Research Article

Shear Strength Prediction Model of FRP Bar-Reinforced Concrete Beams without Stirrups

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The shear strength prediction model for fiber-reinforced polymer (FRP) bar-reinforced concrete beams without stirrups in ACI440.1R-2015 does not consider the “size effect” and the effect of shear span-to-depth ratio and predicts the zero-shear strength for concrete members without longitudinal reinforcement. A modified shear strength prediction model for FRP bar-reinforced concrete beams without stirrups was presented in this paper. The proposed model takes into account the effect of concrete strength, size of the beam, shear span-to-depth ratio, reinforcement ratio, and modulus of elasticity of the longitudinal reinforcement and the “size effect.” The superiority of the proposed model has been evaluated by comparing the calculated shear strength of FRP bar-reinforced concrete beams without stirrups by the proposed model with the experimental results and calculated values by the models in design codes, respectively. It confirmed that the shear strength of FRP bar-reinforced concrete beams without stirrups by the proposed model was in better agreement with the experimental results.

1. Introduction

Fiber-reinforced polymer (FRP) bars have gained the acceptance as an alternative to conventional steel bars for concrete structures due to their corrosion resistance, high strength-to-weight ratio, and magnetic neutrality. It has been recognized that the flexural capacity of FRP bar-reinforced concrete beams can be predicted by the traditional assumptions used in steel bar-reinforced concrete beams. However, while FRP bars have two drawbacks including brittle failure and low modulus of elasticity compared with the steel bars, the shear behavior (including shear strength, deformation, and crack width) of concrete beams reinforced with the FRP bar is different from those reinforced with similar amount of steel reinforcement [1–4]. For example, the stiffness [3] and dowel action [4] of FRP bar-reinforced beams are smaller compared to the concrete beams with steel bars, subsequently resulting in the larger deformation and lower shear strength. Therefore, the

existing shear strength prediction models for steel bar-reinforced beams cannot be directly applied to FRP bar-reinforced beams.

The shear strength prediction model of FRP bar-reinforced concrete beams in ACI440.1R-2015 [5] was based on the research by Tureyen and Frosch [6]. The ACI440.1R-2015 model was a function of the width (b) and effective depth (d) of the beam, concrete compressive strength (f'_c), reinforcement ratio (ρ_f), and modulus of elasticity (E_f) of FRP bars, and the shear span-to-depth ratio (a/d) was not included [7, 8]. Several investigations confirmed that shear strength V_c of FRP bar-reinforced concrete beams decreases as the a/d increases [7, 9–13]. Some investigators [7] revealed that V_c decreases almost linearly with $(a/d)^{2/3}$, while the others [10] reported that it decreases linearly with $(a/d)^{1/3}$. In addition, the ACI440.1R-2015 model did not take into account the effect of concrete in the tensile zone of the beam on the shear strength for FRP bar-reinforced concrete beams without longitudinal reinforcement and

predicted the zero-shear strength for concrete beams without longitudinal reinforcement [8]. Thirdly, the ACI440.1R-15 model did not take into account the “size effect” [14–17] which explains the phenomenon that the normalized shear strength of FRP bar-reinforced concrete beams decreases with the increasing of beam depth.

It has been recognized that f'_c , b , d , a/d , ρ_f , and E_f are the important parameters affecting the shear strength of FRP bar-reinforced concrete beams without stirrups. An equation that cannot predict the effects of known parameters would lack generality, and its applicability to general design situations would be uncertain [18]. Thus, there is a need to develop a modified shear strength prediction model for properly reflecting the effects of important parameters, which are known to affect the shear strength of FRP bar-reinforced beams without stirrups.

