Journal of Southeast University (English Edition) Vol. 39, No. 3, pp. 301 − 313 Sept. 2023 ISSN 1003—7985

Database-based error analysis of calculation methods for shear capacity of FRP-reinforced concrete beams without web reinforcement

Wang Tao[1] Fan Xiangqian[1,2] Gao Changsheng[1] Qu Chiyu[1] Liu Jueding[1]

([1]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing 210024, China)

([2]Cooperative Innovation Center for Water Safety and Hydro Science, Hohai University, Nanjing 210098, China)

Abstract: A comprehensive database consisting of 461 samples was established considering the shear capacity experimental data from the literature. The effects of six factors, namely the concrete compressive strength, beam width, effective depth, shear span-to-depth ratio, reinforcement ratio, and elastic modulus of fiber-reinforced polymer bars, on shear capacity were analyzed. Furthermore, the prediction performance of each calculation method was evaluated. The results revealed inconsistencies among the calculation methods regarding the consideration of the size effect and the shear span-to-depth ratio, with varying degrees of conservatism in their predictions. Strong correlations existed between the factors and the shear capacity. Among the design provisions recommended by different countries, CSA/CAN-S806-2012 exhibited the most accurate prediction, while ACI440.1R-2015 demonstrated the highest level of conservatism, and CNR-DT203-2006 exhibited the lowest safety margin. Regarding the calculation models proposed by scholars, Ahmed-2021 reported the most accurate prediction, Alam-2013 was the most conservative, and Mari-2014 exhibited the lowest safety level.

Key words: database; fiber-reinforced polymer(FRP) bars; concrete beams without web reinforcement; shearing capacity; calculation method; error analysis

DOI: 10.3969/j.issn.1003 −7985.2023.03.011

Corrosion of steel bars leads to cracking and spalling of the concrete cover, resulting in a sharp decline in the durability of the structure. Consequently, this leads to high economic losses and even casualties[1−3]. Fiber-reinforced polymer (FRP) bars, with their advantages of lightweight, high strength, and corrosion resistance, can fundamentally address the durability issue caused by the corrosion of steel bars in concrete structures[4−6]. Therefore, the use of FRP bars as reinforcing bars in concrete structures has a wide range of applications in practical engineering[7−9]. Currently, research on the flexural behavior of FRP-reinforced concrete beams is relatively mature, but the research on their shear performance is limited[10−12].

The shear capacity of beams with web reinforcement, as specified in widely used design provisions, is primarily composed of two components: concrete action and web reinforcement action[13−15]. Therefore, it is crucial to study the shear capacity of FRP-reinforced concrete beams without web reinforcement as a basis for understanding the shear performance of concrete beams[16−18]. The shear mechanism of FRP-reinforced concrete beams without web reinforcement is complex and consists of five main components: the shear strength of uncracked concrete in the compression zone, the dowel action of the longitudinal reinforcements, aggregate interlock, residual tensile stresses between the cracks, and arching action provided by struts and ties[19−21]. Owing to the complexity of the shear problem, different design provisions and calculation models based on various theories have been proposed, resulting in variations in form and predictive accuracy[22−23]. Most of these methods are semitheoretical and semiempirical formulas derived from the statistical analysis of data[24−26]. In the case of complex research problems, a larger data sample of the research target provides a better reflection of its actual performance, reducing the margin of error in the statistical analysis[27−28]. In recent years, there has been an increase in relevant test data for the shear performance of FRP-reinforced concrete beams without web reinforcement[29−30], which helps to address the scarcity of test data to a certain extent. Consequently, both domestic and international scholars have conducted numerous studies to develop a calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement. These studies consider more comprehensive factors and strive for more accurate predictions by establishing a database with a relatively large sample size[31−34].

In this study, a database comprising of 461 sets of experimental data was established through the collection and organization of published literature from both domestic and international sources. This database serves as a foundation for the application of artificial intelligence-based

Received 2023-03-20, **Revised** 2023-06-08.

Biographies: Wang Tao (1995—), male, Ph. D. candidate; Fan Xiangqian (corresponding author), male, doctor, professorate senior engineer, xqfan@nhri.cn.

Foundation items: The National Natural Science Foundation of China (No. 52171270, 51879168, 51679150), the Joint Fund for Water Science Research of the Yellow River (No. U2243223).

Citation: Wang Tao, Fan Xiangqian, Gao Changsheng, et al. Database-based error analysis of calculation methods for the shear capacity of FRP-reinforced concrete beams without web reinforcement [J]. Journal of Southeast University (English Edition), 2023, 39(3): 301 − 313. DOI: 10.3969/j.issn.1003 −7985.2023.03.011.

prediction methods in the field of FRP-reinforced concrete beams. Through the correlation analysis method, this paper explores the relationship between various factors and shear capacity, thus validating the applicability of the multifactor analysis approach in FRP-reinforced concrete beams without web reinforcement. Considering the database, this research analyzes the errors associated with shear capacity calculation methods based on different design provisions and calculation models. Additionally, it elucidates the influence of size effect and shear span ratio on shear capacity. The findings of this study hold a certain reference value for further research on the calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement.

1 Experimental Database

1.1 Database overview

A shear capacity database consisting of 461 samples was established by collecting and organizing shear test data from 47 published literature sources on FRP-reinforced concrete beams without web reinforcement. The following principles were followed during the specimen collection process:

1) The specimens were loaded under concentrated conditions.

2) The specimens featured equal rectangular cross sections.

3) The specimens were supported using a simple method.

4) The specimens exhibited shear failure.

5) The specimens were reinforced with FRP bars.

Fig. 1 illustrates the distribution of different longitudinal bar types in the database, including 285 groups of GFRP specimens, 128 groups of CFRP specimens, 46 groups of BFRP specimens, and 2 groups of AFRP specimens.

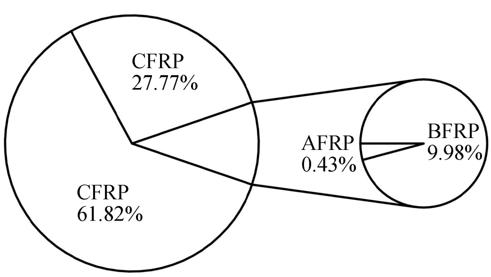

Fig. 1 Proportions of specimens with different longitudinal reinforcement types

Tab. 1 presents the factors influencing the shear capacity in the database, which mainly include the beam width, the effective depth of the beam, the shear span-to-depth ratio, the compressive strength of concrete, the elastic modulus of the FRP bar, and the reinforcement ratio of the FRP bars. Moreover, the table provides their minimum, maximum, and average values.

Furthermore, Fig. 2 illustrates the specific distribution of the beam width, the effective depth, the shear span-to-depth ratio, the compressive strength of concrete, the elastic modulus of the FRP bar, and the reinforcement ratio of the FRP bars within the database. The following conclusions can be drawn from Fig. 2:

1) The data for the beam width in the database are mostly concentrated in the range of 100 to 400 mm.

2) The data for the effective depth of the beam in the database are mostly concentrated in the range of 100 to 300 mm.

3) There are relatively few samples with a shear span-to-depth ratio of less than 1 in the database (only three groups).

4) The compressive strengths of concrete samples in the database are mostly concentrated in the range of 30 to 50 MPa.

5) There are relatively few FRP bar samples in the database with an elastic modulus of 60 to 105 GPa.

6) The FRP reinforcement ratios of the samples are mostly concentrated in the range of 0.5% to 1.0%.

1.2 Parameter conversion principle in database

During data collection, certain conversions were applied when the original literature only provided the compressive strength of the concrete cube. The compressive strength is obtained as follows[34]:

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

where f_{cu} is the compressive strength of the concrete cube, MPa.

When the elastic modulus of concrete is not provided in the original literature, it is derived as follows[31]:

$$E_c = 4\,733\sqrt{f_c'} \tag{2}$$

where E_c is the elastic modulus of concrete, MPa.

When the tensile strength of concrete is not provided in the original literature, it is derived as follows[13]:

$$f_t = 0.623\sqrt{f_c'} \tag{3}$$

where f_t is the tensile strength of concrete, MPa.

