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Research paper

A new model for predicting the axial compression capacity of reinforced concrete cylinders strengthened with CFRP

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Abstract: Numerous scholars have identified the shortcomings of imprecise terminology and substantial computational inaccuracies in the current models for predicting the axial compression capacity of CFRP-strengthened reinforced concrete (RC) cylinders. To improve the prediction accuracy of the axial compressive capacity model for CFRP-strengthened RC cylinders, the present axial compressive capacity model for CFRP-strengthened RC cylinders was scrutinized and evaluated. Drawing on Mander's constraint theory and the concrete triaxial strength model, a novel axial compressive capacity model for CFRP-strengthened RC cylinders was proposed. This study collected 116 experimental data on the axial compression of CFRP-strengthened RC cylinders and analyzed the accuracy of various models using the data. The findings indicate that the model proposed in this study outperforms other models in predicting axial compression capacity and demonstrates high prediction accuracy. Furthermore, an analysis is conducted on the variation law of the model's predicted value with respect to the design parameters. The proposed model in this study identifies concrete strength, stirrup spacing, and elastic modulus of CFRP as the primary factors that influence the axial compression capacity of CFRP-strengthened RC cylinders.

Keywords: innovative model, axial compression capacity, reinforced concrete, cylinder, CFRP

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1. Introduction

During the operation of buildings, due to factors such as functional changes in space, requirements for installing equipment, and degradations in materials, the structural members of buildings need to be strengthened. Reinforced concrete (RC) structure is the most commonly used building structure in the world. Hence, the reinforcement of the concrete members has received much attention. Carbon fiber reinforced polymer (CFRP), as a lightweight, high strength and corrosion resistant composite material, is widely used in strengthening concrete structures [1]. Previous studies have shown that the utilization of CFRP can significantly improve the compressive strength and ductility of concrete [2].

RC columns are the most important components in the structural system, its performance directly affects the structural safety of buildings. Therefore, the strengthening performance of such components has received widespread attention. In the past two decades, scholars from various countries have conducted in-depth research on CFRP-strengthened RC columns, a large number of cylinders have been fabricated for testing the mechanical properties of the columns. Demers and Neale [3] conducted tests on 16 CFRP-strengthened RC columns to investigate the effects of concrete strength, longitudinal reinforcement, stirrups, and pre-damage on the axial compressive bearing capacity of the columns. Additionally, the nominal loading strength of the concrete was also derived. Unfortunately, the relationship between the lateral confinement and the axial compressive strength of the column has not been thoroughly studied. Harajli [4] proposed a prediction model by considering the combined effects of CFRP and stirrups. Although the model has a certain prediction accuracy, it still shows slight shortcomings. The main issue is that the interaction between the two constraints has not been explored yet, and the predicted values are too high. Hu and Seracino [5] compared and analyzed previous axial compressive capacity models of CFRP-strengthened RC cylinders. To obtain a more accurate prediction model, the interaction between CFRP and stirrup constraints was considered. Unfortunately, during the calculation of the bearing capacity of CFRP-strengthened RC columns, this proposed model only simply superimposes the strength growth values brought about by the separate constraints of the stirrups and CFRP. Teng et al. [6] proposed a new model for predicting the axial compression capacity of CFRP-strengthened RC columns, which was deduced from the model recommended by Jiang and Teng [7]. In which, the bearing capacity growth value brought by stirrup constraints was considered. This study indicates that the predicted values of the proposed model are relatively close to the test values. But in some cases, the predicted value is higher than the test value.

For CFRP-strengthened RC cylinders, a great number of prediction models were proposed by scholars to predict the axial compression capacity of this kind of cylinder [4–6, 8–18]. It should be noted that most of these models are derived from the strength theory of actively confined concrete, which was proposed by Richard et al. in 1928. According to the literature written by Teng and Lam [19], the axial compression capacity model of CFRP-strengthened RC cylinders can be roughly divided into two categories: (1) the design-oriented model and (2) the analysis-oriented model. In the first category, the stress-strain model is represented by a closed-form expression, and the mathematical model is directly fitted based on experimental data. In the second category, the incremental iterative numerical method was used to predict the bearing capacity of CFRP-strengthened RC cylinders, which has a deeper theoretical foundation and can also be extended to specimens with similar constraints, making the prediction model more applicable. Among the existing axial compression capacity prediction models of CFRP-strengthened RC cylinders, most of them are design-oriented models [4, 8–16], while there are few analysis-oriented models [5, 17, 18]. In addition, the predicted values of these models are generally larger than the test values.