In this paper, a database of published test results on shear strength of 369 beams reinforced with FRP bars without stirrups was compiled. Considering the effects of a/d on the shear strength of FRP bar-reinforced concrete beams without stirrups and the “size effect” and the contribution of the concrete to the shear strength for concrete beams without longitudinal reinforcement, a more accurate and rational-modified prediction model was proposed based on the ACI440.1R-2015 model. The efficiencies of the proposed model and ACI440.1R-2015, CAN/CSA-S806-2012 [19], JSCE-1997 [20], AASHTO LRFD-2017 [21], and CNR-DT203-2006 [22] models were evaluated by comparing the calculated values with the experimental values in the database and the test data which are not contained in the database.

2. Experimental Database

To present a new shear strength prediction model of FRP bar-reinforced concrete beams without stirrups, a relatively large database including 369 beams reinforced with FRP bars without stirrups from 42 different investigations was established. The criteria for collecting the data of beam specimens were as follows: (1) rectangular cross sections; (2) simply supported; (3) tested under one- or two-point loading; (4) statically loaded; and (5) failed in shear. This database included various parameters which are known to affect the shear strength of FRP bar-reinforced concrete beams without stirrups, such as a/d , f'_c , b , d , ρ_f , and E_f . The variation range of each parameter and the corresponding shear strength of the beam used in this study are given in Table 1, which is collected from the original source.

3. Review of Shear Strength Prediction Models in Design Codes

The shear strength prediction models of FRP bar-reinforced concrete beams without stirrups were highly valued by many countries, such as America, Japan, Canada, and Italy. The “size effect” and effects of a/d , ρ_f , and E_f on the shear strength of FRP bar-reinforced concrete beams without stirrups were mainly considered in the shear strength prediction models of different design codes.

3.1. ACI440.1R-2015 Guidelines [5]. The shear strength calculating model of FRP bar-reinforced concrete beams without stirrups recommended by ACI Committee 440 is as follows:

$$V_c^{\text{aci}} = \frac{2}{5} \sqrt{f'_c} b (kd), \quad (1)$$

where $k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$, $n_f = E_f/E_c$.

It can be clearly seen that equation (1) of the ACI440.1R-2015 model predicts zero-shear strength for concrete beams without longitudinal reinforcement and does not consider the effect of a/d on the shear strength of FRP bar-reinforced concrete beams without stirrups and the “size effect.”

3.2. JSCE-1997 Design Recommendations [20]. The shear strength calculating model of FRP bar-reinforced concrete beams without stirrups recommended by Japan Society of Civil Engineering (JSCE-1997) is as follows:

$$V_c^{\text{jsce}} = \beta_d \beta_\rho \beta_n f_{vcd} b d, \quad (2)$$

where $\beta_d = (1000/d)^{1/4} \leq 1.5$, $\beta_\rho = (100\rho_f E_f/E_s)^{1/3} \leq 1.5$, and $f_{vcd} = 0.2 \sqrt[3]{f'_c} \leq 0.72 \text{ MPa}$

It is the same as equation (1) of the ACI440.1R-15 model that equation (2) of the JSCE-1997 model predicts zero-shear strength for concrete beams without longitudinal reinforcement and does not consider the effect of a/d on the shear strength of FRP bar-reinforced concrete beams without stirrups although it takes into account the “size effect” through β_d .

3.3. CAN/CSA-S806-2012 Design Provisions [19]. The shear strength calculating model of FRP bar-reinforced concrete beams without stirrups recommended by the Technical Committee on Design and Construction of Building Structures with Fibre-Reinforced Polymers of Canadian Standards Association (CAN/CSA-S806) is as follows:

$$V_c^{\text{s806}} = 0.05 k_m k_r k_a k_s \sqrt[3]{f'_c} b d, \quad (3)$$

$$0.11 \sqrt{f'_c} b d \leq V_c^{\text{s806}} \leq 0.22 \sqrt{f'_c} b d, \quad (4)$$

where $k_m = \sqrt{d/a} \leq 1.0$, $k_r = 1 + \sqrt[3]{E_f \rho_f}$, $1.0 \leq k_a = 2.5 d/a \leq 2.5$, and $k_s = 750/(450 + d) \leq 1.0$.

