Proposition of new applicable strength models for concrete columns confined with fiber reinforced polymers

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Abstract

In the present paper, several well-known existing design-oriented relations for circular and rectangular columns confined with fiber reinforced polymers (FRP) are reviewed and their accuracy are compared using a comprehensive database set up by the experimental results extracted from the previous research works. The main motivation for this study is the fact that despite several performed studies to develop practical models for predicting compressive strength of concrete confined with fiber reinforced polymer wraps in the past two decades, which some of them are reviewed in the present paper, it is not known clearly that which model has the most accuracy and applicability. In addition to the performed review and evaluation, new and more accurate relations are proposed using nonlinear regression techniques and their accuracy verified using same experimental data. Based on the attained results, the new proposed relationships displayed better accuracy than the existing FRP confined concrete strength models. The average values of error for the proposed relations correspond to circular and square cross sections were about 13.0 and 15.5%, respectively.

Keywords FRP · Confined concrete column · Strength models · Rectangular section · Circular section · Nonlinear regression

1 Introduction

One of the most applicable and effective method for strengthening reinforced concrete (RC) structures is to utilize fiber reinforced polymers (FRP). First research works in this field started in the early 80 s. Severe earthquakes in the United States, Japan and elsewhere were the true motivations which led to conducting extensive researches on application of FRP to rehabilitate existing RC structures. Positive characteristics of FRPs, such as high tensile strength, modulus of elasticity, corrosion resistance and durability in addition to light weight and non-conductiveness have introduced this method as one of the most common and efficient techniques for strengthening RC structures. Therefore, in the past decades several studies

are performed on different aspects of FRP applications in reinforced concrete (RC) structures. For instance, various researchers investigated effect of externally bonded FRP on performance of RC beams [22, 46, 56]. The application of FRP sheets for strengthening wall-like structures was considered by different investigators [50]. The use of FRPs for rehabilitation of beam-column joints is another interesting topic for researchers [57]. In recent years, some of the investigators evaluated reliability of the available relations for RC structures retrofitted with FRPs [6–9]. In addition to the mentioned topics, many studies are available regarding application of FRP for strengthening concrete columns.

In early stages, steel jackets were used to strengthen RC columns. This method is difficult to implement and

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increases the stiffness of members where such increase is not necessary. Wrapping FRP layers around a column is an acceptable alternative. FRP wraps increase strength and ductility of RC columns. Although the major internal force in columns is axial compressive force, a column seldom experiences pure compressive loading due to developing moments at connections or eccentricity of the axial loads. Therefore, an accurate relationship to estimate confined concrete strength is necessary for a reliable and economic design of FRP wrapped columns. Chaallal and Shahawy [13] demonstrated that the effect of FRP wraps on compressive strength in rectangular columns is less than circular ones due to non-uniform distribution of confining pressure. Consequently, many studies were conducted on circular columns to investigate effects of FRP wraps on concrete strength and various models were proposed to evaluate the ratio of confined to unconfined concrete strength (f'_{cc}/f'_{co}). It should be noted that similar relations were also suggested for rectangular sections. These strength models, whether for circular columns or rectangular ones, can be categorized into experimental and the analytical based. The first strength model for confined concrete is suggested by Richart et al. [53]. They proposed a relation for concrete columns confined by steel casing. Later, Fardis and Khalili [19] studied the FRP confinement in large scale specimens and concluded that with minor modifications, the Richart model can be used for FRP confined concrete columns as well. For modifications, they considered the effects of rebar distribution as ratio of the longitudinal to the lateral reinforcing bars. More recent studies by Mirmiran and Shahawy [42], Samaan et al. [58] and Saafi et al. [55] indicated that the Fardis and Khalili model provides non-conservative results for FRP confined concrete, because it assumes confining pressure to be constant which is not true for FRP wraps. Nevertheless, the Richart model is considered as a basis for development of several new relations. In other words, many of the later models such as those suggested by Samaan et al. [58], Saafi et al. [55], and Karbhari and Gao [29] take advantage of the Richart model and only modify the assumption of constant confining pressure. Many of these new models were formulated based on experimental outcomes resulted from small scale testing but some relations such as the one proposed by Youssef et al. [77] were derived from large-scale experiments and provide more reliable results. Karbhari and Gao [29] suggested a strength model for confined concrete that take effects of the mechanical characteristics of concrete into account while most researches showed that the effect of mechanical characteristics of concrete other than compressive strength is negligible. Another topic that is considered by some of the previous researchers is the slenderness effect on the performance of FRP confined concrete columns [5,

63]. Effect of other issues such as eccentricity of loading or aggregate size on the behavior of FRP confined concrete columns is also investigated so far [27, 71, 72]. In addition to the mentioned topics, some of the proposed relations are valid for a limited range of variation or are proposed only for a special type of FRP wrap.

Due to existence of many available strength relations for FRP confined concrete columns in the literature, there is a question regarding the accuracy of these models. Another issue that rises questions regarding reliability of the existing models is the fact that in most cases, the accuracy of these relations is evaluated using the database of experimental results which were used for their calibration. Therefore, the objectives of this study is to review some of the well-known available strength models for FRP confined concrete columns and also propose new strength models for rectangular and circular FRP confined concrete columns that provide more accurate estimation for a wide range of concrete and FRP mechanical characteristics. For this purposes, some of the available strength models for FRP wrapped circular and rectangular columns were reviewed and their accuracy were evaluated based on a database of the existing experimental data in the literature. Then using nonlinear regression, new and more accurate relations were developed. The suggested strength models are more applicable because their dimensionless feature which facilitate their application for practical design purposes. Finally, accuracy of the suggested models was evaluated using the experimental data.

2 Reviewed strength models for FRP confined circular columns

As mentioned earlier, Richart model was the first strength based relation to compute confined concrete strength. This model has the following simple form:

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

In this equation, f'_{co} , f'_{cc} are strength of unconfined and confined concrete, respectively. k_1 is the effective confinement coefficient which was taken equal to 4.1 and f_l is the confining pressure produced by FRP wraps and is computed by the following equation:

$$f_l = \frac{2f_{frp}t_{frp}}{d} = \frac{\rho_{frp}f_{frp}}{2} \quad (2)$$

In this relation, d , f_{frp} and t_{frp} are column diameter, tensile strength and thickness of the FRP layers. ρ_{frp} is the volume

Table 1 Strength models for FRP confined circular concrete columns

No.	References	Model	FRP type
1	Richart et al. [53]	$\frac{f_{cc}}{f_{co}} = \left(1 + 4.1 \frac{f_l}{f'_{co}}\right)$	Any type
2	Fardis and Khalili [19]	$\frac{f_{cc}}{f_{co}} = 1 + 3.7 \left(\frac{f_l}{f'_{co}}\right)^{0.86}$	Any type
3	Mander et al. [38]	$\frac{f_{cc}}{f_{co}} = \left(-1.254 + 2.254 \left(1 + \frac{7.94 f_l}{f'_{co}}\right)^{0.5}\right) - 2 \frac{f_l}{f'_{co}}$	Any type
4	Mirmiran and Shahawy [42]	$\frac{f_{cc}}{f_{co}} = 1 + 4.269 \frac{f_l^{0.587}}{f'_{co}}$	Any type
5	Karbhari and Gao [29]	$\frac{f_{cc}}{f_{co}} = 1 + 2.1 \left(\frac{f_l}{f'_{co}}\right)^{0.87}$	Any type
6	Samaan et al. [58]	$\frac{f_{cc}}{f_{co}} = 1 + 6 \frac{f_l^{0.7}}{f'_{co}}$	Any type
7	Kono et al. [30]	$\frac{f_{cc}}{f_{co}} = 1 + 0.0572 f_l$	Any type
8	Matthys et al. [40]	$\frac{f_{cc}}{f_{co}} = 1 + 2.3 \left(\frac{f_l}{f'_{co}}\right)^{0.85}$	Any type
9	Spoelstra and Monti [60]	$\frac{f_{cc}}{f_{co}} = 0.2 + 3 \left(\frac{f_l}{f'_{co}}\right)^{0.5}$	Any type
10	Saafi et al. [55]	$\frac{f_{cc}}{f_{co}} = 1 + 2.2 \left(\frac{f_l}{f'_{co}}\right)^{0.84}$	Any type
11	Razvi and Saatcioglu [51]	$\frac{f_{cc}}{f_{co}} = 1 + 6.7 \left(\frac{f_l^{0.83}}{f'_{co}}\right)$	Any type
12	Toutanji [64]	$\frac{f_{cc}}{f_{co}} = 1 + 3.5 \left(\frac{f_l}{f'_{co}}\right)^{0.85}$	Any type
13	Miyauchi et al. [45]	$\frac{f_{cc}}{f_{co}} = 1 + 2.98 \frac{f_l}{f'_{co}}$	Any type
14	Realfonzo and Napoli [52]	$\frac{f_{cc}}{f_{co}} = 1 + 3.57 \left(\frac{f_{la}}{f'_{co}}\right)$	Any type
15	Karabinis and Rousakis [28]	$\frac{f_{cc}}{f_{co}} = 1 + 2.1 \left(\frac{f_l}{f'_{co}}\right)^{0.87}$	Any type
16	Lam and Teng [34]	$\frac{f_{cc}}{f_{co}} = 1 + 2 \frac{f_l}{f_{co}}$	Any type
17	Lam and Teng [35, 36]	$\frac{f_{cc}}{f_{co}} = 1 + 3.3 \frac{f_{la}}{f_{co}}$	Any type
18	CSTR [15]	$\frac{f_{cc}}{f_{co}} = 1 + 0.052 t_{frp} \left(\frac{E_{frp}}{df'_{co}}\right)$	Any type
19	CNR-DT200 [47]	$\frac{f_{cc}}{f_{co}} = 1 + 2.6 \left(\frac{f_l}{f'_{co}}\right)^{0.67}$	Any type
20	Bisby et al. [11] -1st eq	$\frac{f_{cc}}{f_{co}} = 1 + 2.425 \frac{f_l}{f'_{co}}$	Any type
21	Bisby et al. [11] -2nd eq	$\frac{f_{cc}}{f_{co}} = 1 + 2.217 \left(\frac{f_l}{f'_{co}}\right)^{0.911}$	Any type
22	Bisby et al. [11] -3rd eq	$\frac{f_{cc}}{f_{co}} = 1 + 3.587 f_l^{0.84}$	Any type
23	Youssef et al. [77]	$\frac{f_{cc}}{f_{co}} = 1 + 2.25 \left(\frac{f_l}{f'_{co}}\right)^{1.25}$	Any type
24	Kumutha et al. [32]	$\frac{f_{cc}}{f_{co}} = 1 + 0.93 \left(\frac{f_l}{f'_{co}}\right)$	Any type
25	Wu and Wang [73]	$\frac{f_{cc}}{f_{co}} = 1 + 2.2 \left(\frac{f_l}{f'_{co}}\right)^{0.94}$	Any type
26	Hu and Wang [24]	$\frac{f_{cc}}{f_{co}} = 0.5 + 2.7 \left(\frac{f_l}{f'_{co}}\right)^{0.68}$	Any type
27	Wu and Zhou [75]	$\frac{f_{cc}}{f_{co}} = \frac{f_l}{f_{co}} + \sqrt{\left(\frac{16.7}{f'_{co} 0.42} - \frac{f'_{co} 0.42}{16.7}\right) \frac{f_l}{f'_{co}}} + 1$	Any type
28	Wei and Wu [74]	$\frac{f_{cc}}{f_{co}} = 0.5 + 2.7 \left(\frac{f_l}{f_{co}}\right)^{0.73}$	Any type