On the basis of previous research by scholars, this study aims to establish an innovative model for predicting the axial compression capacity of CFRP-strengthened RC cylinders. In this model, the axial compression capacity of CFRP-strengthened RC cylinders can be divided into four parts: the contribution of unconstrained concrete, the contribution of longitudinal steel bars, the increment of bearing capacity of the core concrete under the combined constraint of stirrups and CFRP, and the increment of bearing capacity of the external concrete under the constraint of CFRP. In addition, we also realize that the bearing capacity of concrete in the core area should not exceed its triaxial ultimate compressive strength value. Subsequently, 116 experimental data were collected [3, 8, 11, 12, 20–27], and the prediction accuracy of each model was analyzed using these data. Finally, an analysis is conducted on the variation law of the model's predicted value with respect to the design parameters. We hope that the results of this study can provide a reference for the actual engineering design of CFRP-strengthened RC cylinders.

2. Test data and existing models

2.1. Test data

A total of 116 axial compression test data of CFRP- strengthened RC cylinders from existing literature were collected. The collected data includes the geometric dimensions of cylinders, material strength, spacing of steel bars, the elastic modulus of materials, and ultimate fracture strain of CFRP, etc. The details of the test data are listed in Table 1. To simplify the expression, the table mainly listed the range of the design parameters.

Table 1. Test data of CFRP-strengthened RC cylinders

Literature	Number of cylinders	Height-diameter ratio	Diameter (mm)	Concrete strength (MPa)	Stirrup constraint ratio	CFRP constraint ratio	Intensity ratio
Demers et al [3]	8	4.00	300	24.50~38.24	0.00~0.05	0.11~0.17	1.31~1.51
Pessiki et al [20]	2	3.60	508	29.15	0.01	0.09~0.13	1.33~1.72
Carrazedo [25]	4	3.00	190	29.33~32.27	0.10~0.21	0.08~0.18	1.60~2.13

Continued on next page

Table 1 – *Continued from previous page*

Literature	Number of cylinders	Height-diameter ratio	Diameter (mm)	Concrete strength (MPa)	Stirrup constraint ratio	CFRP constraint ratio	Intensity ratio
Matthys et al [26]	2	5.00	400	29.16	0.03	0.10~0.21	1.86~1.87
Rigazzo and Moreno [27]	2	8.00	200	12.59	0.06	0.20~0.79	2.47~3.44
Ilki et al [8]	14	2.00	250	15.11~27.58	0.03~0.14	0.16~0.83	1.97~5.77
Eid et al [21]	14	3.96~4.74	303~253	25.76~43.46	0.05~0.24	0.07~0.21	1.67~2.73
Chastre and Silva [11]	6	3.00~5.00	150~250	32.27~32.30	0.004~0.01	0.09~0.36	1.75~3.05
Lee et al [12]	12	2.00	150	36.2	0.13~0.46	0.10~0.50	1.39~4.17
Benzaid [24]	39	2.00~6.45	155~197	21.43~61.80	0.01~0.02	0.06~0.56	1.05~4.22
Wang [22]	8	3.00	204~305	22.46	0.02~0.08	0.12~0.35	1.85~3.09
Zhang [23]	5	3.71	350	22.12~40.69	0.00~0.03	0.07~0.18	1.34~2.00
Total	116	2.00~8.00	150~508	12.59~61.80	0.00~0.46	0.06~0.83	1.05~5.77

Note: concrete strength refers to the axial compressive strength of an unconstrained concrete cylinder, which can be represented by f_{co}; stirrup constraint ratio is the ratio of effective lateral restraint force of stirrups to concrete strength, which can be expressed as $f'_{\mathrm{ls}}/f_{\mathrm{co}}$; CFRP constraint ratio is the ratio of effective lateral restraint force of CFRP to concrete strength, which can be expressed as $f'_{\mathrm{lf}}/f_{\mathrm{co}}$; intensity ratio is the ratio of the axial compressive capacity of the CFRP- strengthened RC cylinder to concrete strength, which can be expressed as $f_{\mathrm{cc}}/f_{\mathrm{co}}$.

2.2. Existing models

For the convenience of conducting the following research, the symbols used in the calculation model should be clarified first. The sketch view of the CFRP-strengthened RC cylinder and symbols are shown in Fig. 1. According to the schematic analysis in the figure, the symbol definitions are as follows: N is the axial compressive bearing capacity of CFRP-strengthened RC cylinders; ε_f and E_f are the ultimate fracture strain and elastic modulus of

CFRP, respectively; f'_{ls} is the effective circumferential restraint force of the stirrup, which can be calculated by Eq. (2.1); f_{lf} is the circumferential restraint force of CFRP, which can be calculated by Eq. (2.2); $f_{l,\text{core}}$ and $f_{l,\text{cover}}$ are the compressive strength of the core concrete and the external concrete, respectively. For the effective circumferential restraint force induced by the stirrup and CFRP, the calculation expressions are as follows:

$$f'_{\text{ls}} = \frac{2k_e A_{\text{sh}} f_{yh}}{s d_s} \tag{2.1}$$

$$f_{\text{lf}} = \frac{2E_f \varepsilon_f t_f}{D} \tag{2.2}$$

where: k_e – the effective constraint coefficient of the stirrup; A_{sh} and f_{yh} – the cross-sectional area and yield strength of the stirrup, respectively; s and d_s – the longitudinal center spacing of the stirrups and the cross-sectional diameter of the concrete in the core area, respectively; t_f – the calculated thickness of CFRP; D – the diameter of the cylinders.

