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Research Article

Prediction about Effect of Span-to-Depth Ratio on Shear Capacity for FRP Bar Reinforced Concrete Beams without Web Reinforcement

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Most of the prediction models for the shear capacity of FRP bar reinforced concrete beams without web reinforcement in current codes are reported to be conservative and do not consider the effect of span-to-depth ratio. Grey relational analysis (GRA) method was used in this paper to investigate the relevance of span-to-depth ratio with the shear capacity, and the results shown that the span-to-depth ratio greatly affects the shear capacity of FRP bar reinforced concrete beams without web reinforcement. A prediction model which considers the effect of span-to-depth ratio was proposed for the shear capacity of FRP bar reinforced concrete beams without web reinforcement by regression analysis, which is more accurate and reasonable in comparison with the current models.

1. Introduction

For the concrete structures exposed to severe environments, the corrosion of steel bars has always been one of the main reasons for structural damage, and it will bring relatively expensive repair and reinforcement costs. To solve this problem, several different types of steel reinforcements have been used, such as stainless, epoxy coated, and galvanized steel, but none of them can fundamentally solve the problem. At the same time, comparing with traditional steel reinforcement, fiber reinforced polymer (FRP) bars have better specific strength, corrosion resistance, and weak electromagnetic properties [1, 2]. Due to the aforementioned advantages, the FRP bars are considered to be an effective substitute for traditional reinforcement, and the application of FRP bars in reinforced concrete beams has been rapidly developed over the last few decades.

As the FRP bars have several differences in the mechanical properties from steel bars, such as lower elastic modulus, brittleness and lower transverse shear strength, a large number of experiments on the shear behavior of FRP bar reinforced concrete beams and one-way slabs have been carried out. In general, the reinforced concrete (RC) beams without web reinforcement resist the shear stresses by means of five possible mechanisms, including shear resistance of the uncracked concrete compression zone, aggregate interlock, residual tensile stresses across cracks, dowel action of the longitudinal reinforcement and arch action [3]. The previous studies showed that the FRP bar reinforced concrete beam typically has a smaller neutral axis depth in comparison with the steel bar reinforced concrete beam with equal areas of longitudinal reinforcement [4, 5]. As a result, the shear capacity generated by FRP bar reinforced concrete beams through the shear resistance of the uncracked concrete compression zone is weaker than that generated by traditional steel bar reinforced concrete beams. Moreover, because of the lower elastic modulus of FRP bars, the axial stiffness of FRP bar reinforced concrete beams is relatively low, which makes the width and depth of the diagonal cracks in the beams increase accordingly, thereby leading to the lower shear capacity generated by the aggregate interlock and residual tensile stresses across cracks [6]. Additionally, owing to the lower transverse shear strength of FRP bars, the dowel action of the longitudinal reinforcement contribution to shear resistance of FRP bar reinforced concrete beams is smaller than that of steel bar reinforced concrete beams [7]. In addition, due to the differences in mechanical properties between FRP bars and steel bars, the failure mode of FRP bar reinforced concrete beams is different from that of traditional steel bar reinforced concrete beams. Therefore, the prediction models of the shear capacity of steel bar reinforced concrete beams are not suitable for FRP bar reinforced concrete beams.

The current researches [8, 9] have confirmed that the shear capacity of FRP bar reinforced concrete beams without web reinforcement, as shown in Figure 1, is influenced by several factors, such as concrete compressive strength (f_c'), shear span-to-depth ratio (a/d), elastic modulus of FRP bars (E_f), reinforcement ratio of longitudinal FRP bars (ρ_f), width of the beam (b) and effective depth of the beam (d). However, the influence of span-to-depth ratio (L/d) on the shear capacity of FRP bar reinforced concrete beams without web reinforcement is rarely involved, which represents the ratio of two sizes of the specimen, including effective span (L) and effective depth of the beam (d), respectively. Existing experimental studies showed that the ultimate shear capacity of steel bar reinforced concrete beams without web reinforcement under uniformly distributed loads will gradually decrease as the L/d increases [10, 11]. Because the uniform load can be equivalent to two concentrated loads, and shear span is $L/4$, where L is the effective span of the beam [12, 13], the L/d affects the shear capacity of the steel bar reinforced concrete beams. Furthermore, the effect of L/d on the shear capacity of the reinforced concrete beams is also reflected in the calculation models in codes. The GB50010-2010 in China stipulates that the beams with L/d of less than 5 are collectively called the deep flexural member [14]. At the same time, GB50010-2010 provides a different calculation model for the calculation of the shear capacity of deep flexural members in comparison with the beams with L/d of more than 5, which considers the effect of L/d. The ACI318R-19 stipulates that the beams that satisfy the following two criteria are called deep beams: the effective span does not exceed four times the overall member depth (h) and the concentrated loads exist within a distance $2h$ from the face of the support [15]. The Eurocode 2 stipulates that the span of a beam is not less than 3 times the overall section depth, otherwise it should be considered as a deep beam [16]. Both ACI318R-19 and Eurocode 2 deem that the deep beams are designed with strut and tie models, which is different from the design model for slender beams. In recent years, Uday Naik has proved that the change of L/d has an effect on the shear capacity of steel bar reinforced concrete beams by the artificial neural network technology [17], which has been widely used in civil engineering because of its excellent performance in the development of accurate and reliable prediction models for the shear capacity of reinforced concrete beams without web reinforcement [18–23]. The previous experimental study indicated that although FRP bars and steel bars have the great differences in elastic modulus and some mechanical properties, FRP bar reinforced concrete beams and steel bar reinforced concrete beams are still similar in shear-carrying mechanism [1, 9, 24]. Thus, the L/d also plays a certain role in the structural analysis of shear capacity of FRP bar reinforced concrete beams.

