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Ultimate Compressive Strength of non-Circular Concrete Columns Retrofitted by Fiber Reinforced Polymer

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ABSTRACT

In the present study, a new equation was proposed and detected. The equation was presented in accordance to axil compressive stress. The impact of several parameters impacting the strength was reviewed, from previous experimental research, and behavior of non-circular (rectangular and square) concrete columns wrapped with Fiber reinforced polymer FRP. When the proposed equation's results were compared to the experimental data, a good agreement between the two was found. The test results also compared with the proposed equations in literature, and show good matching where the mean square error MSE (0.07) in comparison to less value (0.19) for the previous equations.

1. Introduction

One of the important and crucial responsibilities in civil engineering is strengthening concrete structures including columns, beams, bridges, buildings, transit systems, and parking lots. This occurs because the building's structural system has altered, such as when certain load-bearing parts have been removed, external causes have damaged the building, or the building's role has changed, increasing the applied load and necessitating the need to strengthen the columns. The RC columns were repaired, strengthened, or provided with a lateral confinement using traditional techniques like concrete or steel jacketing (ChaiI, 1991; Priestley, 1994). Although both technologies are excellent at boosting structural strength, they require a lot of labor force, an increase the cross-sectional area of the strengthened column, having a high density, and take a considerable time to install; are challenging to use, and require ongoing maintenance. For these reasons, a significant percentage of the research and application effort in the field of repair and restoration of structural elements has gone into the development of novel rehabilitation and strengthening methods for reinforced concrete structures, particularly with composite materials.

Fiber reinforced polymer (FRP) composites are used widely, as a retrofitting material in concrete construction, due to the great advantages. The primary benefits include reduced self-weight and corrosion resistance. Using externally bonded FRP composites, one of the most significant utilization of FRP in civil engineering is reinforcing and retrofitting all the structures' component parts. FRP composites have a significant impact on retrofitted members' responses and can increase their strength, ductility, and stiffness (Siddika, 2019). Using FRP composites,

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as a wrapped material especially in concrete columns, is a popular method for resistance to earthquakes (Eslami, 2013). The stress-strain behavior of FRP wrapped concrete must be thoroughly examined in order to obtain an appropriate design for the columns. Numerous stress-strain responses have been presented for circular concrete columns encased in FRP laminates as a result of years' worth of research on the behavior of these columns (Teng, 2004; Mirmiran A. , 1998; Xiao, 2000; Lam L. &., 2004; Lam L. &., 2003; Samaan M. M., 1998; Spoelstra, 1999; Jiang, 2007; Rousakis T. C., 2008; Ahmed, 2018).

It is considerably noted that a predicted model of the stress-strain curve of composite confined concrete is rather complex due to the number of related parameters. The characteristics of the concrete (constitutive model which is represented by the elasticity modulus, strength, and Poisson ratio), the cross-section geometry (circular, square, or rectangular), and the size of the column cross section are the factors that have the greatest influence on the curve trend (Abd El Fattah, 2018). Aspect ratio affects the stress-strain curve for rectangular cross section columns, and the radius to which the section's corners are roundish affects the curve for both square and rectangular cross sections in order to prevent fiber breakage.

This work presents the preliminary results of an experimental study on the behaviour of non-circular (rectangular and square) concrete columns, with different aspect ratio 1 to 3, externally confined with FRP sheets. The obtained experimental data was compared with proposed equation data proposed recently and in the literature.

In this study a new model presented to estimate the compressive strength of rectangular and square columns with different aspect ratios 1 to 3 confined externally by FRP. Focused on the compressive strength because it is the most important in columns compare with other parameter.

2. Literature review

Numerous analytical and experimental research on the axial load and stress-strain response of RC columns covered in fiber-reinforced polymer (FRP) sheets have been done in recent years (ACI Committee, 2002). These studies came to the conclusion that concrete columns retrofitted with FRP sheets significantly increased their axial load capacity and their ability to absorb energy under monotonic and cyclic loads (Haji, 2019).

In literature, several confinement expressions have been proposed to estimate the axial force and describe the stress-strain response of concrete columns strengthened by FRP sheets. According to (Cao, 2021) there are two categories of stress-strain relationships for FRP-enhanced concrete columns: expressions that are analytically and designably directed. The stress-strain curve is constructed in the designable oriented expressions as a straightforward form resolution based on evaluation and justification of empirical results. The interaction between the core of concrete columns and the jacket FRP results in a more complex stress-strain curve in analytically oriented formulas. Complexity forces the use of analytically oriented statements solely in numerical calculation analysis. The following confinement expression serves as the foundation for the first proposed stress-strain expression (Richart F. E., 1928; Richart, 1929).

$$f'_{cc} = f'_{co} + k\ f'_{\ell} \tag{1}$$

Where f_{cc} is the confined concrete compressive strength; f_{co} is the compressive strength un-confined concrete; k is the confinement effectiveness factor and f_l is the lateral hydrostatic pressure. Based on previous studies and the results tests data, (Richart F. E., 1928; Richart, 1929) proposed values for k= 4.1.

The model proposed by (Mander, 1988) for steel jacket concrete columns it is considered the most popular. In this model, the effective constant lateral confining pressure is given as a function of the confined concrete compressive strength f_{cc}, which was computed during the first stage of transverse steel yielding.

$$f'_{cc} = f'_{co}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f'_{\ell}}{f'_{co}}} - 2\frac{f'_{\ell}}{f'_{co}}\right) \tag{2}$$

Depending on the length and width of the column section, longitudinal and transverse reinforcement, different models were developed by (Mander, 1988) for calculating f_l.

Numerous prior research has demonstrated that because to variations in the constitutive laws between FRP and steel, the behavior of columns reinforced with FRP confined concrete significantly differs from columns strengthened by steel jacketing. Since their lateral action is activated as a result of the axially loaded member's lateral dilation, both types of confining systems offer passive confinement; however, the linear-elastic performance of FRP materials up until rupture results in an augmented level of confinement throughout the load record, and the FRP jacket failure happens abruptly and brittlely (Realfonzo, 2011). Contrarily, in the case of steel contained concrete, confining stresses depend on the load history only until the transverse steel reinforcement yields; thereafter, confining stresses stay roughly constant (Realfonzo, 2011).

