Steel and Composite Structures, *Vol. 29, No. 4 (2018) 465-481*
DOI: https://doi.org/10.12989/scs.2018.29.4.465

Ultimate strength and strain models proposed for CFRP confined concrete cylinders

Mohammed Berradia * and Amar Kassoul [a]

Department of Civil Engineering, Laboratory of Structures, Geotechnics and Risks (LSGR), Hassiba Benbouali University of Chlef, Algeria, BP 151, Hay Essalam, UHB Chlef, Chlef (02000), Algeria

(*Received March 27, 2018, Revised October 27 2018, Accepted November 8, 2018*)

Abstract. The use of external carbon-fiber-reinforced polymer (CFRP) laminates is one of the most effective techniques existing for the confinement of circular concrete specimens. Currently, several researches have been made to develop models for predicting the ultimate conditions of this type of confinement. As most of the major existing models were developed based on limited experimental database. This paper presents the development of new confinement ultimate conditions, strength and strain models, for concrete cylinders confined with CFRP composites based on a statistical analysis of a large existing experimental database of 310 cylindrical concrete specimens wrapped with CFRP. The database is used to evaluate the performance of the proposed and major existing strength and strain models. Based on the two different statistical indices, the coefficient of determination (R^2) and the Root Mean Square Error (RMSE), the two proposed confinement ultimate conditions presents a good performance compared to the major existing models except the models of Lam and Teng (2003) and Youssef *et al*. (2007) which have relatively similar performance to the proposed models.

Keywords: concrete cylinders; CFRP; strength model; strain model; confinement

1. Introduction

The need for strengthening deficient existing reinforced concrete (RC) structures is suggested for many reasons. For years, engineers have been studying ways to retrofit or strengthen existing deficient RC columns to meet new code requirements, especially in earthquake prone areas (Youssef *et al*. 2007). Various methods for strengthening and rehabilitation of RC structures have been developed in the past several decades (Nam *et al*. 2016, Lezgy-Nazargah *et al*. 2018). Recently, the use of externally fiber-reinforced polymer (FRP) reinforcement for the strengthening or repair of reinforced concrete structures has become a popular technology (Fanggi and Ozbakkaloglu 2015). The FRP composites have been used successfully for rehabilitation and repair of deficient reinforced-concrete structures such as buildings, bridges, etc (Morsy and Mahmoud 2013). One of the important applications of the FRP strengthening technology is on the enhancement of RC column load-carrying capacity through the provision of confining FRP warps (Ozbakkaloglu 2013, Mahdi Razavi and Zahiraniza 2018). The column wrapping technique is particularly effective for circular columns as the strength and ductility of concrete in circular section can be substantially increased through lateral confinement. FRP is characterized by high strength fibers embedded in polymer resin (Lu *et al*. 2015). FRP offers such advantages as high strength and stiffness, low density, chemical stability, high durability, and ease of installation. The most common type of FRP in the industry is made with carbon, aramid or glass fibers (Zhang *et al*. 2016). In this context, several studies have been conducted on the compressive behavior of concrete cylinder confined externally with carbon fiber reinforced polymer (CFRP). Consequently, several confinement models for the ultimate condition of confined concrete under axial compression loadings have been proposed (Sadeghian and Fam 2015). The ultimate condition of an FRP-confined concrete refers to the axial compressive strength f_{cu} and the ultimate axial strain ε_{cu}, as shown in Fig. 1. Fardis and Khalili (1982) are the first who studies the behavior of FRP confined concrete. They adopted the two ultimate compressive strength models f_{cu} from Richart *et al*. (1929), Newman and Newman (1971) and proposed their own ultimate strain model ε_{cu}. Recently, the use of externally wrapped CFRP has become increasingly popular for civil structure applications, including wrapping the concrete columns. Accordingly, several confinement strength and strain models are developed by various researchers such as Lam and Teng (2003), Ilki *et al*. (2004), Youssef *et al*. (2007), Jiang and Teng (2007), Teng *et al*. (2009), Benzaid *et al*. (2010), Fahmy and Wu (2010) and Ozbakkaloglu and Lim (2013). However, the disadvantage of the most of these existing models proposed based on limited database. This paper presents the development of new confinement ultimate conditions, strength and strain models, for concrete cylinders confined with CFRP composites based on a large existing experimental database of 310 cylindrical concrete specimens wrapped with CFRP. In the first, the authors evaluate by a statistical analysis the performance of existing

∗Corresponding author, Ph.D.,
E-mail: mberradia125@yahoo.fr
[a] Professor, E-mail: amarkassoul@gmail.com

http://www.techno-press.org/?journal=scs&subpage=6 ISSN: 1229-9367 (Print), 1598-6233 (Online)

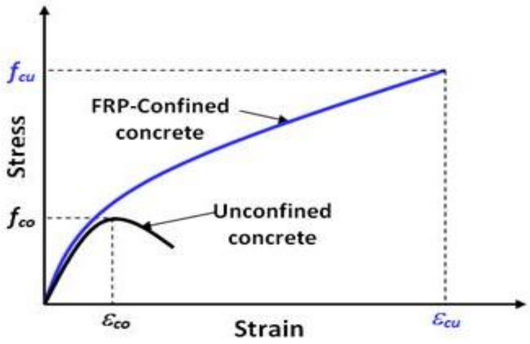


Fig. 1 Model for FRP-confined concrete

strength and strain models for CFRP-confined concrete using a 310 experimental database on cylindrical concrete specimens wrapped with CFRP composites. Then, they used a regression analysis on the same 310 existing experimental database to develop a new tow empirical ultimate confinement conditions, and evaluated it with the 310 experimental databases.

2. Experimental database

2.1 Selection criteria of database

Several experimental studies were conducted on CFRP confined concrete under axial compressive loading. In the present study, a database containing the test results of 310 cylindrical concrete specimens wrapped with CFRP published between 1992 and 2013 was compiled from the literature. The results included in the database were chosen by using a set of carefully considered selection criteria to ensure reliability and consistency of the database. This required the use of a total of four selection criteria listed in this section in the order of importance (as established by the number of data set exclusions resulted by a given criterion). Assessment by using these criteria resulted in a final database of CFRP-confined concrete cylinders of 310 data sets from 28 sources. All the test results included in this database, listed in Table 1, met the following requirements:

(1) Only concrete cylinders confined with CFRP laminates were selected;
(2) Only the specimens that were confined with continuous confinement were selected. Specimens with partial wrapping (i.e., FRP strips) were ignored;
(3) Only specimens with unconfined concrete compressive strengths (f_{co}) comprise between 19.7 and 169.7MPa were selected;
(4) Only specimens with height-to-diameter (H/D) ratio equal to two were included from the database.

2.2 Construction of the database

The database consists of the following information for each specimen: the geometric properties of cylindrical specimens (diameter, D, and height, H, and height-to-diameter (H/D) ratio); the concrete properties (unconfined concrete strength (f_{co}) and corresponding strain (ε_{co})); the materials properties of the CFRP (elastic modulus (E_{frp}), total thickness (t_{frp}), and hoop rupture strain ($\varepsilon_{h,rup}$) at ultimate). This database presents also the two ultimate conditions, the ultimate compressive strength (f_{cu}) and corresponding strain (ε_{cu}) of confined concrete.

3. Evaluation of existing models

3.1 Statistical analyses

The performance of existing confinement models for CFRP-confined concrete cylinders using the experimental database are presented in Table 1. In all evaluations, the values predicted by strength and strain models are compared with experimental values. Two indices, namely the coefficient of determination (R^2) and the Root Mean Square Error (RMSE), are used for the evaluations (Sadeghian and Fam 2015). R^2 is the square of the correlation coefficient which is defined to determine the relationship between predicted and experimental values as

$$R^2(X,Y)=\left(\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}\right)^2 \quad (1)$$

Where X and Y are the vector of experimental and predicted values, respectively; x and y are experimental and predicted values, respectively; and $\bar{x}$ and $\bar{y}$ are the averages of experimental and predicted values, respectively. R^2 ranges from zero to one, with one indicating a perfect correlation between predicted and experimental values and zero indicating no correlation. The important point is that R^2 = 1 does not guarantee a perfect prediction. It only shows that there is a linear correlation between predicted and experimental values. Thus, R^2 is not the most proper index for this kind of evaluation. Instead, another statistical index, RMSE, is implemented to evaluate the accuracy of predictions. RMSE is the square root of the variance of the residuals which is defined as the following

$$RMSE=\sqrt{\frac{\sum(x-y)^2}{n}} \quad (2)$$

Where n is the number of data points. RMSE indicates how close the predicted values (y) to the experimental values (x). While R^2 is a relative measure of fit, RMSE is an absolute measure of fit without any upper limit. Lower values of RMSE indicate a better fit, with zero indicating a perfect prediction that means all data points are located on a 45-degree line (R^2 = 1). For a hypothetical case, if all data points were located on a 10-degree line which is clearly a poor prediction, R^2 would be equal to one whereas RMSE would be able to show the poor prediction. Indeed, R^2 is not intended to evaluate ‘‘experimental vs. analytical’’ data along the 45-degrees line. For this reason, preciously the authors choose RMSE index in this work, which is more appropriate than R^2 in the context of the current study.