Table 1 (continued)

No.	References	Model	FRP type
29	Pham and Hadi [49]	$\frac{f_{cc}}{f_{co}} = 0.91 + 1.88 \frac{f_l}{f_{co}} + 7.6 \frac{t_f}{df_{co}}$	Any type
30	Lobo et al. [37]	$\frac{f_{cc}}{f_{co}} = 1 + 3.1 \frac{f_{la}}{f_{co}}$	Aramid
31	Djafar-Henni and Kassoul [18]	$\frac{f_{cc}}{f_{co}} = 1 + 1.2 \left(\frac{f_l}{f_{co}} \right)^{1.25} \left(\frac{k_f}{f_{co}} \right)^{0.37}$	Aramid

Table 2 Strength models for FRP confined rectangular concrete columns

No.	References	Model	FRP type
1	Mirmiran et al. [44]	$\frac{f_{cc}}{f_{co}} = 1 + 6 \left(\frac{2R}{D} \right) \left(\frac{f_l^{0.7}}{f_{co}} \right)$	Any type
2	Shehata et al. [59]	$\frac{f_{cc}}{f_{co}} = 1 + 0.7 \left(\frac{f_l}{f_{co}} \right)$	Any type
3	Teng et al. [62]	$\frac{f_{cc}}{f_{co}} = 1 + 2.98 K_s \left(\frac{f_l}{f_{co}} \right)$	Any type
4	Lam and Teng [35, 36]	$\frac{f_{cc}}{f_{co}} = 1 + 3.3 \left(\frac{A_e}{A_c} \right) \left(\frac{f_l}{f_{co}} \right)$	Any type
5	Campione and Miraglia [12]	$\frac{f_{cc}}{f_{co}} = 1 + 2 K_s \left(\frac{f_l}{f_{co}} \right)$	Aramid
6	Ilki et al. [25]	$\frac{f_{cc}}{f_{co}} = 1 + 2.4 \left(\frac{f_{la}}{f_{co}} \right)^{1.2}$	Any type
7	Kumutha et al. [32]	$\frac{f_{cc}}{f_{co}} = 1 + 0.93 \frac{f_l}{f_{co}}$	Any type
8	Toutanji et al. [65]	$\frac{f_{cc}}{f_{co}} = 1 + 4 \left(\frac{2R}{D} \right)^{0.1} \left(\frac{D}{b} \right)^{1.2} \left(\frac{A_e}{A_c} \right) \left(\frac{f_l}{f_{co}} \right)$	Any type
9	Youssef et al. [77]	$\frac{f_{cc}}{f_{co}} = 0.5 + 1.225 \left(\frac{K_s f_l}{f_{co}} \right)^{0.6}$	Any type
10	Al-Salloum [4]	$\frac{f_{cc}}{f_{co}} = 1 + 3.14 K_s \left(\frac{b}{D} \right) \left(\frac{f_l}{f_{co}} \right)$	Any type
11	Hu and Wang [24]	$\frac{f_{cc}}{f_{co}} = 0.5 + 2.7 \left(\frac{A_e}{A_c} \right)^{2.24} \left(\frac{f_l}{f_{co}} \right)^{0.68}$	Any type
12	Wang and Wu [68]	$\frac{f_{cc}}{f_{co}} = 0.7 + 2.4 \frac{f_l}{f_{co}}$	Aramid
13	Wei and Wu [70]	$\frac{f_{cc}}{f_{co}} = 0.5 + 2.7 \left(\frac{h}{b} \right)^{-1} \left(\frac{2r}{b} \right)^{0.4} \left(\frac{f_l}{f_{co}} \right)^{0.73}$	Any type
14	ACI 440.2R-17 [2]	$\frac{f_{cc}}{f_{co}} = -1.254 + 2.254 \sqrt{1 + \frac{7.94 K_s f_l}{f_{co}}} - 2 \frac{K_s f_l}{f_{co}}$	Any type
15	Lobo et al. [37]	$\frac{f_{cc}}{f_{co}} = 1 + 4.38 \left(\frac{2r}{b} \right) \frac{f_{la}}{f_{co}}$	Aramid

ratio of FRP layers in circular column which is derived from the next equality:

$$\rho_{frp} = \frac{\pi d t_{frp}}{\pi d^2} = \frac{4 t_{frp}}{d} \quad (3)$$

Because this model was proposed for concrete columns confined by steel casing, Fardis and Khalili [19] stated that it can be used for FRP confined columns provided that the effective confinement coefficient, k_f , be modified. Since then, many strength models have been suggested by other researchers and 30 of these models are listed in Table 1.

Table 3 The proposed models for circular FRP wrapped columns

Model no.	Proposed model for FRP confined circular column
1	$f'_{cc} = f'_{co} \left(x_1 + x_2 \times \left(\frac{f_{lp}^{x_3} \times t_{lp}^{x_4} \times E_{lp}^{x_5}}{(d \times f'_{co})^{x_6}} \right) \right)^{x_7}$
2	$f'_{cc} = f'_{co} \sqrt{x_1 + x_2 \times \left(\frac{f_{lp}^{x_3} \times t_{lp}^{x_4}}{(d \times f'_{co})^{x_5}} \right)}$
3	$f'_{cc} = f'_{co} \sqrt{x_1 + x_2 \times \left(\frac{f_{lp}}{f'_{co}} \right)^{x_3} \times \left(\frac{t_{lp}}{d} \right)^{x_4}}$

It is evident that many of the relations are constructed based on the one proposed by Richart et al. [53]. Also it can be seen that the mentioned relations are functions of the same parameters, namely column diameter (d), thickness, tensile strength and modulus of elasticity of the FRP wraps (t_{frp} , f_{frp} and E_{frp}) and unconfined concrete characteristics such as compressive strength, modulus of elasticity and Poisson's ratio (f'_{co} , E_c and ν_c). It is noteworthy that in some of the models, instead the confinement pressure, the actual confinement pressure, f_{la} , is used which is derived from the following equation:

$$f_{la} = \frac{2E_{frp}\epsilon_{hrup}t_{frp}}{d} \quad (4)$$

In this relation, ϵ_{hrup} is the hoop rupture strain of FRP wraps. Since this value is not reported by the producers and therefore is not known by the designers a priori, using this parameter in the formulation of strength models is not appropriate, however it might lead to better accuracy.

3 Reviewed strength models for FRP confined rectangular columns

Based on the findings of Chaallal and shahawy [13], Mirmiran and Shahawy [42], due to non-uniform distribution of confining pressure in rectangular sections, strength models for FRP confined rectangular columns are different than the ones for circular section. This non-uniform distribution is caused by stress concentrations at the corners. Most of the existing strength model for FRP confined rectangular columns are derived based on testing of small scale samples. Because the stress concentration varies with respect to the dimensions of the specimens, it seems that large scale testing is needed to propose more reliable models. Nevertheless, several existing strength model for FRP wrapped rectangular concrete columns are listed in Table 2.