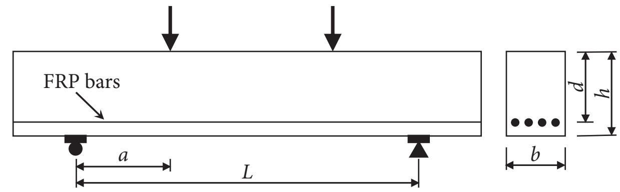

Figure 1: FRP bar reinforced concrete beams without web reinforcement.

The calculation models of the shear capacity of FRP bar reinforced concrete beams without web reinforcement in codes, such as CSA/CAN-S806-12, ACI440.1R-15, CNR-DT203–2006, GB50608-2020, and a modified model by Gao and Zhang are summarized in Table 1 [9, 25–28]. The factors that have been considered are listed in Table 2. Obviously, some of the factors which affect the shear capacity, such as a/d and L/d, have not been considered by the codes listed. Previous research results have confirmed that the current shear capacity calculation models of FRP bar reinforced concrete beams without web reinforcement in codes are conservative [9, 29]. This may be due to the lack of the proper consideration of a/d and L/d. The CSA/CAN-S806-12 model and the Gao and Zhang model consider the effect of a/d on shear capacity and are proven to be more accurate in comparing with other models [29]. In spite of this, the effect of L/d on the shear capacity is not fully embodied. The models that are unable to accurately predict the shear capacity will lead to excessive shear design, which results in high costs. Therefore, establishing a more comprehensive and accurate prediction model, which can correctly reflect the relevance of L/d and other parameters on the shear capacity of FRP bar reinforced concrete beams without web reinforcement, is essential at present.

In the present investigation, a database which contains the experimental results of 314 FRP bar reinforced concrete beams without web reinforcement was compiled to propose a more accurate calculation model for the shear capacity of FRP bar reinforced concrete beams. The method of grey relational analysis was used to analyze the relevance of L/d and other parameters with the shear capacity of FRP bar reinforced concrete beams without web reinforcement. On this basis, a new model was proposed based on the CAN/CSA-S806-12 model, which considered the influence of L/d.

2. Database

2.1. Test Data. This study collected 314 the experimental data of FRP bar reinforced concrete beams without web reinforcement failed in shear from the literature. The effects of a/d, E_f, ρ_f, f_c', b, d and L/d on the shear capacity of FRP bar reinforced concrete beams are considered. In addition, all

Table 1: Models for the shear capacity of FRP bar reinforced concrete beams without web reinforcement.

Model	Equations
CAN/CSA-S806-12	$V_c = 0.05k_m k_r k_a k_s \sqrt[3]{f_c'}b\ d$ $k_m = \sqrt{d/a} \le 1, k_r = 1 + (E_f \rho_f)^{1/3}, 1 \le k_a = 2.5d/a \le 2.5,$ $k_s = 750/(450 + d) \le 1, 0.11\sqrt{f_c'}b\ d \le V_c \le 0.22\sqrt{f_c'}bd$
ACI440.1R-15	$V_c = 0.4\sqrt{f_c'}bk\ d, n_f = E_f/E_c$ $k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$
CNR-DT203-2006	$V_c = 1.3(E_f/E_s)^{1/2}\tau_r k_d (1.2 + 40\rho_f)bd$ $1.3(E_f/E_s)^{1/2} \le 1, \tau_r = 0.25f_t$ $k_d = 1.6 - (d/1000) \ge 1, \rho_f \le 0.02$
GB50608-2020	$V_c = 0.86f_t bk\ d, n_f = E_f/E_c$ $k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$
Gao and Zhang	$V_c = k_{fad}k_d (f_c')^{2/3}bd$ $k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f, n_f = E_f/E_c$ $k_d = \begin{cases} 1.25 - d/1000, d \le 600 \\ 0.65, d > 600 \end{cases}$ $k_{fad} = \begin{cases} 1 - a/d/2 + a/d + 2ka/d, a/d \le 1 \\ k/a/d - 0.5, 1 < a/d \le 3 \\ 0.4k, 3 < a/d \le 6 \\ 2.4k/a/d, 6 < a/d \end{cases}$