Table 1 Experimental database

N°	Authors and years	D (mm)	H (mm)	H/D	f_{co} (Mpa)	ε_{co} (‰)	E_{frp} (GPa)	t_{frp} (mm)	$\varepsilon_{h, rup}$ (‰)	f_{cu} (MPa)	f_{cu}/f_{co}	ε_{cu} (‰)	$\varepsilon_{cu}/\varepsilon_{co}$
1	Harmon and Slattery (1992)	51	102	2	41.0	2.4	235	0.09	11.3	86.0	2.10	11.5	4.79
2		51	102	2	41.0	2.4	235	0.18	10.0	120.5	2.94	15.7	6.54
3		51	102	2	41.0	2.4	235	0.34	7.5	158.4	3.86	25.0	10.42
4		51	102	2	103.0	3.0	235	0.18	2.0	131.1	1.27	11.0	3.67
5		51	102	2	103.0	3.0	235	0.34	7.3	193.2	1.88	20.5	6.83
6		51	102	2	103.0	3.0	235	0.69	5.5	303.6	2.95	34.5	11.50
7	Howie and Karbhari (1995)	152	304	2	42.5	2.4	227	0.33	4.5	44.9	1.06	11.0	4.58
8		152	304	2	42.5	2.4	227	0.66	5.5	59.7	1.40	13.5	5.63
9		152	304	2	42.5	2.4	227	0.99	5.5	77.7	1.83	21.0	8.75
10		152	304	2	42.5	2.4	227	1.32	3.4	89.5	2.11	22.9	9.54
11	Picher *et al*. (1996)	153	305	2	39.7	2.4	83	0.60	8.4	56.0	1.41	10.7	4.46
12	Watanable *et al*. (1997)	100	200	2	30.2	2.2	612	0.14	2.3	41.7	1.38	5.7	2.59
13		100	200	2	30.2	2.2	612	0.28	2.2	56.0	1.85	8.8	4.00
14		100	200	2	30.2	2.2	612	0.42	2.2	63.3	2.10	13.0	5.91
15		100	200	2	30.2	2.2	225	0.17	9.4	46.6	1.54	15.1	6.86
16		100	200	2	30.2	2.2	225	0.50	8.2	87.2	2.89	31.1	14.14
17		100	200	2	30.2	2.2	225	0.67	7.6	104.6	3.46	41.5	18.86
18	Kono *et al*. (1998)	100	200	2	34.3	2.3	235	0.17	8.8	61.2	1.78	9.5	4.13
19		100	200	2	32.3	2.2	235	0.17	7.9	59.2	1.83	10.7	4.86
20		100	200	2	32.3	2.2	235	0.33	8.9	80.2	2.48	17.5	7.95
21		100	200	2	32.3	2.2	235	0.50	7.2	88.5	2.74	16.2	7.36
22		100	200	2	34.8	2.3	235	0.17	8.0	54.7	1.57	9.9	4.30
23		100	200	2	34.8	2.3	235	0.33	7.7	82.1	2.36	20.6	8.96
24		100	200	2	34.8	2.3	235	0.50	8.5	106.7	3.07	24.3	10.57
25	Matthys *et al*. (1999)	150	300	2	34.9	2.3	420	0.24	1.9	41.3	1.18	4.0	1.74
26		150	300	2	34.9	2.3	420	0.24	1.8	40.7	1.17	3.6	1.57
27		150	300	2	34.9	2.3	200	0.12	11.5	44.3	1.27	8.5	3.70
28		150	300	2	34.9	2.3	200	0.12	10.8	42.2	1.21	7.2	3.13
29	Rochette and Labossiere (2000)	100	200	2	42.0	2.4	83	0.60	8.9	73.5	1.75	16.5	6.88
30		100	200	2	42.0	2.4	83	0.60	9.5	73.5	1.75	15.7	6.54
31		100	200	2	42.0	2.4	83	0.60	8.0	67.6	1.61	13.5	5.63
32	Xiao and Wu (2000)	152	305	2	33.7	2.3	105	0.38	8.4	47.9	1.42	12.0	5.22
33		152	305	2	33.7	2.3	105	0.38	11.5	49.7	1.47	14.0	6.09
34		152	305	2	33.7	2.3	105	0.38	8.7	49.4	1.47	12.4	5.39
35		152	305	2	33.7	2.3	105	0.76	9.1	64.6	1.92	16.5	7.17
36		152	305	2	33.7	2.3	105	0.76	10.0	75.2	2.23	22.5	9.78
37		152	305	2	33.7	2.3	105	0.76	10.0	71.8	2.13	21.6	9.39
38		152	305	2	33.7	2.3	105	1.14	8.2	82.9	2.46	24.5	10.65
39		152	305	2	33.7	2.3	105	1.14	9.0	95.4	2.83	30.3	13.17
40		152	305	2	43.8	2.4	105	0.38	8.1	54.8	1.25	9.8	4.08
41		152	305	2	43.8	2.4	105	0.38	7.6	52.1	1.19	4.7	1.96
42		152	305	2	43.8	2.4	105	0.38	2.8	48.7	1.11	3.7	1.54
43		152	305	2	43.8	2.4	105	0.76	9.2	84.0	1.92	15.7	6.54
44		152	305	2	43.8	2.4	105	0.76	10.0	79.2	1.81	13.7	5.71
45		152	305	2	43.8	2.4	105	0.76	10.1	85.0	1.94	16.6	6.92

Table 1 Continued

N°	Authors and years	D (mm)	H (mm)	H/D	f_{co} (Mpa)	ε_{co} (‰)	E_{frp} (GPa)	t_{frp} (mm)	$\varepsilon_{h, rup}$ (‰)	f_{cu} (MPa)	f_{cu}/f_{co}	ε_{cu} (‰)	$\varepsilon_{cu}/\varepsilon_{co}$
46	Xiao and Wu (2000)	152	305	2	43.8	2.4	105	1.14	7.9	96.5	2.20	17.4	7.25
47		152	305	2	43.8	2.4	105	1.14	7.1	92.6	2.11	16.8	7.00
48		152	305	2	43.8	2.4	105	1.14	8.4	94.0	2.15	17.5	7.29
49		152	305	2	55.2	2.6	105	0.38	7.0	57.9	1.05	6.9	2.65
50		152	305	2	55.2	2.6	105	0.38	6.2	62.9	1.14	4.8	1.85
51		152	305	2	55.2	2.6	105	0.38	1.9	58.1	1.05	4.9	1.88
52		152	305	2	55.2	2.6	106	0.76	7.4	55.2	1.00	12.1	4.65
53		152	305	2	55.2	2.6	105	0.76	8.3	77.6	1.41	8.1	3.12
54		152	305	2	55.2	2.6	105	1.14	7.6	106.5	1.93	14.3	5.50
55		152	305	2	55.2	2.6	105	1.14	8.5	108.0	1.96	14.5	5.58
56		152	305	2	55.2	2.6	105	1.14	7.0	103.3	1.87	11.8	4.54
57	Shahawy *et al*. (2000)	152	305	2	19.7	2.0	207	0.5	7.4	33.8	1.72	15.9	7.95
58		152	305	2	19.7	2.0	207	1	6.3	46.4	2.36	22.1	11.05
59		152	305	2	19.7	2.0	207	1.5	5.7	62.6	3.18	25.8	12.90
60		152	305	2	19.7	2.0	207	2	5.9	75.7	3.84	35.6	17.80
61		152	305	2	49.0	2.5	207	0.5	6.2	59.1	1.21	6.2	2.48
62		152	305	2	49.0	2.5	207	1	6.2	76.5	1.56	9.7	3.88
63		152	305	2	49.0	2.5	207	1.5	6.3	98.8	2.02	12.6	5.04
64		152	305	2	49.0	2.5	207	2	6.2	112.7	2.30	19.0	7.60
65	Aire *et al*. (2001)	150	300	2	42.0	2.4	240	0.12	9.5	46.0	1.10	11.0	4.58
66		150	300	2	42.0	2.4	240	0.35	10.5	77.0	1.83	22.6	9.42
67	Micelli *et al*. (2001)	152	305	2	26.2	2.1	38	1.00	8.1	50.6	1.93	14.4	6.86
68		152	305	2	26.2	2.1	38	2.00	7.2	64.0	2.44	16.5	7.86
69	De Lorenzis *et al*. (2002)	120	240	2	43.0	2.4	91	0.30	7.0	58.5	1.36	11.6	4.83
70		120	240	2	43.0	2.4	91	0.30	8.0	65.6	1.53	9.5	3.96
71		150	300	2	38.0	2.3	91	0.45	8.0	62.0	1.63	9.5	4.13
72		150	300	2	38.0	2.3	91	0.45	8.0	67.3	1.77	13.5	5.87
73	Shehata *et al*. (2002)	150	300	2	29.8	2.2	235	0.17	12.3	57.0	1.91	12.3	5.59
74		150	300	2	29.8	2.2	235	0.33	11.9	72.1	2.42	17.4	7.91
75	Youssef (2003)	406	813	2	29.4	2.2	105	1.17	8.2	45.9	1.56	6.3	2.86
76		406	813	2	29.4	2.2	105	2.34	12.1	64.8	2.20	11.6	5.27
77		406	813	2	29.4	2.2	105	3.51	12.0	85.9	2.92	15.6	7.09
78		406	813	2	29.4	2.2	105	5.84	12.4	126.4	4.30	28.4	12.91
79		153	305	2	44.1	2.4	105	0.58	10.3	86.1	1.95	19.0	7.92
80		153	305	2	44.1	2.4	105	1.17	12.6	96.6	2.19	19.9	8.29
81		153	305	2	44.1	2.4	105	1.75	9.7	130.7	2.96	28.3	11.79
82		406	813	2	45.6	2.4	105	2.34	8.9	79.5	1.74	16.8	7.00
83		406	813	2	38.3	2.3	105	2.34	9.6	73.1	1.91	10.5	4.57
84	Carey and Harries (2003, 2005)	152	305	2	33.5	2.3	250	0.20	10.7	47.0	1.40	9.7	4.22
85		152	305	2	33.5	2.3	250	0.20	11.4	47.6	1.42	8.8	3.83
86	Bullo (2003)	150	300	2	32.5	2.2	390	0.17	4.7	52.6	1.62	8.3	3.77
87		150	300	2	32.5	2.2	390	0.17	5.2	56.6	1.74	9.3	4.23
88		150	300	2	32.5	2.2	390	0.17	4.2	61.1	1.88	8.3	3.77
89		150	300	2	32.5	2.2	390	0.50	6.4	97.3	2.99	18.2	8.27
90		150	300	2	32.5	2.2	390	0.50	4.4	83.8	2.58	12.7	5.77

Table 1 Continued

N°	Authors and years	D	H	H/D	f_{co}	ε_{co}	E_{frp}	t_{frp}	$\varepsilon_{h, rup}$	f_{cu}	f_{cu}/f_{co}	ε_{cu}	$\varepsilon_{cu}/\varepsilon_{co}$
		(mm)	(mm)		(Mpa)	(‰)	(GPa)	(mm)	(‰)	(MPa)		(‰)	
91	Bullo (2003)	150	300	2	32.5	2.2	390	0.50	5.4	100.2	3.08	16.9	7.68
92		152	305	2	35.9	2.3	259	0.17	11.5	50.4	1.40	12.7	5.52
93		152	305	2	35.9	2.3	259	0.17	9.7	47.2	1.31	11.1	4.83
94		152	305	2	35.9	2.3	259	0.17	9.8	53.2	1.48	12.9	5.61
95		152	305	2	35.9	2.3	259	0.33	9.9	68.7	1.91	16.8	7.30
96		152	305	2	35.9	2.3	259	0.33	10.0	69.9	1.95	19.6	8.52
97	Lam and Teng (2004)	152	305	2	34.3	2.3	259	0.33	9.5	71.6	2.09	18.5	8.04
98		152	305	2	34.3	2.3	259	0.5	8.0	82.6	2.41	20.5	8.91
99		152	305	2	34.3	2.3	259	0.5	8.8	90.4	2.64	24.1	10.48
100		152	305	2	34.3	2.3	259	0.5	9.7	97.3	2.84	25.2	10.96
101		152	305	2	34.3	2.3	259	0.17	9.1	50.3	1.47	10.2	4.43
102		152	305	2	34.3	2.3	259	0.17	8.9	50.0	1.46	10.8	4.70
103		152	305	2	34.3	2.3	259	0.17	9.3	56.7	1.65	11.7	5.09
104		150	300	2	25.2	2.1	377	0.17	7.0	41.6	1.65	14.4	6.86
105		150	300	2	25.2	2.1	377	0.17	5.8	38.8	1.54	12.1	5.76
106		150	300	2	25.2	2.1	377	0.17	6.4	44.1	1.75	15.3	7.29
107		150	300	2	25.2	2.1	377	0.34	6.4	60.1	2.38	18.8	8.95
108		150	300	2	25.2	2.1	377	0.34	5.5	55.9	2.22	21.0	10.00
109		150	300	2	25.2	2.1	377	0.34	5.7	61.6	2.44	20.8	9.90
110		150	300	2	25.2	2.1	377	0.51	4.5	67.0	2.66	24.5	11.67
111		150	300	2	25.2	2.1	377	0.51	3.7	67.3	2.67	24.3	11.57
112		150	300	2	25.2	2.1	377	0.51	4.4	70.0	2.78	24.4	11.62
113		150	300	2	51.8	2.5	377	0.17	5.4	78.7	1.52	7.5	3.00
114	Rousakis and Tepfers (2004)	150	300	2	51.8	2.5	377	0.17	4.0	72.8	1.41	6.6	2.64
115		150	300	2	51.8	2.5	377	0.17	5.2	79.2	1.53	6.8	2.72
116		150	300	2	51.8	2.5	377	0.34	5.5	95.4	1.84	10.5	4.20
117		150	300	2	51.8	2.5	377	0.34	3.6	90.7	1.75	10.0	4.00
118		150	300	2	51.8	2.5	377	0.34	5.1	90.3	1.74	10.2	4.08
119		150	300	2	51.8	2.5	377	0.51	4.4	110.5	2.13	12.9	5.16
120		150	300	2	51.8	2.5	377	0.51	3.1	103.6	2.00	12.0	4.80
121		150	300	2	51.8	2.5	377	0.51	5.6	117.2	2.26	15.3	6.12
122		150	300	2	51.8	2.5	377	0.85	2.9	112.7	2.18	15.9	6.36
123		150	300	2	51.8	2.5	377	0.85	3.6	126.7	2.45	16.1	6.44
124		150	300	2	51.8	2.5	377	0.85	5.3	137.9	2.66	18.1	7.24
125		320	2	40.1	2.4	230	0.17	8.5	54.7	1.36	6.2	2.58	7.76
126		320	2	40.1	2.4	230	0.17	10.4	51.8	1.29	6.4	2.67	4.43
127		160	320	2	25.0	2.1	230	0.17	9.6	45.8	1.83	16.7	7.95
128		160	320	2	25.0	2.1	230	0.33	9.0	56.7	2.27	17.3	8.24
129		160	320	2	25.0	2.1	230	0.33	9.1	55.2	2.21	15.8	7.52
130	Berthet *et al*. (2005)	160	320	2	25.0	2.1	230	0.33	9.1	56.1	2.24	16.8	8.00
131		160	320	2	40.1	2.4	230	0.11	10.2	49.8	1.24	5.5	2.29
132		160	320	2	40.1	2.4	230	0.11	9.5	50.8	1.27	6.6	2.75
133		160	320	2	40.1	2.4	230	0.11	12.0	48.8	1.22	6.1	2.54
134		160	320	2	40.1	2.4	230	0.17	8.8	53.7	1.34	6.6	2.75
135		160	320	2	40.1	2.4	230	0.17	8.5	54.7	1.36	6.2	2.58