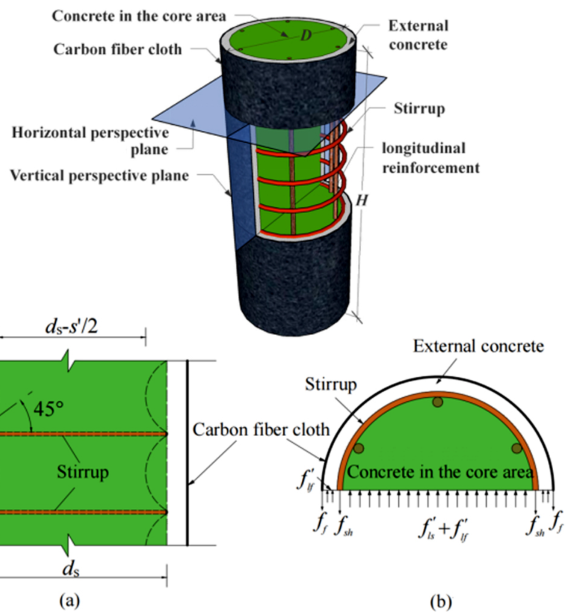

Fig. 1. Sketch view of CFRP-strengthened RC cylinders: a) Longitudinal section, b) Transverse section

According to the calculation model proposed by Mander et al. [28], the effective constraint coefficient of the stirrup can be calculated using the following equation:

$$k_e = \begin{cases} \dfrac{\left(1-\dfrac{s'}{2d_s}\right)^2}{(1-\rho_{\text{cc}})} & \text{Circular stirrup} \\[2ex] \dfrac{\left(1-\dfrac{s'}{2d_s}\right)}{(1-\rho_{\text{cc}})} & \text{Spiral stirrup} \end{cases} \tag{2.3}$$

where: s' – the longitudinal net spacing of the stirrups; ρ_{cc} – the volume reinforcement ratio of the longitudinal bars relative to the concrete in the core area.

Based on the defined symbols, the symbols in the expressions of the existing models have been unified, which is conducive to comparison.

2.2.1. Model proposed by megalooikonomou et al.

Based on the prediction model proposed by Spoelstra and Monti [29] and Braga et al. [17], Megalooikonomou et al. [18] developed a new model for predicting the axial compression capacity of CFRP-strengthened RC cylinders. The model is similar to the model proposed by Braga et al. [17]. The improvement of the model lies in the discussion of the difference between the actual fracture strain and the ultimate fracture strain of CFRP. Moreover, the influence of design factors such as buckling of longitudinal reinforcement on the bearing capacity of cylinders was discussed in detail. The expression of the proposed model is shown below.

$$N = A_{\text{core}} f_{c,\text{core}} + A_{\text{cover}} f_{c,\text{cover}} \tag{2.4}$$

$$\frac{f_{c,\text{core}}\left(f_{c,\text{cover}}\right)}{f_{\text{co}}} = 2.254\sqrt{1 + 7.94\frac{f_{l,\text{core}}\left(f_{l,\text{cover}}\right)}{f_{\text{co}}}} - 2\frac{f_{l,\text{core}}\left(f_{l,\text{cover}}\right)}{f_{\text{co}}} - 1.254 \tag{2.5}$$

$$f_{l,\text{cover}} = f_{\text{lf}},\ f_{l,\text{core}} = f_{\text{lf}} + f'_{\text{ls}} \tag{2.6}$$

where: $f_{c,\text{core}}$ and $f_{c,\text{cover}}$ – the axial compressive strength of the core concrete and the external concrete, respectively; A_{core} and A_{cover} – the cross-sectional areas of the core concrete and the external concrete, respectively.

2.2.2. Model proposed by hu and seracino

Hu and Seracino [5] proposed a new model for predicting the axial compression capacity of CFRP-strengthened RC cylinders. The proposed model is developed based on the models proposed by Jiang and Teng [7] and Mander et al. [28]. In the new model, the relative constraint stiffness of stirrups and CFRP was introduced as an important parameter of the model. However, it should be noted that the calculation of the axial compression capacity of CFRP-strengthened RC cylinders only simply superimposes the bearing capacity growth values brought about by the separate constraints of the stirrup and CFRP, ignoring the combinatorial constraint relationship between CFRP and the stirrups. This results in a relatively large predicted value for the new model. The expression of this model is presented as follows:

$$N = f_{\text{co}}A + 3.5 f_{\text{lf}}A + \left(2.254\sqrt{1 + 7.94\left(\frac{f'_{\text{ls}}}{f_{\text{co}}}\right)} - 2\left(\frac{f'_{\text{ls}}}{f_{\text{co}}}\right) - 2.254\right) f_{\text{co}} A_{\text{core}} \tag{2.7}$$

where: A – the cross-sectional area of the cylinder.