The transverse strain in the FRP sheets is frequently or frequently assumed to be equivalent to the transverse strain in the external surface of the concrete under the assumption that there is a strong link between the specimen's concrete surface and the FRP sheets (Zhao, (2004). Therefore, using the provisions of transversal strain compatibility and force equilibrium between the concrete and confining FRP jacket, the transverse confining pressure f_l is determined for FRP jacketing of circular columns sections as a function of the bulk ratio ρ_f and transverse strain ε_l of the FRP sheets as follows (Fossetti, 2018).

$$f_\ell' = \left(\frac{\rho_f\ E_f}{2}\right)\varepsilon_\ell \tag{3}$$

Where

$$\rho_f = \frac{4\ n_f\ \ t_f}{D} \tag{4}$$

In which n_f is the count of FRP layers; t_f is the total thickness of the FRP sheets; D is the diameter of the column. For non-circular column sections, the equivalent value of D is taken according to (ACI Committee, 2002) as $D=2bh/(b+h)$.

With regard to the non circular column sections FRP confined it is difficult to predict for the increases in strength, so (ACI Committee, 2002) recommends using the model of (Mander, 1988).

Numerous studies have been investigating the stress-strain behavior of constrained circular FRP concrete columns Saadatmanesh, 1994; Samaan M. M., 1998; Spoelstra, M. R., & Monti, G, 1999; Toutanji, 1999; Fam, 2001), The stress-strain behavior of constrained circular FRP concrete columns has been the subject of numerous investigations (Lin, 2010).

In order to assess the axial load capability and stress-strain response of concrete enclosed by fiber-reinforced polymer (FRP) laminae, a variety of analytical and experimentally based confinement models were presented. The top five models that have been suggested are listed below:

2.1. Lam and Teng's model:

(Lam L. &., 2003) proposed the next stress–strain relationship, which follows their design– directed stress–strain procedure for FRP–wrapped concrete in circular concrete columns. According to Figure 1, the relationship consists of a parabolic segment with a decreased E_2 slope. The relationship can also be mathematically represented as:

$$\begin{Bmatrix} f_c' = E_c\varepsilon_c - \dfrac{(E_c - E_2)^2}{4f_{co}'}\varepsilon_c^{\ 2} & (0 \le \varepsilon_c \le \varepsilon_0)\ ;\ \varepsilon_0 = \dfrac{2f_{co}'}{E_c - E_2} \\ f_c' = f_{co}' + E_2\varepsilon_c & (\varepsilon_0 \le \varepsilon_c \le \varepsilon_{cu})\ ;\ E_2 = \dfrac{f_{cu}' - f_{co}'}{\varepsilon_{cu}} \end{Bmatrix} \tag{5}$$

Where f_c and ε_c are the stress and strain of confined concrete, respectively; ε_o is the transitionary strain at the junction between the first and second categories of express; ε_{co} is the strain of the unconfined concrete column corresponding to f_{co}; E_c is the modulus of elasticity of unconfined concrete; E_2 is a linear second category with a decreased slope, f_{cu} and ε_{cu} are the ultimate stress and corresponding axial strain, at the utmost failure point, respectively.

In this relation, compressive strength of FRP wrapped circular concrete columns, were modified for non-circular sections using effective shape factor of k_{s1}.

$$k_{s1} = \left(\frac{b}{h}\right)^{\alpha} \frac{A_e}{A_c} \tag{6}$$

The value of α is 0.5 suggested by (Lam L. &., 2003) based on their experimental database.

$$\frac{A_e}{A_c} = \frac{1-\left[\left(\frac{b}{h}\right)(h-2r)^2+\left(\frac{h}{b}\right)(h-2r)^2\right] / \left[3A_g-\rho_{sc}\right]}{1-\rho_{sc}} \tag{7}$$

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 k_{s1} \frac{f'_{\ell}}{f'_{co}} \tag{8}$$

Where b and h are Length and Width of rectangular cross-section, respectively; Ac is the effective confinement area ratio; r is the corner radius of cross-section; Ag is the gross area of the column section and ρ_{cs} is the gross sectional area ratio of the longitudinal steel reinforcement. The value of k_1 is 3,3 has been proposed by (Lam L. &., 2003) based on their experimental database.

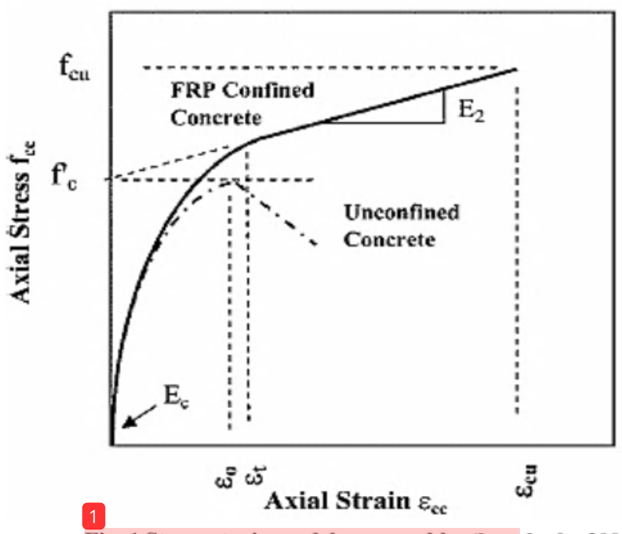


Fig. 1 Stress-strain model proposed by (Lam L. &., 2003)

2.2. Harajli model:

The stress-strain response of FRP-jacketed concrete columns is predicted to have a two-segment relationship. Harajli (2006). The ascending parameter of the stress-strain equations treated for unconfined concrete or steel confined concrete can be used to describe the stress-strain curve response in the first segment because the transverse strains and, as a result, the lateral confinement pressure are relatively minimal (Sheikh, 1980; Mander, 1988). For the sake of simplicity, it is assumed at this point that the stress-strain curve will follow a second-degree parabola similar to that provided by (Sheikh, 1980; Mander, 1988). internal steel ties or stirrups and their effects on the relationship In general, it can be explained as shown in Fig. 1 and as follows.