Table 1 Continued

N°	Authors and years	D (mm)	H (mm)	H/D	f_{co} (Mpa)	ε_{co} (‰)	E_{frp} (GPa)	t_{frp} (mm)	$\varepsilon_{h, rup}$ (‰)	f_{cu} (MPa)	f_{cu}/f_{co}	ε_{cu} (‰)	$\varepsilon_{cu}/\varepsilon_{co}$
136	Berthet *et al*. (2005)	160	320	2	40.1	2.4	230	0.17	10.4	51.8	1.29	6.4	2.67
137		160	320	2	40.1	2.4	230	0.22	7.9	59.7	1.49	6.0	2.50
138		160	320	2	40.1	2.4	230	0.22	8.3	60.7	1.51	6.9	2.88
139		160	320	2	40.1	2.4	230	0.22	8.1	60.2	1.50	7.3	3.04
140		160	320	2	40.1	2.4	230	0.44	9.2	91.6	2.28	14.4	6.00
141		160	320	2	40.1	2.4	230	0.44	9.7	89.6	2.23	13.6	5.67
142		160	320	2	40.1	2.4	230	0.44	8.9	86.6	2.16	11.7	4.88
143		160	320	2	40.1	2.4	230	0.99	9.9	142.4	3.55	24.6	10.25
144		160	320	2	40.1	2.4	230	0.99	10.0	140.4	3.50	23.9	9.96
145		160	320	2	40.1	2.4	230	1.32	10.0	166.3	4.15	27.0	11.25
146		160	320	2	52.0	2.5	230	0.33	9.3	82.6	1.59	8.3	3.32
147		160	320	2	52.0	2.5	230	0.33	8.7	82.8	1.59	7.0	2.80
148		160	320	2	52.0	2.5	230	0.33	8.9	82.3	1.58	7.7	3.08
149		160	320	2	52.0	2.5	230	0.66	6.7	108.1	2.08	11.4	4.56
150		160	320	2	52.0	2.5	230	0.66	8.7	112.0	2.15	11.2	4.48
151		160	320	2	52.0	2.5	230	0.66	8.8	107.9	2.08	11.2	4.48
152		70	140	2	112.6	3.1	230	0.33	7.1	141.1	1.25	4.5	1.45
153		70	140	2	112.6	3.1	230	0.33	7.4	143.1	1.27	4.9	1.58
154		70	140	2	112.6	3.1	230	0.82	7.5	189.5	1.68	7.2	2.32
155		70	140	2	112.6	3.1	230	0.82	7.3	187.9	1.67	7.0	2.26
156		70	140	2	169.7	3.4	230	0.33	4.6	186.4	1.10	6.7	1.97
157		70	140	2	169.7	3.4	230	0.99	8.0	296.4	1.75	10.2	3.00
158	Modarelli *et al*. (2005)	150	300	2	28.0	2.2	221	0.17	15.3	55.3	1.98	9.0	4.09
159		150	300	2	38.0	2.3	221	0.17	13.2	62.7	1.65	4.8	2.09
160	Lam *et al*. (2006)	152	305	2	41.1	2.4	250	0.17	8.1	52.6	1.28	9.0	3.75
161		152	305	2	41.1	2.4	250	0.17	10.8	57.0	1.39	12.1	5.04
162		152	305	2	41.1	2.4	250	0.17	10.7	55.4	1.35	11.1	4.63
163		152	305	2	41.1	2.4	250	0.17	13.2	60.2	1.46	13.4	5.58
164		152	305	2	41.1	2.4	250	0.17	10.3	56.8	1.38	11.7	4.88
165		152	305	2	41.1	2.4	250	0.17	11.3	56.5	1.37	12.0	5.00
166		152	305	2	38.9	2.3	250	0.33	10.6	76.8	1.97	19.1	8.30
167		152	305	2	38.9	2.3	250	0.33	11.3	79.1	2.03	20.8	9.04
168		152	305	2	38.9	2.3	250	0.33	7.9	65.8	1.69	12.5	5.43
169		152	305	2	38.9	2.3	250	0.33	12.2	81.5	2.10	24.4	10.61
170		152	305	2	38.9	2.3	250	0.33	10.8	78.2	2.01	18.9	8.22
171		152	305	2	38.9	2.3	250	0.33	12.2	85.6	2.20	23.4	10.17
172	Jiang and Teng (2007)	152	305	2	38.0	2.3	241	0.68	9.8	110.1	2.90	25.5	11.09
173		152	305	2	38.0	2.3	241	0.68	9.7	107.4	2.83	26.1	11.35
174		152	305	2	38.0	2.3	241	1.02	8.9	129.0	3.39	27.9	12.13
175		152	305	2	38.0	2.3	241	1.02	9.3	135.7	3.57	30.8	13.39
176		152	305	2	38.0	2.3	241	1.36	8.7	161.3	4.24	37.0	16.09
177		152	305	2	38.0	2.3	241	1.36	8.8	158.5	4.17	35.4	15.39
178		152	305	2	37.7	2.3	260	0.11	9.4	48.5	1.29	9.0	3.91
179		152	305	2	37.7	2.3	260	0.11	10.9	50.3	1.33	9.1	3.96
180		152	305	2	44.2	2.4	260	0.11	7.3	48.1	1.09	6.9	2.88

Table 1 Continued

N°	Authors and years	D (mm)	H (mm)	H/D	f_{co} (Mpa)	ε_{co} (‰)	E_{frp} (GPa)	t_{frp} (mm)	$\varepsilon_{h, rup}$ (‰)	f_{cu} (MPa)	f_{cu}/f_{co}	ε_{cu} (‰)	$\varepsilon_{cu}/\varepsilon_{co}$
181	Jiang and Teng (2007)	152	305	2	44.2	2.4	260	0.11	9.7	51.1	1.16	8.9	3.71
182		152	305	2	44.2	2.4	260	0.22	11.8	65.7	1.49	13.0	5.42
183		152	305	2	44.2	2.4	260	0.22	9.4	62.9	1.42	10.3	4.29
184		152	305	2	47.6	2.5	260	0.33	9.0	82.7	1.74	13.0	5.20
185		152	305	2	47.6	2.5	260	0.33	11.3	85.5	1.80	19.4	7.76
186		152	305	2	47.6	2.5	260	0.33	10.6	85.5	1.80	18.2	7.28
187	Valdmanis *et al*. (2007)	150	300	2	61.6	1.8	234	0.17	1.8	80.5	1.31	2.7	1.5
188		150	300	2	61.6	1.8	234	0.34	1.6	95.3	1.54	3.2	1.78
189		150	300	2	61.6	1.8	234	0.51	3.2	104.9	1.70	3.6	2.00
190	Wang and Wu (2008)	150	300	2	30.9	2.2	219	0.17	11.1	55.8	1.81	25.0	11.36
191		150	300	2	52.1	2.5	219	0.17	11.1	67.9	1.30	33.6	13.44
192		150	300	2	52.1	2.5	197	0.33	14.4	99.3	1.91	20.0	8.00
193	Cui and Sheikh (2010)	152	305	2	48.1	2.5	85	1.00	10.5	80.9	1.68	15.1	6.04
194		152	305	2	48.1	2.5	85	1.00	11.2	86.6	1.80	15.3	6.12
195		152	305	2	48.1	2.5	85	2.00	9.7	109.4	2.27	20.1	8.04
196		152	305	2	48.1	2.5	85	2.00	12.2	126.7	2.63	26.6	10.64
197		152	305	2	48.1	2.5	85	3.00	11.6	162.7	3.38	30.9	12.36
198		152	305	2	48.1	2.5	85	3.00	10.4	153.6	3.19	28.9	11.56
199		152	305	2	48.1	2.5	85	1.00	10.5	84.2	1.75	15.5	6.2
200		152	305	2	48.1	2.5	85	1.00	12.2	87.9	1.83	16.9	6.76
201		152	305	2	48.1	2.5	85	2.00	10.6	123.3	2.56	23.7	9.48
202		152	305	2	48.1	2.5	85	2.00	8.9	108.2	2.25	19.3	7.72
203		152	305	2	48.1	2.5	85	3.00	10.9	156.5	3.25	31.3	12.52
204		152	305	2	48.1	2.5	85	3.00	11.4	157.0	3.26	28.4	11.36
205		152	305	2	79.9	2.8	85	1.00	11.0	90.9	1.14	5.3	1.89
206		152	305	2	79.9	2.8	85	1.00	9.2	105.3	1.32	7.4	2.64
207		152	305	2	79.9	2.8	85	2.00	9.9	142.1	1.78	11.3	4.04
208		152	305	2	79.9	2.8	85	2.00	11.0	140.8	1.76	9.7	3.46
209		152	305	2	79.9	2.8	85	3.00	9.8	172.9	2.16	14.8	5.29
210		152	305	2	79.9	2.8	85	3.00	11.1	181.8	2.28	14.7	5.25
211		152	305	2	110.6	3.0	85	1.00	10.3	107.3	0.97	5.2	1.73
212		152	305	2	110.6	3.0	85	1.00	8.6	116.6	1.05	5.5	1.83
213		152	305	2	110.6	3.0	85	3.00	8.7	198.4	1.79	8.4	2.80
214		152	305	2	110.6	3.0	85	3.00	7.5	182.3	1.65	7.3	2.43
215		152	305	2	45.6	2.4	241	0.11	16.8	57.7	1.27	12.1	5.04
216		152	305	2	45.6	2.4	241	0.11	16.0	55.4	1.21	13.1	5.46
217		152	305	2	45.6	2.4	241	0.22	16.2	78.0	1.71	19.7	8.21
218		152	305	2	45.6	2.4	241	0.22	18.0	86.8	1.90	21.4	8.92
219		152	305	2	45.6	2.4	241	0.33	17.9	106.5	2.34	29.0	12.08
220		152	305	2	45.6	2.4	241	0.33	18.0	106.0	2.32	28.3	11.79
221		152	305	2	45.6	2.4	241	0.11	15.7	56.3	1.23	12.3	5.13
222		152	305	2	45.6	2.4	241	0.11	15.8	58.8	1.29	11.9	4.96
223		152	305	2	45.6	2.4	241	0.22	10.3	81.9	1.80	18.7	7.79
224		152	305	2	45.6	2.4	241	0.22	11.4	82.8	1.82	21.7	9.04

