subjected to a harsh environment such as high temperature, heating and cooling cycles and prolonged heat temperature. The study found when change the temperature to 70°C The ultimate strength and deflection at ultimate load of cylinder wrapped with 2 layers of CFRP are not significantly increase while the ultimate deflection decreased after being exposed to 70°C. The energy absorption and displacement ductility of cylinder wrapped with 2 layer of CFRP increased after being exposed to 70°C. While when change the temperature between

(20-45°C) that no significant difference of strength was observed for both wrapped and unwrapped specimens subject to heating and cooling cycle compared to the room temperature specimen. And when change the temperature between (20-18°C) slightly negative effect was monitored on the compressive strength of both wrapped and unwrapped specimens under freezing and thawing cycles as well as fresh and salt water immersion. and were freeze-thaw cycles and moisture exposure were observed as noticeable effects on the bond properties of single lap bonded specimen.

RESULTS AND DISCUSSION

Predict the ultimate compressive strength of FRP confined concrete columns: The majority of models devoted to predict the compressive strength of FRP confined concrete columns are based on the general equation proposed by Richart and Teng (2007) (Eq. 1) which has been developed to estimate the confined concrete with steel:

$$f'_{cc} = f'_{co}+k_1\times f'_l \quad (1)$$

Where:

f'_{cc} and f'_{co} = The compressive strength of confined and unconfined concrete, respectively

k_1 = The confinement effectiveness factor

f'_l = The effective lateral confining stress

Number of models have been suggested to investigate the FRP confinement effect on the behaviour of concrete columns. Tang *et al.* (2002) classified them as design oriented models and analysis oriented models. The design oriented models are normally in simple closed form (Lam and Tang, 2003) and the analysis oriented models predict the stress-strain behaviour using iterative process (Spoelstra and Monti, 1999; Jiang and Tang, 2007). The first well-known study on the stress-strain curve of concrete with and without steel confinement was conducted by Richart *et al.* (1929). The following well known relation was based on a linear relationship, for expressing, the enhancement of compressive strength based on their test results (Eq. 1). Since then, there have been numerous analytical models presented in the literature that employ (Eq. 1) which have been based either on tests of plain concrete specimens or reinforced concrete columns. Most of these models used a constant value for k_1 and it was limited to between 2 and 5 (Hanna and Jones, 1997; Rousakis *et al.*, 2012; Mohamed and Masmoudi, 2010; Mander *et al.*, 1988). Moreover, other researchers expressed k_1 in a non-linear form (Afifi *et al.*, 2015; Realfonzo and Napoli, 201; Rousakis *et al.*, 2012; Mohamed and Masmoudi, 2010).

Fardis and Khalil (1982) developed a linear relationship between the ultimate strength and the effective lateral confining stress:

$$f'_{cc} = f'_{co}+4.1\times f'_l \quad (2)$$

where, f'_l is the effective lateral confining stress. Mander *et al.* (1988) also derived a non-linear relationship between the ultimate strength and the effective lateral confining pressure of confined concrete cylinders based on the tri-axial test data. The MPP Model is the most widely used:

$$f'_{cc} = f'_{co}\left[-1.254+2.254\sqrt{1+\frac{7.94\times f'_l}{f'_{co}}}-2\frac{f'_l}{f'_{co}}\right] \quad (3)$$

Li *et al.* (2003) proposed a constitutive model for confined concrete columns reinforced with CFRP materials. They studied the behaviour of cylinders with various strengths of concrete:

$$f'_{cc} = f'_{co}+f'_l\tan^2(45°+\theta/2) \quad (4)$$

$$\theta = 36°+1°\left(\frac{f'_{co}}{35}\right)\leq 45° \quad (5)$$

where, θ is the angle of internal friction of concrete. Ozbakkaloglu and Jian (2013) developed a new model based on over 500 experimental results for CFRP and GFRP confined concrete cylinders: for CFRP confined concrete cylinders:

$$\frac{f'_{cc}}{f'_{co}} = 1+3.64\times\frac{f'_{lu,a}}{f'_{co}} \quad (6)$$

For GFRP confined concrete cylinders:

$$\frac{f'_{cc}}{f'_{co}} = 1+2.64\times\frac{f'_{lu,a}}{f'_{co}} \quad (7)$$

where, $f'_{lu,a}$ is the effective lateral confining stress. Pham and Hadi (2014) proposed new confinement model for FRP confined normal- and high-strength concrete circular columns:

$$f'_{cc} = 0.7f'_{co}+1.8f'_l+5.7\frac{t}{D}+13 \quad (8)$$

Where:

- t = The thickness of the composite jacket
- D = The diameter of the concrete core

Touhari and Mitiche-Kettab (2016) proposed new confinement model for FRP confined normal and high strength concrete circular columns: for CFRP confined concrete cylinders:

$$\frac{f'_{cc}}{f'_{co}} = 1+2.8\frac{f'_l}{f'_{co}} \tag{9}$$

For GFRP confined concrete cylinders:

$$\frac{f'_{cc}}{f'_{co}} = 1+1.85\frac{f'_l}{f'_{co}} \tag{10}$$

All of the above models assumed that the compressive strength of confined concrete is a function of the unconfined concrete strength and the effective lateral confining pressure. And there are a few approaches to develop an equation for strength enhancement of confined concrete.