Table 2: Factors considered in the models.

Models	Design parameters						
	a/d	E_f	ρ_f	f_c'	b	d	L/d
CSA-S806-12	√	√	√	√	√	√	×
ACI440.1R-15	×	√	√	√	√	√	×
CNR-DT203-2006	×	√	√	√	√	√	×
GB50608-2020	×	√	√	√	√	√	×
Gao and Zhang	√	√	√	√	√	√	×

test specimens in the database are simply supported and subjected to concentrated loads, and the shape of the cross section is rectangular. The details of the database and the minimum, maximum, average and range of each parameter are shown in Table 3.

2.2. Data Processing Principles. If the cubic compression strength of concrete (f_{cu}) corresponding to the beams is only provided in the original paper, it can be converted to the cylinder compression strength of concrete (f_c') according to the following formula [30].

$$f_c' = 0.85f_{cu}. \tag{1}$$

If the elastic modulus (E_c) and tensile strength (f_t) of concrete corresponding to the beams are not provided in the original paper, they can be obtained according to the following formula [15].

$$\begin{aligned} E_c &= 4733\sqrt{f_c'} \\ f_t &= 0.623\sqrt{f_c'}. \end{aligned} \tag{2}$$

3. Relevance Analysis of Experimental Parameters with Shear Capacity

3.1. Grey Relational Analysis (GRA) Method. Grey relational analysis (GRA) method [57, 58], as one of multi-factor statistical analysis methods, is mainly used to investigate the relevance between the reference sequence and comparison sequences by calculating the grey relational grade. The purpose of GRA method is to determine the main factors that affect the target value. The advantage of GRA method is that it does not require high sample size, and the workload is relatively small. The grey correlation degree can be calculated as following.

Table 3: Database of parameters of test beams.