Table 1 Continued

N°	Authors and years	D (mm)	H (mm)	H/D	f_{co} (Mpa)	ε_{co} (‰)	E_{frp} (GPa)	t_{frp} (mm)	$\varepsilon_{h, rup}$ (‰)	f_{cu} (MPa)	f_{cu}/f_{co}	ε_{cu} (‰)	$\varepsilon_{cu}/\varepsilon_{co}$
225	Cui and Sheikh (2010)	152	305	2	45.6	2.4	241	0.33	11.5	107.3	2.35	28.6	11.92
226		152	305	2	45.6	2.4	241	0.33	11.5	108.6	2.38	27.8	11.58
227		152	305	2	85.6	2.9	241	0.11	8.2	64.4	0.75	4.4	1.52
228		152	305	2	85.6	2.9	241	0.11	7.6	66.6	0.78	4.4	1.52
229		152	305	2	85.6	2.9	241	0.22	7.4	78.9	0.92	5.6	1.93
230		152	305	2	85.6	2.9	241	0.22	7.6	86.1	1.01	5.8	2.00
231		152	305	2	85.6	2.9	241	0.44	8.9	125.4	1.46	10.0	3.45
232		152	305	2	85.6	2.9	241	0.44	9.2	126.5	1.48	9.9	3.41
233		152	305	2	111.8	3.0	241	0.22	9.4	101.1	0.90	3.2	1.07
234		152	305	2	111.8	3.0	241	0.22	8.3	94.3	0.84	4.8	1.60
235		152	305	2	111.8	3.0	241	0.56	7.5	152.1	1.36	5.0	1.67
236		152	305	2	111.8	3.0	241	0.56	6.0	145.3	1.30	5.8	1.93
237		152	305	2	45.7	2.4	438	0.16	7.9	67.5	1.48	11.1	4.63
238		152	305	2	45.7	2.4	438	0.16	7.7	64.1	1.40	10.3	4.29
239		152	305	2	45.7	2.4	438	0.33	6.4	84.2	1.84	13.3	5.54
240		152	305	2	45.7	2.4	438	0.33	6.3	83.1	1.82	12.3	5.13
241		152	305	2	45.7	2.4	438	0.49	6.0	99.7	2.18	15.6	6.50
242		152	305	2	45.7	2.4	438	0.49	5.5	94.9	2.08	14.3	5.96
243		152	305	2	45.7	2.4	438	0.16	7.2	65.8	1.44	9.7	4.04
244		152	305	2	45.7	2.4	438	0.16	7.7	65.9	1.44	10.3	4.29
245		152	305	2	45.7	2.4	438	0.33	6.9	88.1	1.93	14.2	5.92
246		152	305	2	45.7	2.4	438	0.33	6.1	82.0	1.79	12.3	5.13
247		152	305	2	45.7	2.4	438	0.65	3.6	103.2	2.26	15.3	6.38
248		152	305	2	45.7	2.4	438	0.65	4.4	105.6	2.31	18.6	7.75
249		152	305	2	85.7	2.9	438	0.16	3.0	91.5	1.07	4.2	1.45
250		152	305	2	85.7	2.9	438	0.16	4.2	94.5	1.10	5.4	1.86
251		152	305	2	85.7	2.9	438	0.33	4.4	117.7	1.37	7.1	2.45
252		152	305	2	85.7	2.9	438	0.33	4.1	117.5	1.37	5.5	1.90
253		152	305	2	85.7	2.9	438	0.65	3.8	161.6	1.89	10.2	3.52
254		152	305	2	85.7	2.9	438	0.65	3.8	162.6	1.90	9.5	3.28
255		152	305	2	111.8	3.0	438	0.33	2.2	139.1	1.24	3.2	1.07
256		152	305	2	111.8	3.0	438	0.33	1.7	123.3	1.10	3.1	1.03
257		152	305	2	111.8	3.0	438	0.82	2.4	176.4	1.58	4.9	1.63
258		152	305	2	111.8	3.0	438	0.82	2.1	172.5	1.54	5.0	1.67
259	Xiao *et al*. (2010)	152	305	2	70.8	3.2	237.8	0.34	11.0	104.2	1.47	10.7	3.34
260		152	305	2	70.8	3.2	237.8	0.34	12.1	110.3	1.56	14.3	4.37
261		152	305	2	70.8	3.2	237.8	1.02	10.0	180.5	2.55	21.6	6.75
262		152	305	2	70.8	3.2	237.8	1.02	9.0	197.7	2.79	23.3	7.28
263		152	305	2	70.8	3.2	237.8	1.7	6.7	191.5	2.70	22.8	7.12
264		152	305	2	70.8	3.2	237.8	1.7	5.2	162.4	2.29	13.9	4.34
265		152	305	2	111.6	3.4	237.8	0.68	5.7	141.2	1.26	9.7	2.85
266		152	305	2	111.6	3.4	237.8	0.68	5.8	134.0	1.20	7.5	2.21
267		152	305	2	111.6	3.4	237.8	1.02	5.2	170.4	1.53	9.8	2.88
268		152	305	2	111.6	3.4	237.8	1.02	6.0	176.6	1.58	11.2	3.29
269		160	320	2	49.46	1.7	34	1.00	2.9	52.75	1.066	2.5	1.49
270		160	320	2	49.46	1.7	34	3.00	13.2	82.9	1.676	7.3	4.3

Table 1 Continued

N°	Authors and years	D (mm)	H (mm)	H/D	f_{co} (Mpa)	ε_{co} (‰)	E_{frp} (GPa)	t_{frp} (mm)	$\varepsilon_{h, rup}$ (‰)	f_{cu} (MPa)	f_{cu}/f_{co}	ε_{cu} (‰)	$\varepsilon_{cu}/\varepsilon_{co}$
271	Xiao *et al*. (2010)	160	320	2	61.8	2.8	34	1.00	2.5	62.68	1.01	3.3	1.15
272		160	320	2	61.8	2.8	34	3.00	12.9	93.2	1.51	10.5	3.71
273		150	300	2	20.6	2.0	242	0.17	14.1	50.4	2.45	19.7	9.85
274		150	300	2	20.6	2.0	242	0.17	15.6	53.0	2.57	21.4	10.7
275		150	300	2	20.6	2.0	242	0.17	14.3	53.2	2.58	22.7	11.35
276		150	300	2	20.6	2.0	242	0.33	18.4	83.7	4.06	38.6	19.3
277	Wu and Jiang (2013)	150	300	2	20.6	2.0	242	0.33	18.6	86.6	4.20	40.2	20.1
278		150	300	2	20.6	2.0	242	0.33	22.6	88.8	4.31	29.7	14.85
279		150	300	2	20.6	2.0	242	0.50	17.9	110.2	5.35	48.2	24.1
280		150	300	2	20.6	2.0	242	0.50	13.7	108.1	5.25	48.6	24.3
281		150	300	2	20.6	2.0	242	0.50	17.3	110.0	5.34	41.3	20.65
282		150	300	2	20.6	2.0	242	0.67	19.2	127.7	6.20	54.9	27.45
283		150	300	2	20.6	2.0	242	0.67	18.5	132.5	6.43	55.2	27.6
284		150	300	2	20.6	2.0	242	0.67	17.1	140.6	6.83	52.0	26.00
285		150	300	2	24.8	2.1	242	0.17	18.1	61.7	2.49	22.1	10.52
286		150	300	2	24.8	2.1	242	0.17	15.6	56.7	2.29	20.2	9.62
287		150	300	2	24.8	2.1	242	0.17	20.4	56.9	2.29	21.3	10.14
288		150	300	2	24.8	2.1	242	0.33	18.7	87.2	3.52	34.5	16.43
289		150	300	2	24.8	2.1	242	0.33	17.1	87.8	3.54	36.1	17.19
290		150	300	2	24.8	2.1	242	0.33	16.5	88.3	3.56	35.2	16.76
291		150	300	2	24.8	2.1	242	0.50	17.3	118.6	4.78	40.8	19.43
292		150	300	2	24.8	2.1	242	0.50	17.5	114.7	4.63	43.6	20.76
293		150	300	2	24.8	2.1	242	0.50	20.0	114.6	4.62	41.9	19.95
294		150	300	2	24.8	2.1	242	0.67	13.6	133.8	5.40	50.9	24.24
295		150	300	2	24.8	2.1	242	0.67	14.4	135.0	5.44	49.5	23.57
296		150	300	2	24.8	2.1	242	0.67	15.1	139.1	5.61	49.6	23.62
297		150	300	2	36.7	2.3	242	0.17	15.2	61.9	1.69	15.8	6.87
298		150	300	2	36.7	2.3	242	0.17	19.1	71.6	1.95	20.2	8.78
299		150	300	2	36.7	2.3	242	0.17	16.0	65.5	1.78	16.3	7.09
300		150	300	2	36.7	2.3	242	0.33	16.0	92.4	2.52	27.2	11.83
301		150	300	2	36.7	2.3	242	0.33	16.8	97.6	2.66	27.9	12.13
302		150	300	2	36.7	2.3	242	0.33	17.1	95.7	2.61	29.0	12.61
303		150	300	2	36.7	2.3	242	0.50	15.2	121.2	3.30	25.2	10.96
304		150	300	2	36.7	2.3	242	0.50	15.4	128.6	3.50	33.7	14.65
305		150	300	2	36.7	2.3	242	0.50	17.0	116.5	3.17	32.5	14.13
306		150	300	2	36.7	2.3	242	0.67	16.2	141.8	3.86	34.9	15.17
307		150	300	2	36.7	2.3	242	0.50	15.2	121.2	3.30	25.2	10.96
308		150	300	2	36.7	2.3	242	0.50	15.4	128.6	3.50	33.7	14.65
309		150	300	2	36.7	2.3	242	0.50	17.0	116.5	3.17	32.5	14.13
310		150	300	2	36.7	2.3	242	0.67	16.2	141.8	3.86	34.9	15.17