Mechanism of confinement: The lateral confinement pressure provided by a FRP jacket to concrete is naturally passive. In FRP confined concrete cylinders, the concrete core extends laterally and this expansion is restrained by the FRP material when it is subjected to an axial compression load. This pressure produces a circular tension resultant in the envelope. The action of expansion and the reaction of the confinement are represented by a uniform lateral pressure fl in the interface and the response of FRP material (Fig. 1). This expansion of the concrete core is confined by the FRP jackets and thus transforms the concrete core to a 3-D compressive stress condition. The mechanism of confinement goes from uniaxial loading to tri-axial loading (Touhar and Mitiche-Kettab, 2016). The maximum confinement pressure is reached when the circumferential strain in the FRP reaches its ultimate strain ε_{frp} corresponding to the failure of the cylinder. Based on static analysis, equilibrium of forces, deformation compatibility and by considering one unit length section along the column span, the forces acting on the section shown in Fig. 1 can be written as:

$$Df'_l = 2t_f \times f_{frp,u} \tag{11}$$

The lateral confining pressure reaches its maximum value f'_l at the rupture of FRP with:

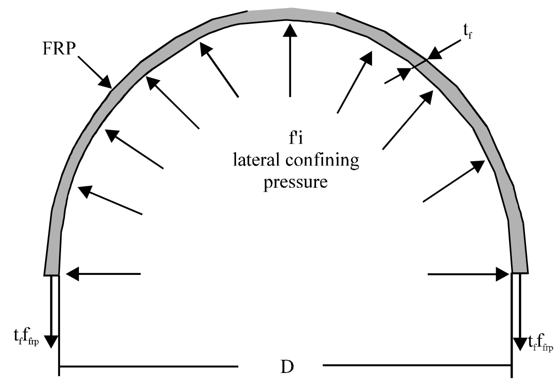

Fig. 1: Mechanism of confinement (Touhar and Mitiche-Kettab, 2016)

$$f'_l = \frac{2t_f \times f_{frp}}{D} = \frac{2E_{frp,u} \times \varepsilon_{frp}, u \times t_f}{D} \tag{12}$$

Where:

- f'_l = The lateral confining pressure
- E_{frp} = The tensile modulus of FRP material
- t_f = The thickness of the composite jacket
- $\varepsilon_{frp,u}$ = The ultimate circumferential strain in the composite jacket
- D = The diameter of the concrete core
- p_{frp} = The FRP volumetric ratio which is given by the following equation for entirely wrapped circular cross section:

$$\rho_{frp} = \frac{4t_f}{D} \tag{13}$$

The effective lateral confining stress at ultimate condition of the FRP jacket is defined as Youssef *et al*. (2007):

$$f'_{lu} = k_e \times f_{lu} \tag{14}$$

Where:

- k_e = The confinement effectiveness coefficient for circular columns
- $k_e = 1.0$, f'_{lu} = Effective lateral confining stress at ultimate condition of FRP jacket
- f_{lu} = Lateral confining stress at ultimate condition of FRP jacket

Similarly, for rectangular sections, it can be shown that:

$$f_{lu} = \frac{1}{2}\rho_j \times f_{ju} \tag{15}$$

Where:

- ρ_j = Volumetric ratio of FRP jacket
- f_{lu} = Tensile strength of FRP jacket

Unlike the circular section, however, the confinement effectiveness coefficient for rectangular section is less than unity (i.e., k_e is <1). The values of k_e are calculated using the expression proposed by Restrepo and Devino (1995). For rectangular and square columns:

$$k_e = \frac{1-\left[\frac{(b-2rc)^2+(h-2rc)^2}{3hb}\right]-\rho_l}{1-\rho_l} \tag{16}$$

The Mohr-Coulomb failure criterion and effective FRP strain factor: The mechanisms of the tri-axial of the soil or rock and the mechanism of the concrete confined with FRP wraps are very similar. According to the mohr-coulomb failure criterion, the strength of concrete under a tri-axial stress can be written (Goodman, 1989) :

$$f'_{cc} = f'_{co} + \frac{1+\sin\theta}{1-\sin\theta} \times f'_l \tag{17}$$

Where:

θ = The angle of internal friction of concrete
f'_l = The lateral confinement pressure

Generally, it is very intricate to estimate the angle of internal friction at the time of full expansion of lateral confining stress. Bieniawski (1974) has developed an empirical failure criterion:

$$\frac{f'_{cc}}{f'_{co}} = 1+N\left(\frac{f'_l}{f'_{co}}\right)^M \tag{18}$$

The constants N and M will be determined by fitting a curve to the group of points:

$$\left(\frac{f'_{cc}}{f'_{co}} \times \frac{f'_{cc}}{f'_{co}} -1\right)$$

As mentioned earlier, the effective FRP failure strain when confined concrete cylinders are reaching the ultimate state is lower than the ultimate FRP tensile strain $\varepsilon_{frp,u}$. Therefore, the proposed effective FRP strain factor, k_{ef}, accounts the ratio of in-situ wrap rupture strains observed in tests of FRP confined concrete cylinders and those observed in tensile coupon test that is:

$$k_{ef} = \frac{\varepsilon_{hrp,u}}{\varepsilon_{frp,u}} \tag{19}$$

Using Eq. 12-16 can be rewritten as:

$$f'_l = \frac{2t_f \times f_{frp}}{D} = \frac{2E_{frp} \times \varepsilon_{frp,u}}{D} \times \frac{1}{k_{ef}} = \frac{f'_{l,eff}}{k_{ef}} \tag{20}$$

where, $f'_{l,eff}$ is the effective lateral confining pressure corresponding to a maximum effective failure strain $\varepsilon_{hrp,u}$. Substituting Eq. 20 into Eq. 18, this latter becomes:

$$\frac{f'_{cu}}{f'_c} = 1+N \times k_{ef}{}^M \left(\frac{f'_{leff}}{f'_{co}}\right)^M \tag{21}$$

where, k_{ef} is referred to in this study as the effective FRP strain factor. Marwan *et al*. the following strength model is proposed, depending on the geometry of the cross-section: for circular sections:

$$\frac{f'_{cu}}{f'_c} = 1+2.25 \times \left(\frac{f'_{lu}}{f'_c}\right)^{\frac{5}{4}} \tag{22}$$

For rectangular sections:

$$\frac{f'_{cu}}{f'_c} = 0.5+1.225 \times \left(\frac{f'_{lu}}{f'_c}\right)^{\frac{3}{5}} \tag{23}$$

Where:

f'_{cu} = Ultimate strength of FRP-confined concrete
f'_c = Compressive strength of unconfined concrete
f'_{lu} = Effective lateral confining stress at ultimate condition of FRP jacket