References	Amount	a/d	$f_c'(MPa)$	$E_f(GPa)$	$\rho_f(\%)$	$b(mm)$	$d(mm)$	L/d	$V_c^{exp}(kN)$
Gross et al [31]	18	4.06–4.08	36.3	40.3	1.11–2.27	178–279	224–225	9.48–9.53	28.1–51
Razaqpur et al [32]	7	1.82–4.5	40.5–49	145	0.25–0.88	200	225	8.89	36.1–96.2
Ashour et al [30]	12	2.53–4.10	28.9–50.15	32–38	0.14–1.39	150	162.6–263	7.6–12.3	9–30
Tureyen et al [4]	6	3.4	39.7–42.6	37.6–47	0.96–1.92	457	360	6.77	94.7–177
Alkhrdaji et al [33]	3	2.61–2.69	24.1	40	0.77–2.3	178	279–287	5.23–5.38	36.1–53.4
Bentz et al [24]	6	3.26–4.05	35–46	37	0.51–2.54	450	188–937	6.96–8.28	54.5–232
Alam et al [34, 35]	37	1.5–3.5	34.5–88.3	46.3–144	0.18–1.47	250–300	291–744	4.84–10.16	43.7–155.8
Issa et al [6]	6	5.65–7.00	35.9	48–53	0.8–4.12	300	165–170	14.35–14.79	29.3–51.5
Tomlinson et al [36]	3	4.07–4.49	56.5–60	70	0.39–0.85	150	245–270	10.74–11.84	20.9–29.2
Abed et al. [37]	9	1–1.52	43–65	51	0.92–1.84	200	230–330	3.03–4.35	116.55–373.85
Guadagnini et al. [38]	3	1.1–3.3	42.84–47.685	45	1.28	150	223	4.48–10.31	27.2–81
Kim et al. [39]	40	1.5–4.5	30–40.3	40–147.9	0.33–0.79	150–200	213.5–215.5	9.28–10.3	16.6–85.1
Olivito et al. [40]	20	5.6	20.4–27.2	115	0.87–1.45	150	180	11.11	16.6–29.9
Matta et al. [41]	12	3.11–3.13	29.5–59.7	41–48.2	0.12–0.28	114–457	146–883	7.3–8.35	19.7–220.7
Thomas et al. [42]	8	0.5–1.75	40.6–65.3	40	1.16–1.75	100–170	270–416	2.38–4.07	30–300
Wegian et al. [43]	6	6.45–9.52	32.5	42–147	0.23–0.96	1000	105–155	14.84–21.9	23.5–127
Andermatt et al. [44]	12	1.07–2.07	39.9–68.5	37.9–42.3	1.47–2.13	300–310	257–891	2.75–5.95	96–1134.5
Ashour et al. [45]	6	2.7–5.9	22.95–29.75	141.4	0.12–0.52	200	169.5–370.4	7.56–16.52	17.585–36.115
Huaxin et al. [46]	13	1.11–2.02	34.85–54.57	51.3–210	0.76–1.16	200	260–360	3.33–4.62	83.8–309.7
Xiaoliang [47]	3	2.54–2.67	47.26–50.405	44.6	2.14–5.62	300	300–315	7.62–8.0	85.3–122.7
El Refai et al. [48]	8	2.5–3.3	49	50	0.31–1.53	152	195–215	7.44–8.21	16.9–31.6
Chang et al. [49]	14	5.8–8.0	30	44–50	0.24–1.22	1200	130–182	19.78–27.69	26.3–158.95
Abdul-Salam et al. [50]	16	5.67–6.34	41.3–86.2	40.8–147.8	0.51–3.78	1000	134–150	23.33–26.12	94–213
El-Sayed et al. [51–53]	18	3.04–6.45	40–63	40–135	0.39–2.63	205–1000	155–326	8.44–16.13	60–190
Ahmed et al. [54]	4	1.13–1.15	38.7–49.3	47.6–144	0.26–1.24	300	1088–1111	2.70–2.76	595.5–953
Alia et al. [55]	12	2.3–3.0	13–33.5	51.5	0.3–0.91	130	195.7–200	6.64–8.0	12.7–39.4
Jumaa et al. [56]	12	2.52–2.62	42.2–73.4	58	0.71–2.69	200	234–635	5.59–6.28	54.5–169.5
Minimum		0.5	13	32	0.12	100	105	2.38	9
Maximum		9.52	88.3	210	5.66	1200	1111	27.69	1134.5
Average		3.48	40.26	73.49	0.99	336.37	289.54	9.88	99.16
Range		9.02	75.3	178	5.54	1100	1006	25.31	1125.5

Step 1. Determining the reference sequence and the comparison sequences.

The data sequence that reflects the characteristics of the system behavior is called reference sequence and expressed as follows.

$$x_0(k) = x_0(1), x_0(2) \ldots x_0(n). \tag{3}$$

The data sequence composed of the factors affecting system behavior is called comparison sequence and expressed as follows.

$$x_i(k) = x_i(1), x_i(2) \ldots x_i(n), \tag{4}$$

where $k = 1, 2, 3 \ldots, n$ and $i = 1, 2, 3 \ldots, m$.

Step 2. Making the reference sequence and comparison sequences being dimensionless as follows.

$$x_i'(k) = \frac{x_i(k)}{1/n \sum_{k=1}^{n} x_i(k)}. \tag{5}$$

Step 3. Calculating the grey correlation coefficient $\xi_i(k)$ of the reference sequence and the comparison sequences as follows.

$$\xi_i(k) = \frac{\min_i \min_k |x_0'(k) - x_i'(k)| + \rho \max_i \max_k |x_0'(k) - x_i'(k)|}{|x_0'(k) - x_i'(k)| + \rho \max_i \max_k |x_0'(k) - x_i'(k)|}, \tag{6}$$

where ρ is the grey resolution coefficient, and generally $\rho = 0.5$.

Step 4. Calculating the grey relational grade γ_i as follows.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k). \tag{7}$$

Step 5. Evaluating the relevance as follows.

The grey relational grade is a manifestation of the degree of the relevance between the reference sequence and comparison sequences. Basically, the greater the grey relational grade, the higher the degree of the influence factors affecting the characteristics of the system behavior. It can be considered that the characteristics of the system behavior is greatly influenced by the influence factor while $\gamma \geq 0.8$ or $\gamma = 0.5 \sim 0.8$, not influenced by the influence factor while $\gamma < 0.5$ [59]. In this paper, to further illustrate the function of the factors, especially the L/d on the shear capacity of FRP bar reinforced concrete beams without web reinforcement, the GRA method will be used.