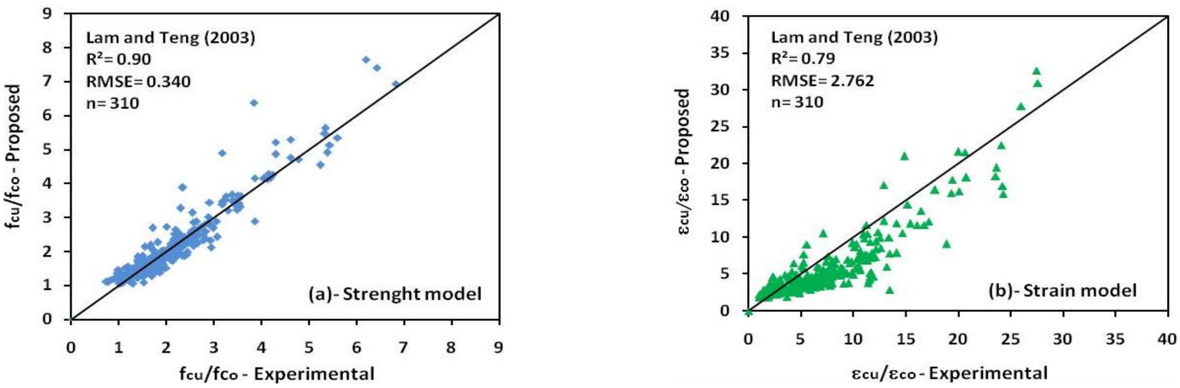


Fig. 2 Performance of Lam and Teng (2003) model

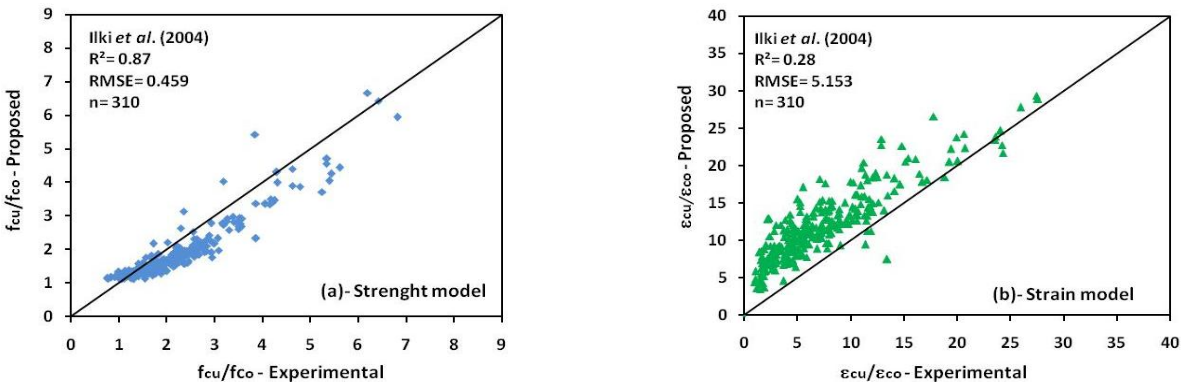


Fig. 3 Performance of Ilki *et al*. (2004) model

3.2 Lam and Teng (2003) model

The strength and strain models, given by Eqs. (3)-(4) were developed for confined concrete with carbon fiber reinforced polymer (CFRP) laminates based on 76 experimental results.

$$\frac{f_{cu}}{f_{co}} = 1 + 3.3\frac{f_l}{f_{co}} \tag{3}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = \left(1.75 + 5.53\left(\frac{f_l}{f_{co}}\right)\left(\frac{\varepsilon_{frp}}{\varepsilon_{co}}\right)^{0.45}\right) \tag{4}$$

The strength model predicts the strength ration (f_{cu}/f_{co}) as a linear function of the confinement ratio (f_l/f_{co}). Using the database with 310 data points, the performance of this model is shown in Fig. 2(a) with R^2 = 0.90 and RMSE = 0.34. The indices show that the performance of the strength model is good.

The performance of the strain model is shown in Fig. 2(b) with R^2 = 0.79 and RMSE = 2.762. The indices and figure demonstrate that the model underestimates ε_{cu} of the most of data points, its performance is relatively good.

3.3 Ilki et al. (2004) model

The model was developed for confined concrete with CFRP laminates. The model predicts the strength (f_{cu}/f_{co}).and strain ($\varepsilon_{cu}/\varepsilon_{co}$) ratio as a power function of the confinement ratio (f_l/f_{co}). The expressions of the strength and strain models proposed are given as follow.

$$\frac{f_{cu}}{f_{co}} = 1 + 2.4\left(\frac{f_l}{f_{co}}\right)^{1,2} \tag{5}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1 + 20\left(\frac{f_l}{f_{co}}\right)^{0,5} \tag{6}$$

Using the database, the performance of the strength model, given by Eq. (5) is shown in Fig. 3(a) with R^2 = 0.87 and RMSE = 0.459. The figure demonstrates that major data points are located under the diagonal (45-degree line). Moreover, the R^2 index shows that this model presents a good correlation with the database (n = 310). In the same way, the RMSE index confirms the performance of this model.

The performance of the strain model, expressed in Eq. (6) is shown in Fig. 3(b). The figure shows that the data points of the strain ratio ($\varepsilon_{cu}/\varepsilon_{co}$) are located over the diagonal (45-degree line), with R^2 = 0.28. The R^2 index shows that this model presents a very weak correlation with the database (n = 310). The RMSE = 5.153 confirms the very weak performance of this model.

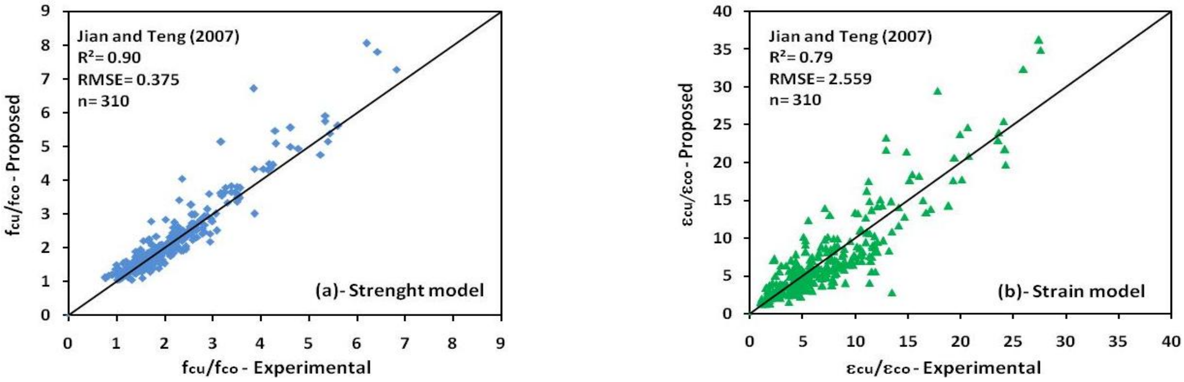


Fig. 4 Performance of Jian and Teng (2007) model

3.4 Jiang and Teng (2007) model

The modeles, given by Eqs. (6)-(8), were developed by Jiang and Teng (2007), for confined concrete with CFRP. The models predict the strength (f_{cu}/f_{co}) and strain ($\varepsilon_{cu}/\varepsilon_{co}$) ratio as a linear function of the confinement ratio (f_l/f_{co}). Using the database, the performance of the strength model is shown in Fig. 4(a) with R^2 = 0.90 and RMSE = 0.37. The indices show a good performance and similar to the model of Lam and Teng (2003).

The performance of the strain model is shown in Fig. 4(b) with R^2 = 0.79 and RMSE = 2.559. The indices show that the model presents a relatively good performance, and similar to the model of Lam and Teng (2003).

$$f_{cu} = f_{co}\left(1+3.5\left(\frac{f_l}{f_{co}}\right)\right) \tag{7}$$

$$\varepsilon_{cu} = \varepsilon_{co}\left(2+17.5\left(\frac{f_l}{f_{co}}\right)\right) \tag{8}$$

3.5 Youssef et al. (2007) model

The strength and strain Models developed by Youssef *et al*. (2007) are expressed in Eqs. (9)-(10), respectively. The strength model proposed has a power form. Using the database, the performance of this model is shown in Fig. 5(a) with R^2 = 0.87 and RMSE = 0.589. The figure demonstrates that this model underestimates the f_{cu} of the most of data points. The indices show that the model presents a relatively similar performance to the models developed by Ilki *et al*. (2004) and Lam and Teng (2003).

The performance of the strain model developed by Youssef *et al*. (2007), given in Eq. (10) is shown in the Fig. 5(b) with R^2 = 0.78 and RMSE = 2.926. The visual evaluation shows that the proposed model presents a performance relatively good and similar to the model proposed by Lam and Teng (2003), although the major data points are located under the diagonal.

$$\frac{f_{cu}}{f_{co}} = 1+2.25\left(\frac{f_l}{f_{co}}\right)^{1,25} \tag{9}$$

$$\varepsilon_{cu} = 0.003368+0.2590\left(\frac{f_l}{f_{co}}\right)\left(\frac{f_{prf}}{E_{prf}}\right)^{0,5} \tag{10}$$

3.6 Teng et al. (2009) model

The strength and strain models proposed by Teng *et al*. (2009) are expressed in Eqs. (11)-(12), respectively. The models were developed for confined concrete with CFRP. These models were the first to have separate parameters for the confinement stiffness (ρ_K), and the CFRP strain capacity (ρ_ε). The strength model developed has a linear form. Using