$$\begin{cases} f_c' = f_o'\left[\dfrac{2\varepsilon_c}{\varepsilon_o} - \left(\dfrac{\varepsilon_c}{\varepsilon_o}\right)^2\right] - \dfrac{(E_c - E_2)^2}{4f_o'}\varepsilon_c^{\,2} \quad (0 \le \varepsilon_c \le \varepsilon_0) \\ f_c' = f_o'\left[G(\varepsilon_\ell), \rho_f E_f, \rho_{st}, f_{yt}, \textit{section geometry}\right] \le f_{cu}' \; (\varepsilon_0 \le \varepsilon_c \le \varepsilon_{cu}) \end{cases} \quad \textbf{(9)}$$

Where, $\varepsilon_{cu} = G \;\; \varepsilon_{cl}$ is the association between the axial strain and transverse strain in the FRP laminates; ε_{cu} and f_{cu} are the ultimate concrete axial strain and the ultimate corresponding axial stress respectively; ρf and f_{yt} are the volume ratio and yield strength of steel hoops, respectively.

$$f_{cc}' = f_{co}' + k_1\left(f_{\ell f} + f_{\ell s}\frac{A_{cc}}{A_g}\right) \quad \textbf{(10)}$$

$$k_1 = 1.25\left(\frac{f_{\ell f} + f_{\ell s}\left(A_{cc}/A_g\right)}{f_{co}'}\right) \quad \textbf{(11)}$$

Where A_{cc} is the area of the concrete core enveloped with internal lateral steel (stirrups), measured to the center axis of stirrup. The terms f_{lf} and f_{ls} are the active transverse confining pressure applied by FRP and traditional transverse steel on the concrete section, respectively.

$$f_{\ell f} = \left(\frac{k_{ef}\,k_{vf}\,\rho_f\,E_f}{2}\right)\varepsilon_\ell \quad \textbf{(12)}$$

$$f_{\ell s} = \left(\frac{k_{es}\,k_{vs}\,\rho_{st}}{2}\right)f_{yt} \quad \textbf{(13)}$$

The items (k_{ef} or k_{es}) and (k_{vf} or k_{vs}) stand for the effectiveness of the transverse reinforcement in confining the concrete along the horizontal level, and the concrete between transverse ties or FRP strips, respectively. For circular columns, k_{ef} = k_{es} = 1.0. For columns confined with continuous FRP sheets, k_{vf} = 1.0. Formulation for the coefficients k_e and k_v for rectangular columns based on the proposed method by (Sheikh, 1980), and more recently by (ACI Committee, 2002; Mander, 1988). More details on the expressions for k_e and k_v are described by (Mander, 1988; Harajli, 2006).

2.3. Wu model:

(Wu, 2007) three models were proposed: Model I include the curvilinear function recommended by (Xing, 1987) or steel-confined concrete and a parabola in the first section. Only when they confinement effectiveness is relatively low is this concept applicable. Model II was inspired by the model put forth by (Saadatmanesh, 1994), while Model III is comparable to the model put forth by (MIYAUCHI, 2000). There is no smooth transition between the first portion, which employs a parabolic curve, and the second, which connects it with a straight line. The recent two models can be used for both strain-softening and strain-hardening response, although Model III, which is given as follows, and as explained in Fig. 2.

$$\begin{cases} f_c' = f_o'\left[\dfrac{2\varepsilon_c}{\varepsilon_0} - \left(\dfrac{\varepsilon_c}{\varepsilon_0}\right)^2\right]; \qquad (0 \le \varepsilon_c \le \varepsilon_o) \\ f_c' = f_o' + \left[\dfrac{(f_{cu}' - f_o')(\varepsilon_c - \varepsilon_o)}{\varepsilon_{cu} - \varepsilon_o}\right]; (\varepsilon_o \le \varepsilon_c \le \varepsilon_{cu}) \end{cases} \quad \textbf{(14)}$$

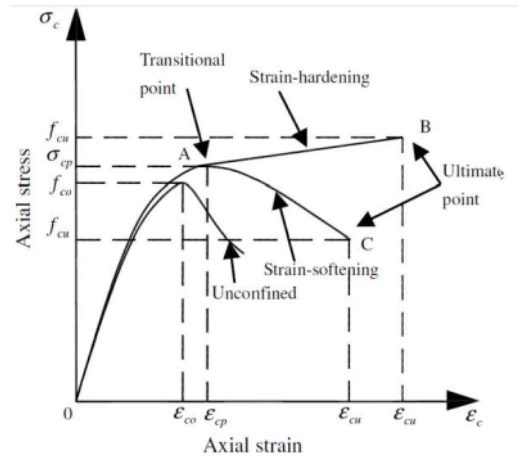


Fig. 2 Typical stress–strain curves of FRP-confined concrete prism (Wu, 2007)

2.4. Youssef model:

The two-part model put forth by (Youssef, 2007) uses a straight line for the second segment and a polynomial curve for the first. It applies to both circular and rectangular columns, and the second part of the model can allow either a strain-hardening or strain-softening response. On the basis of a regression analysis of the experimental data, the model parameters for various kinds of circular and rectangular columns were chosen and assessed independently. This model's explanation and formulation are shown in Fig. 3:

$$\left\{\begin{array}{ll} f_c' = E_c \varepsilon_c \left[1 - \frac{1}{n}\left(1 - \frac{E_2}{\varepsilon_c}\right)\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^{n-1}\right]; & (0 \le \varepsilon_c \le \varepsilon_o),\ E_2 > 0 \\ f_c' = E_c \varepsilon_c \left[1 - \frac{1}{n}\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^{n-1}\right]; & (0 \le \varepsilon_c \le \varepsilon_o),\ E_2 < 0 \\ f_c' = f_o' + E_2(\varepsilon_c - \varepsilon_o); & (\varepsilon_0 \le \varepsilon_c \le \varepsilon_{cu}) \\ n = \frac{(E_c - E_2)\varepsilon_o}{E_c \varepsilon_o - f_o'} \quad E_2 > 0, & n = \frac{E_c \varepsilon_o}{E_c \varepsilon_o - f_o'} \quad E_2 < 0 \end{array}\right\} \tag{15}$$