2 Calculation Method of Shear Capacity

2.1 Shear capacity calculating methods in codes

2.1.1 CSA/CAN-S806-2012

Existing research results have demonstrated that the shear capacity calculation method proposed in the CSA/CAN-S806-2012[35] design code considers the factors influencing shear capacity more comprehensively than other widely used design provisions and provides a more accurate prediction[32]. The shear capacity calculation method provided by CSA/CAN-S806-2012 is shown as follows:

$$0.11\sqrt{f_c'}bd \leqslant V_c = 0.05 k_m k_r k_a k_s \sqrt[3]{f_c'}bd \leqslant 0.22\sqrt{f_c'}bd \tag{4}$$

Tab. 1 Database of shear capacity of FRP-reinforced concrete beams without web reinforcement

Reference	Number	b/mm	d/mm	a/d	f'_c/MPa	E_f/GPa	ρ_f%	V_c^{exp}/kN
Ref. [28]	36	89-420	73-250	0.85-6.45	31.00-92.00	40.80-139.00	0.33-3.02	8.80-63.00
Ref. [36]	12	200	234-635	2.52-2.62	42.20-73.40	58.00	0.71-2.69	54.50-169.50
Ref. [37]	6	300	165-170	5.65-7.00	35.90	48.00-53.00	0.80-4.12	29.30-51.50
Ref. [38]	8	100-170	270-416	0.50-1.75	40.60-62.30	40.00	1.16-1.75	30.00-300.00
Ref. [39]	8	152	195-215	2.50-3.30	49.00	50.00	0.31-1.53	16.90-31.60
Ref. [40]	16	1 000	134-150	5.67-6.34	41.30-86.20	40.80-147.70	0.51-3.78	94.00-213.00
Ref. [41]	2	100	175	2.29	31.31-36.53	50.00	0.90	25.00-25.90
Ref. [42]	4	100	180	5.56	41.00-66.00	40.80-124.00	0.35-1.48	8.90-14.00
Ref. [43]	3	150	245-270	4.07-4.49	56.50-60.00	70.00	0.39-0.85	20.90-29.20
Ref. [44]	9	200	260-360	1.11-2.02	35.11-54.57	51.30	0.76-1.16	83.80-237.20
Ref. [45]	40	150-200	214	1.50-4.50	30.00-40.30	40.00-147.90	0.33-0.79	16.60-85.10
Ref. [46]	6	200	170-370	2.70-5.90	22.95-29.75	141.44	0.12-0.52	17.59-36.12
Ref. [47]	8	130	195-200	2.30-3.00	13.00-33.50	51.50	0.60-0.91	18.60-39.40
Ref. [48]	3	400	575	2.92	32.00-102.00	61.20-71.20	1.00	154.00-163.50
Ref. [49]	4	200	217-219	3.06-3.09	28.50-49.10	52.31-56.71	0.52-0.93	25.90-37.10
Ref. [50]	12	300-310	257-891	1.07-2.07	39.90-68.50	37.90-42.30	1.47-2.13	96.00-1 134.50
Ref. [51]	1	300	350	4.00	30.20	100.00	0.77	105.00
Ref. [52]	12	114-457	146-883	3.11-3.13	29.50-59.70	41.00-48.20	0.12-0.28	17.90-220.70
Ref. [53]	4	300	1 088-1 111	1.13-1.15	38.70-49.30	47.60-144.00	0.26-1.24	595.50-953.00
Ref. [54]	8	250-300	305-744	2.40-2.50	34.50-44.70	46.30-144.00	0.40-0.91	61.00-155.70
Ref. [55]	11	400	250	3.00-8.00	48.00-52.00	47.50-51.90	0.57-4.05	56.00-135.00
Ref. [56]	9	200	230-330	1.00-1.52	43.00-65.00	51.00	0.92-1.84	116.55-373.85
Ref. [57]	14	1 200	130-182	5.80-8.00	30.00	44.00-50.00	0.24-1.22	26.30-158.95
Ref. [58]	6	300	155-163	5.70-7.00	35.80	48.26-55.84	0.71-4.30	29.27-51.51
Ref. [59]	20	635-1 854	202-240	4.47-6.04	56.00-87.00	40.80	0.54-0.96	97.90-389.60
Ref. [60]	4	150	280	2.50-5.00	24.00-49.00	148.00	0.11-0.21	6.30-13.80
Ref. [61]	6	450	188-937	3.26-4.05	35.00-46.00	37.00	0.51-2.54	54.50-232.00
Ref. [62]	20	150	180	5.60	20.40-27.20	115.00	0.87-1.45	16.60-29.90
Ref. [63]	14	800	200	6.00-6.50	27.40-39.60	41.00-49.00	0.33-0.66	27.50-54.00
Ref. [64]	29	250-300	291-744	1.50-3.50	34.50-88.30	46.30-144.00	0.18-1.47	43.70-155.80
Ref. [65]	3	300	300-315	2.54-2.67	47.26-50.41	44.60	2.14-5.62	85.30-122.70
Ref. [66]	8	150	150	1.36-2.33	34.70-63.10	134.00	1.13-2.26	45.75-234.10
Ref. [67]	6	250	326	3.07	43.60-50.00	39.00-134.00	0.87-1.71	60.00-124.50
Ref. [34]	12	150	163-263	2.53-4.10	28.90-50.15	32.00-38.00	0.14-1.39	9.00-30.00
Ref. [68]	6	250	326	3.07	43.60-63.00	42.00-135.00	1.71-2.20	77.50-174.00
Ref. [69]	3	150	223	1.10-3.30	42.84-47.69	45.00	1.28	27.20-81.00
Ref. [70]	6	1 000	105-155	6.45-9.52	32.50	42.00-147.00	0.23-0.96	23.50-127.00
Ref. [71]	8	1 000	155-180	5.56-6.45	40.00	40.00-114.00	0.39-2.63	113.00-190.00
Ref. [72]	12	420	78-83	3.61-6.41	61.00-93.00	40.00-42.00	0.61-2.61	19.50-40.00
Ref. [73]	7	200	225	1.82-4.22	40.50-49.00	145.00	0.25-0.88	36.10-96.20
Ref. [74]	12	130-160	310-346	2.75-3.71	34.10-43.20	42.00-120.00	0.72-1.54	42.70-63.70
Ref. [75]	6	457	360	3.40	39.70-42.60	37.60-47.00	0.96-1.92	94.70-177.00
Ref. [76]	18	178-279	224-225	4.06-4.08	36.30	40.30	1.11-2.27	28.10-51.00
Ref. [77]	12	65-203	224-225	4.06-4.08	79.60	40.30	1.25-2.56	30.40-48.30
Ref. [78]	3	178	279-287	2.61-2.69	24.10	40.00	0.77-2.30	36.10-53.40
Ref. [79]	2	150	210	3.65	27.97-32.39	45.00	1.31	21.95-26.50
Ref. [80]	2	300	150	3.00	22.70-27.80	29.00	1.30-1.80	33.00-36.00
Minimum		65	73	0.50	13.00	29.00	0.11	6.25
Maximum		1 854	1 111	9.52	102.00	148.00	5.62	1 134.50
Average value		364	262	3.93	44.90	70.21	1.06	87.74

Note: b is the beam width; d is the depth of the beam; a/d is the shear span-to-depth ratio; f'_c is the compressive strength of the concrete cylinder; E_f is the elastic modulus of FRP bar; ρ_f is the reinforcement ratio of FRP bars; V_c^{exp} is the test value of shear capacity.

$$k_m = \sqrt{\frac{d}{a}} \leqslant 1.0 \qquad 1.0 \leqslant k_a = 2.5\frac{d}{a} \leqslant 2.5$$

$$k_r = \sqrt[3]{1 + E_f\rho_f} \qquad k_s = \frac{750}{450 + d} \leqslant 1.0$$

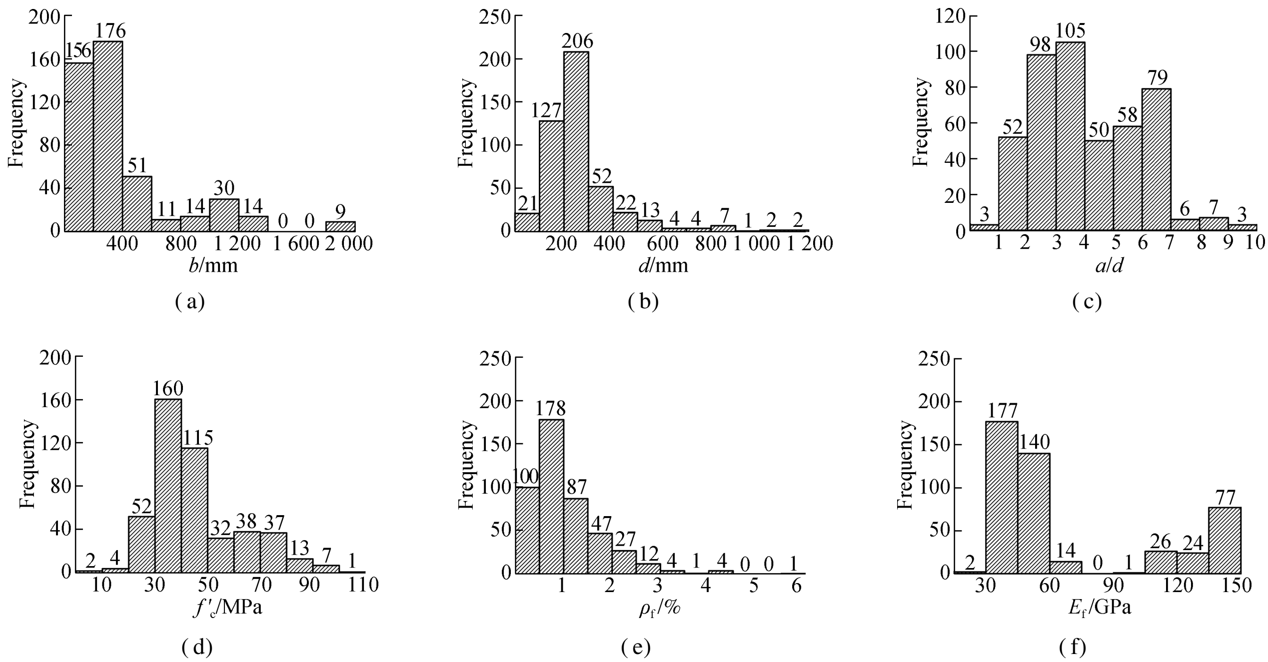

Fig. 2 Distribution of parameters in the database. (a) Beam width; (b) Effective depth of the beam; (c) Shear span-to-depth ratio; (d) Compressive strength of concrete; (e) Elastic modulus of the FRP bar; (f) Reinforcement ratio of FRP bars

Plain concrete members and members with a low reinforcement ratio of FRP bars also have a certain shear capacity; hence, the lower limit value of concrete shear capacity is represented as $0.11\sqrt{f_c'}bd$ in Eq. (4).