2.2.3. Model proposed by teng et al.

In 2007, Jiang and Teng [7] proposed a calculation model for predicting the axial compression capacity of plain concrete cylinders strengthened with CFRP. Subsequently, a new model was proposed by Teng [6] for predicting the axial compression capacity of CFRP-strengthened RC cylinders, which is based on the model proposed by Jiang and Teng [7]. The establishment of the model is based on experimental data, taking into account the strength increase caused by stirrup constraints, introducing the relative stiffness ratio of CFRP and stirrups, and improving the calculation model of concrete cylinders constrained by stirrups proposed by Mander et al. [28]. The expression of the proposed model is as follows:

$$N = \left(f_{\text{co}} + 3.5 f_{\text{lf}} + 3.12 f_{\text{co}} \left[\frac{f'_{\text{ls}}}{f_{\text{co}} \left(1 + 0.202 \rho_f^{0.145} \right)} \right]^{0.736} \right) A \tag{2.8}$$

where: ρ_f – the relative stiffness ratio between CFRP and stirrups, which can be calculated by the following equation.

$$\rho_f = \frac{\dfrac{2E_f t_f}{D}}{\dfrac{2k_e E_{\text{sh}} A_{\text{sh}}}{s d_s}} = \frac{E_f t_f s d_s}{k_e E_{\text{sh}} A_{\text{sh}} D} \tag{2.9}$$

where: E_{sh} – the elastic modulus of the stirrup.

Among the existing models, the above three models are commonly used to predict the axial compression capacity of CFRP-strengthened RC cylinders. Thus, the models were selected as reference models for comparative analysis.

3. Model proposed in this study

Based on existing research, it can be concluded that the axial compressive bearing capacity of CFRP-strengthened RC cylinders can be divided into four parts: the contribution of unconstrained concrete, the contribution of longitudinal steel bars, the increment of bearing capacity of the core concrete under the combined constraint of stirrups and CFRP, and the increment of bearing capacity of the external concrete under the constraint of CFRP. Based on the above analysis, the load-bearing components of CFRP-strengthened RC cylinders can be divided into three parts: the longitudinal steel bars, the core concrete, and the external concrete. For the load-bearing contribution of longitudinal steel bars, it is necessary to clarify the strength of the steel during the compression process. For the load-bearing contribution of the external concrete, the material strength of the external concrete under CFRP constraints needs to be clarified. For the load-bearing contribution of the core concrete, the material strength of the core concrete under combinatorial constraints of CFRP and stirrups needs to be clarified.

For better analysis, it is necessary to unify the strength of unconstrained concrete in the collected test data. In the data collected in this study, most of the specimens are medium to large-sized specimens with a diameter of no less than 250 mm (maximum 508 mm), as shown in Table 1. Numerous studies have shown that the ultimate compressive strength of an unconstrained concrete cylinder with a large size may be significantly lower than that of the standard cylinder with dimensions of 150 × 300 mm [3, 11, 23, 30]. Therefore, this study uses the strength conversion formula proposed by Chastre and Silva [11] to calculate the compressive strength of unconstrained concrete cylinders, which is expressed as follows.

$$f_{co} = \frac{1.5 + D/H}{2} f_c \tag{3.1}$$

where: f_c – the compressive strength of a standard cylinder; D and H – the diameter and height of the cylinder, respectively.

3.1. Load-bearing contribution of longitudinal steel bars

Wang et al. [22] found that longitudinal steel bars generally do not buckle before the stirrups or CFRP of CFRP-strengthened RC cylinders break. In addition, for CFRP-strengthened RC cylinders with loading plates at both ends and well-constrained, it is evident that the vertical displacement of their longitudinal reinforcement is equal to that of the cylinder [23]. Therefore, this study does not consider the impact of buckling and sliding of longitudinal reinforcement on the axial compression capacity of CFRP-strengthened RC cylinders. Hence, the load-bearing contribution of longitudinal steel bars can be expressed as follows.

$$N_s = f_{yl} A_{sl} \tag{3.2}$$

where: f_{yl} and A_{sl} – the yield strength and total cross-sectional area of the longitudinal reinforcements, respectively.

3.2. Load-bearing contribution of the external concrete

In CFRP-strengthened RC cylinders, due to the smaller area of the external concrete compared to the core concrete, and the combined constraints of CFRP and stirrups on the core concrete, the resistance of the cylinder under compression mainly comes from the core concrete. In addition, the external concrete is destroyed before the destruction of the core concrete. Therefore, this study assumes that the constraint effect of CFRP mainly acts on the core concrete, thus ignoring the load-bearing capacity increment of CFRP on the external concrete. Hence, the load-bearing contribution of the external concrete can be expressed as follows.

$$N_{\text{cover}} = f_{co} A_{\text{cover}} \tag{3.3}$$

where: A_{cover} – the cross-sectional area of the external concrete.