In these relations, h and b are length and width of the cross sections and D is the equivalent diameter which is derived using the following relation:

Table 5 The proposed models for rectangular FRP wrapped columns

Model no.	Proposed model for FRP confined circular columns
1	$f'_{cc} = f'_{co} \left(x_1 + \frac{\left(\frac{A_e}{A_c}\right)^{x_2} \times f_{frp}^{x_3} \times t_{frp}^{x_4}}{(D^{x_5} \times f'_{co})} \right)$
2	$f'_{cc} = f'_{co} \left(x_1 + \left(\left(\frac{A_e}{A_c} \right)^{x_2} \times \left(\frac{t_{frp}}{D} \right)^{x_3} \times \left(\frac{f_{frp}}{f'_{co}} \right)^{x_4} \right)^{x_5} \right)^{x_6}$

$$D = \sqrt{b^2 + h^2} \quad (5)$$

R is the radius of curvature for the corners of the section and K_s is a shape factor which is derived using the succeeding equation:

$$K_s = \left(\frac{b}{h} \right)^2 \frac{A_e}{A_c} \quad (6)$$

where $\frac{A_e}{A_c}$ is the ratio of confined area to the gross concrete area and can be computed by taking advantage of the following formulae:

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

$$A_g = bh - (4 - \pi)R^2 \quad (8)$$

In the present models, ρ_{sc} stands for the ratio of the longitudinal bars area to the gross concrete area. The other parameters are those which were introduced in the previous section. The only difference is that the confining pressure is computed using the following relation:

$$f_l = \frac{2f_{frp}t_{frp}}{D} = \frac{2f_{frp}t_{frp}}{\sqrt{h^2 + b^2}} \quad (9)$$

$$f_{la} = \frac{2E_{frp}\epsilon_{frp}t_{frp}}{D} = \frac{2E_{frp}\epsilon_{frp}t_{frp}}{\sqrt{h^2 + b^2}} \quad (10)$$

Table 4 Optimum coefficients of the proposed strength models for circular columns

Model no.	Optimum coefficients
1	$x_1 = 1 \ x_2 = 84251 \ x_3 = 2.67 \ x_4 = 2.75 \ x_5 = 0.03 \ x_6 = 3.2 \ x_7 = 0.2$
2	$x_1 = 1 \ x_2 = 47.46 \ x_3 = 1.3 \ x_4 = 1.4 \ x_5 = 1.47$
3	$x_1 = 1 \ x_2 = 7.72 \ x_3 = 1.46 \ x_4 = 1.36$

Table 6 Optimum coefficients of the proposed strength models for rectangular columns

Model no.	Optimum coefficients
1	$x_1 = 1 \ x_2 = 0.81 \ x_3 = 1.14 \ x_4 = 0.96 \ x_5 = 1.1$
2	$x_1 = 1 \ x_2 = 1.75 \ x_3 = 0.49 \ x_4 = 0.49 \ x_5 = 2.5$

Fig. 1 RMSE error of the confined strength models for circular sections

4 Proposed strength models for circular columns

To propose new strength models for circular columns, first a database of experimental test results on circular FRP confined concrete columns is collected. The collected database includes 200 experimental tests results, in which 100 of the tests do not reported the hoop rupture strain of FRP wraps. This database is presented in Table 7 of the Appendix. In the next step, in order to propose new relations, the 100 test results of the experimental data in Table 7 in which the hoop rupture strain is not reported, are used for nonlinear regression. Before performing nonlinear

regression, various general forms were considered to propose more accurate and practical strength models. The proposition is based on the expected or observed behavior of confined concrete. For example, when the column diameter increases, effects of the confinement on concrete strength decreased. Another expected behavior is that there must be a direct relation between confined concrete strength and the FRP strength. Having such considerations in mind, three different general models were considered. The mathematical forms of these models are presented in Table 3. The first models include FRP modulus of elasticity as an influential parameter. In addition, the suggested formulas can be categorized in two different distinct forms. In

Fig. 2 MAE error of the confined strength models for circular sections

the first two models, parameters such as column diameter, (d), thickness, tensile strength and modulus of elasticity of the FRP layers (t_{frp} , f_{frp} and E_{frp}) and unconfined concrete characteristics such as compressive strength, modulus of elasticity and Poisson's ratio (f'_{co} , E_c and ν_c) independently possess different powers. Therefore, consistent unites of measurement must be used which in the present study mm and MPa were considered. In the last model, different ratios of effective parameters are used and consequently, the proposed relations are dimensionless. The unknown coefficients for these models are computed

using nonlinear regression to provide the most accurate estimations. The obtained results are listed in Table 4.

5 Proposed strength models for rectangular columns

A methodology similar to the one used for circular columns is utilized to suggest accurate strength models for rectangular columns. For the rectangular columns, another set of existing experimental data listed in Table 8 of the Appendix are used. Again, 100 of the collected

Fig. 3 IAE error of the confined strength models for circular sections

experiments reported the value of hoop rupture strain, while in the rest this parameter is not reported. Two different models with unknown coefficients and powers are proposed. These models must provide desirable limit state behavior. According to the attained results for the circular columns, in the suggested general form effect of E_{frp} is not considered. The proposed models are listed in the following Table 5.

The unknown coefficients and powers of the suggested models are computed by performing nonlinear regression on part of the experimental data sets without

hoop rupture strain. The calculated values are presented in Table 6.

6 Performance evaluation

The part of the collected experimental data including the test results in which hoop rupture strain of FRP is reported, is used to evaluate the accuracy of the proposed models as well as the previous relations. These data collections consist of a 100 experimental results for each section

Fig. 4 R^2 of the confined strength models for circular sections

geometry which are listed in the Tables 7 and 8 of the Appendix. To evaluate the accuracy of the models, three different methods of error calculation were used which are introduced in the following.

- Root mean square error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n \left(\frac{X_{the} - X_{exp}}{X_{exp}} \right)^2}{n}} \quad (11)$$

- Mean absolute error:

$$MAE = \frac{\sum_{i=1}^n \left| \frac{X_{the} - X_{exp}}{X_{exp}} \right|}{n} \quad (12)$$

- Integral absolute error:

$$IAE = \frac{\left(\sum_{i=1}^n \sqrt{|(X_{the} - X_{exp})^2|} \right)}{\sum_{i=1}^n X_{exp}} \quad (13)$$

In the previous relations, X_{the} and X_{exp} are the theoretical and experimental values, respectively, and n stands for the number of specimens. $\bar{X}_{the}$ and $\bar{X}_{exp}$ are the mean values of the theoretical and experimental estimations, respectively. A lower value of each of these error measures indicates better accuracy of a relation. In addition to the mentioned error criteria, the coefficient of determination

Fig. 5 Scattering diagrams of experimental results versus theoretical estimations for circular sections

Fig. 6 RMSE error of the confined strength models for rectangular sections

Fig. 7 MAE error of the confined strength models for rectangular sections

Fig. 8 IAE error of the confined strength models for rectangular sections

for the experimental and theoretical values of confined strength is calculated using the following equation:

$$R^2 = \left[\frac{\left(\sum_{i=1}^n (X_{the} - \bar{X}_{the})(X_{exp} - \bar{X}_{exp}) \right)}{\left(\sqrt{\sum_{i=1}^n (X_{the} - \bar{X}_{the})^2 \sum_{i=1}^n (X_{exp} - \bar{X}_{exp})^2} \right)} \right]^2 \quad (14)$$

This parameter varies between 0 and 1 and the upper bound indicates perfect fit of a model.

Using the part of experimental data including hoop rupture strains, different error measures and the coefficient of determination are computed for the reviewed models and the proposed confined strength relations. The results for the circular sections are provided in Figs. 1, 2, 3 and 4. In addition to these error measures, the scattering diagrams of some of the models are demonstrated in Fig. 5.

Similar diagrams and charts demonstrate outcomes of the numerical evaluations for the models of rectangular sections. These diagrams are depicted in Figs. 6, 7, 8, 9 and 10.

7 Discussion

Based on the attained results for the models of FRP confined circular columns, the third proposed model is the most accurate one according to the RMSE error. The models suggested by Miyauchi et al. [45] and Fardis and Khalili [19] are in the next ranks. Considering the MAE error measure, again the third proposed model is the best performing one, and the suggested model by Miyauchi et al. [45] is the second most accurate model. However, the third best strength model based on MAE is the relation proposed by Mander et al. [38] which is in the fourth place based on RMSE results. It should be noted that the

Fig. 9 R^2 of the confined strength models for rectangular sections

relation suggested by Fardis and Khalili [19] is still one of the best performing models and is ranked four among the 35 evaluated models. The four mentioned models again are the top four according to the IAE error criteria, but this time the relation proposed by Miyauchi et al. [45] is the best one and the third proposed model, and the relations suggested by Mander et al. [38] and Fardis and Khalili [19] are in the next places.

Considering the Fig. 4, the coefficient of determination for most of the evaluated models is about 0.9, which shows acceptable performance of most the models based on this criterion. However, there are exceptions such as the models suggested by Richart et al. [53] Samaan et al. [58] and Karabinis and Rousakis [28], which have R^2 value as low as 0.55. This value shows that there is no meaningful correlation between experimental and theoretical values estimated by these models. Based on the overall outcomes, it is possible to claim that the third proposed model is the most accurate one among the evaluated strength models. Another advantage of this relation is its dimensionless property. On the other hand, the very promising performance of the models suggested by Fardis and Khalili [19] and Mander et al. [38] is an interesting finding knowing that these are among the first proposed models. Besides the Fardis and Khalili [19] model has a simple non-dimensional form, which makes it more interesting for design purpose. Another ironic finding is the poor performance

of the relation suggested by CNR-DT200 [15] for design of FRP confined concrete columns. This results justifies the main motivation of this study and shows that the models currently suggested by design codes may not be the most accurate and reliable ones. Regarding the models which are proposed for special type of FRP, such as those suggested by Lobo et al. [37] or Djafar-Henni and Kassoul [18] as it was expected, their performance for general type of FRP is not satisfactory.