Equation (3) of the CAN/CSA-S806-2012 model considers the effects of nearly all parameters on the shear strength of FRP bar-reinforced concrete beams without stirrups.

3.4. AASHTO LRFD-2017 Design Guide Specifications [21]. The shear strength calculating model of FRP bar-reinforced concrete beams without stirrups recommended by the American Association of State Highway and Transportation Officials is as follows:

TABLE 1: Specimen details.

Investigator	No. of specimens	a/d	f'_c (MPa)	b (mm)	d (mm)	E_f (GPa)	ρ_f (%)	V_c (kN)
Ashour and Kara [15, 23]	18	2.5~5.9	23~50.2	150~200	163~371	32~142	0.12~1.39	9~36.1
Gross [4, 24, 25]	42	4.1~6.5	36.3~81.4	65~279	141~225	41~139	0.33~2.56	8.8~51
El-Sayed and El-Salakawy [26~28]	18	3.1~6.5	40~63	250~1000	155~326	39~135	0.39~2.63	60~190
Razaqpur et al. [10]	7	1.8~4.2	40.5~49	200	225	145	0.25~0.88	36.1~96.2
Benmokrane [29]	12	2.8~3.7	34.1~43.2	130~160	310~346	42~120	0.72~1.54	42.7~63.7
Tureyen and Frosch [30]	6	3.4	39.7~42.6	457	360	38~47	0.96~1.92	94.7~177
Nanni [31]	3	2.6~2.7	24.1	178	279~287	40	0.77~2.3	36.1~53.4
Deitz and Harik [32]	5	4.5~5.8	27~30.8	305	158	40	0.73	26.8~29.2
Mizukawa [33]	1	2.7	34.7	200	260	130	1.3	62.2
Duranovic [34]	3	3.7	32.9~38.1	150	210	45~130	1.31~1.36	26.2~62.2
Swamy [35]	2	3.2~4.1	38~39	154~305	192~222	34~42	0.36~1.55	19.5~26.7
Suzuki [36]	3	3	34.3	150	250	105	1.51~3.02	40.5~46
Alam and Hussein [7, 17]	37	1.5~3.5	34.5~88.3	250~300	291~744	47~144	0.18~1.47	43.7~155.8
Nakamura and Higai [37]	2	3	22.7~27.8	300	150	29	1.3~1.8	33~36
Bentz et al. [14]	6	3.3~4.1	35~46	450	188~937	37	0.51~2.54	54.5~232
Bazant and Yu [38]	1	3.1	40	450	970	40	0.46	136
Wakui and Tottori [39]	4	3.2	44.6~46.9	200	325	58~192	0.7~0.9	87~118
Nagasaka and Fukuyama [40]	2	3.1	22.9~34.1	250	265	56	1.9	83~113
Issa et al. [41]	6	5.7~7	35.9	300	165~170	48~53	0.8~4.12	29.3~51.5
Tomlinson and Fam [42]	3	4.1~4.5	56.5~60	150	245~270	70	0.39~0.85	20.9~29.2
Abed et al. [3]	9	1~1.5	43~65	200	230~330	51	0.92~1.84	116.6~373.9
Guadagnini et al. [43]	3	1.1~3.3	42.8~47.7	150	223	45	1.28	27.2~81
Kim and Jang [44]	40	1.5~4.5	30~40.3	150~200	214~216	40~148	0.33~0.79	16.6~85.1
Olivito and Zuccarello [45]	20	5.6	20.4~27.2	150	180	115	0.87~1.45	16.6~29.9
Matta et al. [46]	12	3.1	29.5~59.7	114~457	146~883	41~49	0.12~0.28	17.9~220.7
Thomas and Ramadass [9]	8	0.5~1.8	40.6~65.3	100~170	270~416	40	1.16~1.75	30~300
Wegian and Abdalla [47]	6	6.5~9.5	32.5	1000	105~155	42~147	0.23~0.96	23.5~127
Andermatt and Lubell [11]	12	1.1~2.1	39.9~68.5	300~310	257~891	38~43	1.47~2.13	96~1134.5
Huaxin and Genjin [13]	13	1.1~2	34.9~54.6	200	260~360	52~210	0.76~1.16	83.8~309.7
Xiaoliang and Wenjun [48]	3	2.5~2.7	47.3~50.4	300	300~315	45	2.14~5.62	85.3~122.7
El Refai and Abed [8]	8	2.5~3.3	49	152	195~215	50	0.31~1.53	16.9~31.6
Chang and Seo [49]	14	5.8~8	30	1200	130~182	44~50	0.24~1.22	26.3~159
Abdul-Salam et al. [50]	16	5.7~6.3	41.3~86.2	1000	134~150	41~148	0.51~3.78	94~213
Farghaly and Benmokrane [51]	4	1.1	38.7~49.3	300	1088~1111	48~144	0.26~1.24	595.5~953
Ali et al. [12]	12	2.3~3	13~33.5	130	196~200	52	0.3~0.91	12.7~39.4
Omeman et al. [1]	8	1.4~2.3	34.7~63.1	150	387~662	134	1.13~2.26	45.8~234.1
Total	369	0.5~9.5	13~88.3	65~1200	105~1111	29~210	0.12~5.62	8.8~1134.5