3.3. Load-bearing contribution of the core concrete

Previous experimental studies have shown that the circumferential fracture strain of CFRP generally does not reach the material's ultimate fracture strain during the loading process of CFRP-strengthened RC cylinders [20, 31–33]. Lam and Teng [33] collected a large amount of experimental data for analysis and found that the fracture strain rate of CFRP was between 0.586 and 0.851, with an average value of 0.6. Therefore, in this study, the fracture strain rate of CFRP was taken as 0.6.

$$\varepsilon_{h,\mathrm{rup}} = 0.6\varepsilon_f \tag{3.4}$$

where: $\varepsilon_{h,\mathrm{rup}}$ – the actual circumferential ultimate fracture strain of CFRP, ε_f – the ultimate fracture strain of CFRP.

As shown in Fig. 1b, the circumferential restraint force on the core concrete can be calculated using the following equation.

$$f'_{l,\mathrm{core}} = f'_{\mathrm{ls}} + f'_{\mathrm{lf}} \tag{3.5}$$

where: f'_{lf} – the effective circumferential restraint force provided by CFRP, according to Eqs. (2.2) and (3.4), $f'_{\mathrm{lf}} = 0.6 f_{\mathrm{lf}}$; f'_{ls} – the effective circumferential restraint force provided by stirrups.

This study uses the three-parameter strength model proposed by Mander et al. [28] to calculate the stress increment of core concrete under combined constraints, and the calculation formula is as follows.

$$\Delta f_{c,\mathrm{core}} = \left(2.254\sqrt{1 + 7.94\frac{f'_{l,\mathrm{core}}}{f_{\mathrm{co}}}} - 2\frac{f'_{l,\mathrm{core}}}{f_{\mathrm{co}}} - 2.254\right) f_{\mathrm{co}} \tag{3.6}$$

Therefore, the axial compressive strength of core concrete can be expressed as

$$f'_{c,\mathrm{core}} = f_{\mathrm{co}} + \Delta f_{c,\mathrm{core}} \tag{3.7}$$

In the actual calculation process, the compressive strength value of concrete calculated by Eq. (3.7) may exceed the limit value of concrete triaxial strength. Therefore, for the compressive strength of the core concrete, the smaller value between the value calculated by Eq. (3.7) $f'_{c,\mathrm{core}}$ and the triaxial compressive strength $f''_{c,\mathrm{core}}$ should be selected.

According to the research findings of Qian et al. [34], the strength criterion of concrete under triaxial stress conditions is shown as follows.

$$(\sigma_1 - \sigma_3)^2 + \left(K_c - 1 - \frac{1}{K_c}\right)\sigma_1 + \frac{\sigma_3}{K_c} + \left(\frac{1}{K_c} - 1\right) = 0 \tag{3.8}$$

where: σ_1 – the ratio of the lateral constraint strength of the core concrete to the uniaxial compressive strength of the concrete standard cylinder ($\sigma_1 = -f'_{l,\mathrm{core}}/f_c$); σ_3 – the ratio of the vertical triaxial compressive strength of the core concrete to the uniaxial compressive strength of the concrete standard cylinder ($\sigma_3 = -f''_{c,\text{core}}/f_c$); K_c – the ratio of the uniaxial compressive strength to the uniaxial tensile strength of concrete, which can be calculated as follows.

$$K_c = \frac{f_{\text{ck}}}{f_{\text{tk}}} \tag{3.9}$$

where: f_{ck} – the uniaxial compressive strength of concrete; f_{tk} – the uniaxial tensile strength of concrete.

According to the method proposed in the literature [35, 36], the relationship between the axial strength of concrete and the compressive strength of concrete with standard cubes is shown below.

$$f_{\text{ck}} = 0.4 f_{\text{cuk}}^{7/6} \tag{3.10}$$

$$f_{\text{tk}} = 0.24 f_{\text{cuk}}^{2/3} \tag{3.11}$$

where: f_{cuk} – the compressive strength of concrete with standard cubes.

In this study, the relationship between f_{cuk} and f_c is determined according to the method suggested by Zhou and Su [37].

In summary, considering the contribution of the above three components to the bearing capacity of CFRP-strengthened RC cylinders, the expression for predicting the axial compression capacity of CFRP-strengthened RC cylinders proposed in this study is as follows.

$$N = f_{yl} A_{sl} + f_{\text{co}} A_{\text{cover}} + \min\left\{f'_{c,\text{core}}, f''_{c,\text{core}}\right\} A_{\text{core}} \tag{3.12}$$

4. Validation of models

The models described in Section 2.2 and the model proposed in this study were selected to verify the prediction accuracy. Based on the collected 116 test data, the predictive effects of each model for predicting the axial compression capacity of CFRP- strengthened RC cylinders were analyzed. The comparison between predicted and experimental values is shown in Fig. 2. In which, AV represents the average value, SD represents the standard deviation, and AAE represents the coefficient of variation, which can be calculated according to Eqs. (4.1)–(4.3). In addition, the distribution characteristics of the ratio of predicted values to experimental values are shown in Fig. 3.