Predict the ultimate axial strain of FRP confined concrete columns: For FRP confined concrete cylinders, numerous studies suggested that the ultimate axial strain can be correlated to the lateral confining pressure (Micelli and Modarelli, 2013; Scholefield, 2003; Shehata *et al*., 2002). Existing models can be classified into two categories, empirical or analytical models and numerical models or plasticity analysis. Richart *et al*. (1929) proposed that the effectiveness in the enhancement of axial strain in the FRP confined concrete cylinders is around 5 times that in the enhancement of axial stress:

$$\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 1+k_2\frac{f'_l}{f'_{co}} \tag{24}$$

Where:

$k_2 = 5k_1$, ε'_{co} = The strain of unconfined concrete
ε'_{cc} = The ultimate strain of FRP confined concrete

From Shehata *et al*. (2002), the strain enhancement ratio FRP confined concrete can be written:

$$\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 1+6.32\left(\frac{f'_l}{f'_{co}}\times\frac{f'_{cc}}{f'_{co}}\right) \quad (25)$$

From Lam and Tang (2004), the strain enhancement ratio FRP confined concrete can be written:

$$\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 1.75+5.53\left(\frac{f'_l}{f'_{co}}\right)\left(\frac{\varepsilon'_{frp}}{\varepsilon'_{co}}\right)^{0.45} \quad (26)$$

where, ε'_{frp} is the ultimate tensile strain of FRP material. From Ozbakkaloglu and Jian (2013), the strain enhancement ratio FRP confined concrete can be written:
For CFRP:

$$\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 2+17.41\frac{f'_{lu,a}}{f'_{co}} \quad (27)$$

For GFRP:

$$\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 2+17.41\frac{f'_{lu,a}}{f'_{co}} \quad (28)$$

Kwan *et al*. (2015) proposed a new Axial strength model for FRP confined concrete:

$$\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 1+17.4\left(\frac{\sigma_r}{f'_c}\right)^{1.06} \quad (29)$$

where σ_r is the confining stress. Marwan *et al*. the following the ultimate concrete compressive strain is proposed, depending on the geometry of the cross-section: for circular sections:

$$\varepsilon_{cu} = 0.003368+0.2590\left(\frac{f'_{lu}}{f'_c}\right)\left(\frac{f_{ju}}{E_j}\right)^{\frac{1}{2}} \quad (30)$$

For rectangular sections:

$$\varepsilon_{cu} = 0.004325+0.2625\left(\frac{f'_{lu}}{f'_c}\right)\left(\frac{f_{ju}}{E_j}\right)^{\frac{1}{2}} \quad (31)$$

Where:
ε_{cu} = Ultimate confined concrete compressive strain
f_{ju} = Tensile strength of FRP jacket
E_j = Tensile modulus of FRP jacket in the hoop direction

Proposed equations

The ultimate compressive strength of FRP confined concrete cylinder columns: When the application results of the studies (Touhar and Mitiche-Kettab, 2016; Jiang and Teng, 2007; Valdmanis *et al*., 2007; Lam and Teng, 2004; Vincent and Ozbakkaloglu, 2013; Cui and Sheikh, 2010; Teng *et al*., 2007) on the some previous equations, we notice that there are large differences between the experimental results and the theory results, as shown in Table 2, so that, the ratio between the experimental results and the theory results of some equations between (0.37-2) and this is a very big difference and does not give the safety factor at the design. This is due to neglecting change in the tensile modulus of FRP material E_{frp} in the previous equations because adding adhesives between the layers when increasing the number of layers, leads to a decrease in the tensile modulus of FRP material E_{frp} according to Eq.12 the lateral confining pressure f'_{1at} also decreases.

Therefore, it is difficult to obtain the tensile modulus of FRP composite material after increasing the number of layers because the absence of sufficient the experimental results, so, a new model has been proposed as shown in Eq. 24 and 25 to compensate for the decrease in the tensile modulus of FRP material E_{frp} by adding [(f_{1at}-n×5), (f_{1at}-n×8)] for CFRP confined, for GFRP confined, respectively at the end of the equations to decrease the lateral confining pressure f'_{1at}.

In addition to there are a few approaches to develop an equation for strength enhancement of confined concrete. And based on the analysis and study results of the studies by Touhar and Mitiche-Kettab (2016), Jiang and Teng (2007), Valdmanis *et al*. (2007), Lam and Teng (2004), Vincent and Ozbakkaloglu (2013), Cui and Sheikh (2010) and Teng *et al*. (2007). So, a new model has been proposed in this study assumed (k) variable value depending on the number of layers (FRP) and the value the effective lateral confining pressure according to the Table 3 and assumed that the compressive strength of confined concrete is a function of the unconfined concrete strength and the effective lateral confining pressure with number of layer (CFRP) or (GFRP). For CFRP confined concrete cylinders:

$$f'_{cc} = f'_{co}+k\times f'_{lat}+\left[\left(f'_{lat}-n\times 5\right)\right] \quad (32)$$

For GFRP confined concrete cylinders:

$$f'_{cc} = f'_{co}+k\times f'_{lat}+\left[\left(f'_{lat}-n\times 8\right)\right] \quad (33)$$

Table 2: Comparison between the experimental and predicted results for previous equations of concrete cylinders confined by FRP