2.1.2 ACI440.1R-2015

The ACI440.1R-2015[81] calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement considers the influence of the beam section size, compressive strength of concrete, elastic modulus of FRP bars, and reinforcement ratio of FRP bars. The shear capacity calculation method provided by ACI440.1R-2015 is expressed as follows:

$$V_c = 0.4\sqrt{f_c'}bkd \tag{5}$$
$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$$
$$n_f = \frac{E_f}{E_c}$$

According to Eq. (5), when the reinforcement ratio is low, the shear capacity of the beam approaches 0. However, according to the recommendations of ACI318-2002, the shear resistance of plain concrete members without reinforcement is $0.16\sqrt{f_c'}$, indicating that Eq. (5) underestimates the shear resistance of plain concrete[82]. Additionally, Eq. (5) does not consider the influence of shear span-to-depth ratio and size effect on shear capacity.

2.1.3 JSCE-1997

The JSCE-1997[83] calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement considers the influences of beam section size, the axial stiffness of FRP bars, size effect, the compressive strength of concrete, and the elastic modulus of steel bars. The shear capacity calculation method provided by JSCE-1997 is as follows:

$$V_c = \beta_d \beta_\rho f_{vcd} bd \tag{6}$$
$$\beta_d = \left(\frac{1\,000}{d}\right)^{1/4} \leqslant 1.5$$
$$\beta_\rho = \left(\frac{100 E_f \rho_f}{E_s}\right)^{1/3} \leqslant 1.5$$
$$f_{vcd} = 0.2\sqrt[3]{f_c'} \leqslant 0.72$$

where E_s is the elastic modulus of the steel bar, MPa.

In Eq. (6), an upper limit value is set for the effect of the compressive strength of concrete, while the influence of the shear span-to-depth ratio is not considered. Additionally, the influence of the elastic modulus of the steel bar is considered. However, the shear resistance of plain concrete is neglected; consequently, the calculated shear capacity provided by Eq. (6) is 0 when the reinforcement ratio of FRP bars is 0.

2.1.4 AASHTO-LRFD-2017

The AASHTO-LRFD-2017[84] calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement considers the influences of the beam section size, the FRP reinforcement ratio, the shear span-to-depth ratio, and the compressive strength of concrete. The shear capacity calculation method provided by AASHTO-LRFD-2017 is as follows:

$$V_c = \left(0.067\,6\sqrt{f_c'} + 4.6\frac{A_s}{bd}\frac{d}{a}\right)bd \leqslant 0.126\sqrt{f_c'}bd \tag{7}$$

where A_s is the total area of the FRP bar section, mm^2.

According to Eq. (7), a linear correlation exists between the FRP reinforcement ratio and shear capacity. Furthermore, Eq. (7) establishes an upper limit value for shear capacity, addressing the problem of excessively high calculated shear capacity due to large FRP reinforcement ratios. However, the influence of the size effect on shear capacity is not considered in the equation.

2.1.5 CNR-DT203-2006

In CNR-DT203-2006[85], the calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement considers the influences of the beam section size, the FRP reinforcement ratio, the elastic modulus of FRP bars, the size effect, and the tensile strength of concrete. The shear capacity calculation method provided by CNR-DT203-2006 is as follows:

$$V_c = 1.3\left(\frac{E_f}{E_s}\right)^{1/2} \tau_r k_d (1.2 + 40\rho_f) bd \tag{8}$$

$$1.3\left(\frac{E_f}{E_s}\right)^{1/2} \leqslant 1$$

$$\tau_r = 0.25 f_t$$

$$k_d = 1.6 - \frac{d}{1\ 000} \geqslant 1$$

$$\rho_f \leqslant 0.02$$

According to Eq. (8), the influence of the shear span-to-depth ratio on the shear capacity is not considered in this calculation method. Additionally, the tensile strength of concrete is used as a parameter to reflect the relationship between concrete strength and shear capacity in Eq. (8), which is different from the aforementioned design provisions. Eq. (8) depicts a linear correlation between shear capacity and the reinforcement ratio of FRP bars; however, it also sets an upper limit for the reinforcement ratio to prevent excessive shear capacity due to large FRP reinforcement ratios.

2.1.6 BISE-1999

The BISE-1999[86] calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement considers the influences of factors such as the beam section size, the compressive strength of concrete, the elastic modulus of FRP bar, the reinforcement ratio of FRP bars, and the size effect. The shear capacity calculation method provided by BISE-1999 is as follows:

$$V_c = 0.79\left(100\rho_f \frac{E_f}{E_s}\right)^{1/3} \left(\frac{400}{d}\right)^{1/4} \left(\frac{f_{cu}}{25}\right)^{1/3} bd \tag{9}$$

The influence of the elastic modulus of the steel bar is also considered in Eq. (9), similar to the shear capacity calculation methods proposed in JSCE-1997 and CNR-DT203-2006. However, Eq. (9) does not consider the influence of the shear span-to-depth ratio on shear capacity or the shear resistance of plain concrete.

2.1.7 GB 50608—2020

The calculation method for the shear capacity of FRP-reinforced concrete beams without web reinforcement proposed in GB 50608—2020[87] is similar to that of ACI440.1R-2015. The main factors considered are the section size of the beam, the tensile strength of concrete, the elastic modulus of FRP bars, and the reinforcement ratio of FRP bars. The calculation method of shear capacity provided by GB 50608—2020 is as follows:

$$V_c = 0.86 f_t bc \tag{10}$$

$$c = k_{fE} d$$

$$k_{fE} = \sqrt{2\rho_f \alpha_{fE} + (\rho_f \alpha_{fE})^2} - \rho_f \alpha_{fE}$$

$$\rho_f = \frac{A_s}{bd}$$

$$\alpha_{fE} = \frac{E_f}{E_c}$$

The mechanical properties of concrete are represented by its tensile strength in Eq. (10), similar to the shear capacity calculation method suggested in CNR-DT203-2006. However, Eq. (10) does not consider the impact of the shear span-to-depth ratio and the size effect in the calculation method. Furthermore, it does not address the issue of the calculated shear capacity being 0 when the reinforcement ratio of FRP bars is 0.

2.2 Modified shear capacity calculation methods

In recent years, the calculation methods for the shear capacity of FRP-reinforced concrete beams without web reinforcement have garnered significant attention from both domestic and foreign scholars. During the research process, scholars have addressed the limitations of shear capacity calculation methods proposed by various design provisions and have proposed alternative methods that offer more comprehensive considerations and more accurate predictions.