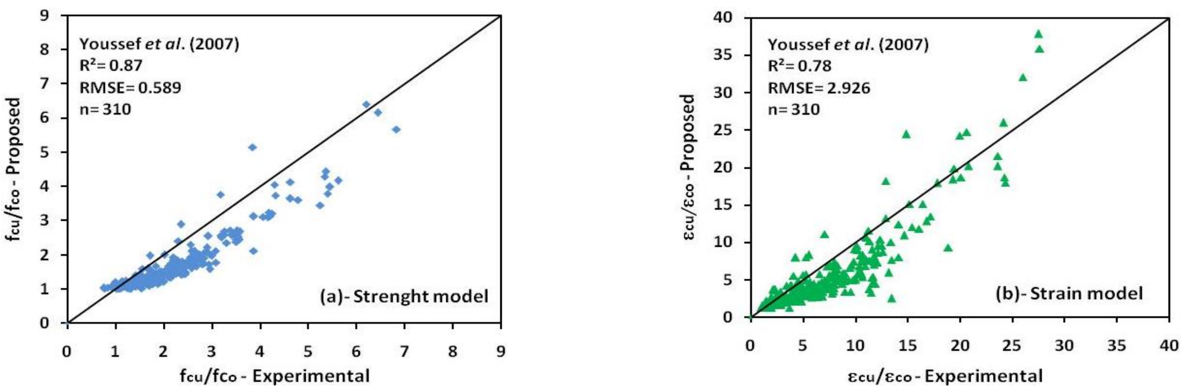


Fig. 5 Performance of Youssef *et al*. (2007) model

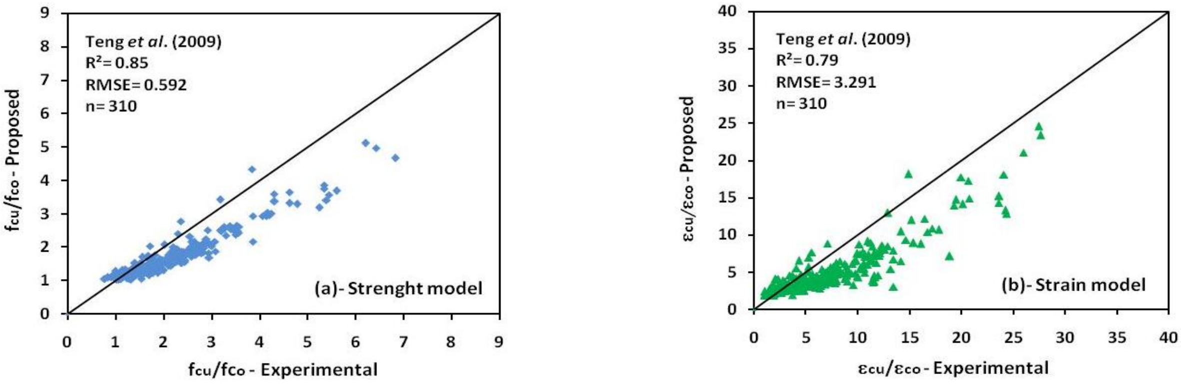


Fig. 6 Performance of Teng *et al*. (2009) model

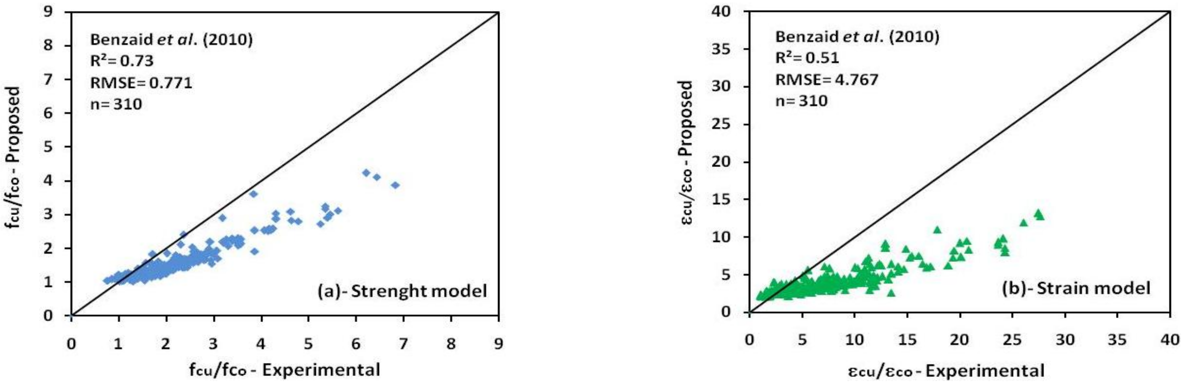


Fig. 7 Performance of Benzaid *et al*. (2010) model

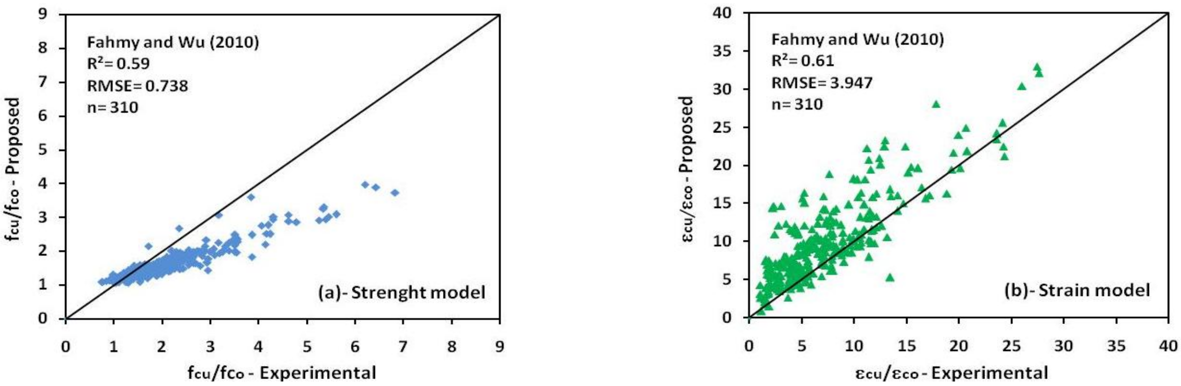


Fig. 8 Performance of Fahmy and Wu (2010) model

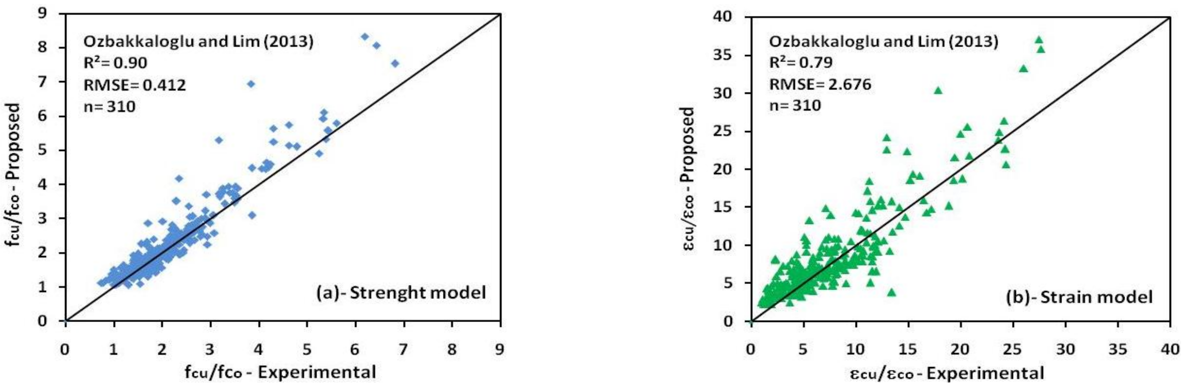


Fig. 9 Performance of Ozbakkaloglu and Lim (2013) model

the database, the performance of this model is shown in Fig. 6(a) with R^2 = 0.85 and RMSE = 0.592. The figure shows that the most of the data points are located under the diagonal. Consequently, it was noted that its performance is not better than the models of Lam and Teng (2003) and Jiang and Teng (2007). For the strain model, the performance with R^2 = 0.79 and RMSE = 3.291 is shown in Fig. 6(b). This figure demonstrates that the data points take a similar position as the strength model. The performance indices show that the model presents a weak performance compared to the models developed by Lam and Teng (2003), Jiang and Teng (2007) and Youssef *et al*. (2007).

$$f_{cu} = f_{co}\left(1+3.5\left(\rho_k - 0.001\right)\rho_\varepsilon\right)\ldots\rho_\varepsilon \geq 0.01 \tag{11}$$

$$\varepsilon_{cu} = \varepsilon_{co}\left(1.75+6.5\rho_k^{0.8}\rho_\varepsilon^{1.45}\right) \tag{12}$$

Where ρ_K represents the stiffness ratio of the CFRP relative to that of the concrete core and ρ_ε is a measure of the strain capacity of the CFRP.

3.7 Benzaid et al. (2010) model

The strength and strain models proposed by Benzaid *et al*. (2010) are expressed in Eqs. (13)-(14), respectively. The models were developed for circular concrete columns confined with CFRP laminates based on their experimental results. The models have a simple linear form. The expressions of these models are as follows

$$f_{cu} = f_{co}\left(1+1.6\left(\frac{f_l}{f_{co}}\right)\right) \tag{13}$$

$$\varepsilon_{cu} = \varepsilon_{co}\left(2+5.55\left(\frac{f_l}{f_{co}}\right)\right) \tag{14}$$

Using the database the performance of the strength model is shown in Fig. 7(a) with R^2 = 0.73 and RMSE = 0.771. The RMSE index and visual evaluation demonstrate that the model underestimates ε_{cu} of the most of data points. Consequently, its performance is not better than the previous models. For the strain model, the Fig. 7(b) presents its performance with R^2 = 0.51 and RMSE = 4.767. While, the figure demonstrates that the data points form an angle of 20 degree. The performance indices show that the model presents a weak performance compared to the previous models except the model of Ilki *et al*. (2004).

3.8 Fahmy and Wu (2010) model

The strength and strain models of Fahmy and Wu (2010) are given as follows

$$\begin{aligned} f_{cu} &= f_{co} + k_1 f_l \\ k_1 &= 4.5 f_{lu}^{-0.3}\ si\ \ f_{co} \leq 40\,\text{MPa} \\ k_1 &= 3.75 f_{lu}^{-0.3}\ si\ \ f_{co} > 40\,\text{MPa} \end{aligned} \tag{15}$$

$$\varepsilon_{cu} = \frac{f_{cu} - f_{co}}{E_2} \tag{16}$$

The strength model proposed has a power form. It has two expressions for the confined concrete with various unconfined compressive strength concrete. The performance of the model is shown in Fig. 8(a) with R^2 = 0.59 and RMSE = 0.738. The indices show that the proposed model presents a very weak performance compared to all the models studies, although it largely underestimates the f_{cu} of the most of data points. For the strain model, the performance of this model is shown in Fig. 8(b) with R^2 = 0.61 and RMSE = 3.947. The performance indices show that the proposed model overestimates the ε_{cu} of the most of data points. Consequently, its performance is very weak compared to the strain models developed by Lam and Teng (2003), Jiang and Teng (2007), Youssef *et al*. (2007) and Teng *et al*. (2009), nevertheless, the model presents a good performance compared to the models of Benzaid *et al*. (2010) and Ilki *et al*. (2004).

3.9 Ozbakkaloglu and Lim (2013) model

Ozbakkaloglu and Lim (2013) develop a strength and strain models for confined concrete with FRP. The models have a linear and simple form. The expressions of these models are given as follows

$$f_{cu} = f_{co}\left(1+3.64\left(\frac{f_l}{f_{co}}\right)\right) \tag{17}$$

$$\varepsilon_{cu} = \varepsilon_{co}\left(2+17.41\left(\frac{f_l}{f_{co}}\right)\right) \tag{18}$$

Using the database, the performance of the strength model, given in Eq. (17) is shown in Fig. 9(a) with R^2 = 0.90 and RMSE = 0.412. The figure demonstrates that there is a good adjustment between the strength values predict and experimental results. In addition, the performance indices show that this model presents a very good performance compared to all the strength models studied except the strength models developed by Lam and Teng (2003) and Jiang and Teng (2007) and Youssef *et al*. (2007) which have the minimum RMSE compared to other models. Nevertheless, this model overestimates f_{cu} of the most of data points. For the performance of the strain model, the Fig. 9(b) presents R^2 = 0.79 and RMSE = 2.676, which shows that the model proposed overestimate ε_{cu} of the most of data points. The indices show that the model presents a good performance compared to the other models. Nevertheless, it was noted that it has a similar performance with the strain models proposed by Lam and Teng (2003) and Jiang and Teng (2007). In the context, the uniform distribution of the data points confirms this conclusion.

4. Empirical modeling

The empirical model proposed in this section. In particular, models for calculating the strength and strain coordinates which correspond to experimental database are provided.

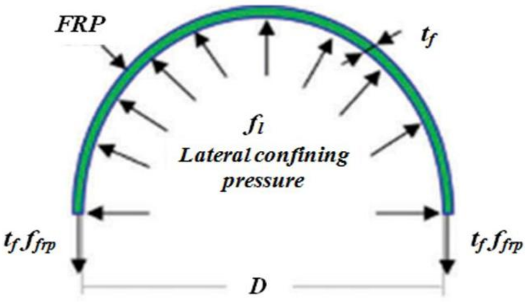


Fig. 10 Mechanism of confinement

4.1 Lateral confinement pressure

The lateral confinement pressure is produced in confined concrete when the member is loaded such that the concrete starts to dilate and expands laterally. The value of such pressure depends on the geometry of the confined member and the amount and mechanical properties of confinement materials provided (see Fig. 10) Berradia and Kassoul (2017).

According to ACI 440 (2008), the lateral confinement pressure (f_l) resulting from the external CFRP laminates for circular sections is given by the following expression

$$f_l = \frac{2.f_{prf}.t_{prf}}{D} \quad (19)$$

Where t_{frp} is the thickness of the CFRP laminates, f_{frp} is the tensile strength of CFRP and D is diameter of the specimen.