Note: if the concrete cylinder compressive strength f'_c and modulus of elasticity of concrete E_c were not provided by the investigator while the concrete cube compressive strength f_{cu} was only measured, it is assumed that $f'_c = 0.8f_{cu}$ and $E_c = 4733\sqrt{f'_c}$. If the unit of data was BS provided by the investigator, it is converted by the following factors: 1 ksi = 6.895 MPa, 1 in = 25.4 mm, and 1 kip = 4.448 KN.

$$V_c^{\text{lrfd}} = \left(0.0676\sqrt{f'_c} + 4.6\rho_f\frac{d}{a} \right) bd \leq 0.126\sqrt{f'_c}bd. \quad (5)$$

Equation (5) of the AASHTO LRFD-2017 model considers the effects of a/d and ρ_f on the shear strength of FRP bar-reinforced concrete beams without stirrups while the effect of E_f and the “size effect” are not included.

3.5. *CNR-DT203-2006* [22]. The shear strength of FRP bar-reinforced concrete beams without stirrups recommended by Advisory Committee Technical Recommendations Construction of Italian National Research Council is as follows:

$$V_c^{\text{cnr}} = 1.3(E_f/E_s)^{1/2}\tau_r k_d (1.2 + 40\rho_f)bd, \quad (6)$$

where $1.3(E_f/E_s)^{1/2} \leq 1$, $\tau_r = 0.25f_t$, $k_d = 1.6 - (d/1000) \geq 1$, and $\rho_f \leq 0.02$.

Equation (6) of the CNR-DT203-2006 model considers the “size effect” through k_d and does not consider the effect of a/d on the shear strength of FRP bar-reinforced concrete beams without stirrups.

4. Proposed Shear Strength Prediction Model

According to the experimental database mentioned above, the normalized shear strength $V_c^{\text{exp}}/\sqrt{f'_c}bd$ was plotted against $\rho_f n_f$ ($n_f = E_f/E_c$) as shown in Figure 1(a). It can be seen that the relationship between the normalized shear strength $V_c^{\text{exp}}/\sqrt{f'_c}bd$ and $\rho_f n_f$ fits into the trendline in Figure 1(a) except some plots. To express this trendline with a reasonable equation, the normalized shear strength $V_c^{\text{exp}}/\sqrt{f'_c}bd$ was also plotted against k ($k =$

FIGURE 1: Effect of $\rho_f n_f$ and k on $V_c^{\text{exp}} / \sqrt{f'_c} b d$.