(CFRP)										(GFRP)		
f'_{cc} theo. / f'_{cc} exp. Eq. 2	f'_{cc} theo / f'_{cc} exp. Eq. 3	f'_{cc} theo. / f'_{cc} exp. Eq. 4	f'_{cc} theo. / f'_{cc} exp. Eq. 6	f'_{cc} theo. / f'_{cc} exp. Eq. 8	f'_{cc} theo. / f'_{cc} exp. Eq. 9	f'_{cc} the / f'_{cc} exp. Eq. 22	ε'_{cc} theo. / ε'_{cc} exp. Eq. 27	ε'_{cc} theo. / ε'_{cc} exp. Eq. 28	ε'_{cc} theo. / ε'_{cc} exp. Eq. 29	f'_{cc} theo. / f'_{cc} exp. Eq. 7	f'_{cc} theo. / f'_{cc} exp. Eq. 10	ε'_{cc} theo. / ε'_{cc} exp. Eq. 30
Touhari and Mitiche-Kettab (2016)												
0.98	1.12	0.55	0.93	0.84	0.83	0.51	0.61	0.70	0.95	1.02	0.92	1.16
1.01	1.16	0.57	0.96	0.87	0.86	0.53	0.64	0.75	1.02	1.12	1.01	1.36
1.12	1.25	0.84	1.08	1.14	1.02	0.81	0.50	0.81	1.04	1.03	0.93	1.26
1.17	1.27	0.49	1.09	0.86	0.94	0.43	0.81	0.74	1.05	1.03	0.98	1.47
1.21	1.31	0.49	1.12	0.88	0.96	0.44	0.92	0.85	1.20	1.03	0.88	1.20
1.16	1.26	0.47	1.08	0.84	0.93	0.42	0.83	0.74	1.04	0.99	0.84	1.16
1.08	1.11	0.37	0.99	0.72	0.84	0.32	1.13	0.74	1.06	0.99	0.82	1.17
1.07	1.09	0.36	0.98	0.71	0.82	0.32	1.11	0.72	1.03	1.06	0.88	1.24
1.11	1.15	0.39	1.02	0.75	0.86	0.34	1.12	0.78	1.12	1.09	0.91	1.27
1.07	1.18	0.89	1.04	0.95	1.00	0.84	0.48	0.78	1.00	0.97	0.91	1.23
1.01	1.15	0.75	0.97	0.83	0.90	0.68	0.52	0.76	1.01	0.98	0.92	1.28
1.00	1.13	0.74	0.96	0.82	0.89	0.66	0.53	0.75	1.00	0.95	0.88	1.19
1.05	1.20	0.67	0.99	0.79	0.89	0.57	0.65	0.79	1.10	0.99	0.88	1.31
1.08	1.23	0.66	1.02	0.78	0.91	0.54	0.64	0.74	1.05	0.97	0.86	1.26
1.08	1.23	0.66	1.02	0.78	0.91	0.54	0.60	0.69	0.97	0.95	0.85	1.22
1.04	1.16	0.57	0.97	0.70	0.85	0.43	0.76	0.68	1.00	1.04	0.90	1.35
1.04	1.16	0.57	0.97	0.71	0.85	0.43	0.81	0.74	1.07	1.03	0.88	1.21
1.06	1.18	0.58	0.99	0.72	0.87	0.45	0.79	0.74	1.08	1.02	0.88	1.29
1.03	1.15	0.96	1.00	0.81	0.95	0.77	0.47	0.74	0.95	1.05	1.00	1.29
1.02	1.13	0.95	0.99	0.81	0.94	0.78	0.49	0.79	1.01	1.01	0.96	1.28
1.01	1.13	0.94	0.98	0.80	0.93	0.76	0.52	0.82	1.06	0.97	0.92	1.14
1.04	1.18	0.93	0.99	0.76	0.91	0.64	0.65	0.89	1.20	1.08	0.99	1.23
1.01	1.15	0.90	0.97	0.74	0.89	0.62	0.57	0.76	1.03	1.12	1.03	1.30
1.05	1.20	0.93	1.00	0.76	0.91	0.63	0.54	0.72	0.98	1.12	1.02	1.26
1.05	1.20	0.92	1.00	0.74	0.90	0.59	0.59	0.75	1.03	1.07	0.95	1.31
1.05	1.20	0.91	0.99	0.71	0.89	0.53	0.67	0.76	1.06	1.07	0.95	1.24
1.09	1.24	0.95	1.03	0.75	0.93	0.58	0.62	0.77	1.07	1.06	0.94	1.24
Lam and Teng (2004) and Jiang and Teng (2007)												
1.31	1.50	0.81	1.24	1.02	1.12	0.71	0.44	1.52	0.88	1.04	0.96	1.51
1.40	1.60	0.86	1.33	1.09	1.20	0.76	0.49	1.76	1.01	1.06	0.98	1.17
1.24	1.42	0.77	1.18	0.97	1.06	0.67	0.45	1.50	0.86	1.40	1.32	1.24
1.43	1.55	0.67	1.33	0.95	1.14	0.53	0.73	2.15	1.11	1.40	1.32	0.95
1.41	1.53	0.66	1.31	0.94	1.13	0.52	0.63	1.84	0.96	1.28	1.16	1.53
1.37	1.49	0.64	1.27	0.91	1.10	0.51	0.68	1.95	1.01	1.23	1.11	1.23
1.53	1.55	0.58	1.41	0.94	1.18	0.44	0.96	2.48	1.17	1.22	1.06	1.33
1.40	1.42	0.53	1.29	0.86	1.08	0.41	0.89	2.12	1.00	1.40	1.23	2.06
1.30	1.32	0.49	1.20	0.80	1.00	0.38	0.92	2.03	0.96			
Cui and Sheikh (2010)												
1.28	1.46	0.77	1.21	1.00	1.09	0.68	0.53	1.84	1.01	1.18	1.07	1.02
1.29	1.47	0.77	1.22	1.01	1.10	0.69	0.50	1.74	0.96	1.17	1.06	1.20
1.14	1.30	0.68	1.08	0.89	0.97	0.61	0.50	1.62	0.89	1.03	0.88	1.05
1.33	1.52	0.89	1.27	1.09	1.17	0.81	0.61	2.16	1.30	1.04	0.89	1.05
1.33	1.53	0.89	1.28	1.09	1.17	0.81	0.57	2.03	1.22	1.01	0.83	1.14
1.36	1.55	0.91	1.30	1.11	1.19	0.82	0.57	2.03	1.22	1.02	0.84	1.63
1.36	1.55	0.91	1.30	1.11	1.19	0.82	0.57	2.03	1.22	1.02	0.84	1.63
1.36	1.52	0.74	1.27	0.96	1.12	0.60	0.59	1.92	1.03			
Teng *et al.* (2007)												
1.31	1.46	0.71	1.22	0.92	1.07	0.58	0.56	1.76	0.94	1.36	1.27	1.25
1.44	1.61	0.75	1.35	1.02	1.18	0.62	0.72	2.39	1.27	1.30	1.22	1.42
1.34	1.50	1.30	1.30	1.04	1.22	0.98	0.71	2.19	1.61	1.12	1.00	0.86
1.27	1.43	1.24	1.24	0.99	1.17	0.94	0.75	2.26	1.67	1.09	0.97	1.00
1.30	1.46	1.23	1.26	1.01	1.19	0.95	0.66	2.02	1.48	1.10	0.95	0.98
1.56	1.78	1.49	1.49	1.10	1.35	0.89	0.67	2.35	1.50	1.18	1.02	1.40
1.62	1.85	1.46	1.54	1.14	1.39	0.91	0.88	3.16	2.01			
1.65	1.89	1.56	1.57	1.16	1.42	0.94	0.73	2.67	1.71			
1.61	1.81	1.52	1.51	1.05	1.33	0.75	0.76	2.59	1.55			
1.72	1.94	1.62	1.62	1.13	1.43	0.80	0.72	2.59	1.55			
1.62	1.79	1.52	1.51	1.01	1.31	0.65	0.89	2.82	1.64			
1.57	1.73	1.36	1.47	0.98	1.27	0.62	0.93	2.84	1.64			
1.56	1.73	1.54	1.46	0.98	1.27	0.63	0.91	2.81	1.63			