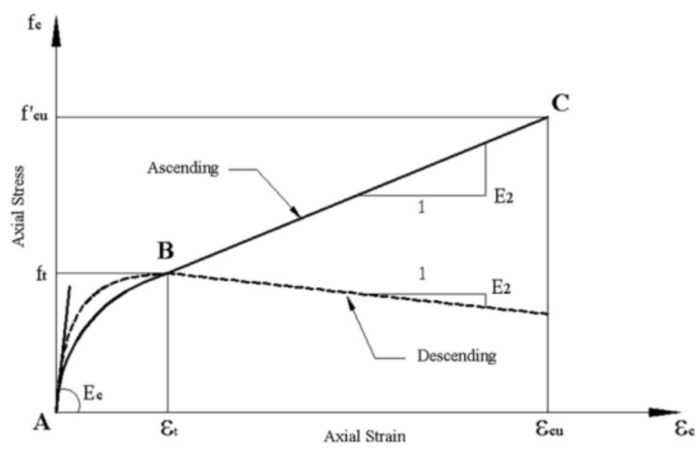


Fig. 3 Proposed model for FRP-confined concrete by (Youssef, 2007)

2.5. Wei model:

For FRP-wrapped concrete columns, (Wei, 2012) provided a unified stress-strain expression that is applicable to all column cross sections: circular, rectangular, and square. They chose a mathematical phrase with two categories: a parabola in the first category and a straight line in the second. This phrase has two benefits.:

- The slope of the parabola at, $\varepsilon_c = 0$, has the same modulus of elasticity of unconfined concrete columns, E_c.
- At the transition point, the slope is the same for the two categories of expression as (Wei, 2012).

This model can be explained in Fig. 3 and expressed as:

$$\left\{\begin{array}{ll} f_c' = E_c\varepsilon_c + \dfrac{f_o' - E_c\varepsilon_o}{\varepsilon_o^{\,2}}\varepsilon_c^{\,2}; & (0 \le \varepsilon_c \le \varepsilon_o) \\ f_c' = f_o' + E_2(\varepsilon_c - \varepsilon_o); & (\varepsilon_0 \le \varepsilon_c \le \varepsilon_{cu}) \\ \varepsilon_o = \dfrac{(f_o' + f_{cu}' + E_c\varepsilon_{cu}) - \sqrt{(f_o' + f_{cu}' + E_c\varepsilon_{cu})^2 - 8f_o'E_c\varepsilon_{cu}}}{2E_c}, & E_2 = \dfrac{f_{cu}' + f_o'}{\varepsilon_{cu} - \varepsilon_o} \end{array}\right\} \tag{16}$$

The predictions of the stress-strain curve of FRP-confined concrete in square and rectangular columns with various properties are compared with the experimental findings of the 406 specimens that were gathered from the literature in order to evaluate the performance of the models previously described, 329 specimens were wrapped with CFRP layers, 19 with GFRP, 18 with Armid, 20 with PEN and 20 with PET. 259 specimens plain concrete and 161 specimens reinforced concrete. Length, *L* ranging from 76-450 mm, width *b* ranging from 76-305 mm, height *h* ranging from 300-1500 mm, number of layer *n* from 1-5, eccentricity *ex* from 0-300 mm and slenderness ratio S_l ranged from 5.33-35.66. The unconfined concrete column strengths f_{co} ranged from 26-69.5 MPa. All details of the specimens are listed in Table 1.

Table 1 – Main data and results from compression tests performed on FRP confined concrete non circular columns

No	b mm	h mm	r_c mm	H mm	E Gpa	n	t mm	FRP	f_{co} Mpa	F_{frp} Mpa	Lon. reo. steel	Tran reo. steel	e_x mm	S_l	No. Of Spic
							(Rochette, 2000)								
1.	152	152	38 25 5	500	83 14	3 4 5 6 9 12	0.3	C A	42 43.9 35.8 43	1265 230	-	-	-	10.9	24
							(Suter, 2001)								
2.	150	150	5 25	300	125 240 640 73	1 2 3 4	0.29	A C	33.9 34.9 35.9 36.6	2100 3800 2650 2400	-	-	-	6.67	16
							(Parvin, 2001)								
3.	108	108	8.26	305	188.9	1 2	0.17	C	22.5 18.5 17	3022	-	-	0 7.6 15.2	9.41	6
							(Pessiki, 2001)								
4.	150	150	20	800	38	3	1	C	69.5	580	4Φ12	6@120	15 25	17.7	2
							(Shehata, 2002)								
5.	150 94	150 188	10	300	235	1 2	0.17	C	23.7 29.5 28.8	3550	-	-	-	6.67 10.6	8

(Ilki, 2003)															
6.	250 150	250 300	40	500	230	1 3 5	0.17	C	32.8 34	3430	-	-	-	6.67 11.1	12
(Chaallal, 2003)															
7.	133 108 95	133 165 190	25 15 30	305	231	1 2 3 4	0.12	C	21.5 54.6 25 55.3 22 48	3650	-	-	-	7.64 9.41 10.70	24
(Lam L. &., 2003)															
8.	150	150 225	15 25	600	257	1 2 3 4	0.17 0.33 0.49 0.66	C	33.7 24 41.5	4519	-	-	-	13.3	8
(Masia, 2004)															
9.	100 125 150	100 125 150	25	300 375 450	230	1 2 3	0.13	C	25.5 22.8 23.8 21.7 24.5	3500	-	-	-	10.0	15
(Harajli, 2006)															
10.	132 102 79	132 176 214	15	300	230	1 2 3	0.13	C	18.5 17 19.5 20.6 18	3500	- 4Φ8	- 6@1 00	-	7.58 9.8 12.6	18
(Rousakis T. C., 2007)															
11.	200	200	30	320	240 65	1 2 3 4	0.12	C G	33.0 34.0 38.0 40.0	3720 1820	-	-	-	5.33	13
(Kumutha, 2007)															
12.	125	125 156 207	0	750	10.5	1 2	1.05	G	40.26 39.55 38.56	250	4Φ10	6@1 25	-	20.0	6
(Al-Salloum, Y. A, 2007)															
13.	150	150	5 25 38 50	500	75.1	1	1.2	C	28.7 31.8 28.5 30.3	935	-	-	-	11.1	8
(Tao, 2008)															
14.	150	150 230 300	20 35 50	300	239	1 2	0.17	C	22 19.5 49.5	4470	-	-	-	6.67	24
(Wang, 2008)															
15.	150	150	15 30 45 60	300	219 226	1 2	0.17	C	32.9 55 49	4364	-	-	-	6.67	48
(Wu Y. F., 2010)															
16.	150	150 188 225	30	300	229	1 2	0.17	C	34.1 4 33.5	4192	-	-	-	6.67	30