$\sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$ as shown in Figure 1(b), where k can be defined as the relative depth of the compressive zone because the depth of compressive zone c can be calculated by multiplying d by k ($c = kd$). From the regression of the results of FRP bar-reinforced concrete beams without stirrups, there is a linear equation between $V_c^{\text{exp}} / \sqrt{f'_c} b d$ and k , which can be written as

$$\frac{V_c^{\text{exp}}}{\sqrt{f'_c} b d} = 0.4(k + 0.1). \quad (7)$$

Equation (7) can take into account the effects of ρ_f and E_f on the shear strength for FRP bar-reinforced concrete beams without stirrups and the contribution of concrete on shear strength for FRP bar-reinforced concrete beams without longitudinal reinforcement.

4.1. Effect of Shear Span-to-Depth Ratio (a/d) on the Shear Strength. In order to eliminate the influence of ρ_f and E_f on shear strength of FRP bar-reinforced concrete beams without stirrups, the normalized shear strength was taken as $V_c^{\text{exp}} / 0.4\sqrt{f'_c} b (k + 0.1)d$ on the basis of equation (7), which was plotted against a/d according to the experimental database mentioned above, as shown in Figure 2. Evidently, $V_c^{\text{exp}} / 0.4\sqrt{f'_c} b (k + 0.1)d$ decreases as a/d increases, and there is a trendline between $V_c^{\text{exp}} / 0.4\sqrt{f'_c} b (k + 0.1)d$ with a/d . The relationships between $V_c^{\text{exp}} / 0.4\sqrt{f'_c} b (k + 0.1)d$ and a/d can be obtained by the regressions based on the following three criteria:

- (1) The regressions can be described in four forms depending upon the value of a/d or determined by the types of failure referred to those for steel bar-reinforced beams [52].

Diagonal compression failure (when $0 \leq a/d < 1$):

$$\frac{V_c^{\text{exp}}}{0.4\sqrt{f'_c} b (k + 0.1)d} = f_1(a/d). \quad (8)$$

Shear compression failure (when $1 \leq a/d < 3$):

$$\frac{V_c^{\text{exp}}}{0.4\sqrt{f'_c} b (k + 0.1)d} = f_2\left(\frac{a}{d}\right). \quad (9)$$

Diagonal tension failure (when $3 \leq a/d < 6$):

$$\frac{V_c^{\text{exp}}}{0.4\sqrt{f'_c} b (k + 0.1)d} = f_3\left(\frac{a}{d}\right). \quad (10)$$

Bending failure (when $a/d \geq 6$):

$$\frac{V_c^{\text{exp}}}{0.4\sqrt{f'_c} b (k + 0.1)d} = f_4\left(\frac{a}{d}\right). \quad (11)$$

- (2) The regressions remain coordinated on boundary conditions

$$\begin{aligned} f_1(1) &= f_2(1), \\ f_2(3) &= f_3(3), \\ f_3(6) &= f_4(6). \end{aligned} \quad (12)$$

- (3) According to Reinforced Concrete Design to Eurocode 2 [53], when $\rho_f = 0$ and $a/d = 0$, the shear strength can be calculated by the following equation:

$$V_c^{\rho_f=0, a/d=0} = \tau b d. \quad (13)$$

The shear strength of concrete τ can be expressed by the tension strength of concrete f_t as follows [52]:

$$\tau = \alpha f_t, \quad (14)$$

where α is a constant, generally, $\alpha = 1.5 - 2.5$. Conservatively, here, $\alpha = 1.6$.

The concrete tension strength f_t can be evaluated with the equation in ACI318-14 [54] as follows:

$$f_t = \frac{5}{8} \sqrt{f'_c}. \quad (15)$$

FIGURE 2: Effect of a/d on $V_c^{\text{exp}}/0.4\sqrt{f'_c}b(k+0.1)d$.