In the case of rectangular models, based on RMSE error, the second proposed model is the most accurate one and the models proposed by Lobo et al. [37], Campione and Miraglia [12] and Mirmiran et al. [44] are the next places. Again, the poor performance of the relation suggested by ACI440-17 [2] is really questionable. Considering the MAE error, the top four models are the same, with this difference that the models proposed by Mirmiran et al. [44] is the third one, and the Campione and Miraglia [12] relation ranked fourth. The situation is the same for IAE error measure, with the difference that the proposed relation by Lobo et al. [37] is the best method. In the case of coefficient of determination, the situation is completely different with the circular models. All of the evaluated models have R^2 value less than 0.8. This indicates lack of correlation between experimental and estimated confined strength for rectangular sections. According to the overall results, it seems that the second proposed model is the most

Fig. 10 Scattering diagrams of experimental results versus theoretical estimations for rectangular sections

accurate one. There are few interesting findings. First of all, it is surprising that the model suggested by Lobo et al. [37] for Aramid FRP perform very well for estimating ultimate strength of rectangular concrete columns confined by any type of FRP wraps. Moreover, the very poor performance of the relation proposed by ACI-440 was unexpected and again proves importance of the present study.

8 Conclusion

In this paper, several existing strength models for FRP confined columns were reviewed briefly, and their accuracy were evaluated based on the experimental outcomes. In addition, new more accurate models were proposed based on outcomes of nonlinear regression on the set of experimental data recorded from literature review. Based on the performed calculation and accuracy evaluation of the suggested models it is revealed that the relations suggested by some of the current design code and standards perform unexpectedly poor in estimating strength of FRP confined concrete columns. Moreover, it is shown that many of the earlier models are more accurate than the more recent ones. These findings prove importance of an extensive review program to determine accuracy and reliability of countless available confined strength model. In fact, this was the main motivation of the present study, as well.

Based on the implemented numerical evaluation it is concluded that two of the proposed models in this study perform better than the other reviewed models. These models for the FRP confined circular and rectangular concrete columns are as follows:

$$f'_{cc} = f'_{co} \sqrt{\left(1 + 7.72 \left(\frac{f_{frp}}{f'_{co}}\right)^{1.46} \left(\frac{t_{frp}}{d}\right)^{1.36}\right)} \quad \text{For circular cross sections}$$

$$f'_{cc} = f'_{co} \left(1 + \left(\frac{A_e}{A_c}\right)^{1.75} \left(\frac{t_{frp}}{D}\right)^{0.49} \left(\frac{f_{frp}}{f'_{co}}\right)^{0.49}\right)^{2.5}$$

For rectangular cross sections

Based on the collected experimental database, the average error of these models is about 13.0% and 15.5% respectively. Moreover, R^2 value for these models is about 0.7 and 0.9, respectively. In addition to the higher accuracy, the proposed models are dimensionless which facilitates their application for design purposes.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

The collected experimental data for circular and rectangular columns in this study, are listed in Tables 7 and 8.

Table 7 Collected experimental data for circular columns

No	Reference	Concrete prop- erties		Specimen dimensions		AFRP properties			Experimental outcome			
		f_{co} (MPa)	ε_{co} (%)	d (mm)	L (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{hrup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type
1	Kshirsagar et al. [31]	38	0.22	102	204	363	19,900	1.42	1.74	57	1.73	E glass
2		39.4	0.22	102	204	363	19,900	1.42	2.07	63.1	1.6	E glass
3		39.5	0.22	102	204	363	19,900	1.42	1.89	60.4	1.79	E glass
4		38	0.22	102	204	363	19,900	1.42	1.74	57	1.73	E glass
5		39.4	0.22	102	204	363	19,900	1.42	2.07	63.1	1.6	E glass
6		39.5	0.22	102	204	363	19,900	1.42	1.89	60.4	1.79	E glass
7		38	0.22	102	204	363	19,900	1.42	1.74	57	1.73	E glass
8		39.4	0.22	102	204	363	19,900	1.42	2.07	63.1	1.6	E glass
9		39.5	0.22	102	204	363	19,900	1.42	1.89	60.4	1.79	E glass
10		38	0.22	102	204	363	19,900	1.42	1.74	57	1.73	E glass
11		39.4	0.22	102	204	363	19,900	1.42	2.07	63.1	1.6	E glass
12		39.5	0.22	102	204	363	19,900	1.42	1.89	60.4	1.79	E glass
13	Xiao and Wu [76]	33.7	0.23	152	305	1577	105,000	0.38	0.84	47.9	1.2	Carbon
14		33.7	0.23	152	305	1577	105,000	0.38	0.85	49.7	1.4	Carbon
15		33.7	0.23	152	305	1577	105,000	0.76	0.88	64.6	1.65	Carbon
16		33.7	0.23	152	305	1577	105,000	0.76	0.98	75.2	2.25	Carbon
17		33.7	0.23	152	305	1577	105,000	1.14	0.76	82.9	2.45	Carbon
18		33.7	0.23	152	305	1577	105,000	1.14	0.48	86.2	2.85	Carbon
19		43.8	0.22	152	305	1577	105,000	0.38	0.82	54.8	0.98	Carbon
20		43.8	0.22	152	305	1577	105,000	0.38	0.79	52.1	0.47	Carbon
21		43.8	0.22	152	305	1577	105,000	0.76	0.99	84	1.57	Carbon
22		43.8	0.22	152	305	1577	105,000	0.76	0.99	79.2	1.37	Carbon
23		43.8	0.22	152	305	1577	105,000	1.14	0.77	96.5	1.74	Carbon
24		43.8	0.22	152	305	1577	105,000	1.14	0.83	92.6	1.68	Carbon
25		55.2	0.27	152	305	1577	105,000	0.38	0.68	57.9	0.69	Carbon
26		55.2	0.27	152	305	1577	105,000	0.38	0.64	62.9	0.48	Carbon
27		55.2	0.27	152	305	1577	105,000	0.76	0.52	74.6	1.21	Carbon
28		55.2	0.27	152	305	1577	105,000	0.76	0.53	77.6	0.81	Carbon
29		55.2	0.27	152	305	1577	105,000	1.14	0.72	108	1.45	Carbon
30		55.2	0.27	152	305	1577	105,000	1.14	0.70	103.3	1.18	Carbon
31		33.7	0.23	152	305	1577	105,000	0.38	0.84	47.9	1.2	Carbon
32	Aire et al. [3]	30	0.24	150	300	3000	65,000	0.149	0.55	41	0.73	Glass Sheet
33		30	0.24	150	300	3000	65,000	0.447	1.3	61	1.74	Glass Sheet
34		30	0.24	150	300	3000	65,000	0.894	1.1	85	2.5	Glass Sheet
35		30	0.24	150	300	3900	240,000	0.117	0.95	46	1.1	Carbon
36		30	0.24	150	300	3900	240,000	0.351	1.05	77	2.26	Carbon
37		30	0.24	150	300	3900	240,000	0.702	1.06	108	3.23	Carbon
38		60	0.24	150	300	3900	240,000	0.149	0.62	79	0.47	Carbon
39		60	0.24	150	300	3900	240,000	0.447	0.74	81	0.78	Carbon
40		60	0.24	150	300	3900	240,000	0.894	1.1	107	1.24	Carbon
41		60	0.24	150	300	3900	240,000	1.341	1.05	137	1.42	Carbon

Table 7 (continued)

No	Reference	Concrete prop- erties		Specimen dimensions		AFRP properties			Experimental outcome			
		f_{co} (MPa)	ε_{co} (%)	d (mm)	L (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{hrup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type
42		60	0.24	150	300	3900	240,000	1.788	1.11	170	1.42	Carbon
43		60	0.24	150	300	3000	65,000	0.149	0.09	94	0.28	Glass Sheet
44		60	0.24	150	300	3000	65,000	0.447	1.03	99	1.01	Glass Sheet
45		60	0.24	150	300	3000	65,000	0.894	1.08	156	1.6	Glass Sheet
46		60	0.24	150	300	3000	65,000	1.341	1.19	199	2.21	Glass Sheet
47		60	0.24	150	300	3000	65,000	1.788	0.84	217	1.96	Glass Sheet
48	Dias da silva and Santos [17]	28.2	N.r	150	600	3700	240,000	0.111	0.26	31.4	0.39	Carbon
49		28.2	N.r	150	600	3700	240,000	0.222	1.18	57.4	2.05	Carbon
50		28.2	N.r	150	600	3700	240,000	0.333	1.14	69.5	2.59	Carbon
51		28.2	N.r	150	600	3000	390,000	0.167	0.37	41.5	0.75	HM Carbon
52		28.2	N.r	150	600	3000	39,0000	0.334	0.69	65.6	1.81	HM Carbon
53		28.2	N.r	150	600	3000	39,0000	0.501	0.64	79.4	1.69	HM Carbon
54	Micelli et al. [41]	37	N.r	102	204	3790	22,7000	0.16	1.2	60	1.02	Carbon
55		32	N.r	102	204	1520	72,000	0.35	1.25	52	1.25	Glass
56	Wang and Cheong [66]	27.9	0.16	200	600	4400	235,000	0.36	0.85	82	1.52	Carbon
57	Shehata et al. [73]	29.8	0.21	150	300	3550	235,000	0.165	1.23	57	1.23	Carbon
58		29.8	0.21	150	300	3550	235,000	0.33	1.19	72.1	1.74	Carbon
59	Berthet et al. [10]	20	N.r	160	320	3200	230,000	0.165	0.96	42.8	1.63	Carbon
60		20	N.r	160	320	3200	230,000	0.165	0.96	37.8	0.93	Carbon
61		20	N.r	160	320	3200	230,000	0.165	0.96	45.8	1.67	Carbon
62		20	N.r	160	320	3200	230,000	0.33	0.90	56.7	1.73	Carbon
63		20	N.r	160	320	3200	230,000	0.33	0.91	55.2	1.58	Carbon
64		20	N.r	160	320	3200	230,000	0.33	0.91	56.1	1.68	Carbon
65		20	N.r	160	320	2500	74,000	0.33	1.66	42.8	1.70	Glass
66		20	N.r	160	320	2500	74,000	0.33	1.64	42.3	1.69	Glass
67		20	N.r	160	320	2500	74,000	0.33	1.67	43.1	1.71	Glass
68		40	N.r	160	320	3200	230,000	0.11	1.02	49.8	0.55	Carbon
69		40	N.r	160	320	3200	230,000	0.11	0.95	50.8	0.66	Carbon
70		40	N.r	160	320	3200	230,000	0.11	1.20	48.8	0.61	Carbon
71		40	N.r	160	320	3200	230,000	0.165	0.88	53.7	0.66	Carbon
72		40	N.r	160	320	3200	230,000	0.165	0.85	54.7	0.62	Carbon
73		40	N.r	160	320	3200	230,000	0.165	1.04	51.8	0.64	Carbon
74		40	N.r	160	320	3200	230,000	0.22	0.79	59.7	0.60	Carbon
75		40	N.r	160	320	3200	230,000	0.22	0.83	60.7	0.69	Carbon
76		40	N.r	160	320	3200	230,000	0.22	0.81	60.2	0.73	Carbon
77		40	N.r	160	320	3200	230,000	0.44	0.92	91.6	1.44	Carbon
78		40	N.r	160	320	3200	230,000	0.44	9.67	89.6	1.36	Carbon
79		40	N.r	160	320	3200	230,000	0.44	0.89	86.6	1.17	Carbon
80		40	N.r	160	320	3200	230,000	0.99	0.99	142.4	2.46	Carbon
81		40	N.r	160	320	3200	230,000	0.99	1.00	140.4	2.39	Carbon
82		40	N.r	160	320	3200	230,000	1.32	1.00	166.3	2.70	Carbon
83		40	N.r	160	320	2500	74,000	0.22	1.37	44.8	0.53	Glass