It can be seen from Fig. 2 that the predicted values of previous models are higher than those of the model proposed in this study, primarily because the constraint effect of CFRP and stirrups on concrete cylinders were overestimated in previous models. For the model proposed in this study, the average ratio of the predicted value to the experimental value is close to 1.0. Moreover, the standard deviation and the variation coefficient are relatively smaller. This indicates that the model for predicting the axial compression capacity of CFRP-strengthened RC cylinders, which was proposed in this study, has a higher prediction accuracy.

$$AV = \sum \frac{N_{\text{pre}}}{N_{\text{test}}} \Big/ n \tag{4.1}$$

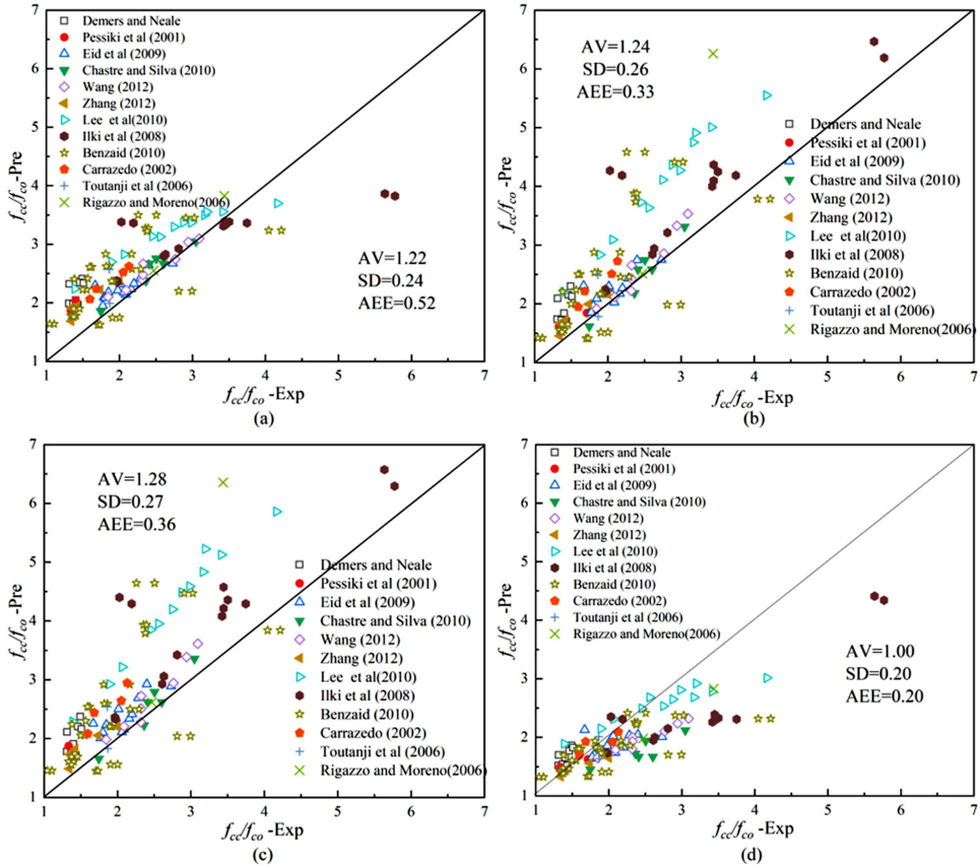

Fig. 2. Comparison between predicted and experimental values: a) Model of Megalooikonomou (2012), b) Model of Hu and Seracino (2013), c) Model of Teng (2015), d) Model of this paper

(4.2)
$$SD = \sqrt{\frac{1}{n}\sum\left(\frac{N_{\text{pre}}}{N_{\text{test}}} - AV\right)^2}$$

(4.3)
$$AAE = \sum \frac{\left|N_{\text{test}} - N_{\text{pre}}\right|}{N_{\text{test}}} \bigg/ n$$

Fig. 3 shows the distribution histogram of the ratio of predicted values to experimental values for each model. The Shapiro-Wilk test (S-W test) on mathematical statistics was adopted. It can be seen that the significance of the model proposed in this study is greater than 0.05, which conforms to the normal distribution. Besides, the model of Megalooikonomou et al. [18] also showed the normal distribution of the data. For the models proposed by Hu and Seracino [5] and Teng [6], the significance of the data is less than 0.05, this indicates that the data does not conform to the normal distribution. In addition, the 95% confidence interval for the ratio of the predicted value to the experimental value of Megalooikonomou et al. [18] is (1.17, 1.26),