4.2 Ultimate strength model proposed

The axial ultimate strength f_{cu} is very important parameter on the stress-strain model as it considers the lateral confinement pressure effect. For the circular concrete columns confined by CFRP, the axial ultimate strength is largely higher than the unconfined concrete strength f_{co}. The relationship between the axial ultimate strength of confined circular concrete by CFRP and the parameters that affect it will be considered as a strength model. Currently, many researchers have formulated the ratio (f_{cu}/f_{co}) and (f_l/f_{co}) as a linear function. In the same way, the statistical analysis of existing models presented in section 3 shows that the models with a linear form have a good performance compared to the others. According to Lam and Teng, (2003), Jiang and Teng (2007), Benzaid *et al*. (2010) and Ozbakkaloglu and Lim (2013), the expression of the ultimate compressive strength is generally given as follows

$$\frac{f_{cu}}{f_{co}} = 1 + k_1 \frac{f_l}{f_{co}} \quad (20)$$

Where k_1 is the confinement effectiveness coefficient; f_l is the lateral confinement pressure provided by CFRP laminates applied to the concrete core and f_{co} is the compressive strength of unconfined concrete.

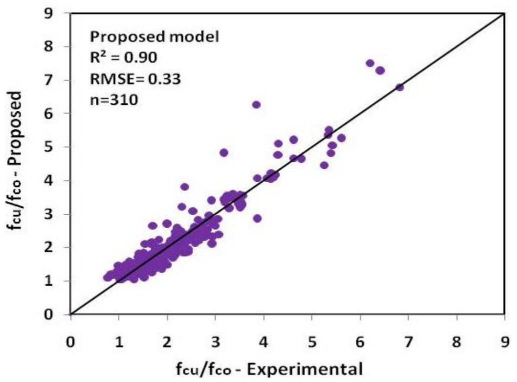


Fig. 11 Comparison between the experimental and proposed ultimate strength

For the development of a new ultimate strength model (f_{cu}) for confined concrete cylinders with CFRP laminates, we uses an analysis of regression on 310 experimental data base represented in Table 1. The principle of this analysis is to have a good correlation between the theoretical and experimental values, i.e., the coefficient of determination R^2 must be close to 1, and minimizing the RMSE index, i.e. tends towards 0. For this technique of analysis, we use the program Microsoft Office Excel. The advantages of the general regression analysis which is used in the current study are that the form of model can be selected and the number of parameters is unlimited. Another new aspect of the study is using the large experimental database with all required parameters in the general regression analysis. The confinement effectiveness coefficient k_1 is calibrated from the regression analysis of the experimental data of 310 specimens illustrated in Table 1.

The proposed expression for the ultimate strength (f_{cu}) is expressed as follows

$$\frac{f_{cu}}{f_{co}} = 1 + 3.2 \frac{f_l}{f_{co}} \quad (21)$$

The Fig. 11 shows a comparison between the experimental and proposed ultimate strength. According to this Figure, we observe that the expression proposed in Eq. (21) presents a good linear correlation with the data of 310 experimental results, where R^2 = 0.90 and RMSE= 0.33.

4.3 Ultimate strain model proposed

The second important parameter of the confinement model by CFRP is the ultimate strain (ε_{cu}). Currently, several researchers formulated the ratio ($\varepsilon_{cu}/\varepsilon_{co}$) according to ($f_l/f_{co}$) like a linear function, where the statistical analysis in the section 3 shows their relevance. According to Lam and Tang (2003), Jiang and Teng (2007), Benzaid *et al*. (2010), Ozbakkaloglu and Lim (2013), this relation is given by

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 2 + k_2 \frac{f_l}{f_{co}} \quad (22)$$

Where ε_{co} is the axial strain in unconfined concrete

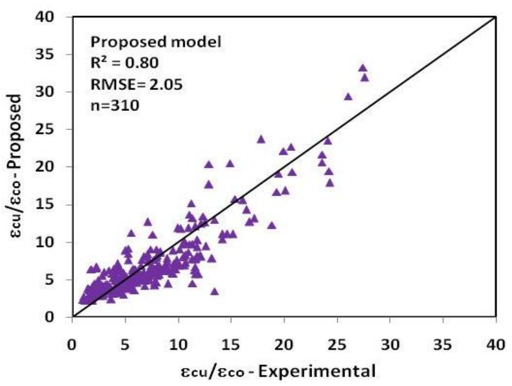


Fig. 12 Comparison between the experimental and proposed ultimate strain

corresponding to f_{co} and k_2 is the confinement effectiveness coefficient.

From the mathematical regression of the 310 experimental database presented in Table 1, k_2 of a new ultimate strain model (ε_{cu}) for concrete cylinders confined by CFRP is calibrated from the regression analysis of the experimental data of 310 specimens illustrated in Table 1, which takes account of the rupture strain of CFRP laminates in hoop direction ($\varepsilon_{h,\ rup}$). The new expression of the ultimate strain model (ε_{cu}) proposed is given as follows

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 2 + 11.5\left(\frac{f_l}{f_{co}}\right)\left(\frac{\varepsilon_{h,rup}}{\varepsilon_{co}}\right)^{0.13} \tag{23}$$

The Fig. 12 illustrates a comparison between the experimental and proposed ultimate strain. This figure shows well that the expression proposed in Eq. (23) presents a relatively good linear correlation with the 310 experimental database, with R^2 = 0.80 and RMSE = 2.05

5. Performance of proposed models

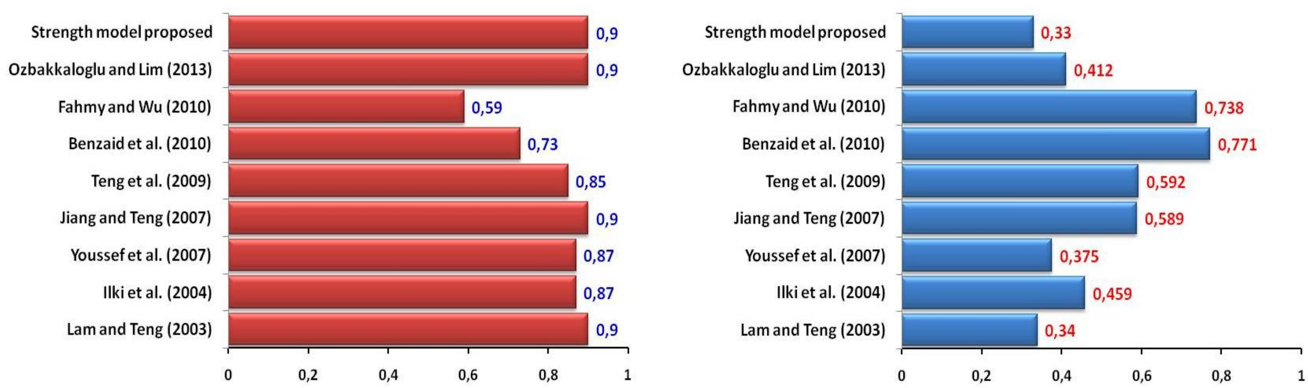
This part presents the performance of the new expressions of ultimate strength given by Eq. (18) and of ultimate strain given by Eq. (20), for the confined concrete with external CFRP laminates. This performance was analyzed using a statistical analysis with 310 experimental database illustrated in Table 1. In this context, the coefficient R^2 and the indicator RMSE are used as indicators of the model performance.

5.1 Ultimate strength of proposed model

The Fig. 13 illustrates a comparison between the two performance indices of the strength model proposed, and the existing models studied in Section 3, namely: Lam and Teng (2003), Ilki *et al*. (2004), Youssef *et al*. (2007), Jiang and Teng (2007), Teng *et al*.(2009), Benzaid *et al*. (2010), Fahmy and Wu. (2010) and Ozbakkaloglu and Lim (2013). The histogram of the Fig. 13(a) shows that the ultimate strength model proposed presents a better correlation with R^2 = 0.90 compared to the models of Teng *et al*. (2009), Benzaid *et al*. (2010) and Fahmy and Wu. (2010), but it presents an identical correlation to the models of Lam and Teng (2003), Jiang and Teng (2007), Ozbakkaloglu and Lim (2013), Ilki *et al*.(2004) and Youssef *et al*. (2007),. Moreover, the histogram of the Fig. 13(b) shows clearly that the index RMSE = 0.33. So far, This model presents the minimum RMSE compared to the models developed by Ilki *et al*. (2004), Jiang and Teng (2007), Teng *et al*. (2009), Benzaid *et al*. (2010), Fahmy and Wu (2010) and Ozbakkaloglu and Lim (2013). But it presents a relatively similar RMSE values compared to the models of Lam and Teng (2003) and Youssef *et al*. (2007). Consequently, the strength model proposed presents a relatively similar performance compared to the models Lam and Teng (2003) and Youssef *et al*. (2007). Nevertheless, it presents a good performance compared to the others.

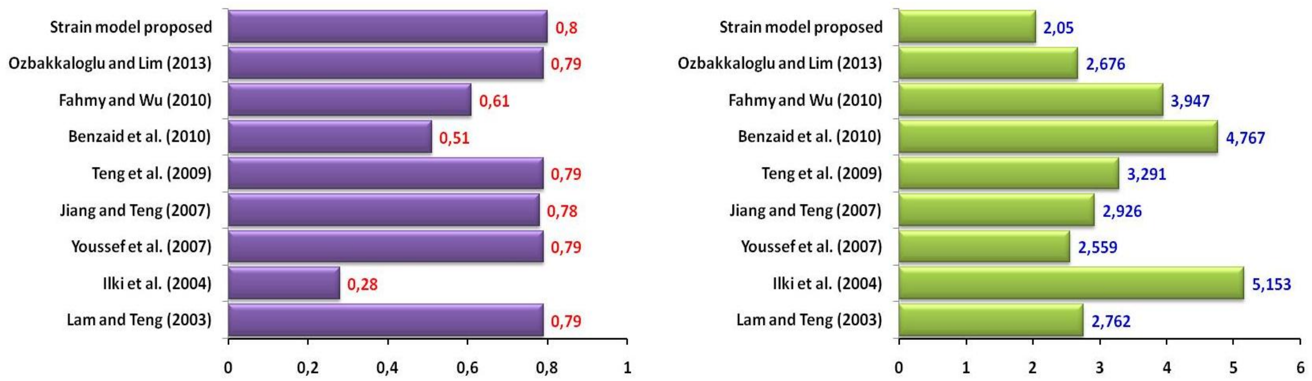
5.2 Ultimate strain of proposed model

The Fig. 14 presents a comparison between the two performance indices of the new strain model proposed and the existing models studied in Section 3, Lam and Teng (2003), Ilki *et al*. (2004), Youssef *et al*. (2007), Jiang and Teng (2007), Teng *et al*.(2009), Benzaid *et al*. (2010), Fahmy and Wu (2010) and Ozbakkaloglu and Lim (2013). The histogram of the Fig 14(a) shows that the proposed model presents a better correlation with R^2 = 0.80 compared



(a) R^2 (b) RMSE

Fig. 13 Performance of the ultimate strength of proposed model



(a) R^2 (b) RMSE

Fig. 14 Performance of the ultimate strain of proposed model

to the models developed by Ilki *et al*. (2004), Benzaid *et al*. (2010) and Fahmy and Wu (2010), but it presents a similar correlation compared to the models of Lam and Teng (2003), Youssef *et al*. (2007), Jiang and Teng (2007), Teng *et al*. (2009) and Ozbakkaloglu and Lim (2013). In the context, the Fig. 14(b) shows that the proposed model presents the minimum RMSE with RMSE = 2.05 compared to other models. Consequently, the proposed stain model presents a relatively good performance compared to the existing models studied in this work.