Table 7 (continued)

No	Reference	Concrete prop- erties		Specimen dimensions		AFRP properties			Experimental outcome			
		f_{co} (MPa)	ε_{co} (%)	d (mm)	L (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{hrup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type
84		40	N.r	160	320	2500	74,000	0.22	1.25	46.3	0.47	Glass
85		40	N.r	160	320	2500	74,000	0.22	1.08	49.8	0.50	Glass
86		40	N.r	160	320	2500	74,000	0.33	0.90	50.8	0.63	Glass
87		40	N.r	160	320	2500	74,000	0.33	1.28	50.8	0.58	Glass
88		40	N.r	160	320	2500	74,000	0.33	1.20	51.8	0.64	Glass
89		40	N.r	160	320	2500	74,000	0.55	1.55	66.7	1.05	Glass
90		40	N.r	160	320	2500	74,000	0.55	1.82	68.2	1.24	Glass
91		40	N.r	160	320	2500	74,000	0.55	1.58	67.7	1.17	Glass
92		50	N.r	160	320	3200	230,000	0.33	0.93	82.6	0.83	Carbon
93		50	N.r	160	320	3200	230,000	0.33	0.87	82.8	0.70	Carbon
94		50	N.r	160	320	3200	230,000	0.33	0.89	82.3	0.77	Carbon
95		50	N.r	160	320	3200	230,000	0.66	0.67	108.1	1.14	Carbon
96		50	N.r	160	320	3200	230,000	0.66	0.87	112	1.12	Carbon
97		50	N.r	160	320	3200	230,000	0.66	0.88	107.9	1.12	Carbon
98		50	N.r	160	320	2500	74,000	0.495	1.12	64.7	0.53	Glass
99		50	N.r	160	320	2500	74,000	0.495	1.27	75.1	1.13	Glass
100		50	N.r	160	320	2500	74,000	0.495	1.27	76.1	1.17	Glass
101	Howie and Karbhari [23]	38.6	N.r	152	305	755	73,300	0.31	N.r	45.5	N.r	Carbon
102		38.6	N.r	152	305	755	73,300	0.31	N.r	41.9	N.r	Carbon
103		38.6	N.r	152	305	755	73,300	0.31	N.r	47.2	N.r	Carbon
104		38.6	N.r	152	305	1047	70,600	0.61	N.r	56.5	N.r	Carbon
105		38.6	N.r	152	305	1047	70,600	0.61	N.r	60.6	N.r	Carbon
106		38.6	N.r	152	305	1047	70,600	0.61	N.r	61.9	N.r	Carbon
107		38.6	N.r	152	305	1105	77,500	0.92	N.r	80.9	N.r	Carbon
108		38.6	N.r	152	305	1105	77,500	0.92	N.r	76.4	N.r	Carbon
109		38.6	N.r	152	305	1105	77,500	0.92	N.r	75.8	N.r	Carbon
110		38.6	N.r	152	305	1352	95,700	1.22	N.r	89.5	N.r	Carbon
111		38.6	N.r	152	305	1352	95,700	1.22	N.r	89.9	N.r	Carbon
112		38.6	N.r	152	305	1352	95,700	1.22	N.r	89	N.r	Carbon
113		38.6	N.r	152	305	660	39,900	0.61	N.r	47.1	N.r	Carbon
114		38.6	N.r	152	305	660	39,900	0.61	N.r	47.7	N.r	Carbon
115		38.6	N.r	152	305	660	39,900	0.61	N.r	50	N.r	Carbon
116		38.6	N.r	152	305	822	54,000	0.92	N.r	68.3	N.r	Carbon
117		38.6	N.r	152	305	822	54,000	0.92	N.r	67.3	N.r	Carbon
118		38.6	N.r	152	305	822	54,000	0.92	N.r	64.7	N.r	Carbon
119		38.6	N.r	152	305	388	27,700	1.22	N.r	52.7	N.r	Carbon
120		38.6	N.r	152	305	388	27,700	1.22	N.r	49.3	N.r	Carbon
121		38.6	N.r	152	305	388	27,700	1.22	N.r	52.6	N.r	Carbon
122		38.6	N.r	152	305	755	73,300	0.31	N.r	45.5	N.r	Carbon
123		38.6	N.r	152	305	755	73,300	0.31	N.r	41.9	N.r	Carbon
124		38.6	N.r	152	305	755	73,300	0.31	N.r	47.2	N.r	Carbon
125		38.6	N.r	152	305	1047	70,600	0.61	N.r	56.5	N.r	Carbon

Table 7 (continued)

No	Reference	Concrete prop- erties		Specimen dimensions		AFRP properties			Experimental outcome			
		f_{co} (MPa)	ε_{co} (%)	d (mm)	L (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{hrup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type
126	Mirmiran et al. [43]	30.9	N.r	153	305	524	37,233	1.45	N.r	53.7	3.1	E glass
127		30.9	N.r	153	305	524	40,336	1.45	N.r	56.5	3.3	E glass
128		30.9	N.r	153	305	579	40,336	2.21	N.r	72.9	4.1	E glass
129		30.9	N.r	153	305	579	40,336	2.21	N.r	65.7	2.9	E glass
130		30.9	N.r	153	305	579	40,749	2.21	N.r	78	4.4	E glass
131		30.9	N.r	153	305	641	40,749	2.97	N.r	85.7	4.4	E glass
132		30.9	N.r	153	305	641	37,233	2.97	N.r	86.8	4.7	E glass
133		29.6	N.r	153	305	524	37,233	1.45	N.r	67.1	2.9	E glass
134		29.6	N.r	153	305	524	37,233	1.45	N.r	55.3	3.8	E glass
135		29.6	N.r	153	305	524	40,336	1.45	N.r	60.2	3.8	E glass
136		29.6	N.r	153	305	579	40,336	2.21	N.r	74.6	4.3	E glass
137		29.6	N.r	153	305	579	40,336	2.21	N.r	93	4.3	E glass
138		29.6	N.r	153	305	579	40,749	2.21	N.r	71.7	3.9	E glass
139		29.6	N.r	153	305	641	40,749	2.97	N.r	86.2	4.6	E glass
140		29.6	N.r	153	305	641	40,749	2.97	N.r	114.7	5.3	E glass
141		29.6	N.r	153	305	641	37,233	2.97	N.r	87.4	4.1	E glass
142		32	N.r	153	305	524	37,233	1.45	N.r	59.1	3.4	E glass
143		32	N.r	153	305	524	40,336	1.45	N.r	60.8	3.4	E glass
144		32	N.r	153	305	579	40,336	2.21	N.r	77.4	3.8	E glass
145		32	N.r	153	305	579	40,749	2.21	N.r	77.1	3.8	E glass
146		32	N.r	153	305	641	40,749	2.97	N.r	86.1	4.2	E glass
147		32	N.r	153	305	641	37,233	2.97	N.r	84	4.3	E glass
148		44.8	N.r	153	305	524	37,233	1.45	N.r	63	N.r	E glass
149		44.8	N.r	153	305	524	40,336	1.45	N.r	57	N.r	E glass
150		44.8	N.r	153	305	579	40,336	2.21	N.r	83.2	N.r	E glass
151		44.8	N.r	153	305	579	40,749	2.21	N.r	75.4	N.r	E glass
152		44.8	N.r	153	305	641	40,749	2.97	N.r	104.5	N.r	E glass
153	La Tegola and Manni [33]	25.6	N.r	150	300	652	25,250	3.34	N.r	71	N.r	E glass
154		25.6	N.r	150	300	652	25,250	3.34	N.r	71.3	N.r	E glass
155		25.6	N.r	150	300	652	25,250	3.34	N.r	74.7	N.r	E glass
156		25.6	N.r	150	300	652	25,250	3.34	N.r	79.2	N.r	E glass
157		25.6	N.r	150	300	652	25,250	3.34	N.r	81.5	N.r	E glass
158		25.6	N.r	150	300	652	25,250	3.34	N.r	77.5	N.r	E glass
159		25.6	N.r	150	300	652	25,250	3.34	N.r	89.9	N.r	E glass
160		25.6	N.r	150	300	670	25,450	5.03	N.r	98.5	N.r	E glass
161	Ilki et al. [26]	9.88	0.21	250	500	3430	230,000	0.165	N.r	29.07	2.2	Carbon
162		10.11	0.21	250	500	3430	230,000	0.165	N.r	30.56	2.4	Carbon
163		10.2	0.21	250	500	3430	230,000	0.495	N.r	54.68	4.5	Carbon
164		10.41	0.21	250	500	3430	230,000	0.495	N.r	59.67	5.4	Carbon
165		10.41	0.21	250	500	3430	230,000	0.495	N.r	34.92	2.8	Carbon
166		10.41	0.21	250	500	3430	230,000	0.495	N.r	32.29	3.2	Carbon