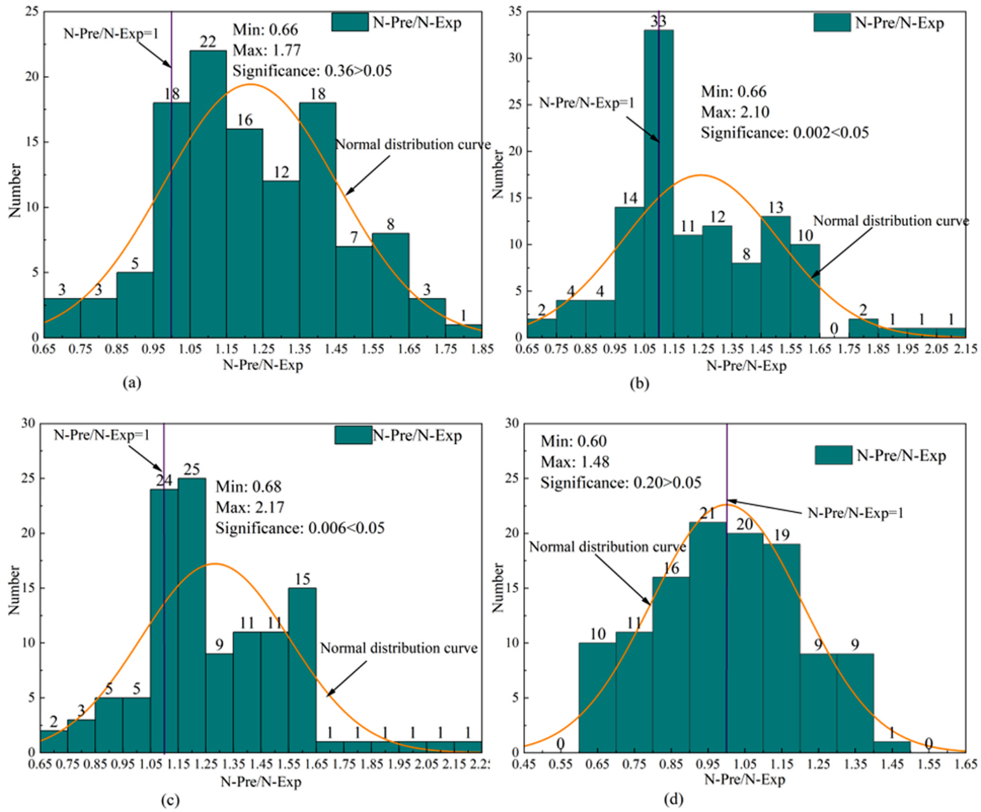

Fig. 3. Distributions of the ratios of predicted values to experimental values: a) Model of Megalooikonomou (2012), b) Model of Hu and Seracino (2013), c) Model of Teng (2015), d) Model of this paper

while the 95% confidence interval for the ratio of the predicted value to the experimental value of the model proposed in this study is (0.96, 1.04). This indicates that the predicted values of the bearing capacity prediction model proposed in this study are close to the experimental values, and the prediction results are more accurate.

5. Sensitivity of the model to various parameters

In order to explore the sensitivity of the proposed model to various parameters, six different specimens were selected from the collected data, and the ratio of the predicted value to the experimental value is in the range of 0.95 to 1.05. The compressive strength of the concrete cylinder, the height-to-diameter ratio, the thickness of the protective layer, the stirrup spacing, the stirrup strength, and the CFRP strength were selected as the analysis parameters. The variations of the predicted values of the model with different parameters were explored, and the analysis results are shown in Fig. 4.