2.2.1 Ahmed-2021

The calculation method of shear capacity provided by Ahmed et al. [88] is shown depicted as follows:

$$V_c = \begin{cases} 0.35(E_f\rho_f)^{1/4}(f_c')^{1/4}\left(\dfrac{1}{1+0.005d}\right)^{1/2}\dfrac{d}{a}bd & \dfrac{a}{d} \geqslant 2.5 \\ 0.35(E_f\rho_f)^{1/4}(f_c')^{1/4}\left(\dfrac{1}{1+0.005d}\right)^{1/2}\left(\dfrac{d}{a}\right)^{1/3}bd & \dfrac{a}{d} < 2.5 \end{cases} \tag{11}$$

2.2.2 Jumaa-2018

The calculation method of shear capacity provided by Jumaa et al. [25] is as follows:

$$V_c = 0.32\left(\frac{1}{d}\right)^{1/3}\left(\frac{E_f\rho_f}{a/d}\right)^{2/5}(f_c')^{1/5}bd \tag{12}$$

2.2.3 Baghi-2018

The calculation method of shear capacity provided by Baghi et al. [89] is as follows:

$$V_c = 0.07\left(\frac{E_f \rho_f}{f'_c}\frac{b}{d}\right)^{0.22}\sqrt{f'_c}\,bd \tag{13}$$

$$0.05\sqrt{f'_c}\,bd \leqslant V_c \leqslant 0.3\sqrt{f'_c}\,bd$$

2.2.4 Frosch-2017

The calculation method of shear capacity provided by Frosch et al. [90] is as follows:

$$V_c = 0.415\sqrt{f'_c}\,bkd\gamma_d \tag{14}$$

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$$

$$n_f = \frac{E_f}{E_c}$$

$$\gamma_d = \frac{1.48}{\sqrt{1 + d/254}}$$

2.2.5 Mari-2014

The calculation method of shear capacity provided by Mari et al. [91] is as follows:

$$V_c = \delta[(1.072 - 0.01n_f)\frac{c}{d} + 0.036]f_t bd \tag{15}$$

$$\delta = 1.2 - 0.2\frac{a}{d}d$$

$$\frac{c}{d} = n_f\rho_f\left(1 + \sqrt{1 + \frac{2}{n_f\rho_f}}\right)$$

$$n_f = \frac{E_f}{E_c}$$

2.2.6 Alam-2013

The calculation method of shear capacity provided by Alam et al. [92] is as follows:

$$V_c = \frac{0.2}{(a/d)^{2/3}}\left(\frac{\rho_f E_f}{d}\right)^{1/3}\sqrt{f'_c}\,bd \tag{16}$$

$$\frac{0.1}{a/d}\sqrt{f'_c}\,bd \leqslant V_c \leqslant \frac{0.2}{a/d}\sqrt{f'_c}\,bd$$

2.2.7 Kara-2011

The calculation method of shear capacity provided by Kara[93] is as follows:

$$V_c = bd\left[\sqrt[3]{\frac{d}{a}f'_c\frac{\rho_f E_f}{E_s}\left(\frac{c_1^2}{c_0}\right)}\right]^{1/3}\frac{c_0}{c_2} \tag{17}$$

$$c_0 = 7.696$$

$$c_1 = 7.254$$

$$c_2 = 7.718$$

Statistical analysis revealed that an inconsistency exists among the calculation methods of shear capacity proposed by design provisions from different countries and the models suggested by various scholars regarding the consideration of each influencing factor. The statistical results are presented in Tab. 2. The variations in calculation methods primarily involve the inclusion of the shear span-to-depth ratio and the size effect as influencing factors.

Tab. 2 Factors considered in the existing calculation methods

Calculation method	b	d	ρ_f	E_f	f'_c	a/d	Size effect
CAN/CSA-S806-2012	√	√	√	√	√	√	√
ACI440.1R-2015	√	√	√	√	√	•	•
JSCE-1997	√	√	√	√	√	•	√
AASHTO-LRFD-2017	√	√	√	•	√	√	•
CNR-DT203-2006	√	√	√	√	√	•	√
BISE-1999	√	√	√	√	√	•	√
GB 50608—2020	√	√	√	√	√	•	•
Ahmed-2021	√	√	√	√	√	√	√
Jumaa-2018	√	√	√	√	√	√	√
Baghi-2018	√	√	√	√	√	•	√
Frosch-2017	√	√	√	√	√	•	√
Mari-2014	√	√	√	√	√	•	√
Alam-2013	√	√	√	√	√	√	√
Kara-2011	√	√	√	√	√	√	•

Note: "√" represents that the corresponding factor is considered in the calculation method; "•" indicates that the calculation method does not consider the factor.

3 Analysis of Factors Based on the Database

3.1 Analysis of calculation coefficients

To further examine the extent to which the shear span-to-depth ratio and the size effect are considered in each calculation method, the calculation coefficients for the shear span-to-depth ratio and the size effect are plotted in Fig. 3 and Fig. 4, respectively.

Fig. 3 displays the relationships between the shear span-to-depth ratio and its calculation coefficient in various calculation methods: CSA/CAN-S806-2012, AASHTO-LRFD-2017, Ahmed-2021, Jumaa-2018, Alam-2013, and Kara-2011. The contribution of the shear span-to-depth ratio to shear capacity is considerably greater in CSA/CAN-S806-2012 than in the other calculation methods. Furthermore, each method shows insensitivity to shear

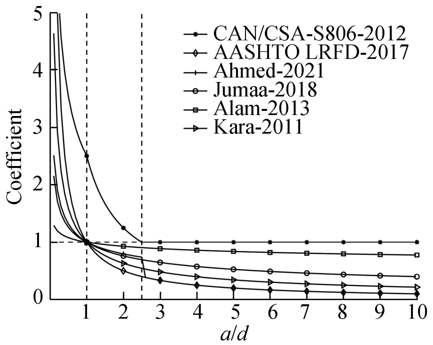

Fig. 3 Shear span-to-depth ratio for different formulas

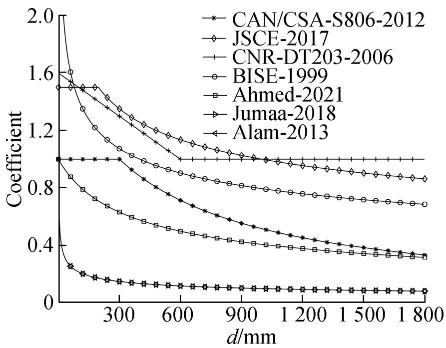

Fig. 4 Size effect for different formulas

span-to-depth ratios greater than 2.5 and exhibits substantial variation for ratios less than 1.

Fig. 4 illustrates the relationships between the size effect and its calculation coefficient in different calculation methods, including CSA/CAN-S806-2012, JSCE-1997, CNR-DT203-2006, BISE-1999, Ahmed-2021, Jumaa-2018, and Alam-2013. As observed in Fig. 4, CSA/CAN-S806-2012 indicates no size effect for specimens with an effective depth of beam less than 300 mm, while CNR-DT203-2006 suggests no size effect for specimens with an effective beam depth of more them 600 mm. Remarkably, Jumaa-2018 and Alam-2013 feature similar considerations regarding the size effect.

3.2 Correlation analysis

To comprehensively analyze the relationship between each factor and shear capacity in the database, correlation analysis was conducted using Pearson distribution, Spearman distribution, and Kendall distribution. The results are represented in the heat map illustrated in Fig. 5. The correlation coefficient ranges from −1 to 1, where values closer to 1 indicate a stronger positive correlation, values closer to −1 indicate a stronger negative correlation, and values closer to 0 indicate a weaker correlation.

As shown in Fig. 5, all factors exhibit varying degrees of correlation with shear capacity. A strong positive correlation exists between section size and shear capacity. The correlation index between the normalized section size and the normalized shear capacity approaches 0, indicating

	b	d	a/d	f'_c	ρ_f	E_f	V_c	$V_c/(bd)$
b	1.0	−0.15	0.55	0.099	−0.030	−0.21	−0.18	0.28
d	−0.15	1.0	−0.48	−0.029	−0.044	−0.007	0.087	0.59
a/d	0.55	−0.48	1.0	0.11	0.069	−0.042	−0.46	−0.24
f'_c	0.099	−0.029	0.11	1.0	0.15	−0.094	0.093	0.13
ρ_f	−0.030	−0.044	0.069	0.15	1.0	−0.28	0.22	0.14
E_f	−0.21	−0.007	−0.042	−0.094	−0.28	1.0	0.062	−0.094
V_c	−0.18	0.087	−0.46	0.093	0.22	0.062	1.0	0.47
$V_c/(bd)$	0.28	0.59	−0.24	0.13	0.14	−0.094	0.47	1.0

(a)

	b	d	a/d	f'_c	ρ_f	E_f	V_c	$V_c/(bd)$
b	1.0	−0.075	0.37	0.17	0.11	−0.27	−0.16	0.61
d	−0.075	1.0	−0.65	0.054	0.027	−0.038	0.11	0.40
a/d	0.37	−0.65	1.0	0.040	0.043	−0.13	−0.42	−0.26
f'_c	0.17	0.054	0.040	1.0	0.22	−0.15	0.28	0.24
ρ_f	0.11	0.027	0.043	0.22	1.0	−0.36	0.52	0.33
E_f	−0.21	−0.038	−0.13	−0.15	−0.36	1.0	0.12	−0.082
V_c	−0.16	0.11	−0.42	0.28	0.52	0.12	1.0	0.45
$V_c/(bd)$	0.61	0.40	−0.26	0.24	0.33	−0.082	0.45	1.0

(b)

	b	d	a/d	f'_c	ρ_f	E_f	V_c	$V_c/(bd)$
b	1.0	−0.004	0.24	0.13	0.076	−0.19	−0.11	0.45
d	−0.004	1.0	−0.48	0.045	0.012	−0.037	0.074	0.30
a/d	0.24	−0.48	1.0	0.023	0.025	−0.091	−0.29	−0.18
f'_c	0.13	0.045	0.023	1.0	0.15	−0.10	0.19	0.18
ρ_f	0.076	0.012	0.025	0.15	1.0	−0.25	0.36	0.23
E_f	−0.19	−0.037	−0.091	−0.10	−0.25	1.0	0.075	−0.055
V_c	−0.11	0.074	−0.29	0.19	0.36	0.075	1.0	0.32
$V_c/(bd)$	0.45	0.30	−0.18	0.18	0.23	−0.055	0.32	1.0

(c)

Fig. 5 Correlation analysis. (a) Pearson distribution; (b) Superman distribution; (c) Kendall distribution

that the normalization method employed in this study is effective. Additionally, a significant negative correlation exists between the shear span ratio and shear capacity, and this negative correlation is further amplified after normalization. These results demonstrate that the correlation analysis method employed is effective in elucidating the relationships between multiple factors and target parameters.