Table 7 (continued)

No	Reference	Concrete prop- erties		Specimen dimensions		AFRP properties			Experimental outcome			
		f_{co} (MPa)	ε_{co} (%)	d (mm)	L (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{hrup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type
167	Wu and Jiang [71, 72]	9.88	0.21	250	500	3430	230,000	0.825	N.r	85.18	6.5	Carbon
168		10.41	0.21	250	500	3430	230,000	0.825	N.r	91.93	6.6	Carbon
169		28.7	0.113	150	300	3400	230,000	0.167	N.r	59.34	1.72	Carbon
170		28.7	0.113	150	300	3400	230,000	0.167	N.r	54.82	1.44	Carbon
171		30.1	0.113	150	300	3400	230,000	0.334	N.r	88.14	2.17	Carbon
172	Jiang et al. [27]	30.1	0.113	150	300	3400	230,000	0.334	N.r	90.40	2.16	Carbon
173		28.38	0.237	150	300	3400	230,000	0.167	N.r	56.6	2.33	Carbon
174		28.38	0.237	150	300	3400	230,000	0.167	N.r	55.6	2.44	Carbon
175		28.38	0.237	150	300	3400	230,000	0.334	N.r	86.27	3.61	Carbon
176		28.38	0.237	150	300	3400	230,000	0.334	N.r	85.59	3.57	Carbon
177		28.38	0.237	150	300	3400	230,000	0.501	N.r	117.16	4.55	Carbon
178		28.38	0.237	150	300	3400	230,000	0.501	N.r	118.57	4.82	Carbon
179		29.88	0.215	150	300	3400	230,000	0.167	N.r	56.78	2.26	Carbon
180		29.88	0.215	150	300	3400	230,000	0.167	N.r	50.77	1.66	Carbon
181		29.88	0.215	150	300	3400	230,000	0.334	N.r	86.78	3.43	Carbon
182		29.88	0.215	150	300	3400	230,000	0.334	N.r	89.38	3.62	Carbon
183		29.88	0.215	150	300	3400	230,000	0.501	N.r	116.25	4.5	Carbon
184		29.88	0.215	150	300	3400	230,000	0.501	N.r	108.9	4.06	Carbon
185		28.36	0.232	150	300	3400	230,000	0.167	N.r	51.47	1.59	Carbon
186		28.36	0.232	150	300	3400	230,000	0.167	N.r	55.45	1.84	Carbon
187		28.36	0.232	150	300	3400	230,000	0.334	N.r	82.02	2.8	Carbon
188		28.36	0.232	150	300	3400	230,000	0.334	N.r	83.61	3.06	Carbon
189		28.36	0.232	150	300	3400	230,000	0.501	N.r	111.33	4.11	Carbon
190		28.36	0.232	150	300	3400	230,000	0.501	N.r	109.92	3.77	Carbon
191		38.58	0.199	150	300	3400	230,000	0.167	N.r	67.04	1.64	Carbon
192		38.58	0.199	150	300	3400	230,000	0.167	N.r	66.61	1.57	Carbon
193		38.58	0.199	150	300	3400	230,000	0.334	N.r	102.5	2.63	Carbon
194		38.58	0.199	150	300	3400	230,000	0.334	N.r	100.75	2.72	Carbon
195		38.58	0.199	150	300	3400	230,000	0.501	N.r	130.62	3.38	Carbon
196		38.58	0.199	150	300	3400	230,000	0.501	N.r	132.48	3.62	Carbon
197		28.7	0.113	150	300	3400	230,000	0.167	N.r	59.34	1.72	Carbon
198		28.7	0.113	150	300	3400	230,000	0.167	N.r	54.82	1.44	Carbon
199		30.1	0.113	150	300	3400	230,000	0.334	N.r	88.14	2.17	Carbon
200		30.1	0.113	150	300	3400	230,000	0.334	N.r	90.40	2.16	Carbon

Table 8 Collected experimental data for rectangular columns

No.	References	Concrete properties			Specimen Dimensions			FRP properties		Experimental Outcomes			
		f_{co} (MPa)	ε_{co} (%)	b (mm)	h (mm)	L (mm)	r (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{hrup} (%)	f_{cc} (MPa)	ε_{cu} (%)
1	Chaallal et al. [14]	20.7	0.2	133	133	305	25.4	3650	231,000	0.033	0.4	26.20	0.35
2		20.7	0.2	133	133	305	25.4	3650	231,000	0.066	0.5	30.75	0.42
3		20.7	0.2	133	133	305	25.4	3650	231,000	0.099	0.52	36.40	0.55
4		20.7	0.2	133	133	305	25.4	3650	231,000	0.132	0.527	42.20	0.65
5		20.7	0.2	108	165	305	25.4	3650	231,000	0.099	0.6	41.23	0.60
6		20.7	0.2	108	165	305	25.4	3650	231,000	0.132	0.5	47.64	0.60
7		20.7	0.2	95	191	305	25.4	3650	231,000	0.099	0.6	37.92	0.65
8		20.7	0.2	95	191	305	25.4	3650	231,000	0.132	0.5	42.20	0.60
9		41.4	0.25	133	133	305	25.4	3650	231,000	0.033	0.08	58.95	0.28
10		41.4	0.25	133	133	305	25.4	3650	231,000	0.099	0.15	68.90	0.38
11		41.4	0.25	108	165	305	25.4	3650	231,000	0.033	0.1	66.14	0.28
12		41.4	0.25	108	165	305	25.4	3650	231,000	0.066	0.12	68.79	0.32
13		41.4	0.25	108	165	305	25.4	3650	231,000	0.132	0.18	53.12	0.38
14		41.4	0.25	95	191	305	25.4	3650	231,000	0.033	0.07	57.32	0.28
15		41.4	0.25	95	191	305	25.4	3650	231,000	0.099	0.1	60.36	0.31
16		41.4	0.25	95	191	305	25.4	3650	231,000	0.132	0.15	63.21	0.31
17	Rousakis et al. [54]	33	1.71	200	200	320	30	4500	240,000	0.117	1.55	38.44	0.48
18		33	1.71	200	200	320	30	4500	240,000	0.351	1.55	45.9	1.01
19		33	1.71	200	200	320	30	2800	65,000	0.414	2.8	42.55	0.60
20		33	1.71	200	200	320	30	2800	65,000	1.242	2.8	51.9	1.12
21		34	1.86	200	200	320	30	4500	240,000	0.117	1.55	42.19	0.40
22		34	1.86	200	200	320	30	4500	240,000	0.585	1.55	54.57	1.40
23		38	2.24	200	200	320	30	2800	65,000	0.414	2.8	40.36	0.58
24		38	2.24	200	200	320	30	2800	65,000	0.816	2.8	52.83	0.94
25		38	2.24	200	200	320	30	2800	65,000	1.242	2.8	59.76	2.21
26		40	1.465	200	200	320	30	2800	65,000	0.414	2.8	43.14	0.31
27	Wang and Wu [67]	40	1.465	200	200	320	30	2800	65,000	0.816	2.8	54.17	0.82
28		40	1.465	200	200	320	30	2800	65,000	1.242	2.8	59.5	1.67
29		32.9	0.25	150	150	300	15	3482	230,500	0.165	0.98	38.8	0.80
30		32.2	0.25	150	150	300	15	3482	230,500	0.165	0.98	31	0.53
31		30.7	0.25	150	150	300	15	3482	230,500	0.165	0.98	30.8	0.41
32		31.9	0.25	150	150	300	15	3482	230,500	0.165	0.98	33.6	0.70
33		32.6	0.25	150	150	300	30	3482	230,500	0.165	1.72	43.4	1.70
34		31.1	0.25	150	150	300	30	3482	230,500	0.165	1.72	38.8	1.18
35		33.1	0.25	150	150	300	30	3482	230,500	0.165	1.72	37.1	0.90
36		32.3	0.25	150	150	300	30	3482	230,500	0.165	1.72	39.8	1.60

Table 8 (continued)