3.2. Grey Relational Grade for Each Experimental Parameter. As a systematic analysis method, GRA can overcome the shortcomings of conventional analysis methods in analyzing the correlation relationship of factor sequences. In this paper, the GRA method is used to analyze the sensitivity factors of shear capacity. Based on the database newly collected in Table 3, the V_c^{exp} is taken as the reference sequence (x_0); the experimental parameters including $a/d\,(x_1)$, $E_f\,(x_2)$, $\rho_f\,(x_3)$, $f_c'(x_4)$, $b\,(x_5)$, $d\,(x_6)$ and $L/d\,(x_7)$ are taken as the comparison sequences, respectively. Then, the new dimensionless sequences were obtained according to equation (5), and the grey relational coefficient and grey relational grade were calculated by equations (6) and (7), respectively. The calculated values of the grey relational grade are shown in Table 4.

From the data in Table 4, the grey relational grade values of seven experimental parameters are all above 0.8, which means that the seven experimental parameters are well correlated with shear capacity of FRP bar reinforced concrete beams without web reinforcement. Among them, the grey relational grade values of ρ_f, f_c', b and d are greater than those of a/d, E_f and L/d, which shows that the effect of ρ_f, f_c', b and d on V_c^{exp} is greater than a/d, E_f and L/d. Besides, the grey relational grade between V_c^{exp} and L/d is 0.88, which is equal to the grey relational grade values of a/d and E_f. It shows that the influence of L/d on the shear capacity of FRP bar reinforced concrete beams without web reinforcement is similar to that of a/d and E_f respectively.

Table 4: Calculated value of the grey relational grade for each experimental parameter.

Parameters	a/d	E_f	ρ_f	f_c'	b	d	L/d
γ_i	0.88	0.88	0.90	0.90	0.90	0.90	0.88

4. Prediction Model of Shear Capacity

4.1. Prediction Model. Considering the effect of L/d, a calculation model for the shear capacity of FRP bar reinforced concrete beams without web reinforcement can be proposed by modifying the model in CAN/CSA-S806-12. Based on the regression analysis for the database newly collected, the model for the shear capacity of FRP bar reinforced concrete beams without web reinforcement has been obtained as follows.

$$V_c = 0.07 k_l k_m k_r k_a k_s \left(f_c'\right)^{1/3} bd, \tag{8}$$

where the coefficients of k_l, k_m, k_r, k_a and k_s are given as follows, of which k_l represents the effect of L/d on the shear capacity.

$$\begin{cases} k_l = \left(\dfrac{L}{d} + 9\right)^{-0.11}, \\ k_m = \sqrt{\dfrac{d}{a}} \le 1, \\ k_r = 1 + \left(E_f \rho_f\right)^{1/3}, \end{cases} \tag{9}$$

$$\begin{cases} 1 \le k_a = 2.5\dfrac{d}{a} \le 2.5, \\ k_s = \dfrac{750}{(450 + d)} \le 1. \end{cases}$$

Considering the shear capacity of plain concrete members or members with extremely low reinforcement ratios, equation (10) needs to be used as the lower limit of the shear capacity for the proposed model as follows [5].

$$V_c \ge 0.11 \left(f_c'\right)^{1/2} bd. \tag{10}$$

4.2. Evaluation of the Models. To evaluate whether the models in Table 1 and equation (8) capture the effect of L/d on the shear capacity, the relationship between the ratios of experimental results to the calculated values V_c^{exp}/V_c^{calc} and L/d is shown in Figure 2. Meanwhile, a line ($V_c^{exp}/V_c^{calc} = 1$) which represents that the calculated value is equal to the experimental value is also plotted. When the data is located above the line, the experimental value is greater than the calculated value; when the data is located below the line, it means that the experimental value is less than the calculated value.

As shown in Figure 2, it is clear to find out that there is a declining trend for V_c^{exp}/V_c^{calc} calculated by the CAN/CSA-S806-12, ACI440.1R-15, CNR-DT203–2006,GB50608-2020, Gao and Zhang models with the increasing of L/d, respectively, when L/d is smaller than 10. Obviously, the smaller the L/d, the larger the conservative degree of the predicted shear capacity of FRP bar reinforced concrete beams without web reinforcement by the CAN/CSA-S806-12, ACI440.1R-15, CNR-DT203–2006, GB50608-2020, Gao and Zhang models. The majority of V_c^{exp}/V_c^{calc} values for the proposed model are scattered around the line $V_c^{exp}/V_c^{calc} = 1$, which indicates that the proposed model can well capture the influence of L/d on the shear capacity of FRP bar reinforced concrete beams without web reinforcement. Moreover, the V_c^{exp}/V_c^{calc} values of CAN/CSA-S806-12, ACI440.1R-15, CNR-DT203–2006, GB50608-2020, Gao and Zhang model and proposed model are scattered in a range of 0.242–4.582, 0.819–17.379, 0.157–4.703, 0.612–12.975, 0.405–2.815, 0.242–1.989, respectively, and the scatter range of V_c^{exp}/V_c^{calc} values of the proposed model is smaller than that of other models. It is apparent that the results of the proposed model for the shear capacity is more consistent with the experimental value compared with the four calculation models in codes and the Gao and Zhang model.