Table 2: Continue

(CFRP)										(GFRP)		
f'_{cc} theo. / f'_{cc} exp. Eq. 2	f'_{cc} theo / f'_{cc} exp. Eq. 3	f'_{cc} theo. / f'_{cc} exp. Eq. 4	f'_{cc} theo. / f'_{cc} exp. Eq. 6	f'_{cc} theo. / f'_{cc} exp. Eq. 8	f'_{cc} theo. / f'_{cc} exp. Eq. 9	f'_{cc} the / f'_{cc} exp. Eq. 22	ε'_{cc} theo. / ε'_{cc} exp. Eq. 27	ε'_{cc} theo. / ε'_{cc} exp. Eq. 28	ε'_{cc} theo. / ε'_{cc} exp. Eq. 29	f'_{cc} theo. / f'_{cc} exp. Eq. 7	f'_{cc} theo. / f'_{cc} exp. Eq. 10	ε'_{cc} theo. / ε'_{cc} exp. Eq. 30
Valdmanis *et al.* (2007)												
0.93	1.06	0.67	0.89	0.76	0.83	0.61	0.64	1.69	1.15			
0.95	1.08	0.56	0.89	0.69	0.79	0.46	0.73	1.71	1.04			
1.08	1.19	0.55	1.01	0.72	0.87	0.42	0.87	1.91	1.10			
0.90	1.02	0.68	0.86	0.73	0.80	0.60	0.65	1.71	1.19			
1.05	1.20	0.67	1.00	0.76	0.89	0.54	1.19	3.12	1.92			
0.94	1.04	0.53	0.88	0.63	0.77	0.39	1.23	2.53	1.47			

Table 3: The effective lateral confining factor k

(CFRP)		else	(GFRP)		else
If n = and f'_{lat} <5.6	k = 1.75	k = 3.7	If n = and f'_{lat} <4.1	k = 0.75	k = 3
If n = and f'_{lat} <11	k = 1.5		If n = and f'_{lat} <9	k = 2.1	
If n = and f'_{lat} <16	k = 1.35		If n = and f'_{lat} <12.4	k = 2.6	
If n = and f'_{lat} <20	k = 1.35		If n = and f'_{lat} <17	k = 3.4	
If n = and f'_{lat} <24	k = 1.25		If n = and f'_{lat} <20	k = 3.45	
If n = and f'_{lat} <27.5	k = 1.15		If n = and f'_{lat} <25	k = 3.6	

Table 4: The effective strain of unconfined concrete

(CFRP)		(GFRP)	
If ε'_{co} ≤0.19	$k_1 = 3.2$	If ε'_{co} (0.2-.29)	$k_1 = 5.5$
If If ε'_{co} (0.2-0.29)	$k_1 = 3.45$	If ε'_{co} (0.3-0.35)	$k_1 = 6.0$
If ε'_{co} (2.6-2.9)	$k_1 = 60$	If ε'_{co} (2.6-2.9)	$k_1 = 60$
If ε'_{co} (3-3.3)	$k_1 = 65$	If ε'_{co} (3-3.3)	$k_1 = 65$

where, k is the effective lateral confining factor according to Table 3, f_{1at} is the effective lateral confining stress, n is the number layer.

The ultimate axial strain of FRP confined concrete cylinder columns: There are a few approaches to develop an equation for ultimate axial strain of confined concrete. All of the above models take the value effective strain of unconfined concrete (K1) a constant value and when applied of the studies does not give results close to the experimental results. so, a new model has been proposed in this study assumed (K1) Variable value depending on the value strain of unconfined concrete according to the Table 4. And the compressive strength of confined concrete is a function of the unconfined concrete strength and the effective lateral confining pressure with the strain of unconfined concrete (CFRP) or (GFRP). And Based on the results of the studies by Touhar and Mitiche-Kettab (2016), Jiang and Teng (2007), Valdmanis *et al.* (2007), Lam and Teng (2004), Vincent and Ozbakkaloglu (2013), Cui and Sheikh (2010) and Teng *et al.* (2007):

$$\varepsilon'_{cc} = \varepsilon'_{co} + k_1\left(\frac{f'_{1at}}{f'_{co}}\right) \quad (34)$$

Where:

ε'_{cc} = The ultimate strain of FRP confined concrete

ε'_{co} = The strain of unconfined concrete

k_1 = The effective strain of unconfined concrete according to Table 4

The strength and strain enhancement proposed model of FRP confined concrete cylinders is compared to the test data obtained by Karbhari and Eckel (1994), Realfonzo and Napoli (2011), Mander *et al.* 1988), Restrepol and DeVino (1996), Anonymous (2003, 2011), ACI Committee 440 (2008 and as shown in Table 5 and 6 on (CFRP) and (GFRP) confined concrete cylinders, respectively.