No.	References	Concrete properties				Specimen Dimensions			FRP properties			Experimental Outcomes			
		f_{co} (MPa)	ε_{co} (%)	b (mm)	h (mm)	L (mm)	r (mm)		f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{frup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type
37		30.1	0.25	150	150	300	45		3482	230,500	0.165	1.64	48.3	2.00	Carbon
38		32.6	0.25	150	150	300	45		3482	230,500	0.165	1.64	42.1	1.37	Carbon
39		29.3	0.25	150	150	300	45		3482	230,500	0.165	1.64	40.8	1.57	Carbon
40		30.7	0.25	150	150	300	45		3482	230,500	0.165	1.64	43.7	1.60	Carbon
41		30.9	0.25	150	150	300	60		3482	230,500	0.165	1.08	50.9	1.78	Carbon
42		31.1	0.25	150	150	300	60		3482	230,500	0.165	1.08	51.7	1.89	Carbon
43		33.5	0.25	150	150	300	60		3482	230,500	0.165	1.08	47.3	1.43	Carbon
44		32.9	0.25	150	150	300	15		3482	230,500	0.33	0.88	40.5	2.20	Carbon
45		32.2	0.25	150	150	300	15		3482	230,500	0.33	0.88	43.6	3.00	Carbon
46		31.9	0.25	150	150	300	15		3482	230,500	0.33	0.88	42.2	2.61	Carbon
47		32.6	0.25	150	150	300	30		3482	230,500	0.33	1.21	58.1	3.20	Carbon
48		33.1	0.25	150	150	300	30		3482	230,500	0.33	1.21	53.8	2.30	Carbon
49		32.3	0.25	150	150	300	30		3482	230,500	0.33	1.21	56.5	2.10	Carbon
50		30.1	0.25	150	150	300	45		3482	230,500	0.33	1.62	64.6	2.57	Carbon
51		32.6	0.25	150	150	300	45		3482	230,500	0.33	1.62	69.4	3.30	Carbon
52		29.3	0.25	150	150	300	45		3482	230,500	0.33	1.62	70.1	3.80	Carbon
53		30.7	0.25	150	150	300	45		3482	230,500	0.33	1.62	68	2.40	Carbon
54		30.9	0.25	150	150	300	60		3482	230,500	0.33	1.48	81.1	3.20	Carbon
55		31.1	0.25	150	150	300	60		3482	230,500	0.33	1.48	73.6	2.90	Carbon
56		33.5	0.25	150	150	300	60		3482	230,500	0.33	1.48	82.1	3.30	Carbon
57		31.8	0.25	150	150	300	60		3482	230,500	0.33	1.48	78.9	3.00	Carbon
58		54.7	0.25	150	150	300	15		3500	230,000	0.165	1.50	55	0.45	Carbon
59		55.2	0.25	150	150	300	15		3500	230,000	0.165	1.50	56.1	0.36	Carbon
60		52.5	0.25	150	150	300	15		3500	230,000	0.165	1.50	56.2	0.36	Carbon
61		54.1	0.25	150	150	300	15		3500	230,000	0.165	1.50	55.8	0.38	Carbon
62		53.5	0.25	150	150	300	30		3500	230,000	0.165	1.00	56.2	0.42	Carbon
63		53.1	0.25	150	150	300	30		3500	230,000	0.165	1.00	55.5	0.40	Carbon
64		49.4	0.25	150	150	300	30		3500	230,000	0.165	1.00	56	0.33	Carbon
65		52	0.25	150	150	300	30		3500	230,000	0.165	1.00	55.9	0.32	Carbon
66		53.2	0.25	150	150	300	45		3500	230,000	0.165	1.57	56.4	0.66	Carbon
67		51.5	0.25	150	150	300	45		3500	230,000	0.165	1.57	58.4	0.72	Carbon
68		53.3	0.25	150	150	300	45		3500	230,000	0.165	1.57	57.9	0.68	Carbon
69		52.7	0.25	150	150	300	45		3500	230,000	0.165	1.57	57.6	0.70	Carbon
70		53.9	0.25	150	150	300	60		3500	230,000	0.165	1.00	62.4	1.00	Carbon
71		52	0.25	150	150	300	60		3500	230,000	0.165	1.00	62.7	0.96	Carbon

Table 8 (continued)

No.	References	Concrete properties				Specimen Dimensions			FRP properties			Experimental Outcomes		
		f_{co} (MPa)	ε_{co} (%)	b (mm)	h (mm)	L (mm)	r (mm)		f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{frup} (%)	f_{cc} (MPa)	ε_{cu} (%)
72		52.3	0.25	150	150	300	60		3500	230,000	0.165	1.00	62.8	0.98
73		52.7	0.25	150	150	300	60		3500	230,000	0.165	1.00	62.6	0.91
74		54.7	0.25	150	150	300	15		3500	230,000	0.33	1.42	59.6	0.38
75		55.2	0.25	150	150	300	15		3500	230,000	0.33	1.42	59.6	0.38
76		52.5	0.25	150	150	300	15		3500	230,000	0.33	1.42	59	0.45
77		54.1	0.25	150	150	300	15		3500	230,000	0.33	1.42	59.4	0.48
78		53.5	0.25	150	150	300	30		3500	230,000	0.33	1.38	65.2	0.64
79		53.1	0.25	150	150	300	30		3500	230,000	0.33	1.38	61.4	0.60
80		49.4	0.25	150	150	300	30		3500	230,000	0.33	1.38	62.5	0.54
81		52	0.25	150	150	300	30		3500	230,000	0.33	1.38	63	0.58
82		53.2	0.25	150	150	300	45		3500	230,000	0.33	1.39	81.3	1.27
83		51.5	0.25	150	150	300	45		3500	230,000	0.33	1.39	78.8	1.19
84		53.3	0.25	150	150	300	45		3500	230,000	0.33	1.39	80.9	1.24
85		52.7	0.25	150	150	300	45		3500	230,000	0.33	1.39	80.3	1.23
86		53.9	0.25	150	150	300	60		3500	230,000	0.33	1.23	89.7	1.59
87		52	0.25	150	150	300	60		3500	230,000	0.33	1.23	90.9	1.64
88		52.3	0.25	150	150	300	60		3500	230,000	0.33	1.23	90.4	1.59
89		52.7	0.25	150	150	300	60		3500	230,000	0.33	1.23	89.8	1.60
90	Wang et al. [69]	25.5	0.32	305	305	915	30		4340	240,000	0.167	0.843	17.20	0.79
91		25.5	0.32	305	305	915	30		4340	240,000	0.167	0.735	24.1	1.54
92		25.5	0.32	305	305	915	30		4340	240,000	0.501	1.103	33.3	2.25
93		25.5	0.32	305	305	915	30		4340	240,000	0.167	1.307	29.6	1.83
94		25.5	0.32	305	305	915	30		4340	240,000	0.334	1.002	30.9	2.10
95		25.5	0.32	204	204	612	20		4340	240,000	0.334	1.212	31.4	2.29
96		25.5	0.32	204	204	612	20		4340	240,000	0.167	1.387	34.4	2.97
97		25.5	0.32	204	204	612	20		4340	240,000	0.334	1.064	40	3.59
98		25.5	0.32	204	204	612	20		4340	240,000	0.167	1.339	31.6	2.56
99		25.5	0.32	204	204	612	20		4340	240,000	0.334	1.41	40.8	4.23
100	Abbasnia and Ziaadiny [1]	32	N.r	150	150	300	13.6		3944	241,000	0.35	0.99	39.18	2.05
101		32	N.r	150	150	300	22.6		3944	241,000	0.35	0.91	45.57	1.85
102		34	N.r	150	150	300	34.5		3944	241,000	0.35	1.09	51.4	1.71
103		34	N.r	150	150	300	42		3944	241,000	0.35	1.11	52.21	1.36
104		35	N.r	120	180	300	18.1		3944	241,000	0.35	1	40.66	1.72
105		32	N.r	120	180	300	27.6		3944	241,000	0.35	1.02	42.7	1.53
106		32	N.r	120	180	300	34.5		3944	241,000	0.35	0.99	46.29	1.43

Table 8 (continued)

No.	References	Concrete properties				Specimen Dimensions			FRP properties			Experimental Outcomes		
		f_{co} (MPa)	ε_{co} (%)	b (mm)	h (mm)	L (mm)	r (mm)		f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{frup} (%)	f_{cc} (MPa)	ε_{cu} (%)
107		34	N.r	90	180	300	13.6		3944	241,000	0.35	1.11	38.69	1.87
108		32	N.r	90	180	300	22.6		3944	241,000	0.35	1.02	38.69	1.65
109		32	N.r	90	180	300	26.8		3944	241,000	0.35	0.87	42.47	1.98
110		49	N.r	150	150	300	13.6		3944	241,000	0.35	1.04	49.65	0.79
111		51.5	N.r	150	150	300	22.6		3944	241,000	0.35	1.09	56.09	1.37
112		51.5	N.r	150	150	300	34.5		3944	241,000	0.35	1.08	62.21	1.12
113		51.5	N.r	120	180	300	27.6		3944	241,000	0.35	0.95	56.3	0.84
114		49	N.r	90	180	300	13.6		3944	241,000	0.35	0.5	51.44	1.04
115		49	N.r	90	180	300	26.8		3944	241,000	0.35	0.8	54.04	1.67
116	Shehata et al. [59]	23.7	N.r	150	150	300	10		3550.0	23,5000	0.17	N.r	27.4	N.r
117		23.7	N.r	150	150	300	10		3550.0	23,5000	0.34	N.r	36.5	N.r
118		29.5	N.r	150	150	300	10		3550.0	23,5000	0.17	N.r	40.4	8.80
119		29.5	N.r	150	150	300	10		3550.0	23,5000	0.34	N.r	43.7	12.30
120		23.7	N.r	94	188	300	10		3550.0	23,5000	0.17	N.r	25.8	N.r
121		23.7	N.r	94	188	300	10		3550.0	23,5000	0.34	N.r	33.2	N.r
122		29.5	N.r	94	188	300	10		3550.0	23,5000	0.17	N.r	32	7.90
123		29.5	N.r	94	188	300	10		3550.0	23,5000	0.34	N.r	38.7	7.50
124	Masia et al. [39]	25.5	0.26	100	100	300	25		3500.0	230,000	0.26	N.r	55.9	2.00
125		22.8	0.26	100	100	300	25		3500.0	230,000	0.26	N.r	48.7	1.82
126		25.1	0.26	100	100	300	25		3500.0	230,000	0.26	N.r	45.7	1.47
127		23.7	0.22	125	125	375	25		3500.0	230,000	0.26	N.r	45	1.62
128		22.9	0.27	125	125	375	25		3500.0	230,000	0.26	N.r	39.9	1.55
129		25.7	0.27	125	125	375	25		3500.0	230,000	0.26	N.r	42.1	1.72
130		24.5	0.27	150	150	450	25		3500.0	230,000	0.26	N.r	35.7	1.06
131		21.3	0.27	150	150	450	25		3500.0	230,000	0.26	N.r	36.2	1.09
132		24.8	0.25	150	150	450	25		3500.0	230,000	0.26	N.r	36.6	1.52
133	Harajli and Rteil [21]	18.3	0.25	131.5	131.5	300	15		3500	230,000	0.13	N.r	28.86	N.r
134		18.3	0.25	131.5	131.5	300	15		3500	230,000	0.26	N.r	39.85	N.r
135		18.3	0.25	131.5	131.5	300	15		3500	230,000	0.39	N.r	42.91	N.r
136		18.3	0.25	102	176	300	15		3500	230,000	0.13	N.r	23.41	N.r
137		18.3	0.25	102	176	300	15		3500	230,000	0.26	N.r	30.96	N.r
138		18.3	0.25	102	176	300	15		3500	230,000	0.39	N.r	36.39	N.r
139		18.3	0.25	79	214	300	15		3500	230,000	0.13	N.r	27.72	N.r
140		18.3	0.25	79	214	300	15		3500	230,000	0.26	N.r	28.30	N.r
141		18.3	0.25	79	214	300	15		3500	230,000	0.39	N.r	30.32	N.r