6. Conclusions

This paper presented the results of an investigation on the axial compressive behavior of CFRP-confined concrete cylinders. A large experimental test database that consisted of 310 test results of CFRP-confined concrete cylinders has been presented in this paper. Using this experimental database, the performance of existing confinement models for the ultimate conditions of CFRP-confined concrete cylinders under uniaxial compression loadings was studied. New empirical models for the ultimate axial compressive strength f_{cu} and the ultimate axial strain ε_{cu}, which were developed on the basis of a general regression analysis and the experimental database, were presented in the section 4 of this paper. These models are applicable to the unconfined concrete compressive strengths f_{co} comprise between 19.7 and 169.7 MPa, specimens with height-to-diameter (H/D) ratio equal to two and incorporates the important factors identified from close examination of the results reported in the database. The performance of the two proposed models was compared to the existing models using the experimental database. The proposed models showed significantly better statistical performance than all existing models studied except the models of Lam and Teng (2003) and Youssef *at al*. (2007) which have statistical indices R^2 and RMSE values relatively similar to the proposed models.

References

ACI 440 (2008), Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures; American Concrete Institute, USA.

Aire, C., Gettu, R. and Casas, J.R. (2001), "Study of the compressive behavior of concrete confined by fiber reinforced composites", *International Conference on Composites in Constructions*, A.A. Balkema Publishers, Lisse, The Netherlands, pp. 239-243.

Benzaid, R., Mesbah, H. and Chikh, N. (2010), "FRP-confined concrete cylinders: axial compression experiments and strength model", *J. Reinf. Plast. Compos.*, **29**(16), 2469-2488.

Berradia, M. and Kassoul, A. (2017), "Combine effect of CFRP-TSR confinement on circular reinforced concrete columns", *Comput. Concrete, Int. J.*, **19**(1), 041-049.

Berthet, J.F., Ferrier, E. and Hamelin, P. (2005), "Compressive behavior of concrete externally confined by composite jackets. Part A: Experimental study", *Constr. Build Mater.*, **19**(3), 223-232.

Bullo, S. (2003), "Experimental study of the effects of the ultimate strain of fiber reinforced plastic jackets on the behavior of confined concrete", *International Conference on Composites Inconstruction*, Cosenza, Italy, pp. 465-470.

Carey, S.A. and Harries, K.A. (2003), "The effects of shape, 'gap', and scale on the behavior and modeling of variably confined concrete", Report no. ST03-05; University of South Carolina, CO, USA.

Carey, S.A. and Harries, K.A. (2005), "Axial behavior and modeling of small-, medium-, and large-scale cylindrical sections confined with CFRP jackets", *ACI. Struct. J.*, **102**(4), 596-604.

Cui, C. and Sheikh, S.A. (2010), "Experimental study of normal- and high-strength concrete confined with fiber-reinforced polymers", *J. Compos. Constr.*, **14**(5), 553-561.

De Lorenzis, L., Micelli, F. and La Tegola, A. (2002), "Influence of specimen size and resin type on the behavior of FRP-confined concrete cylinders", *Proceedings of the 1st International Conference on Advanced Polymer Composites for Structural Applications in Construction*, Thomas Telford, London, UK, pp. 231-39.

Fahmy, M. and Wu, Z. (2010), "Evaluating and proposing models of circular concrete columns confined with different FRP composites", *Compos. Part B: Eng.*, **41**(3), 199-213.

Fanggi, B.A.L. and Ozbakkaloglu, T. (2015), "Square FRP-HSC-steel composite columns: Behavior under axial compression", *Eng. Struct.*, **92**, 156-171.

Fardis, M.N. and Khalili, H.H. (1982), "FRP-encased concrete as a structural material", *Mag. Concr. Res.*, **34**(121), 191-202.

Harmon, T.G. and Slattery, K.T. (1992), "Advanced composite confinement of concrete", *Proceedings of the 1st International Conference on Advanced Composite Materials in Bridges and*

Structures, Canadian Society for Civil Engineering, Sherbrooke, Canada, pp.299-306.

Howie, I. and Karbhari, V.M. (1995), "Effect of tow sheet composite wrap architecture on strengthening of concrete due to confinement. I: Experimental studies", *J. Reinf. Plast. Compos.*, **14**(9), 1008-1030.

Ilki, A., Kumbasar, N. and Koc, V. (2004), "Low strength concrete members externally confined with FRP sheets", *Struct. Eng. Mech., Int. J.*, **18**(2), 167-194.

Jiang, T. and Teng, J.G. (2007), "Analysis-oriented stress-strain models for FRP-confined concrete", *Eng. Struct.*, **29**(11), 2968-2986.

Kono, S., Inazumi, M. and Kaku, T. (1998), "Evaluation of confining effects of CFRP sheets on reinforced concrete members", *Proceedings of the 2nd International Conference on Composites in Infrastructure*, University of Arizona, Tucson, AZ, USA, pp. 343-55.

Lam, L. and Teng, J.G. (2003), "Design-oriented stress-strain model for FRP-confined concrete", *Const. Build. Mater.*, **17**(6-7), 471-489.

Lam, L. and Teng, J.G. (2004), "Ultimate condition of fiber reinforced polymer-confined concrete", *J. Compos. Constr.*, **8**(6), 539-548.

Lam, L., Teng, J.G., Cheung, C.H. and Xiao, Y. (2006) "FRP-confined concrete under axial cyclic compression", *Cem. Concrete Compos.*, **28**(10), 949-958.

Lezgy-Nazargah, M., Dezhangah, M. and Sepehrinia, M. (2018), "The effects of different FRP/concrete bond–slip laws on the 3D nonlinear FE modeling of retrofitted RC beams - A sensitivity analysis", *Steel Compos. Struct., Int. J.*, **26**(6), 347-360.

Lu, W.Y., Yu, H.W., Chen, C.L., Liu, S.L. and Chen, T.C. (2015), "High-strength concrete deep beams with openings strengthened by carbon fiber reinforced plastics", *Comput. Concrete, Int. J.*, **15**(1), 21-35.

Mahdi Razavi, S. and Zahiraniza, M. (2018), "Rehabilitation of notched circular hollow sectional steel beam using CFRP patch", *Steel Compos. Struct., Int. J.*, **26**(2), 151-161.

Matthys, S., Toutanji, H., Audenaert, K. and Taerwe, L. (2005), "Axial load behavior of largescale columns confined with fiber-reinforced polymer composites", *ACI. Struct. J.*, **102**(2), 258-267.

Micelli, F., Myers, J.J. and Murthy, S. (2001), "Effect of environmental cycles on concrete cylinders confined with FRP", *Proceedings of International Conference on Composites in Constructions*, A.A. Balkema Publishers, Lisse, The Netherlands, pp. 317-322.

Modarelli, R., Micelli, F. and Manni, O. (2005), "FRP-confinement of hollow concrete cylinders and prisms", *Proceedings of the 7th international symposium on fiber reinforced polymer reinforcement for reinforced concrete structures* (*FRPRCS-7*), NO. SP-230; American Concrete Institute, Farmington, MI, USA, pp. 1029-1046.

Morsy, A. and Mahmoud, E.T. (2013), "Bonding techniques for flexural strengthening of R.C. beams using CFRP laminates", *Ain. Sha. Eng. J.*, **4**(3), 369-374.

Nam, J.W., Yoon, I.S. and Yi, S.T. (2016), "Numerical evaluation of FRP composite retrofitted reinforced concrete wall subjected to blast load", *Comput. Concrete, Int. J.*, **17**(2), 215-225.

Newman, K. and Newman, J.B. (1971), "Failure theories and design criteria for plain concrete", *Proceedings of International Conference on Structures, Solid Mechanics, and Engineering Design*, Wiley Interscience, New York City, NY, USA, pp. 936-995.

Ozbakkaloglu, T. (2013), "Compressive behavior of concrete-filled FRP tube columns: Assessment of critical column parameters", *Eng. Struct.*, **51**, 188-199.

Ozbakkaloglu, T. and Lim, J.C. (2013), "Axial compressive behavior of FRP-confined concrete: Experimental test database and a new design-oriented model", *Compos. Part B.*, **55**, 607-634.

Picher, F. and Rochette, P. (1996), "Labossiere P. Confinement of concrete cylinders with CFRP", *Proceedings of the 1st International Conference on Composites for Infrastructures*, University of Arizona, Tucson, AZ, USA, pp. 829-841.

Richart, F.E., Brandtzaeg, A. and Brown, R.L. (1929), "The failure of plain and spirally reinforced concrete in compression", Engineering Experiment Station Bulletin No. 190; University of Illinois, Urbana, IL, USA.

Rochette, P. and Labossiere, P. (2000), "Axial testing of rectangular column models confined with composites", *J. Compos. Constr.*, **4**(3), 129-136.

Rousakis, T. and Tepfers, R. (2004), "Behavior of concrete confined by high E-modulus carbon FRP sheets, subjected to monotonic and cyclic axial compressive load", *Nord. Concr. Res. J.*, **31**(1), 73-82.

Sadeghian, P. and Fam, A. (2015), "Improved design-oriented confinement models for FRP-wrapped concrete cylinders based on statistical analyses", *Eng. Struct.*, **87**, 162-182.

Shahawy, M., Mirmiran, A. and Beitelman, A. (2000), "Test and modeling of carbon-wrapped concrete columns", *Compos. B. Eng.*, **31**(6-7), 471-480.

Shehata, I.A.E.M., Carneiro, L.A.V. and Shehata, L.C.D. (2002), "Strength of short concrete columns confined with CFRP sheets", *Mater. Struct.*, **35**(1), 50-58.

Teng, J.G., Jiang, T., Lam, L. and Luo, Y.Z. (2009), "Refinement of a design-oriented stress–strain model for FRP-confined concrete", *J. Compos. Constr.*, **13**(4), 269-78.

Valdmanis, V., De Lorenzis, L., Rousakis, T. and Tepfers, R. (2007), "Behavior and capacity of CFRP-confined concrete cylinders sub-jected to monotonic and cyclic axial compressive load." *Struct. Concrete*, **8**(4), 187-200.

Wang, L.M. and Wu, Y.F. (2008), "Effect of corner radius on the performance of CFRP-confined square concrete columns: test", *Eng. Struct.*, **30**(2), 493-505.

Watanable, K., Nakamura, H., Honda, T., Toyoshima, M., Iso, M., Fujimaki, T., Kaneto, M. and Shirai, N. (1997), "Confinement effect of FRP sheet on strength and ductility of concrete cylinders under uniaxial compression", *Proceedings of the 3rd International Symposium on Non-metallic FRP Reinforcement for Concrete Structures*, Japan Concrete Institute, Sapporo, Japan, pp. 233-240.

Wu, Y.F. and Jiang, J.F. (2013), "Effective strain of FRP for confined cylindrical concrete columns", *Compos. Struct.*, **95**, 479-491.

Xiao, Y. and Wu, H. (2000), "Compressive behavior of concrete confined by carbon fiber composite jackets", *J. Mater. Civil Eng.*, **12**(2), 139-146.

Xiao, Q.G., Teng, J.G. and Yu, T. (2010), "Behavior and modeling of confined high-strength concrete", *J. Compos. Constr.*, 249-259. DOI: 10.1061/(ASCE)CC.1943-5614.0000070

Youssef, M.N. (2003), "Stress strain model for concrete confined by FRP composites", Doctoral Dissertation; University of California-Irvine, Irvine, CA, USA, 310 p.

Youssef, M.N., Feng, M.Q. and Mosallam, A.S. (2007), "Stress-strain model for concrete confined by FRP composites", *Compos. Part B.*, **38**(5-6), 614-628.

Zhang, H.Y., Hao, X. and Fan, W. (2016), "Experimental study on high temperature properties of carbon fiber sheets strengthened concrete cylinders using geopolymer as adhesive", *Proc. Eng.*, **135**, 47-55.

CC