		260 300							36.1 37.3 35.3						
(Sadeghian, 2010)															
17.	200	300	15	1500	41	3 5	0.9	C	5.6 2.6	303	4Φ1 2	6@2 00	200 300	25.0	5
(Waryosh, 2012)															
18.	120	120	0	750	230	1 2	0.13	C	8.3 4.5 9.7 5.2	3500	4Φ1 2	5@2 00	60 120	20.8	8
(Wang Z. W., 2012)															
19.	305 204	305 204	30 20	915 612	240	1 2 3	0.17	C	25.5 32 34 32.5	4340	- 12Φ1 2 8Φ10	- 6@80 6@40 6@95 6@60	-	10.0	14
(Nisticò, 2013)															
20.	150	150	0 15 30 45 60 75	300	230	1	0.17	C	31.7 52.1 31.9 55.8	3450	-	-	-	6.67	24
(Punurai, 2013)															
21.	76	76	0	813	73	1 2	0.33	C	35.6	965	4Φ10	3@7 5	50	35.6	4
(Rahai, 2014)															
22.	150	450	150	1500	40	1 2 3	0.5	C	3.2	336	6Φ12	6@1 50	225 300	33	6
(Abbasnia, 2015)															
23.	150 120 90	150 180	13.6 22.6 34.5 42 18.1 27.6	300	241	2	0.17	C	32	3950	-	-	-	6.67 8.33 11.1 1	20
(Hany, 2015)															
24.	160 140 130	160 180 200	10	500	230	1 2 3	0.13	C	18.5 17.6 20.2	3500	-	-	-	10.42 11.90 12.82	9
(Isleem, 2015)															
25.	200	300 400	30	500	240	2 3 4	0.17	C	46	4340	6Φ1 6 - 8Φ1 6	8@9 0 - 8@9 0	-	8.3	14
(Han, 2020)															
26.	150	150	0 0.2 0.33 0.53 0.80	300	27 18	1	1.27 2 2.54 0.84 1.68	PEN PET	25	713 744	-	-	-	6.67	40
The total of the specimens															406

Comparisons are displayed. The predictions of Lam and Teng's model for column compressive strength are more in line with the findings of the experiments. Except for the transitional stress of rectangular specimens, this model also provides reasonably accurate transition point predictions. While the experimental findings are less relevant to the Harajli model for compressive strength of columns. To model the stress-strain curve of rectangular columns with strain softening responses, neither model is adequate.

for square specimens, model the compressive strength estimates made by Wu et al. models are more accurate than those made by the other models, but when the aspect ratio increases, the model's forecasts become more inaccurate.

The highest performance in estimating transitional stress and strain is provided by the Youssef and Wei models, however their predictions of compressive strength are not sufficiently accurate. Additionally, the strain softening behavior of the specimens that exhibit this response is not captured by this model.

These comparisons suggest that the aforementioned models still have certain shortcomings. Although the Wei and Wu's model makes reasonably accurate predictions for the transitional point, none of the models does so for the stress and strain at the final point. Therefore, additional study is necessary to create a stress-strain model for non-circular columns contained by FRP composites that is more realistic.

3. Predictive strength models

The most crucial factor for columns constrained by FRP composites is compressive strength. The predictions of the compressive strength models for (Mirmiran A. S., 1998; Harajli, 2006; Youssef, 2007; Wu Y. F., 2010) square and rectangular columns with various characteristics are matched with the experimental findings of the 406 specimens that were gathered from the literature in order to assess their performance. Figure 4 shows that all of the models work fairly well in forecasting the ultimate stress of square and rectangular columns that are confined to FRP. After performing the statistical analysis, among the existing models, the (Mirmiran A. S., 1998) model performs the best with an average absolute error AAE 0.29 and mean square error MSE are 0.19. For square columns with tiny corner radius ratios and rectangular columns, the other available models typically produce un conservative estimates. For square and rectangular columns with greater corner radius ratios, the (Youssef, 2007) model provides conservative values. Results of the mean square error MSE and average absolute error AAE for different compressive strength models are shown in Table 2.

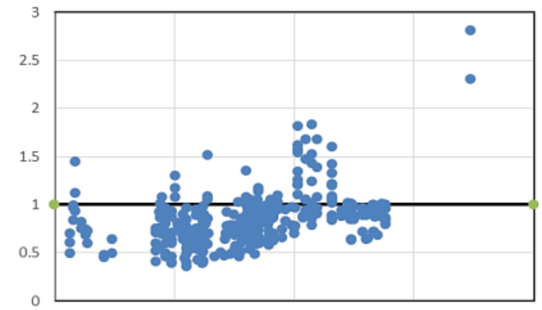
4. Analytical model

The compressive strength of the literature and the projections of the aforementioned models differ significantly, as shown in the previous section. A new compressive strength model is thus proposed in this part based on the regression analysis of literature data. In this concept, the corner radius ratio r/b. and compressive strength are directly correlated. Similar to the (Mirmiran A. S., 1998) model, the effects of confinement ratio f_l/f_{co} and aspect ratio h/b on the compressive strength are also taken into consideration. The form is proposed as the model:

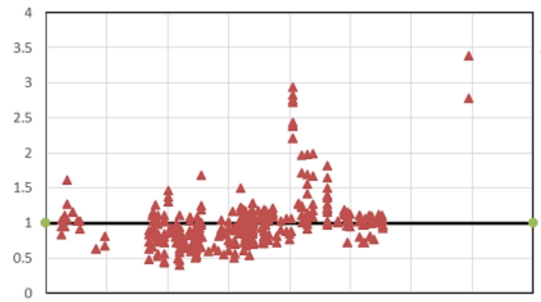
$$f'_{cc} = f'_{co} + k\, f'_{\ell} \quad (17)$$

Where k is the confinement effectiveness coefficient.