These comparisons indicate that the proposed equations is in agreement with the experimental results. So that, the ratio between the experimental results and the theory results mostly equal 1 while the ratio was between (0.37-2) when the applicated the some previous equations. These parameters prove, for confined concrete cylinders, a good correlation between the analytical predictions of the proposed model with the experimental results of an independent test series.

Table 5: Comparison between the experimental and predicted results of concrete cylinders confined by (CFRP)

D (mm)	f'_{co} (MPa)	t (mm)	n	E (GPa)	ε_{frp} (%)	ε'_{co} (%)	k	k_1	f'_{lat} (exp MPa)	f'_{cc} (theo MPa)	f'_{cc} (exp MPa)	ε'_{cc} theo (%)	ε'_{cc} exp (%)	ε'_{cc} theo/ ε'_{cc} exp	f'_{cc} / f'_{cc} exp
Touhari and Mitiche-Kettab (2016)															
160	24	0.13	1	234	14	2.71	3.7	60	5.41	44.43	47	16.24	16.9	0.96	0.95
160	24	0.13	1	234	14	2.71	3.7	60	5.35	44.15	45.3	16.09	15.6	1.03	0.97
160	24	0.13	1	234	14	2.71	3.7	60	2.17	29.20	29.5	8.14	9.31	0.87	0.99
160	24	0.26	2	234	14	2.71	3.7	60	10.1	61.47	55.8	27.96	24.1	1.16	1.10
160	24	0.26	2	234	14	2.71	3.7	60	10.5	63.35	55.5	28.96	21.8	1.33	1.14
160	24	0.26	2	234	14	2.71	3.7	60	10.6	63.82	58	29.21	25.2	1.16	1.10
160	24	0.39	3	234	14	2.71	3.7	60	14.5	77.15	77.3	38.96	32.0	1.22	1.00
160	24	0.39	3	234	14	2.71	3.7	60	14.7	78.09	79	39.46	33.4	1.18	0.99
160	24	0.39	3	234	14	2.71	3.7	60	13.8	73.86	72.9	37.21	29.1	1.28	1.01
160	41.6	0.13	1	234	14	3.11	3.7	65	2.84	49.95	49.8	7.55	9.92	0.76	1.00
160	41.6	0.13	1	234	14	3.11	3.7	65	4.94	59.82	61.3	10.83	12.5	0.87	0.98
160	41.6	0.13	1	234	14	3.11	3.7	65	5.14	60.76	62.9	11.14	12.9	0.86	0.97
160	41.6	0.26	2	234	14	3.11	3.7	65	8.54	71.74	73.2	16.45	15.7	1.05	0.98
160	41.6	0.26	2	234	14	3.11	3.7	65	10	78.60	76.6	18.74	18.4	1.02	1.03
160	41.6	0.26	2	234	14	3.11	3.7	65	10.1	79.07	77	18.89	19.9	0.95	1.03
160	41.6	0.39	3	234	14	3.11	3.7	65	14.5	94.75	96.9	25.77	25.2	1.02	0.98
160	41.6	0.39	3	234	14	3.11	3.7	65	14.2	93.34	95.9	25.30	23.0	1.10	0.97
160	41.6	0.39	3	234	14	3.11	3.7	65	13.8	91.46	92.7	24.67	22.4	1.10	0.99
160	61.5	0.13	1	234	14	3.02	3.7	65	5.08	80.38	80	8.39	10.9	0.77	1.00
160	61.5	0.13	1	234	14	3.02	3.7	65	4.54	77.84	78.9	7.82	9.78	0.80	0.99
160	61.5	0.13	1	234	14	3.02	3.7	65	4.99	79.95	81.1	8.29	9.72	0.85	0.99
160	61.5	0.26	2	234	14	3.02	3.7	65	9.25	94.98	96	12.80	11.6	1.10	0.99
160	61.5	0.26	2	234	14	3.02	3.7	65	9.46	95.96	99.4	13.02	13.7	0.95	0.97
160	61.5	0.26	2	234	14	3.02	3.7	65	10.1	98.97	98.2	13.69	14.9	0.92	1.01
160	61.5	0.39	3	234	14	3.02	3.7	65	11.8	101.96	104.9	15.49	15.6	0.99	0.97
160	61.5	0.39	3	234	14	3.02	3.7	65	15.1	117.47	117.1	18.98	17.8	1.07	1.00
160	61.5	0.39	3	234	14	3.02	3.7	65	12.9	107.13	105.4	16.65	15.9	1.05	1.02