Substituting the values of f_t in equation (15) into equation (14), the equation for shear strength of concrete can be rewritten as

$$\tau = \sqrt{f'_c}. \quad (16)$$

Substituting the values of τ in equation (16) into equation (13), when $\rho_f = 0$ and $a/d = 0$, the equation for the shear strength of the FRP bar-reinforced concrete beams without stirrups can be rewritten as

$$V_c^{\rho_f=0, a/d=0} = \sqrt{f'_c}bd. \quad (17)$$

Based on the regressions of the database aforementioned, as shown in Figure 2, the functions between $V_c^{\text{exp}}/0.4\sqrt{f'_c}b(k+0.1)d$ and a/d can be obtained as follows:

$$\begin{aligned} f_2\left(\frac{a}{d}\right) &= \frac{2.5}{(a/d) - 0.5}, \\ f_3\left(\frac{a}{d}\right) &= 1, \\ f_4\left(\frac{a}{d}\right) &= \frac{6}{a/d}. \end{aligned} \quad (18)$$

As there are only two specimens in the database whose shear span-to-depth ratio is below 1.0, no more data can be employed for regression; therefore, the function of $f_1(a/d)$ could be set up according to the criterions (2) and (3) as follows:

$$f_1\left(\frac{a}{d}\right) = \frac{(1 - (a/d))/(1 + (a/d))}{0.4(k + 0.1)} + 5\left(\frac{a}{d}\right). \quad (19)$$

Then, the equation for shear strength of FRP bar-reinforced concrete beams without stirrups, which considers the effect of shear span-to-depth ratio (a/d), can be modified as follows:

$$V_c = k_{fad}\sqrt{f'_c}bd, \quad (20)$$

where

$$k_{fad} = \begin{cases} \frac{(1 - (a/d))}{(1 + (a/d))} + 2(k + 0.1)\left(\frac{a}{d}\right), & \text{while } \frac{a}{d} \leq 1, \\ \frac{(k + 0.1)}{((a/d) - 0.5)}, & \text{while } 1 < \frac{a}{d} \leq 3, \\ 0.4(k + 0.1), & \text{while } 3 < \frac{a}{d} \leq 6, \\ \frac{2.4(k + 0.1)}{(a/d)}, & \text{while } a/d > 6. \end{cases} \quad (21)$$

4.2. “Size Effect” on the Shear Strength. According to the experimental database mentioned above and equation (21), the normalized shear strength $V_c^{\text{exp}}/k_{fad}\sqrt{f'_c}bd$ was plotted against a/d , f'_c , b , d , ρ_f , and E_f as shown in Figure 3, respectively. It can be seen that $V_c^{\text{exp}}/k_{fad}\sqrt{f'_c}bd$ does not have the obvious variation with the increase of b , d , f'_c , ρ_f , E_f , and a/d , respectively, but there is a relation between $V_c^{\text{exp}}/k_{fad}\sqrt{f'_c}bd$ and d . It indicates that the influence of b , d , f'_c , ρ_f , E_f , and a/d upon the shear strength of FRP bar-reinforced concrete beams without stirrups has been embodied reasonably well by equation (20) except the influence of d . This phenomenon demonstrates the “size effect” exists on the shear strength of FRP bar-reinforced concrete beams without stirrups mentioned in the literature review.

Then, referring to Eurocode 2 for the shear capacity of concrete reinforced with the steel bar, the equation for shear strength of FRP bar-reinforced concrete beams without stirrups, which has taken into account the “size effect” by a linear reduction form [15], can be established as follows:

$$V_c = k_{fad}k_d\sqrt{f'_c}bd, \quad (22)$$

where

FIGURE 3: Effect of parameters on $V_c^{\text{exp}}/k_{fad}\sqrt{f'_c}bd$. FIGURE 4: Comparison of V_c^{exp} and V_c^{calc} .