4 Error Analyses of Calculation Methods

The trends of the test values and calculated values for shear capacity are illustrated in Fig. 6, with the test values plotted on the ordinate and the calculated values on the abscissa. Data points above the 45° line correspond to conservative calculated results. Conversely, data points below the 45° line correspond to over-estimations of the calculated results of the shear capacity of the beam, potentially leading to an unsafe structure.

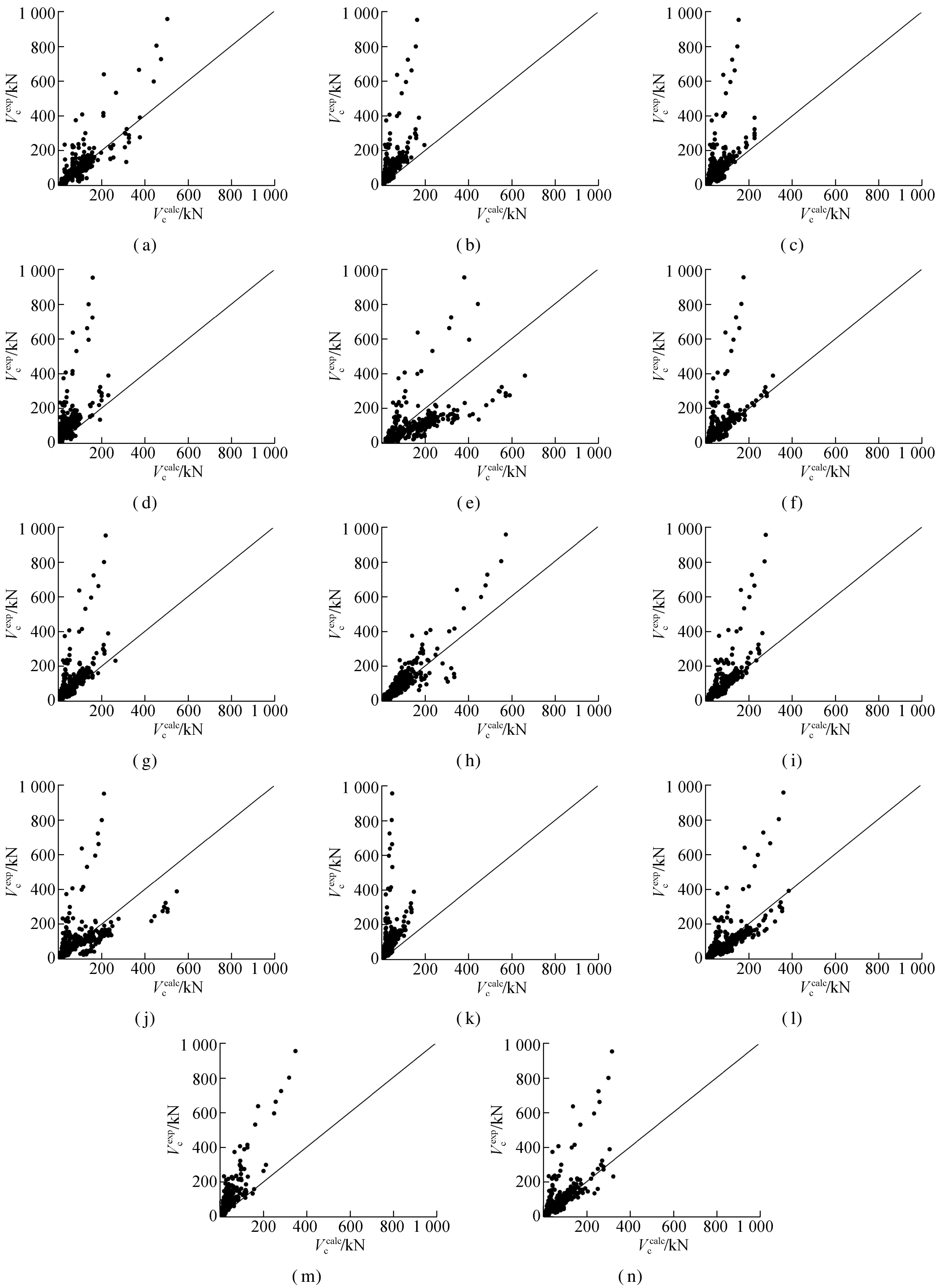

Fig. 6 Comparative analysis of the test values and the calculated values. (a) CAN/CSA-S806-2012; (b) ACI440.1R-2015; (c) JSCE-1997; (d) AASHTO-LRFD-2017; (e) CNR-DT203-2006; (f) BISE-1999; (g) GB 50608—2020; (h) Ahmed-2021; (i) Jumaa-2018; (j) Baghi-2018; (k) Frosch-2017; (l) Mari-2014; (m) Alam-2013; (n) Kara-2011

Fig. 6 reveals that the predictions of ACI 440. 1R-2015 in various design standards tend to overestimate the shear capacity, suggesting the need for significant reconsideration and revision of the shear capacity evaluation approach. A similar phenomenon is observed in the calculation method proposed by Frosch-2017. This discrepancy is attributable to the fact that the method was originally developed for long shallow beams and may not accurately capture the behavior of typical deep beams, including arching action. This complex behavior is usually converted into an equivalent system of compression and tension rods by more advanced methods, such as compression and tension rod models.

To further evaluate the prediction accuracy of each calculation method, an error analysis is performed by calculating the ratio of the calculated value to the test value. The analysis includes calculating the mean (MEAN), standard deviation (SD), coefficient of variation (COV), minimum (MIN), and maximum (MAX) values. A MEAN value close to 1 indicates higher prediction accuracy, and smaller values of SD and COV indicate better prediction effects of the calculation method. Additionally, the proportion of data points where the test value exceeds the calculated value is considered as the conservative value ξ. The statistical results are presented in Tab. 3.

Tab. 3 Statistical parameters

Calculation method	MEAN	SD	COV	MIN	MAX	ξ/%
CSA/CAN-S806-2012	1.11	0.61	0.55	0.19	7.71	46.9
ACI440. 1R-2015	2.46	1.83	0.74	0.58	17.38	96.3
JSCE-1997	1.83	1.46	0.79	0.36	13.08	89.4
AASHTO-LRFD-2017	2.47	2.13	0.86	0.31	24.27	93.1
CNR-DT203-2006	0.75	0.61	0.82	0.08	4.81	15.0
BISE-1999	1.54	1.24	0.81	0.32	10.33	70.3
GB 50608—2020	1.85	1.36	0.74	0.43	12.98	88.7
Ahmed-2021	1.11	0.39	0.35	0.32	2.78	57.0
Jumaa-2018	1.21	0.65	0.53	0.35	5.95	54.9
Baghi-2018	1.38	1.20	0.87	0.20	10.59	51.6
Frosch-2017	3.36	3.08	0.92	0.79	24.08	97.8
Mari-2014	1.02	0.68	0.67	0.26	6.53	24.5
Alam-2013	2.71	1.33	0.49	0.50	11.54	98.3
Kara-2011	1.35	0.93	0.69	0.29	8.73	64.6

According to the findings from Fig. 6 and Tab. 3, the CSA/CAN-S806-2012 design provision demonstrates higher prediction accuracy, with a MEAN value of 1.11, an SD value of 0.61, and a COV value of 0.55. Among the design provisions of various countries, ACI440. 1R-2015, JSCE-1997, AASHTO-LRFD-2017, BISE-1999, and GB 50608—2020 exhibit more conservative predictions, with conservative proportions exceeding 70%. Specifically, ACI440. 1R-2015 exhibits a remarkably high conservative proportion of 96.3%. The prediction effect of the CNR-DT203-2006 design provision tends to be unreliable, with a conservative rate of only 15.0%. Among the calculation models proposed by various scholars, Ahmed-2021 demonstrates the best prediction accuracy for shear capacity, with a MEAN value of 1.11, an SD value of 0.39, and a COV value of 0.35. Frosch-2017 and Alam-2013 exhibit more conservative prediction effects among the calculation models proposed by scholars, with conservative proportions exceeding 90%. Notably, Alam-2013 exhibits an exceptionally high conservative proportion of 98.3%. The prediction result of Mari-2014 tends to be unreliable, with a conservative rate of only 24.5%.

5 Conclusions

1) A comprehensive database is established according to experimental data from the literature. The database features a large sample size and encompasses a wide range of factors, making it suitable for studying the shear performance of FRP-reinforced concrete beams without web reinforcement.