Table 8 (continued)

No.	References	Concrete properties				Specimen Dimensions			FRP properties			Experimental Outcomes			
		f_{co} (MPa)	ε_{co} (%)	b (mm)	h (mm)	L (mm)	r (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{frup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type	
142	Pantelidis and Yan [48]	15.2	0.15	279	279	914	19	1220	87,000	2	N.r	26.14	0.75	Carbon	
143		15.2	0.15	279	279	914	19	228	17,000	9.6	N.r	22.04	1.50	Glass	
144		14.8	0.15	203	381	914	19	1220	87,000	2	N.r	24.12	1.73	Carbon	
145		14.8	0.15	203	381	914	19	228	17,000	9.6	N.r	21.90	1.58	Glass	
146		14.6	0.15	152	457	914	19	1220	87,000	2	N.r	21.31	1.58	Carbon	
147	Al-Salloum [4]	14.6	0.15	152	457	914	19	228	17,000	9.6	N.r	21.31	1.58	Glass	
148		28.68	0.5	150	150	500	5	935	75,100	1.2	N.r	41.18	N.r	Carbon	
149		30.94	0.5	150	150	500	5	935	75,100	1.2	N.r	42.49	N.r	Carbon	
150		31.82	0.667	150	150	500	25	935	75,100	1.2	N.r	48.25	N.r	Carbon	
151		28.5	0.667	150	150	500	25	935	75,100	1.2	N.r	45.59	N.r	Carbon	
152		27.7	0.5	150	150	500	38	935	75,100	1.2	N.r	56.96	N.r	Carbon	
153		30.29	0.5	150	150	500	38	935	75,100	1.2	N.r	54.96	N.r	Carbon	
154		26.72	0.45	150	150	500	50	935	75,100	1.2	N.r	61.67	N.r	Carbon	
155		28.26	0.45	150	150	500	50	935	75,100	1.2	N.r	63.68	N.r	Carbon	
156		22	N.r	150	150	300	20	4470	23,9000	0.17	N.r	33.5	2.53	Carbon	
157	Tao et al. [61]	22	N.r	150	150	300	35	4470	23,9000	0.34	N.r	64.8	3.66	Carbon	
158		22	N.r	150	150	300	50	4470	23,9000	0.34	N.r	76.6	3.87	Carbon	
159		35.3	0.25	150	150	300	30	4192	22,9000	0.17	N.r	40.5	N.r	Carbon	
160		35.3	0.25	150	150	300	30	4192	22,9000	0.17	N.r	40.7	N.r	Carbon	
161		35.3	0.25	150	150	300	30	4192	22,9000	0.17	N.r	42.5	N.r	Carbon	
162		35.3	0.25	150	150	300	30	4192	22,9000	0.34	N.r	59.2	N.r	Carbon	
163		35.3	0.25	150	150	300	30	4192	22,9000	0.34	N.r	59.6	N.r	Carbon	
164		35.3	0.25	150	150	300	30	4192	22,9000	0.34	N.r	62.3	N.r	Carbon	
165		35.3	0.27	150	188	300	30	4192	22,9000	0.17	N.r	38	N.r	Carbon	
166		35.3	0.27	150	188	300	30	4192	22,9000	0.17	N.r	38.9	N.r	Carbon	
167	Wu and Wei [74]	35.3	0.27	150	188	300	30	4192	22,9000	0.17	N.r	39.4	N.r	Carbon	
168		35.3	0.27	150	188	300	30	4192	22,9000	0.34	N.r	48.8	N.r	Carbon	
169		35.3	0.27	150	188	300	30	4192	22,9000	0.34	N.r	51.9	N.r	Carbon	
170		35.3	0.27	150	188	300	30	4192	22,9000	0.34	N.r	53.3	N.r	Carbon	
171		35.3	0.3	150	225	300	30	4192	22,9000	0.17	N.r	37.6	N.r	Carbon	
172		35.3	0.3	150	225	300	30	4192	22,9000	0.17	N.r	35.6	N.r	Carbon	
173		35.3	0.3	150	225	300	30	4192	22,9000	0.17	N.r	39.2	N.r	Carbon	
174		35.3	0.3	150	225	300	30	4192	22,9000	0.34	N.r	43	N.r	Carbon	
175		35.3	0.3	150	225	300	30	4192	22,9000	0.34	N.r	45.2	N.r	Carbon	
176		35.3	0.3	150	225	300	30	4192	22,9000	0.34	N.r	43.4	N.r	Carbon	

Table 8 (continued)

No.	References	Concrete properties				Specimen Dimensions			FRP properties			Experimental Outcomes			
		f_{co} (MPa)	ε_{co} (%)	b (mm)	h (mm)	L (mm)	r (mm)	f_f (MPa)	E_f (MPa)	t_f (mm)	ε_{frup} (%)	f_{cc} (MPa)	ε_{cu} (%)	FRP type	
177		35.3	0.31	150	260	300	30	4192	22,9000	0.17	N.r	35.2	N.r	Carbon	
178		35.3	0.31	150	260	300	30	4192	22,9000	0.17	N.r	37.8	N.r	Carbon	
179		35.3	0.31	150	260	300	30	4192	22,9000	0.17	N.r	37.6	N.r	Carbon	
180		35.3	0.31	150	260	300	30	4192	22,9000	0.34	N.r	38.9	N.r	Carbon	
181		35.3	0.31	150	260	300	30	4192	22,9000	0.34	N.r	41.4	N.r	Carbon	
182		35.3	0.31	150	260	300	30	4192	22,9000	0.34	N.r	41.3	N.r	Carbon	
183		35.3	0.33	150	300	300	30	4192	22,9000	0.17	N.r	36.6	N.r	Carbon	
184		35.3	0.33	150	300	300	30	4192	22,9000	0.17	N.r	37.7	N.r	Carbon	
185		35.3	0.33	150	300	300	30	4192	22,9000	0.17	N.r	38	N.r	Carbon	
186		35.3	0.33	150	300	300	30	4192	22,9000	0.34	N.r	38.6	N.r	Carbon	
187		35.3	0.33	150	300	300	30	4192	22,9000	0.34	N.r	39.1	N.r	Carbon	
188		35.3	0.33	150	300	300	30	4192	22,9000	0.34	N.r	39.3	N.r	Carbon	
189	De luca et al. [16]	48.60	N.r	610.	610	2032	20	3399	76,948	2.40	N.r	47.84	N.r	Glass	
190		37.1	N.r	610	610	2032	20	3241	72,397	2.54	N.r	34.94	N.r	Glass	
191		44.4	N.r	610	610	2032	20	4840	88,945	2.272	N.r	41.92	N.r	Glass-basalt	
192		56.4	N.r	508	737	2032	20	3399	76,948	2.4	N.r	44.61	N.r	glass	
193		47.6	N.r	508	737	2032	20	4840	76,948	2.272	N.r	45.41	N.r	Glass-basalt	
194		53.8	N.r	356	508	2032	20	3399	76,948	2.4	N.r	47.89	N.r	Glass	
195		46.4	N.r	356	508	2032	20	3241	72,397	2.54	N.r	39.31	N.r	Glass	
196		49.7	N.r	356	508	2032	20	3241	72,397	6.35	N.r	48.27	N.r	Glass b	
197		46.8	N.r	356	508	2032	20	4840	76,948	2.272	N.r	44.07	N.r	Glass-basalt	
198	Hadi and Widiarsa [20]	79.5	0.6	200	200	800	34	1399	75,400	0.45	N.r	81.975	0.66	Carbon	
199		79.5	0.6	200	200	800	34	1399	75,400	1.35	N.r	89.625	0.56	Carbon	
200		79.5	0.6	200	200	800	34	1399	75,400	1.35	N.r	88.05	0.63	Carbon	

N.r: Not reported

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