4.3. Performance Checking and Sensitive Analysis. To check the performance of the proposed model, the calculation values by the models are compared with the experimental values. As shown in Figure 3, the proposed model in this study has a better prediction function on the shear capacity of FRP bar reinforced concrete beams without web reinforcement than the CAN/CSA-S806-12, ACI440.1R-15, CNR-DT203–2006, GB50608-2020 and Gao and Zhang models.

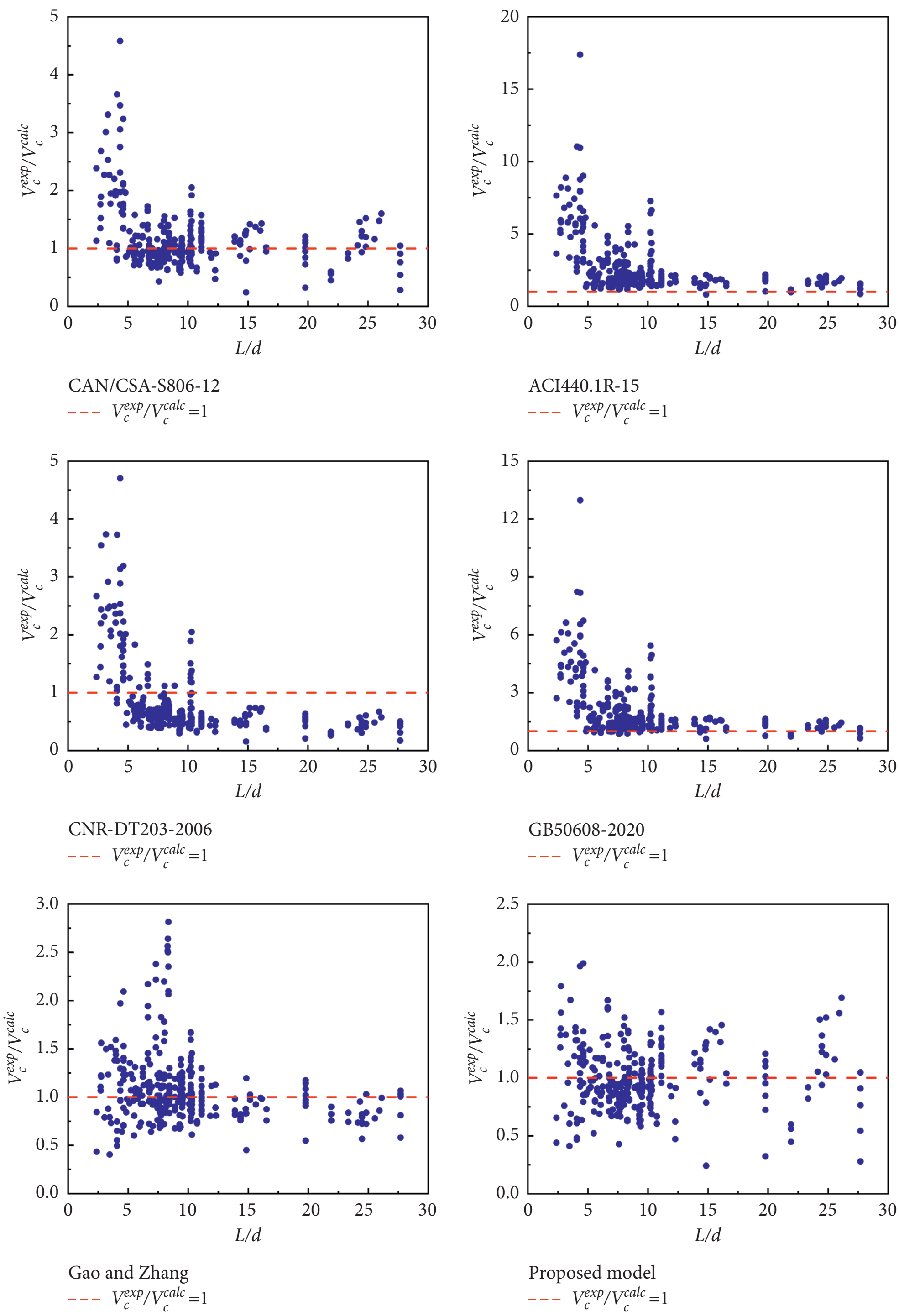

Figure 2: Relationship between $V_c^{\mathrm{exp}}/V_c^{\mathrm{calc}}$ and L/d.