FIGURE 5: Influence of a/d , k , and d on shear strength predictions.

$$k_d = 1.35 - \frac{d}{1000} \geq 0.75. \quad (23)$$

5. Comparison of Predicted Shear Strength and Experimental Results

Figure 4 presents the correlations of the experimental shear strength V_c^{exp} of all 369 specimens in the database mentioned above and another 18 test data of specimens from Jumaa and Yousif [55] and Ovitigala [56] with the calculated shear strengths V_c^{aci} , V_c^{jsc} , V_c^{s806} , V_c^{lrfd} , V_c^{cnr} , and V_c^{prop} , respectively. A line with tolerance of 0% has been represented in the graph, which indicates that the exact prediction $V_c^{\text{exp}}/V_c^{\text{calc}} = 1$ of the shear strength. It can be seen that the ACI440.1R-2015, JSCE-1997, and AASHTO LRFD-2017 models provide conservative predictions of the shear strengths of the most specimens ($V_c^{\text{exp}}/V_c^{\text{calc}} > 1$); the predictions of the CNR-DT203-2006 model are highly unconservative for many specimens; the CAN/CSA-S806-2012 model shows better agreement with the experiment results than other models in the design codes aforementioned; and the predictions of the proposed model by equation (22) fit better with the experiment results than all the models in the design codes aforementioned.

Figure 5 illustrates the relationships among the shear strength ratio of the experimental shear strength to the calculated shear strength $V_c^{\text{exp}}/V_c^{\text{calc}}$ and a/d , k , and d , respectively. As shown in Figure 5, the ratio of $V_c^{\text{exp}}/V_c^{\text{calc}}$ decreases as a/d increases, while $a/d \leq 2.5$ for all the models in the design codes aforementioned; both ratios of $V_c^{\text{exp}}/V_c^{\text{s806}}$ and $V_c^{\text{exp}}/V_c^{\text{lrfd}}$ increase as k increases, for the CAN/CSA-S806-2012 model does not well consider the effects of ρ_f nor E_f , and the AASHTO LRFD-2017 model does not consider the effect of E_f ; and the ratio of $V_c^{\text{exp}}/V_c^{\text{prop}}$ does not have obvious variation with the increase of a/d , k , or d . Moreover, the proposed model has the least scatter range of $V_c^{\text{exp}}/V_c^{\text{prop}}$ from 0.39 to 2.63, whilst the scatter range of $V_c^{\text{exp}}/V_c^{\text{calc}}$ for ACI440.1R-2015, JSCE-1997, CAN/CSA-S806-2012, AASHTO LRFD-2017, and CNR-DT203-2006 models is from 0.82 to 17.38, 0.44 to 12.88, 0.24 to 4.58, 0.39 to 13.91, and 0.18 to 4.87, respectively. Hence, the effect of a/d , ρ_f , E_f , and d on shear strength normalized by the proposed model of equation (22) is captured reasonably well. It should be mentioned that the predicted values by the proposed model for the two specimens with shear span-to-effective depth less than 1 are in good agreement with the experimental values ($V_c^{\text{exp}}/V_c^{\text{prop}} = 1$) though the function of the proposed model ($a/d \leq 1$) was not obtained by the regression method.

The ratios of $V_c^{\text{exp}}/V_c^{\text{prop}}$ are presented graphically using a histogram as shown in Figure 6. The horizontal axis of the figure shows the ratio of $V_c^{\text{exp}}/V_c^{\text{prop}}$, and the vertical axis represents the frequency of the specimens for a certain $V_c^{\text{exp}}/V_c^{\text{prop}}$ ratio. It can be seen that the values of $V_c^{\text{exp}}/V_c^{\text{prop}}$ follow a normal distribution, and 60% of the values is in a narrow range 0.8 to 1.2.