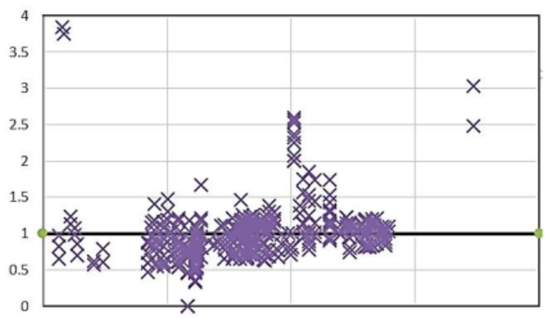
The transverse confining stress fl is developed in wrapped concrete, when the structural member is loaded and initiate to expands transversally. The usefulness of the transverse stress rely upon mainly on: the shape geometry of the wrapped structural member, the magnitude and mechanical properties of wrapped materials used. For example, when wrapping a circular concrete column, the FRP jacket provides a uniform lateral stress around the concrete specimen, and therefore leads to a great improvement in structural member behavior during loading. On the other hand, wrapped FRP non-circular (square or rectangular) structural member inclines to produce confining stress concentrating, around the corners of such structural member, as shown in Fig. 5 (a). In fact, all the non-circular (square and rectangular) concrete columns tested failed by the rupture of the FRP laminates, which focused clearly on the corners.



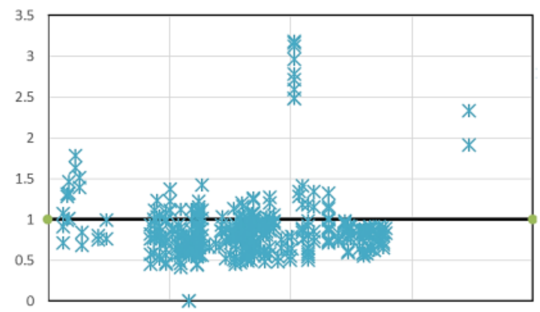
(a) Mirmiran



(b) Harajli



(c) Youssef



(d) Wu Y. F.

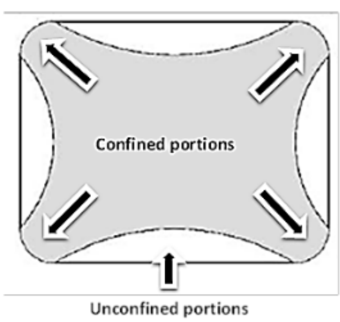
Fig. 4 Performance of compressive stress models.

Investigating the behavior of the member concrete wrapped by FRP sheets, required calculating the magnitude of lateral confining pressure stress provided by the FRP sheets. Depending on static analysis, equilibrium of forces, deformation compatibility, the following expression was adopted to calculate the lateral confining stress as shown in Fig. 5 (b).

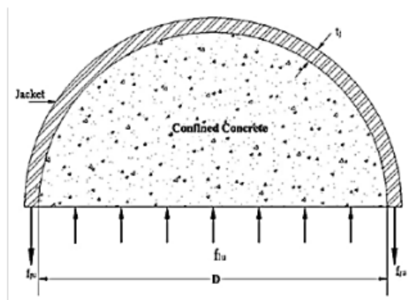
$$f_{\ell}' = \frac{2 f_{frp} t}{D} \qquad \textbf{(18)}$$

Where, D is the diameter of the confined circular section.

Similarly, for non-circular sections, it is possible to modify the effective lateral confining stress given by Eq.18 by multiplying the equation by the confinement effectiveness coefficient k_e such that:



(a)



(b)

Fig 5. (a) Confined and unconfined of noncircular section, (b) Free body diagram of circular column confined by FRP jacket.

$$f_\ell' = \left[\frac{2f_{frp}t}{D}\right]k_e \tag{19}$$

$$f_{frp} = E_{frp}\varepsilon_{h,rup} \tag{20}$$

Where E_{frp} is the modulus of elasticity of FRP and $\varepsilon_{h,rup}$ is the hoop rupture strain of the FRP. According to (Lam L. &., 2003), due to the non-uniform stress distribution and curvature in the FRP sheets, the ultimate tensile strain is bigger than the rupture strain of the FRP sheets, which was obtained from direct sheets tests. Based on evaluation of previous experimental data, conducted by, (Lam L. &., 2003), the proposed values of the rupture strain of the FRP sheets, $\varepsilon_{h,rup}$ for CFRP, GFRP, and Armid FRP was 58.6, 62.4, and 85.1% respectively. For non-circular sections, the term D in Eq. 19 is the equivalent to the diameter of a circular concrete column as follow: $D=(h^2+b^2)^{0.5}$, where h, is the long dimension and b, is the short dimension of the cross section.

Many expressions has been proposed in literature to calculate the confinement effectiveness factor, for non-circular section (Restrepol, 1996; Lam L. &., 2003; Pessiki, 2001; Masia, 2004). The most common expression that proposed by (Lam L. &., 2003) shown as follows:

$$k_e = \left(\frac{b}{h}\right)^2 \frac{A_e}{A_c} \tag{21}$$

$$\frac{A_e}{A_c} = \frac{1-\left(\left(b/h\right)\left(h-2R_c\right)^2+\left(h/b\right)\left(b-2R_c\right)^2/\left(3A_g\right)\right)-\rho_{sc}}{1-\rho_{sc}} \tag{22}$$

Many confinement effectiveness factor k by (Mirmiran A. , 1998; Samaan M. M., 1998; Karbhari, 1997; Toutanji, 1999) were proposed, to calculate the confinement effectiveness factor k for FRP wrapped concrete columns. Other researchers (Richart, 1929; Karbhari, 1997; Samaan M. M., 1998; Toutanji, 1999; Lam L. &., 2003) used a constant value for k (between 2.0 and 5.0). Do not take into account corner radius ratio rc and aspect ratios h/b. The experimental findings of the 406 specimens, which were gathered from the literature, are compared with their predictions in square and rectangular columns with various features. For square columns with tiny corner radius ratios and rectangular columns, the estimates from the current models are typically not conservative. In this section a new model presented to predict the confinement effectiveness factor k of rectangular and square columns with different of the corner radius ratio r_c and aspect ratios h/b. The proposed model of FRP confined non circular concrete is compared to the test experimental data obtained from literature. Table 2 clearly demonstrates that the suggested model's predictions are more close than the literature results. The model is suggested as the form:

$$k = 3.05\left(bh/r_c\right) \tag{23}$$

Thus the final model for prediction of the compressive strength for different cross sections (square and rectangular), externally confined with FRP sheets as follows:

$$f_{cc} = f_{co} + 3.05(bh/r_c)f_l \tag{24}$$

5. Validation of the proposed model

The proposed model of FRP confined non circular concrete is compared to the test experimental data obtained from literature. Table 2 clearly demonstrates that the suggested model's predictions are more close than the literature results, with mean square and average absolute errors of 0.07 and 0.12 respectively, also Figure 6 shows the performance of proposed model in prediction of compressive strength. This figure clearly shows how accurately the suggested model predicts compressive strength.