Figure 4 shows the histogram of the frequency distribution of the $V_c^{\mathrm{exp}}/V_c^{\mathrm{calc}}$ values calculated by proposed model. The horizontal axis of the figure shows the $V_c^{\mathrm{exp}}/V_c^{\mathrm{calc}}$ values calculated by proposed model, and the vertical axis represents the number of the specimens for a certain value of $V_c^{\mathrm{exp}}/V_c^{\mathrm{calc}}$ calculated by proposed model. It can be seen that the values of $V_c^{\mathrm{exp}}/V_c^{\mathrm{calc}}$ calculated by proposed model follow a normal distribution, and most of the values appear in a narrow range between 0.6 and 1.2, which takes up 231 results of test beams in the database (73.6%).

To further investigate the superiority of the proposed model, the mean (MEAN), standard deviation (SD), and coefficient of variation (COV) were employed as the evaluation indicators, which can be calculated by the following formula.

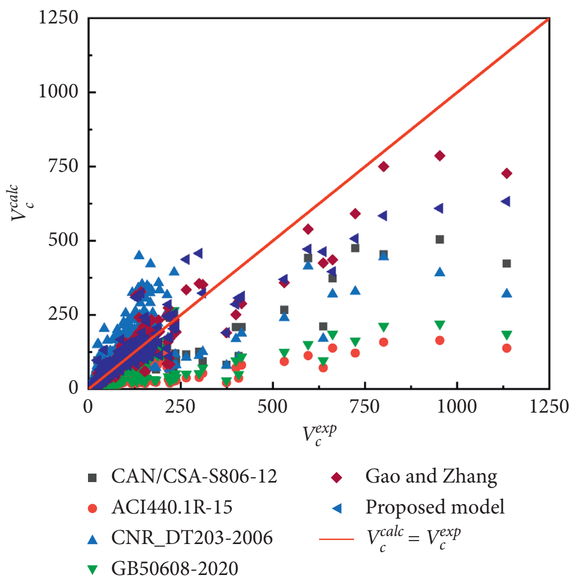

Figure 3: Comparison of V_c^{calc} and V_c^{exp}.

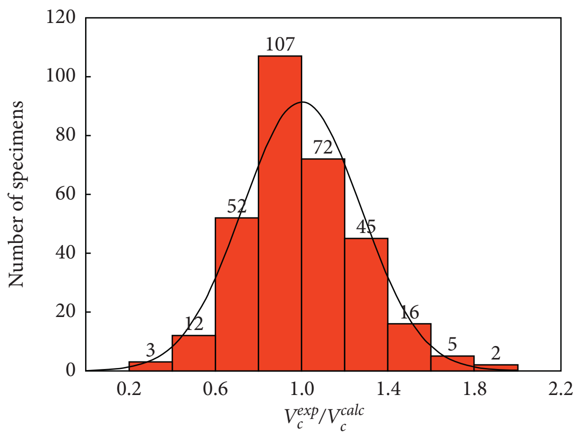

Figure 4: Histogram of the predictions of the proposed model.

Mean:

$$\mu = \frac{\sum_{i=1}^{n} V_{c,i}^{\mathrm{exp}} / V_{c,i}^{\mathrm{calc}}}{n}. \tag{11}$$

Standard deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} \left(V_{c,i}^{\mathrm{exp}} / V_{c,i}^{\mathrm{calc}} - \mu \right)^2}{n}}. \tag{12}$$

Coefficient of variation:

$$\mathrm{COV} = \frac{\sqrt{\sum_{i=1}^{n} \left(V_{c,i}^{\mathrm{exp}} / V_{c,i}^{\mathrm{calc}} - \mu \right)^2 / n}}{\left(\sum_{i=1}^{n} V_{c,i}^{\mathrm{exp}} / V_{c,i}^{\mathrm{calc}} \right) / n}. \tag{13}$$

The MEAN, SD and COV of $V_c^{\mathrm{exp}}/V_c^{\mathrm{calc}}$ are listed in Table 5.

Table 5: Evaluation indicators of the models.