To further investigate the superiority of the proposed shear strength prediction model of FRP bar-reinforced concrete beams without stirrups, a total of three

FIGURE 6: Histogram of the predictions of the proposed model.

TABLE 2: Mean, SD, and COV of the ratio $V_c^{\text{exp}}/V_c^{\text{calc}}$.

Performance checks	Regression database			Test data		
	Mean	SD	COV	Mean	SD	COV
$V_c^{\text{exp}}/V_c^{\text{aci}}$	2.61	1.84	0.70	1.95	0.55	0.28
$V_c^{\text{exp}}/V_c^{\text{lrfd}}$	2.55	1.73	0.68	2.09	0.64	0.30
$V_c^{\text{exp}}/V_c^{\text{jsc}}$	1.92	1.45	0.76	1.63	0.50	0.30
$V_c^{\text{exp}}/V_c^{\text{s806}}$	1.15	0.52	0.45	1.12	0.19	0.17
$V_c^{\text{exp}}/V_c^{\text{cnr}}$	0.90	0.69	0.77	0.69	0.12	0.18
$V_c^{\text{exp}}/V_c^{\text{prop}}$	1.09	0.31	0.28	1.14	0.19	0.17

performance checks were adopted. The mean, standard deviation (SD), and coefficient of variation (COV) of the ratio $V_c^{\text{exp}}/V_c^{\text{calc}}$ are given in Table 2. It can be observed that the proposed model, as a whole, predicts the shear strength of FRP bar-reinforced concrete beams without stirrups with smaller SD and COV values than ACI440.1R-2015, JSCE-1997, AASHTO LRFD-2017, CNR-DT203-2006, and CAN/CSA-S806-2012 models.

6. Conclusions

The impacts of shear span-to-depth ratio upon the shear strength of FRP bar-reinforced concrete beams without stirrups and the “size effect” were investigated by analyzing the collected experimental results. A new model for the shear strength prediction of FRP bar-reinforced concrete beams without stirrups was proposed by using the regression method based on the experimental database. The main conclusions of this research are summarized as follows:

- (1) The proposed model considers the “size effect” and the effect of shear span-to-depth ratio on the shear strength for FRP bar-reinforced concrete beams without stirrups, which decrease as the shear span-to-depth ratio and effective depth increase, respectively.
- (2) The values of experimental results for the shear strength of FRP bar-reinforced concrete beams without stirrups to calculated values by the proposed model follow a normal distribution, and 60% of the values distribute in a narrow range 0.8 to 1.2.

- (3) The proposed model has more reasonable and reliable predictions for the shear strength of FRP bar-reinforced concrete beams without stirrups in comparison with the models in design codes mentioned.

Notations

f'_c :	Cylinder compressive strength of concrete, MPa
f_{cu} :	Cube compressive strength of concrete, MPa
f_t :	Tension strength of concrete, MPa
a :	Shear span, mm
b :	Beam width, mm
d :	Effective depth, mm
a/d :	Shear span-to-depth ratio
k :	Relative depth of the compressive zone
c :	Depth of the compressive zone, mm
ρ_f :	Reinforcement ratio
n_f :	Modular ratio
E_f :	Modulus of elasticity of FRP bars, MPa
E_c :	Modulus of elasticity of concrete, MPa
V_c :	Shear strength of FRP bar-reinforced concrete beams, N
V_c^{exp} :	Experimental shear strength, N
V_c^{calc} :	Calculated shear strength, N
V_c^{prop} :	Calculated shear strength using the proposed model, N
V_c^{aci} :	Calculated shear strength using the ACI440.1R-15 model, N
V_c^{jsc} :	Calculated shear strength using the JSCE-1997 model, N
V_c^{s806} :	Calculated shear strength using the CAN/CSA-S806-2012 model, N
V_c^{lfrd} :	Calculated shear strength using the AASHTO LRFD-2017 model, N
V_c^{cnr} :	Calculated shear strength using the CNR-DT203-2006 model, N.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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