Table 2 – Comparison between the experimental and predicted results from previous equations of FRP confined concrete non circular columns

	(Wu Y. F., 2010)	(Harajli, 2006)	(Lam L. &., 2003)	(Mander, 1988)	(Campione, 2003)	(Mirmiran A. S., 1998)	(Shehata, 2002)	(Ilki, 2003)	(Al-Salloum, 2007)	(TEC, 2006)	(Standard, C. S. A., 2002)	(Concrete-Society, 2002)	(Pellegrino, 2010)	(Pham, 2014)	(Youssef, 2007)	Proposed Model
AAE	0.37	0.31	0.39	0.44	0.48	0.29	0.62	0.64	1.25	0.91	0.51	0.98	1.35	2.27	0.68	0.12
MSE	0.21	0.32	0.45	0.74	0.37	0.19	9.55	4.01	33.5	19.9	0.41	26.1	17.6	125.	0.36	0.07

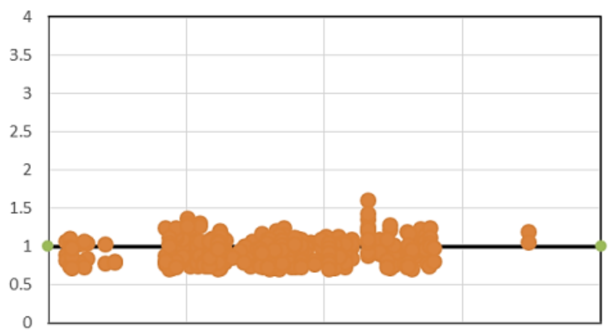


Fig. 6 Performance of proposed model

6. Conclusions

The scientific literature was used to compile a database with the results of 406 compression tests on plain and reinforced concrete that were performed between the years 2000 and 2020. Table 1 include pertinent information regarding the tests gathered in the database.

- A review of numerous earlier studies on the use of FRP laminates (jacketing) to strengthen non-circular concrete columns is done in this work. Additionally, the effectiveness of the stress-strain models for columns is evaluated using literature results. However, new equations are proposed in this paper, based on revisions to earlier equations, to forecast the compressive strength of non-circular concrete columns.
- To account for the differences in radius corner multivariate regression analysis has been used in this study to modify the factor k in the new proposed equation 24, which originally accounted for the efficiency of the strengthening procedure due to the column sectional geometrical features..
- When the proposed equation's results were compared to those of the literature, it was discovered that, in contrast to the previous equations, the proposed equation exhibits very good agreement with test results. The mean square error MSE (0.07) is less than the previous equations' value of (0.19).

7. References

Abbasnia, R. &. (2015). Experimental investigation and strength modeling of CFRP-confined concrete rectangular prisms under axial monotonic compression. Materials and Structures, 48(1), 485-500.

Abd El Fattah, A. (2018). New axial Stress-Strain model of square concrete columns confined with lateral steel and FRP. Composite Structures , 202, 731-751.

ACI Committee, 4. (2002). Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. American Concrete Institute: Farmington Hills, Mich.

Ahmed, S. K. (2018). Ultimate strength and axial strain of FRP strengthened circular concrete columns. Cogent Engineering, 5(1), 1501971.

Al-Salloum, Y. A. (2007). Influence of edge sharpness on the strength of square concrete columns confined with FRP composite laminates. Composites Part B: Engineering, 38(5-6), 640-650.

Campione, G. &. (2003). Strength and strain capacities of concrete compression members reinforced with FRP. Cement and Concrete Composites, 25(1), 31-41.

Cao, Y. G. (2021). Analysis-oriented stress-strain model for FRP-confined predamaged concrete. Journal of Building Engineering, 36, 102121.

Chaallal, O. S. (2003). Performance of axially loaded short rectangular columns strengthened with carbon fiber-reinforced polymer wrapping. Journal of Composites for Construction, 7(3), 200-208.

ChaiI, Y. H. (1991). Seismic retrofit of circular bridge columns for enhanced flexural performance. Structural Journal, 572-584.

Concrete-Society. (2002). Design guideline for strengthening concrete structures using. UK: Crowthorne, UK.

Eslami, A. &. (2013). Effect of FRP wrapping in seismic performance of RC buildings with and without special detailing–A case study. Composites Part B: Engineering, 45(1), 1265-1274.

Fam, A. Z. (2001). Confinement model for axially loaded concrete confined by circular fiber-reinforced polymer tubes. Structural Journal, 98(4), 451-461.

Fossetti, M. B. (2018). FRP-confined concrete columns: a new procedure for evaluating the performance of square and circular sections. Advances in Civil Engineering.

Haji, M. N. (2019). Experimental study on influence of proposed FRP-strengthening techniques on RC circular short columns considering different types of damage index. Composite Structures, 209, 112-128.

Han, Q. Y. (2020). Compressive behavior of large rupture strain (LRS) FRP-confined square concrete columns: experimental study and model evaluation. Materials and Structures, 53(4), 1-20.

Hany, N. F. (2015). Axial stress-strain model of CFRP-confined concrete under monotonic and cyclic loading. Journal of Composites for Construction, 19(6), 04015004.

Harajli, M. H. (2006). Stress-strain model for fiber-reinforced polymer jacketed concrete columns. Structural Journal, 103(5), 672-682.

Ilki, A. &. (2003). Compressive behaviour of carbon fibre composite jacketed concrete with circular and non-circular cross-sections. Journal of Earthquake Engineering, 7(03), 381-406.

Isleem, H. F. (2015). Cyclic axial behavior of rectangular RC columns strengthened with CFRP composites. Harbin Institute of Technology, Doctoral dissertation, Master's Thesis.

Jiang, T. &. (2007). Analysis-oriented stress–strain models for FRP–confined concrete. Engineering Structures, 29(11), 2968-2986.

Kumutha, R. V. (2007). Behaviour of reinforced concrete rectangular columns strengthened using GFRP. . Cement and concrete composites, 29(8), 609-615.

Lam, L. &. (2003). Design-oriented stress–strain model for FRP-confined concrete. Construction and building materials, 17(6-7), 471-489.

Lam, L. &. (2004). Ultimate condition of fiber reinforced polymer-confined concrete. Journal of Composites for Construction, 8(6), 539-548.