	MEAN	SD	COV(%)
CAN/CSA-S806-12	1.157	0.528	45.7
ACI440.1R-15	2.717	1.932	71.1
CNR-DT203-2006	0.825	0.653	79.1
GB50608-2020	2.033	1.440	70.8
Gao and Zhang	1.077	0.368	34.2
Proposed model	1.000	0.273	27.3

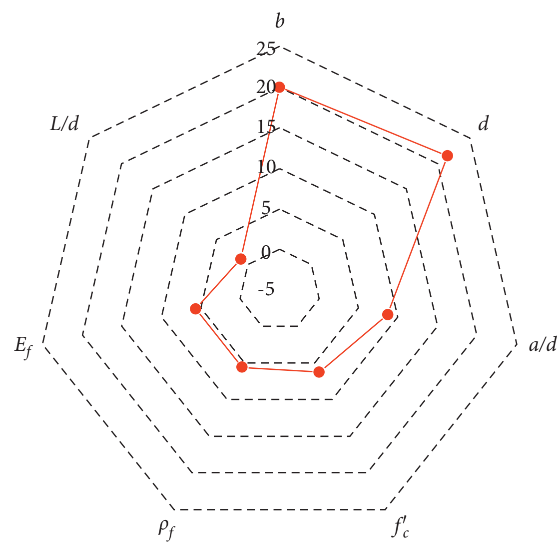

Figure 5: Effect of each parameter on the shear capacity (in percent).

It is obvious that the proposed model of equation (8) can well predict the shear capacity with MEAN, SD and COV of 1.000, 0.273 and 27.3%. Meanwhile, the MEAN of the proposed model is closer to 1, and the SD and COV of the proposed model are smaller than CAN/CSA-S806-12, ACI440.1R-15, CNR-DT203–2006, GB50608-2020 and Gao and Zhang models, respectively. Thus, the proposed model yields more scientific and accurate results for predicting the shear capacity in comparison with the CAN/CSA-S806-12, ACI440.1R-15, CNR-DT203–2006, GB50608-2020 and Gao and Zhang models, which did not consider the effect of L/d. This may be due to the effect of L/d is considered properly by the proposed model.

To analyze the sensitivity of every parameter for the proposed model, a set of data corresponding to the averages in Table 3 is selected as the starting data. When each parameter increases by 20%, the change rate of the calculated shear capacity is considered as the sensitivity index. The calculating results of sensitivity index are shown in Figure 5. It can be seen from the figure that the most important parameter impacting the shear capacity is d. The L/d has less effect on the shear capacity than the other six parameters. Under the fixed values of other parameter, the value of L/d varied from the minimum to maximum, the sensitivity index is 12.08%, which indicates the L/d cannot be ignored for predicting the shear capacity for FRP bar reinforced concrete beams without web reinforcement.

5. Conclusions

Based on the collected experimental data of 314 FRP bar reinforced concrete beams without web reinforcement, the GRA method was used to analyze the relevance of experimental parameters with the shear capacity, and a new shear capacity prediction model was proposed for FRP bar reinforced concrete beams without web reinforcement. The main conclusions can be drawn as follows.

(1) The GRA method can be used to analyze the relevance of experimental parameters on the shear capacity of FRP bar reinforced concrete beams without web reinforcement. The span-to-depth ratio (L/d) affects the shear capacity as the same as the shear span-to-depth ratio (a/d), elastic modulus of FRP bars (E_f), reinforcement ratio of longitudinal FRP bars (ρ_f), concrete compressive strength (f_c'), the width (b) and effective depth (d) of the beam.

(2) The number of the ratios of the experimental results for the shear capacity of FRP bar reinforced concrete beams without web reinforcement to the calculated values by the proposed model follows a normal distribution, and 73.6% of the ratio values distributes in a narrow range of 0.6–1.2.

(3) The proposed model can well capture the influence of span-to-depth ratio (L/d) on the shear capacity of FRP bar reinforced concrete beams without web reinforcement, and the calculation values by the proposed model are more consistent with the experimental values than those by the existing models.

Notation

f_c': Cylinder compressive strength of concrete, MPa.
f_{cu}: Cubic compressive strength of concrete, MPa.
ρ_f: Reinforcement ratio of longitudinal FRP bars.
E_f: Elastic modulus of FRP bars, MPa.
E_s: Elastic modulus of steel bars, MPa.
f_t: Tensile strength of concrete, MPa.
L: Effective span of beam, mm.
L/d: Span-to-depth ratio.
d: Effective depth of beam, mm.
h: Overall member depth, mm.
b: Width of beam, mm.
a: Shear span of beam, mm.
a/d: Shear span-to-depth ratio.
E_c: Elastic modulus of concrete, MPa.
$V_c^{\exp}$: Experimental value of shear capacity, N.
V_c^{calc}: Calculated value of shear capacity, N.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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