Lam and Teng (2004)															
150	35.9	0.16	1	230	15	0.2	1.75	3.45	7.36	51.14	50.4	0.91	1.27	0.71	1.01
150	35.9	0.16	1	230	15	0.2	1.75	3.45	7.36	51.14	47.2	0.91	1.1	0.82	1.08
150	35.9	0.16	1	230	15	0.2	1.75	3.45	7.36	51.14	53.2	0.91	1.29	0.70	0.96
150	35.9	0.33	2	230	15	0.2	1.5	3.45	15.18	63.85	68.7	1.66	1.68	0.99	0.93
150	35.9	0.33	2	230	15	0.2	1.5	3.45	15.18	63.85	69.6	1.66	1.96	0.85	0.92
150	35.9	0.33	2	230	15	0.2	1.5	3.45	15.18	63.85	71.6	1.66	1.85	0.90	0.89
150	34.3	0.49	3	230	15	0.18	1.35	3.2	22.54	72.27	82.6	2.28	2.06	1.11	0.87
150	34.3	0.49	3	230	15	0.18	1.35	3.2	22.54	72.27	90.4	2.28	2.41	0.95	0.80
150	34.3	0.49	3	230	15	0.18	1.35	3.2	22.54	72.27	97.3	2.28	2.51	0.91	0.74
150	34.3	0.16	1	230	15	0.18	1.75	3.2	7.36	49.54	50.3	0.87	1.02	0.85	0.98
150	34.3	0.16	1	230	15	0.18	1.75	3.2	7.36	49.54	50	0.87	1.08	0.80	0.99
150	34.3	0.16	1	230	15	0.18	1.75	3.2	7.36	49.54	56.7	0.87	1.16	0.75	0.87
Vincent and Ozbakkaloglu (2013)															
150	35.5	0.11	1	240	16	0.21	1.75	3.45	5.63	45.99	44	0.76	0.77	0.98	1.05
150	35.5	0.11	1	240	16	0.21	1.75	3.45	5.63	45.99	43.9	0.76	0.82	0.92	1.05
150	35.5	0.11	1	240	16	0.21	1.75	3.45	5.63	45.99	43.1	0.76	0.82	0.92	1.07
150	38	0.23	2	240	16	0.21	1.5	3.45	11.78	56.26	63.5	1.28	1.51	0.85	0.89
150	38	0.23	2	240	16	0.21	1.5	3.45	11.78	56.26	66.1	1.28	1.65	0.78	0.85
150	36.1	0.23	2	240	16	0.21	1.5	3.45	11.78	54.36	58.6	1.34	1.27	1.05	0.93
150	64.5	0.11	1	240	16	0.27	1.75	3.45	5.63	74.99	65.6	0.57	0.59	0.97	1.14
150	64.5	0.11	1	240	16	0.27	1.75	3.45	5.63	74.99	68.7	0.57	0.57	1.00	1.09
150	62.9	0.11	1	240	16	0.27	1.75	3.45	5.63	73.39	66.3	0.58	0.65	0.89	1.11
150	64.5	0.23	2	240	16	0.27	1.5	3.45	11.78	82.76	72.3	0.90	0.93	0.97	1.14
150	62.4	0.23	2	240	16	0.27	1.5	3.45	11.78	80.66	68.4	0.92	0.71	1.30	1.18
150	64.2	0.23	2	240	16	0.27	1.5	3.45	11.78	82.46	68.2	0.90	0.82	1.10	1.21
150	64.5	0.35	3	240	16	0.27	1.35	3.45	17.92	91.61	85.9	1.23	1.19	1.03	1.07
150	64.5	0.35	3	240	16	0.27	1.35	3.45	17.92	91.61	80.3	1.23	1.19	1.03	1.14
150	64.5	0.46	4	240	16	0.27	1.35	3.45	23.55	99.85	99.4	1.53	1.38	1.11	1.00
150	62.4	0.46	4	240	16	0.27	1.35	3.45	23.55	97.75	101	1.57	1.41	1.12	0.97
150	65.8	0.46	4	240	16	0.27	1.35	3.45	23.55	101.15	104	1.50	1.36	1.11	0.97
Valdmanis *et al.* (2007)															
150	40	0.17	1	230	10	0.17	3.7	3.2	5.21	59.50	66	0.59	0.63	0.93	0.90
150	40	0.34	2	230	10	0.17	3.7	3.2	10.43	79.01	87.2	1.00	1.07	0.94	0.91
150	40	0.51	3	230	10	0.17	3.7	3.2	15.64	98.51	96	1.42	1.36	1.05	1.03
150	44.3	0.17	1	230	10	0.17	3.7	3.2	5.21	63.80	73.3	0.55	0.58	0.94	0.87
150	44.3	0.34	2	230	10	0.17	3.7	3.2	10.43	83.31	82.6	0.92	0.54	1.71	1.01
150	44.3	0.51	3	230	10	0.17	3.7	3.2	15.64	102.81	115	1.30	0.94	1.38	0.89