2) The calculation methods based on different design provisions and calculation models vary in their considered factors. Furthermore, some methods do not consider the influence of the shear span-to-depth ratio and the size effect on the shear capacity. The analysis of calculation coefficients reveals that the shear span-to-depth ratio significantly influences the shear capacity in CSA/CAN-S806-2012. Additionally, the analysis of the size effect calculation coefficients shows that Jumaa-2018 and Alam-2013 attribute less significance to the size effect.

3) The correlation analysis based on Pearson distribution, Superman distribution, and Kendall distribution demonstrates that certain correlations exist between the factors and the shear capacity in the database. Notably, the strongest positive correlation exists between the effective depth of the beam and the shear capacity, while the strongest negative correlation exists between the shear span-to-depth ratio and the shear capacity.

4) The design provisions proposed by different countries and the calculation models proposed by various scholars exhibit varying levels of conservatism in predicting shear capacity. Moreover, among the various design provisions, CSA/CAN-S806-2012 demonstrates the most accurate prediction, ACI440. 1R-2015 is the most conservative, and CNR-DT203-2006 shows the lowest safety level. Among the calculation models proposed by scholars, Ahmed-2021 achieves the most accurate predictions, Alam-2013 is the most conservative, and Mari-2014 exhibits the lowest safety level.

References

[1] Naderpour H, Haji M, Mirrashid M. Shear capacity estimation of FRP-reinforced concrete beams using computational intelligence[J]. *Structures*, 2020, **28**: 321 − 328. DOI: 10.1016/j.istruc.2020.08.076.

[2] Yu Q Q, Gu X L, Zeng Y H, et al. Flexural behavior of corrosion-damaged prestressed concrete beams[J]. *Engineering Structures*, 2022, **272**: 114985. DOI: 10.1016/j.engstruct.2022.114985.

[3] Zhang L, Zheng Y, Yu Y, et al. Structural performance evaluation of ECC link slabs reinforced with FRP bars for jointless bridge decks[J]. *Construction and Building Materials*, 2021, **304**: 124462. DOI: 10.1016/j.conbuildmat.2021.124462.

[4] Liu X, Sun Y, Wu T, et al. Flexural cracks in steel fiber-reinforced lightweight aggregate concrete beams reinforced with FRP bars[J]. *Composite Structures*, 2020, **253**: 112752. DOI: 10.1016/j.compstruct.2020.112752.

[5] Jin L, Lei Y, Yu W, et al. Dynamic shear failure and size effect in BFRP-reinforced concrete deep beam[J]. *Engineering Structures*, 2021, **245**: 112951. DOI: 10.1016/j.engstruct.2021.112951.

[6] Zheng Y, Yu T, Yang J, et al. Investigation of the behaviour of reinforcement-free concrete deck slabs restrained by FRP rods[J]. *Engineering Structures*, 2017, **135**: 191－208. DOI: 10.1016/j.engstruct.2017.01.005.

[7] Tan H, Hou Z, Li Y, et al. A flexural ductility model for UHPC beams reinforced with FRP bars[J]. *Structures*, 2022, **45**: 773－786. DOI: 10.1016/j.istruc.2022.09.052.

[8] Feng G, Zhu D, Guo S, et al. A review on mechanical properties and deterioration mechanisms of FRP bars under severe environmental and loading conditions[J]. *Cement and Concrete Composites,* 2022, **134**: 104758. DOI: 10.1016/j.cemconcomp.2022.104758.

[9] Guo X, Xiong C, Jin Z, et al. A review on mechanical properties of FRP bars subjected to seawater sea sand concrete environmental effects[J]. *Journal of Building Engineering*, 2022, **58**: 105038. DOI: 10.1016/j.jobe.2022.105038.

[10] Hoang A L, Duc A L, Thanh T L, et al. An extreme gradient boosting approach to estimate the shear strength of FRP reinforced concrete beams[J]. *Structures*, 2022, **45**: 1307－1321. DOI: 10.1016/j.istruc.2022.09.112.

[11] Truong G T, Choi K K, Kim C S. Punching shear strength of interior concrete slab-column connections reinforced with FRP flexural and shear reinforcement[J]. *Journal of Building Engineering*, 2022, **46**: 103692. DOI: 10.1016/j.jobe.2021.103692.

[12] Jin L, Wang T, Jiang X, et al. Size effect in shear failure of RC beams with stirrups: Simulation and formulation [J]. *Engineering Structures*, 2019, **199**: 109573. DOI: 10.1016/j.engstruct.2019.109573.

[13] American Concrete Institute. Commentary on building code requirements for structural concrete: ACI 318R-14 [S]. Farmington Hill, MI, USA: American Concrete Institute, 2019.

[14] Dong W, Wu Z, Zhou X, et al. Experimental study of equal biaxial-to-uniaxial compressive strength ratio of concrete at early ages[J]. *Construction and Building Materials*, 2016, **126**: 263－273. DOI: 10.1016/j.conbuildmat.2016.09.040.

[15] Wang W, Mo Z, Chouw N, et al. Impact resistance of flax FRP fully wrapped coconut fibre reinforced concrete beams and shear contribution of FRP[J]. *Construction and Building Materials*, 2023, **392**: 131922. DOI: 10.1016/j.conbuildmat.2023.131922.

[16] Tran N L. A mechanical model for the shear capacity of slender reinforced concrete members without shear reinforcement [J]. *Engineering Structures*, 2020, **219**: 110803. DOI: 10.1016/j.engstruct.2020.110803.

[17] Dong W, Wu Z, Tang X, et al. A comparative study on stress intensity factor-based criteria for the prediction of mixed mode Ⅰ-Ⅱ crack propagation in concrete[J]. *Engineering Fracture Mechanics*, 2018, **197**: 217－235. DOI: 10.1016/j.engfracmech.2018.05.009.

[18] Rahman J, Arafin P, Muntasir Billah A H M. Machine learning models for predicting concrete beams shear strength externally bonded with FRP[J]. *Structures*, 2023, **53**: 514－536. DOI: 10.1016/j.istruc.2023.04.069.

[19] Marani A, Nehdi M L. Predicting shear strength of FRP-reinforced concrete beams using novel synthetic data driven deep learning[J]. *Engineering Structures*, 2022, **257**: 114083. DOI: 10.1016/j.engstruct.2022.114083.

[20] Oller E, Marí A, Bairán J M, et al. Shear design of reinforced concrete beams with FRP longitudinal and transverse reinforcement[J]. *Composites Part B*: *Engineering*, 2015, **74**: 104－122. DOI: 10.1016/j.compositesb.2014.12.031.

[21] Fan X H, Qin W H, Xie P, et al. Shear force capacity of steel-glass fiber composite bar reinforced concrete beams under concentrated load[J]. *Journal of Southeast University(Natural Science Edition)*, 2020, **50**(4): 623－629. DOI: 10.3969/j.issn.1001-0505.2020.04.004. (in Chinese)

[22] Borzovič V, Gajdošová K, Halvonik J, et al. Partial factor for the shear resistance model in the 2nd generation of Eurocode 2 for GFRP reinforced concrete members[J]. *Engineering Structures*, 2023, **285**: 116005. DOI: 10.1016/j.engstruct.2023.116005.

[23] Mukhtar F, Deifalla A. Shear strength of FRP reinforced deep concrete beams without stirrups: Test database and a critical shear crack-based model[J]. *Composite Structures*, 2023, **307**: 116636. DOI: 10.1016/j.compstruct.2022.116636.

[24] Alam M S, Sultana N, Hossain S M Z. Bayesian optimization algorithm based support vector regression analysis for estimation of shear capacity of FRP reinforced concrete members [J]. *Applied Soft Computing*, 2021, **105**: 107281. DOI: 10.1016/j.asoc.2021.107281.

[25] Jumaa G B, Yousif A R. Predicting shear capacity of FRP-reinforced concrete beams without stirrups by artificial neural networks, gene expression programming, and regression analysis[J]. *Advances in Civil Engineering,* 2018: 5157824. DOI: 10.1155/2018/5157824.

[26] Luo M, Hu S X, Pan J L. Analysis on shear capacity of ECC deep beams based on strut-and-tie model[J]. *Journal of Southeast University(Natural Science Edition)*, 2021, **51**(4): 551－558. DOI: 10.3969/j.issn.1001-0505.2021.04.001. (in Chinese)

[27] Rahman J, Ahmed K S, Khan N I, et al. Data-driven shear strength prediction of steel fiber reinforced concrete beams using machine learning approach[J]. *Engineering*

Structures, 2021, **233**: 111743. DOI: 10. 1016/j. engstruct. 2020. 111743.

[28] Peng F, Xue W, Xue W. Database evaluation of shear strength of slender fiber-reinforced polymer-reinforced concrete members[J]. *ACI Structural Journal*, 2020, **117** (3): 273 −282. DOI: 10. 14359/51723504.