Lin, G. &. (2020). Advanced stress-strain model for FRP-confined concrete in square columns. Composites Part B: Engineering, 197, 108149.

Mander, J. B. (1988). Theoretical stress-strain model for confined concrete. Journal of structural engineering, 114(8), 1804-1826.

Masia, M. J. (2004). Size effects in axially loaded square-section concrete prisms strengthened using carbon fibre reinforced polymer wrapping. Canadian Journal of Civil Engineering, 31(1), 1-13.

MIYAUCHI, K. I. (2000). Strengthening effects of concrete column with carbon fiber sheet. Transactions of the Japan Concrete Institute, 21, 143-150.

Nisticò, N. &. (2013). RC square sections confined by FRP: Analytical prediction of peak strength. Composites Part B: Engineering, 45(1), 127-137.

Parvin, A. &. (2001). Behavior of FRP jacketed concrete columns under eccentric loading. Journal of Composites for construction, 5(3), 146-152.

Pellegrino, C. &. (2010). Analytical model for FRP confinement of concrete columns with and without internal steel reinforcement. Journal of Composites for Construction, 14(6), 693-705.
Pessiki, S. H. (2001). Axial behavior of reinforced concrete columns confined with FRP jackets. Journal of composites for Construction, 5(4), 237-245.
Pham, T. M. (2014). Stress prediction model for FRP confined rectangular concrete columns with rounded corners. Journal of Composites for Construction, 18(1), 04013019.
Priestley, M. N. (1994). Steel jacket retrofitting of reinforced concrete bridge columns for enhanced shear strength-part 1: Theoretical considerations and test design. Structural Journal, 394-405.
Punurai, W. H. (2013). Biaxially loaded RC slender columns strengthened by CFRP composite fabrics. Engineering Structures, 46, 311-321.
Rahai, A. &. (2014). Experimental investigation on rectangular RC columns strengthened with CFRP composites under axial load and biaxial bending. Composite Structures, 108, 538-546.
Realfonzo, R. &. (2011). Concrete confined by FRP systems: Confinement efficiency and design strength models. Composites Part B: Engineering, 42(4), 736-755.
Richart. (1929). Failure of plain and spirally reinforced concrete in compression. University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station, Bulletin 190.
Richart, F. E. (1928). A study of the failure of concrete under combined compressive stresses. College of Engineering. Engineering Experiment Station, Bulletin 185.
Rochette, P. &. (2000). Axial testing of rectangular column models confined with composites. Journal of composites for construction, 4(3), 129-136.
Rousakis, T. C. (2007). FRP-confined concrete members: Axial compression experiments and plasticity modelling. Engineering Structures, 29(7), 1343-1353.
Rousakis, T. C. (2008). Substandard reinforced concrete members subjected to compression: FRP confining effects. Materials and structures, 41(9), 1595-1611.
Saadatmanesh, H. E. (1994). Strength and ductility of concrete columns externally reinforced with fiber composite straps. Structural Journal, 91(4), 434-447.
Sadeghian, P. R. (2010). Experimental study of rectangular RC columns strengthened with CFRP composites under eccentric loading. Journal of Composites for Construction, 14(4), 443-450.
Samaan, M. M. (1998). Model of concrete confined by fiber composites. Journal of structural engineering, 124(9), 1025-1031.
Shehata, I. A. (2002). Strength of short concrete columns confined with CFRP sheets. Materials and Structures, 35(1), 50-58.
Sheikh, S. A. (1980). Strength and ductility of tied concrete columns. Journal of the structural division, 106(5), 1079-1102.
Siddika. (2019). Strengthening of reinforced concrete beams by using fiber-reinforced polymer composites: A review. Journal of Building Engineering, 25, 100798.
Spoelstra, M. R., & Monti, G. (1999). FRP-confined concrete model. Journal of composites for construction, 3(3), 143-150.
Standard, C. S. A. (2002). Design and construction of building components with fibre-reinforced polymers. Canadial Standards Association.
Suter, R. &. (2001). Confinement of concrete columns with FRP sheets. In Proc., 5th Int. Conf. on Fibre Reinforced Plastics for Reinforced Concrete Structures, pp. 793-802.
Tao, Z. Y. (2008). Compressive behaviour of CFRP-confined rectangular concrete columns. Magazine of Concrete Research, 60(10), 735-745.
TEC. (2006). Turkish Earthquake Code for Buildings. Ankara, Turkey: Ministry of Public.
Teng, J. G. (2004). Behavior and modeling of fiber reinforced polymer-confined concrete. Journal of structural engineering, 130(11), 1713-1723.
Toutanji, H. (1999). Stress-strain characteristics of concrete columns externally confined with advanced fiber composite sheets. Materials Journal, 96(3), 397-404.
Wang, L. M. (2008). Effect of corner radius on the performance of CFRP-confined square concrete columns. Test. Engineering structures, 30(2), 493-505.
Wang, Z. W. (2012). CFRP-confined square RC columns. I: Experimental investigation. Journal of Composites for Construction, 16(2), 150-160.

Waryosh, W. A.-m. (2012). Experimental Study of Reinforced concrete Columns Strengthened with CFRP under Eccentric Loading. Journal of Engineering and Sustainable Development, 16(3).

Wei, Y. Y. (2012). Unified stress–strain model of concrete for FRP-confined columns. Construction and Building Materials, 26(1), 381-392.

Wu, G. W. (2007). Design-oriented stress–strain model for concrete prisms confined with FRP composites. Construction and Building Materials, 21(5), 1107-1121.

Wu, Y. F. (2010). Effect of cross-sectional aspect ratio on the strength of CFRP-confined rectangular concrete columns. Engineering Structures, 32(1), 32-45.

Xiao, Y. &. (2000). Compressive behavior of concrete confined by carbon fiber composite jackets. Journal of materials in civil engineering, 12(2), 139-146.

Xing, Q. S. (1987). Experimental study on the complete stress–strain curve of confined concrete. Proceedings of national conference on application and theory of common and confined concrete, (pp. (pp. 81-7). YinTai, China.

Youssef, M. N. (2007). Stress–strain model for concrete confined by FRP composites. Composites Part B: Engineering, 38(5-6), 614-628.

Zhao, M. &. ((2004). Bond properties of FRP fabrics and concrete joints.13th world conference on earthquake engineering, (p. Paper (No. 35)). Vancouver, BC, Canada.

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