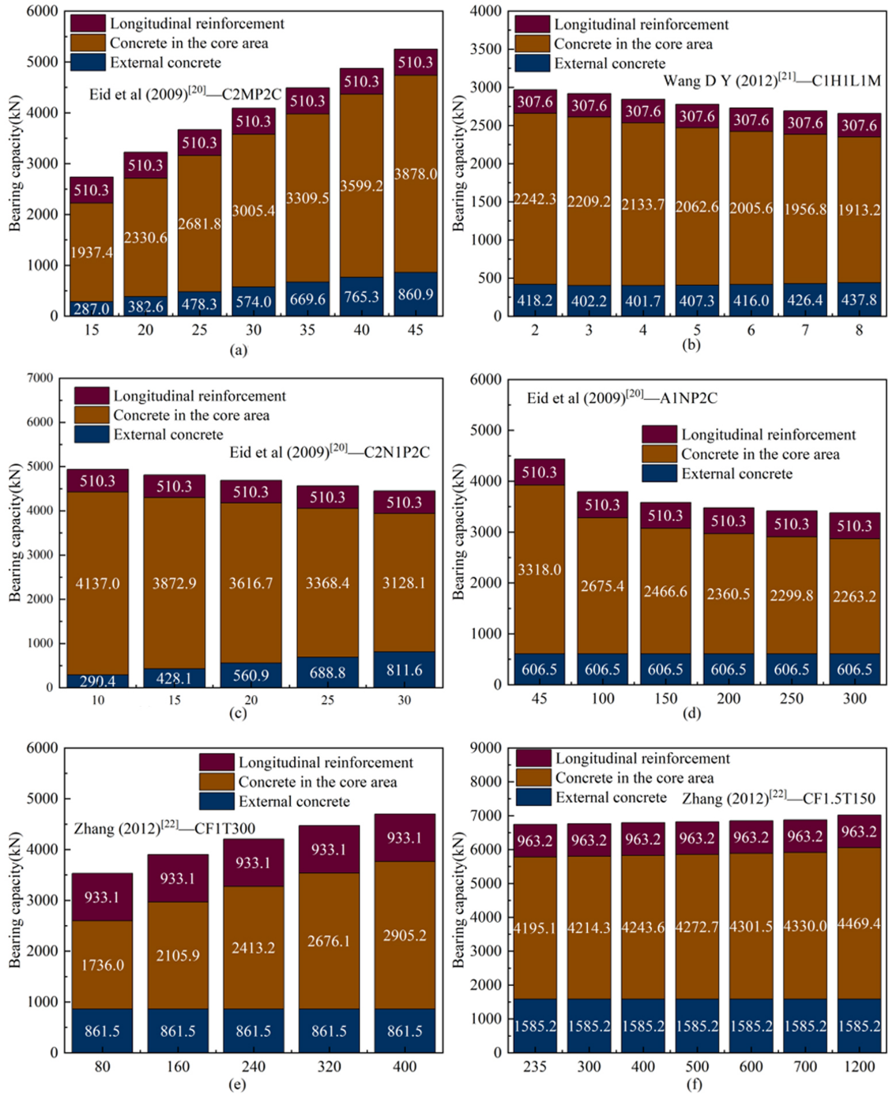

Fig. 4. Variations of the predicted values of the model with different parameters: a) Standard cylinder axial compressive strength f_c' (MPa), b) Height to diameter ratio H/D, c) Concrete cover thickness C (mm), d) Stirrup spacing S (mm), e) Elastic modulus of CFRP E f (GPa), f) Stirrup strength fyh (MPa)

From Fig. 4, it can be observed that the predicted values of the model proposed in this study are more sensitive to the changes in the compressive strength of the concrete cylinder, the CFRP strength, and the stirrup spacing, but less sensitive to the changes in parameters such as the height-to-diameter ratio, the thickness of the protective layer, and the stirrup strength. Among them, concrete strength is the most important factor affecting the bearing capacity of CFRP-strengthened RC cylinders. When the strength of concrete increases, the load-bearing contributions of the external and core concrete are effectively increased. Increasing the spacing of stirrups will lead to a decrease in the bearing capacity of the core concrete. It should be noted that the decrease in bearing capacity is relatively small while the spacing of stirrups exceeds 150 mm. This is due to the fact that the effective restraining effect of the stirrups will be lost while the stirrup spacing exceeds a certain value. The increase in the elastic modulus of CFRP will also significantly increase the axial compression bearing capacity of the core concrete. Due to the neglect of the constraint effect of CFRP on the external concrete in this model, the bearing capacity of the external concrete remains unchanged. Increasing the height-to-diameter ratio will slightly reduce the bearing capacity of CFRP-strengthened RC cylinders, which is consistent with the fact that an increase in the slenderness ratio of the components will lead to a decrease in bearing capacity. Increasing the thickness of the protective layer will slightly reduce the bearing capacity of the component, because as the thickness of the protective layer increases, the area of the constrained core concrete will decrease. Although the bearing contribution of external concrete has increased, its increase is smaller than the decrease in the bearing capacity of the core concrete. In addition, increasing the strength of the stirrup will have very little impact on the bearing capacity of CFRP-strengthened RC cylinders. The possible reason is that the increase in the bearing capacity of core concrete under the dual constraints of CFRP and stirrups will be constrained by CFRP and stirrups, rather than a single factor.

6. Summary and conclusions

To more accurately predict the axial bearing capacity of CFRP-strengthened RC cylinders, this paper summarized and analyzed the existing prediction models. A novel prediction model based on Mander's constraint theory and the concrete triaxial strength model was proposed. In addition, a total of 116 experimental data were collected in this study, and the accuracy of the proposed model was verified through these data. The main research conclusions are as follows.

1. Based on the analysis of existing prediction models, a new prediction model is proposed by considering Mander's constraint theory and the concrete triaxial strength model. In the proposed model, the contribution of components in bearing capacity is divided into three parts: the longitudinal reinforcement contribution, the external concrete contribution, and the core concrete contribution.
2. Compared with existing prediction models, the model proposed in this study has a higher prediction accuracy. For the proposed model, the comparison results show that the average ratio of the predicted value to the experimental value is close to 1.0, and the proposed model has a better standard deviation and variation coefficient. Further, the distribution histogram of the ratio of predicted values to experimental values showed that the data of the proposed model conforms to the normal distribution.
3. The sensitivity of the proposed model to various parameters was studied, and it can be found that the predicted values of the proposed model are more sensitive to the changes in the compressive strength of the concrete cylinder, the CFRP strength, and the stirrup spacing, but less sensitive to the changes in parameters such as the height-to-diameter ratio, the thickness of the protective layer, and the stirrup strength.

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