[29] Elghandour B, Eltahawy R, Shedid M, et al. Prediction of shear strength for CFRP reinforced concrete beams without stirrups[J]. *Engineering Structures*, 2023, **284**: 115946. DOI: 10. 1016/j. engstruct. 2023. 115946.

[30] Nadir W, Kadhimi M M A, Jawdhari A, et al. RC beams strengthened in shear with FRP-reinforced UHPC overlay: An experimental and numerical study[J]. *Structures*, 2023, **53**: 693 − 715. DOI: 10. 1016/j. istruc. 2023. 04. 117.

[31] Gao D, Zhang C. A model for shear strength of FRP bar reinforced concrete beams without stirrups[J]. *Advances in Civil Engineering*, 2020, **2022**: 8881463. DOI: 10. 1155/2020/8881463.

[32] Gao D, Zhang C. Shear strength calculating model of FRP bar reinforced concrete beams without stirrups[J]. *Engineering Structures*, 2020, **221**: 111025. DOI: 10. 1016/j. engstruct. 2020. 111025.

[33] Shahnewaz M, Machial R, Alam M S, et al. Optimized shear design equation for slender concrete beams reinforced with FRP bars and stirrups using genetic algorithm and reliability analysis[J]. *Engineering Structures*, 2016, **107**: 151 − 165. DOI: 10. 1016/j. engstruct. 2015. 10. 049.

[34] Ashour A. Flexural and shear capacities of concrete beams reinforced with GFRP bars[J]. *Construction and Building Materials*, 2006, **20**: 1005-1015. DOI: 10. 1016/j. conbuildmat. 2005. 06. 023.

[35] Canadian Standards Association. Design and construction of building structures with fibre-reinforced polymers: CSA/CAN-S806-2012[S]. Mississauga, Canada: Canadian Standards Association, 2012.

[36] Jumaa G B, Yousif A R. Numerical modeling of size effect in shear strength of FRP-reinforced concrete beams [J]. *Structures*, 2019, **20**: 237 −254. DOI: 10. 1016/j. istruc. 2019. 04. 008.

[37] Issa M A, Ovitigala T, Ibrahim M. Shear behavior of basalt fiber reinforced concrete beams with and without basalt FRP stirrups[J]. *Journal of Composites for Construction*, 2016, **20**(4): 04015083. DOI: 10. 1061/(ASCE) CC. 1943-5614 . 0000638.

[38] Thomas J, Ramadass S. Parametric study of shear strength of concrete beams reinforced with FRP bars[J]. *Journal of The Institution of Engineers (India): Series A*, 2016, **97**: 682022. DOI: 10. 1007/s40030-016 −0161-3.

[39] El Refai A, Abed F. Concrete contribution to shear strength of beams reinforced with basalt fiber-reinforced bars[J]. *Journal of Composites for Construction*, 2015, **20**(4): 04015082. DOI: 10. 1061/(ASCE) CC. 1943 − 5614. 0000648.

[40] Abdulsalam B, Farghaly A, Benmokrane B. Mechanisms of shear resistance of one-way concrete slabs reinforced with FRP bars[J]. *Construction and Building Materials*, 2016, **127**: 959 − 970. DOI: 10. 1016/j. conbuildmat. 2016. 10. 015.

[41] Gopinath S, Meenu S, Murthy R. Shear strength evaluation of concrete beams reinforced with BFRP bars and steel fibers without stirrups[J]. *Computers, Materials and Continua*, 2016, **51**(2): 81 − 103. DOI: 0. 3970/cmc. 2016. 051. 081.

[42] Acciai A, D'Ambrisi A, Stefano M, et al. Experimental response of FRP reinforced members without transverse reinforcement: Failure modes and design issues[J]. *Composites Part B: Engineering*, 2016, **89**(16): 1 − 20. DOI: 10. 1016/j. compositesb. 2016. 01. 002.

[43] Tomlinson D, Fam A. Performance of concrete beams reinforced with basalt FRP for flexure and shear[J]. *Journal of Composites for Construction*, 2014, **19**(2): 04014036. DOI: 10. 1061/(ASCE) CC. 1943 −5614. 0000491.

[44] Liu H, Liu G, Wang X, et al. Shear capacity of basalt fiber reinforced polymer reinforced recycled concrete deep beam without web reinforcement[J]. *Journal of Sichuan University*, 2015, **47**(5): 17 − 22. DOI: 10. 15961/j. jsuese. 2015. 05. 003. (in Chinese)

[45] Kim C, Jang H. Concrete shear strength of normal and lightweight concrete beams reinforced with FRP bars[J]. *Journal of Composites for Construction*, 2014, **18**: 04013038. DOI: 10. 1061/(asce) cc. 1943-5614. 0000440.

[46] Ashour A, Kara I. Size effect on shear strength of FRP reinforced concrete beams[J]. *Composites Part B: Engineering*, 2014, **60**: 612 −620. DOI: 10. 1016/j. compositesb. 2013. 12. 002.

[47] Imohamed A, Rendy T, Abdul Samad A A, et al. Diagonal shear cracks and size effect in concrete beams reinforced with glass fiber reinforced polymer (GFRP) bars [J]. *Applied Mechanics and Materials*, 2014, **621**: 113 − 119. DOI: 10. 4028/www. scientific. net/AMM. 621. 113.

[48] Johnson D. *Investigation of glass fibre reinforced polymer (GFRP) bars as Internal reinforcement for concrete structures*[D]. Toronto, Canada: University of Toronto, 2014.

[49] Ali I, Abdul Samad A A, Miranda S, et al. Evaluation of shear strength of concrete beams with GFRP reinforcement [J]. *Applied Mechanics and Materials*, 2014, **26**(508): 603 − 612. DOI: 10. 4028/www. scientific. net/AMM. 660. 603.

[50] Andermatt M, Lubell A. Behavior of concrete deep beams reinforced with internal fiber-reinforced polymer-experimental study[J]. *ACI Structural Journal*, 2013, **110** (4): 585 −594.

[51] Choi I C, Jung D J. Shear behavior of concrete beams reinforced with FRP bar[J]. *Journal of the Korean Society of Marine Environment and Safety*, 2013, **19**(4): 403 − 409. DOI: 10. 7837/kosomes. 2013. 19. 4. 403.

[52] Matta F, El-Sayed A, Nanni A, et al. Size effect on concrete shear strength in beams reinforced with fiber-reinforced polymer bars[J]. *ACI Structural Journal*, 2013, **110**(4): 617 −628.

[53] Farghaly A, Benmokrane B. Shear behavior of FRP-reinforced concrete deep beams without web reinforcement [J]. *Journal of Composites for Construction*, 2013, **17**: 04013015. DOI: 10. 1061/(ASCE) CC. 1943-5614. 0000385.

[54] Alam M, Hussein A. Size effect on shear strength of FRP reinforced concrete beams without stirrups[J]. *Journal of Composites for Construction*, 2013, **17**: 507 − 516. DOI: 10.1061/(ASCE)CC.1943-5614.0000346.

[55] Khaja M, Sherwood E. Does the shear strength of reinforced concrete beams and slabs depend upon the flexural reinforcement ratio or the reinforcement strain[J]. *Canadian Journal of Civil Engineering*, 2013, **40**: 1068 − 1081. DOI: 10.1139/cjce-2012-0459.

[56] Abed F, El-Chabib H, Al Hamaydeh M. Shear characteristics of GFRP-reinforced concrete deep beams without web reinforcement[J]. *Journal of Reinforced Plastics and Composites*, 2012, **31**: 1063 − 1073. DOI: 10.1177/0731684412450350.

[57] Chang K, Seo D. Behavior of one-way concrete slabs reinforced with GFRP bars[J]. *Journal of Asian Architecture and Building Engineering*, 2012, **11**: 351 − 358. DOI: 10.3130/jaabe.11.351.

[58] Ovitigala T. *Structural behavior of concrete beams reinforced with basalt fiber reinforced polymer (BFRP) bars* [D]. Chicago, IL, USA: University of Illinois at Chicago, 2012.

[59] Liu R. *Precast concrete bridge deck panels reinforced with glass fiber reinforced polymer bars*[D]. Salt Lake City, NT, USA: The University of Utah, 2011.

[60] Zeidan M, Barakat M, Mahmoud Z, et al. Evaluation of concrete shear strength for FRP reinforced beams[J]. *Structures Congress,* 2011, **401**: 1816 − 1826. DOI: 10.1061/41171(401)158.

[61] Bentz E, Massam L, Collins M. Shear strength of large concrete members with FRP reinforcement[J]. *Journal of Composites for Construction*, 2010, **14**(6): 637 − 646. DOI: 10.1061/(ASCE)CC.1943-5614.0000108.

[62] Olivito R S, Zuccarello F A. On the shear behaviour of concrete beams reinforced by carbon fibre-reinforced polymer bars: An experimental investigation by means of acoustic emission technique[J]. *Strain*, 2010, **46**: 470 − 481. DOI: 10.1111/j.1475-1305.2009.00699.x.