Table 6: Comparison between the experimental and predicted results of concrete cylinders confined by GFRP

D (mm)	f'_{co} (MPa)	t (mm)	n	E (GPa)	ε_{frp} (%)	ε'_{co} (%)	k	k_1	f'_{lat} (exp MPa)	f'_{cc} (theo MPa)	f'_{cc} (exp MPa)	ε'_{cc} theo (%)	ε'_{cc} exp (%)	ε'_{cc} theo / ε'_{cc} exp	f'_{cc} theo / f'_{cc} exp
Touhari and Mitiche-Kettab (2016)															
160	26.2	0.17	1	76	19	2.67	3	60	4.83	37.52	38.3	13.73	15.0	0.92	0.98
160	26.2	0.17	1	76	19	2.67	3	60	4.71	37.04	34.6	13.46	12.6	1.07	1.07
160	26.2	0.17	1	76	19	2.67	3	60	4.87	37.68	38.0	13.82	13.9	0.99	0.99
160	26.2	0.34	2	76	19	2.67	2.1	60	1.86	15.97	30.2	6.93	6.81	1.02	0.53
160	26.2	0.34	2	76	19	2.67	3	60	9.42	47.88	49.4	24.24	24.1	1.01	0.97
160	26.2	0.34	2	76	19	2.67	3	60	9.75	49.20	52.5	25.00	25.5	0.98	0.94
160	26.2	0.51	3	76	19	2.67	3	60	13.71	57.04	62.8	34.06	33.9	1.00	0.91
160	26.2	0.51	3	76	19	2.67	3	60	12.70	53.00	56.4	31.75	29.8	1.07	0.94
160	26.2	0.51	3	76	19	2.67	3	60	12.60	52.60	54.7	31.52	28.9	1.09	0.96
160	42.6	0.17	1	76	19	2.89	3	60	4.66	53.24	56.5	9.45	11.0	0.86	0.94
160	42.6	0.17	1	76	19	2.89	3	60	4.55	52.80	55.5	9.30	10.4	0.89	0.95
160	42.6	0.17	1	76	19	2.89	3	60	5.31	55.84	59.8	10.37	12.3	0.84	0.93
160	42.6	0.34	2	76	19	2.89	3	60	9.52	64.68	68.5	16.30	16.5	0.99	0.94
160	42.6	0.34	2	76	19	2.89	3	60	9.60	65.00	70.0	16.41	17.2	0.95	0.93
160	42.6	0.34	2	76	19	2.89	3	60	9.77	65.68	71.7	16.65	18.1	0.92	0.92
160	42.6	0.51	3	76	19	2.89	3	60	13.6	73.00	75.5	22.04	21.0	1.05	0.97
160	42.6	0.51	3	76	19	2.89	3	60	14.6	77.00	78.8	23.45	24.9	0.94	0.98
160	42.6	0.51	3	76	19	2.89	3	60	13.9	74.20	77.5	22.47	22.4	1.00	0.96
160	61.7	0.17	1	76	19	3.11	3	65	4.20	70.50	69.4	7.53	8.85	0.85	1.02
160	61.7	0.17	1	76	19	3.11	3	65	4.71	72.54	73.1	8.07	9.37	0.86	0.99
160	61.7	0.17	1	76	19	3.11	3	65	5.20	74.50	77.5	8.59	11.1	0.77	0.96
160	61.7	0.34	2	76	19	3.11	3	65	9.78	84.82	80.8	13.41	14.9	0.90	1.05
160	61.7	0.34	2	76	19	3.11	3	65	9.23	82.62	76.7	12.83	13.5	0.95	1.08
160	61.7	0.34	2	76	19	3.11	3	65	9.67	84.38	78.0	13.30	14.4	0.92	1.08
160	61.7	0.51	3	76	19	3.11	3	65	13.1	90.10	90.1	16.91	17.1	0.99	1.00
160	61.7	0.51	3	76	19	3.11	3	65	13.8	92.90	92.1	17.65	18.8	0.94	1.01
160	61.7	0.51	3	76	19	3.11	3	65	14.6	96.10	94.4	18.49	19.5	0.95	1.02
Jiang and Teng (2007)															
150	33.1	0.17	1	80.1	23	0.30	3.0	6.0	4.12	41.58	42.4	1.05	1.00	1.05	1.06
150	33.1	0.17	1	80.1	23	0.30	3.0	6.0	4.12	41.58	41.6	1.05	1.29	0.81	1.06
150	45.9	0.17	1	80.1	23	0.24	3.0	5.5	4.12	54.38	40.5	0.73	0.81	0.91	1.08
150	45.9	0.17	1	80.1	23	0.24	3.0	5.5	4.12	54.38	40.5	0.73	1.06	0.69	0.91
150	45.9	0.34	2	80.1	23	0.24	2.1	5.5	8.24	55.44	52.8	1.23	1.00	1.23	0.87
150	45.9	0.34	2	80.1	23	0.24	2.1	5.5	8.24	55.44	55.2	1.23	1.25	0.98	0.95
150	45.9	0.51	3	80.1	23	0.24	2.6	5.5	12.36	66.41	64.6	1.72	1.55	1.11	1.15
150	45.9	0.51	3	80.1	23	0.24	2.6	5.5	12.36	66.41	55.9	1.72	1.00	1.72	1.10
Cui and Sheikh (2010)															
150	47.8	1.25	2	22	23	0.22	2.1	5.5	8.32	57.59	59.1	1.18	1.35	0.87	0.97
150	47.8	1.25	2	22	23	0.22	2.1	5.5	8.32	57.59	59.8	1.18	1.15	1.02	0.96
150	47.8	2.5	4	22	23	0.22	3.4	5.5	16.65	89.04	88.9	2.14	2.21	0.97	1.00
150	47.8	2.5	4	22	23	0.22	3.4	5.5	16.65	89.04	88	2.14	2.21	0.97	1.01
150	47.8	3.75	6	22	23	0.22	3.6	5.5	24.97	114.65	113	3.09	2.85	1.09	1.01
150	47.8	3.75	6	22	23	0.22	3.6	5.5	24.97	114.65	112	3.09	2	1.55	1.02
Teng *et al.* (2007)															
152	39.6	0.17	1	80.1	23	0.26	0.75	5.5	4.1	38.78	37.2	0.83	0.94	0.88	1.04
152	39.6	0.17	1	80.1	23	0.26	0.75	5.5	4.1	38.78	38.8	0.83	0.83	1.00	1.00
152	39.6	0.34	2	80.1	23	0.26	2.10	5.5	8.21	49.05	54.6	1.40	2.13	0.66	0.90
152	39.6	0.34	2	80.1	23	0.26	2.10	5.5	8.21	49.05	56.3	1.40	1.83	0.77	0.87
152	39.6	0.51	3	80.1	23	0.26	2.60	5.5	12.32	59.96	65.7	1.97	2.56	0.77	0.91
152	39.6	0.51	3	80.1	23	0.26	2.60	5.5	12.32	59.96	60.9	1.97	1.79	1.10	0.98

CONCLUSION

Fiber Reinforced Polymer (FRP) has emerged as a new material have found expanded used in structural engineering due to its attractive mechanical properties such as: high tensile strength, light weight, high resistance for corrosion, high fatigue endurance, low thermal coefficient, short period of installation, easy application and low cost for maintenance. Further, these are being careplacement to the conventional steel in reinforced concrete structures due to continuing drop in the cost of FRP materials.

RECOMMENDATIONS

Through a review of previous studies for columns strengthened by FRP sheets provided in the form of wrapping such as (Jacket) or tubes has proved extremely beneficial. The FPR has achieved enhancement in strength, the ability to carry an extra load, energy absorption an increase in the durability, improved rigidity in failure modes as well as strengthening Improves stress transfer capability across the crack and hence delays crack formation.

The parameters affecting the performance of confined columns systems by using FRP sheets are concrete strength, shape of column section (depth-width) ratio, longitudinal steel, stirrups, corrosion of steel, type of fiber, direction of fiber, thickness of FRP sheets, slenderness ratio, deformability of the concrete, stiffness of the jacket in the lateral direction, concrete dilation ratio, number of cycles per unloading and reloading and heating and cooling cycles, etc.

There are a few approaches to develop an equation for strength enhancement and the ultimate axial strain of confined concrete. All previous studies the number of layers was not taken into account knowing that it was a fundamental variable with the effective lateral confining pressure.

These comparisons indicate that the a new model has been proposed in this study is in agreement with the test results which are countrified during the use of statistical indicators. These parameters prove, for confined concrete cylinders, a good correlation between the analytical predictions of the proposed model with the experimental results of an independent test series.

Research is needed to determine the endurance limit of FRP during fire, effect of chemical and ultra-violet radiation on FRP, etc. Long term studies are required to examine effect of alkalinity. And columns subjected to dynamic loading condition is another important area for consideration.

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