[63] Lee J H, Son H A, Shin S J. Failure behavior of FRP RC beams without shear reinforcements[J]. *Journal of the Korea Concrete Institute*, 2010, **22**(2): 199 − 208. DOI: 10.4334/JKCI.2010.22.2.199.

[64] Alam M, Hussein A. Relationship between the shear capacity and the flexural cracking load of FRP reinforced concrete beams[J]. *Construction and Building Materials*, 2017, **154**: 819 − 828. DOI: 10.1016/j.conbuildmat.2017.08.006.

[65] Zhang X, Qu W. Shear behavior test of GFRP-reinforced concrete beams without stirrups[J]. *China Journal of Highway and Transport*, 2010, **23**(5): 51 − 57. DOI: 10.19721/j.cnki.1001-7372.2010.05.008. (in Chinese)

[66] Nehdi M, El-Chabib H, Omeman Z. Experimental study on shear behavior of carbon-fiber-reinforced polymer reinforced concrete short beams without web reinforcement [J]. *Canadian Journal of Civil Engineering*, 2008, **35**: 1 − 10. DOI: 10.1139/L07-080.

[67] El-Sayed A, El-Salakawy E, Benmokrane B. Shear strength of FRP-reinforced concrete beams without transverse reinforcement[J]. *ACI Structural Journal,* 2006, **103**: 235 − 243.

[68] El-Sayed A, El-Salakawy E, Benmokrane B. Shear capacity of high-strength concrete beams reinforced with FRP bars[J]. *ACI Structural Journal*, 2006, **103**(3): 383 − 389.

[69] Guadagnini M, Pilakoutas K, Waldron P. Shear resistance of FRP RC beams: Experimental study[J]. *Journal of Composites for Construction*, 2006, **10**(06): 464 − 473. DOI: 10.1061/(ASCE)1090-0268(2006)10:6(464).

[70] Wegian F M, Abdalla H. Shear capacity of concrete beams reinforced with fiber reinforced polymers[J]. *Composite Structures*, 2005, **71**: 130 − 138. DOI: 10.1016/j.compstruct.2004.10.001.

[71] El-Sayed A, El-Salakawy E, Benmokrane B. Shear strength of one-way concrete slabs reinforced with fiber-reinforced polymer composite bars[J]. *Journal of Composites for Construction*, 2005, **9**(2): 147 − 157. DOI: 10.1061/(ASCE)1090-0268(2005)9:2(147).

[72] Kilpatrick A, Easden L. Shear capacity of GFRP reinforced high strength concrete slabs[C]// *Australasian Conference on the Mechanics of Structures and Materials*. London, UK, 2005: 119 − 124.

[73] Razaqpur G, Isgor B, Greenaway S, et al. Concrete contribution to the shear resistance of fiber reinforced polymer reinforced concrete members[J]. *Journal of Composites for Construction*, 2004, **8**(5): 452 − 460. DOI: 10.1061/(ASCE)1090-0268(2004)8:5(452).

[74] Tariq M, Newhook J. Shear testing of FRP reinforced concrete without transverse reinforcement[C]// *Annual Conference of the Canadian Society for Civil Engineering*. Moncton, Canada, 2003: 1330 − 1339.

[75] Tureyen K, Frosch R. Shear tests of FRP-reinforced concrete beams without stirrups[J]. *ACI Structural Journal*, 2002, **44**(99): 427 − 434.

[76] Yost J, Gross S, Dinehart D. Shear strength of normal strength concrete beams reinforced with deformed GFRP bars[J]. *Journal of Composites for Construction*, 2001, **5**(4): 268 − 275. DOI: 10.1061/(ASCE)1090-0268(2001)5:4(268).

[77] Gross S, Yost J, Dinehart D, et al. Shear strength of normal and high strength concrete beams reinforced with GFRP bars[C]//*International Conference on High Performance Materials in Bridges.* Kona, HI, USA, 2003: 426 − 437.

[78] Alkhrdaji T, Wideman M, Belarbi A, et al. Shear strength of GFRP RC beams and slabs[C]// *Composites in Construction*. Porto, Portugal, 2001: 409 − 414.

[79] Duranovic N, Pilakoutas K, Waldron P. Tests on concrete beams reinforced with glass fibre reinforced plastic bars[C]// *Proceedings of the Third International Symposium on Non-metallic (FRP) Reinforcement for Concrete structures(FRPRCS-3)*. Sheffield, UK, 1997: 1 − 8.

[80] Hikaru N, Takeshi H. Evaluation of shear strength of concrete beams reinforced with FRP[J]. *Proceedings of the Japan Society of Civil Engineers,* 1995, **26**(508): 111 − 123.

[81] American Concrete Institute. Guide for the design and construction of concrete reinforced with fiber reinforced polymers (FRP bars): ACI 440.1R-2015[S]. Farmington Hills, MI, USA: American Concrete Institute, 2015.

[82] Razaqpur G, Isgor B. Proposed shear design method for FRP-reinforced concrete members without stirrups[J]. *ACI Structural Journal*, 2006, **103**(11): 93 - 102.
[83] Japan Society of Civil Engineers. Recommendation for design and construction of concrete structures using continuous fiber reinforcing materials: JSCE-1997[S]. Tokyo, Japan: Japan Society of Civil Engineers, 1997.
[84] AASHTO. Bridge design guide specifications for GFRP-reinforced concrete bridge decks and traffic railings: AASHTO-LRFD-2017 [S]. Washington, DC, USA: AASHTO, 2017.
[85] Advisory Committee Technical Recommendations Construction. Guide for the design and structural of concrete reinforced with fiber-reinforced: CNR-DT203-2006[S]. Rome, Italy: Advisory Committee Technical Recommendations Construction, 2006.
[86] British Institution of Structural Engineers. Interim guidance on the design of reinforced concrete structures using fiber composite reinforcement: BISE-1999[S]. London, UK: British Institution of Structural Engineers, 1999.
[87] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Technical standard for fiber reinforced polymer(FRP) in construction: GB 50608—2020[S]. Beijing, China: China Planing Press, 2020. (in Chinese)
[88] Ahmed A, Mohamed H, Chalioris C, et al. Evaluating the shear design equations of FRP-reinforced concrete beams without shear reinforcement[J]. *Engineering Structures,* 2021, **235**: 112017. DOI: 10.1016/j.engstruct.2021.112017.
[89] Baghi H, Barros J, Kaszubska M, et al. Shear behavior of concrete beams reinforced exclusively with longitudinal glass fiber reinforced polymer bars: Analytical model[J]. *Structural Concrete*, 2018, **19**: 162 - 173. DOI: 10.1002/suco.201700175.
[90] Frosch R J, Qiang Y, Cusatis G, et al. A unified approach to shear design[J]. *Journal of Chemical & Engineering Data*, 2017, **19**: 162 - 173.
[91] Mari A, Cladera A, Oller E, et al. Shear design of FRP reinforced concrete beams without transverse reinforcement [J]. *Composites Part B Engineering*, 2014, **57**: 228 - 241. DOI: 10.1016/j.compositesb.2013.10.005.
[92] Alam M, Hussein A. Unified shear design method for FRP reinforced concrete members without stirrups[J]. *Journal of Composites for Construction*, 2013, **17**(5): 575 - 587. DOI: 10.1061/(asce)cc.1943-5614.0000342.
[93] Kara I. Prediction of shear strength of FRP-reinforced concrete beams without stirrups based on genetic programming[J]. *Advances in Engineering Software*, 2011, **42**(06): 295 - 304. DOI: 10.1016/j.advengsoft.2011.02.002.

基于数据库的无腹筋 FRP 筋混凝土梁受剪承载力误差分析

王　涛[1]　范向前[1,2]　高长胜[1]　屈池玉[1]　刘决丁[1]

([1] 南京水利科学研究院水文水资源与水利工程科学国家重点实验室,南京 210024)
([2] 河海大学水安全与水科学协同创新中心,南京 210098)

摘要:基于国内外已发表文献中的受剪承载力试验数据,建立了样本容量为 461 的无腹筋 FRP 筋混凝土梁受剪承载力试验数据库. 综合分析了混凝土抗压强度、梁宽度、梁有效高度、剪跨比、FRP 筋配筋率以及 FRP 筋弹性模量等 6 个因素对无腹筋 FRP 筋混凝土梁受剪承载力的影响,并对各规范建议公式以及各修正计算公式预测效果进行评价. 结果表明,各计算方法对尺寸效应和剪跨比的考虑并不一致,均存在不同程度的保守计算,各因素与受剪承载力之间存在较好的相关性. 在各规范建议公式中,CSA/CAN-S806-2012 的预测效果较为准确,ACI440.1R-2015 的预测效果最为保守,CNR-DT203-2006 的安全度最低. 在各修正计算公式中,Ahmed-2021 的预测效果较为准确,Alam-2013 最为保守,Mari-2014 的安全程度最低.

关键词:数据库;FRP 筋;无腹筋混凝土梁;抗剪能力;计算方法;误差分析

中图分类号:TU375.1