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Sustainability of Using Steel Fibers in Reinforced Concrete Deep Beams without Stirrups

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Abstract: Reinforced Concrete (RC) deep beams perform better structurally when steel fibers are added, as this reduces the need for web steel reinforcements, boosts shear strength, and helps to bridge cracks. The current ACI 318-19 code does not include predicting shear strength models to account for the added steel fibers in Steel Fibers Reinforced Concrete (SFRC) deep beams without stirrups; therefore, structural engineers are less motivated to use them. To fill this gap, the databases of 281 RC and 172 SFRC deep beams were compiled, and the preliminary investigation of the collected databases revealed that (1) Longitudinal steel reinforcement significantly increases the shear strength of SFRC specimens, as the steel fibers make deep beams better at carrying loads by assisting them in bridging cracks; and (2) Although shear stress and span-to-depth ratio are inversely related, SFRC deep beams encounter larger shear loads than RC deep beams because when the span-to-depth ratio of beams increases, the failure mode switches from crushing struts to diagonal shear failure. To help structural engineers adopt SFRC deep beams, a nonlinear regression-based model was developed to estimate the shear strength of SFRC deep beams using the experimental database of SFRC beams. Three factors—feature selection, data preprocessing, and model development—were considered. Additionally, the model's effectiveness was evaluated and compared with other models found in the literature. The proposed shear strength model of SFRC performed better than the other models in the literature, providing the lowest Root Mean Square Error (RMSE) of 1.58 MPa. The results of this study give practitioners a strong platform for establishing precise and useful estimations of shear strength in SFRC deep beams without stirrups.

Keywords: SFRC; deep beams; shear strength; beams without stirrups; nonlinear regression



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1. Introduction

Concrete, a common construction material in the building business, has various limitations, such as a low resistance capability against tensile stresses. Concrete reinforcement fixes this vulnerability. One of these strengthening techniques involves using fibers with various steel or synthetic materials. Fiber reinforced concrete (FRC), a type of concrete reinforced with fibers, can provide better qualities than regular concrete. The fibers improve the energy absorbed during the fracture process by reducing the likelihood of cracking [1,2]. Moreover, the addition of fiber to precast concrete elements benefits the precast construction elements.

Reinforced concrete (RC) beams with a shear span ratio ($a/d \leq 2.5$) are classified as “deep beams” and are widely used in special constructions such as transfer girders, foundation pile caps, deep foundations, and squat walls, as shown in Figure 1. The load transfer through deep beams is best simulated using the strut-and-tie model [3], since the sectional strain distribution is not linear; hence, the beam theory is not applicable to designing deep beams. In general, the failure mode of deep beams is characterized as a brittle failure with sudden crushing in concrete. Additional horizontal and vertical steel

reinforcements distributed through the depth of beams are an option to avoid brittle failure. The ACI 318-19 code [3] imposes minimum horizontal and vertical reinforcement to classify struts as “Reinforced” for sustaining greater shear loads.

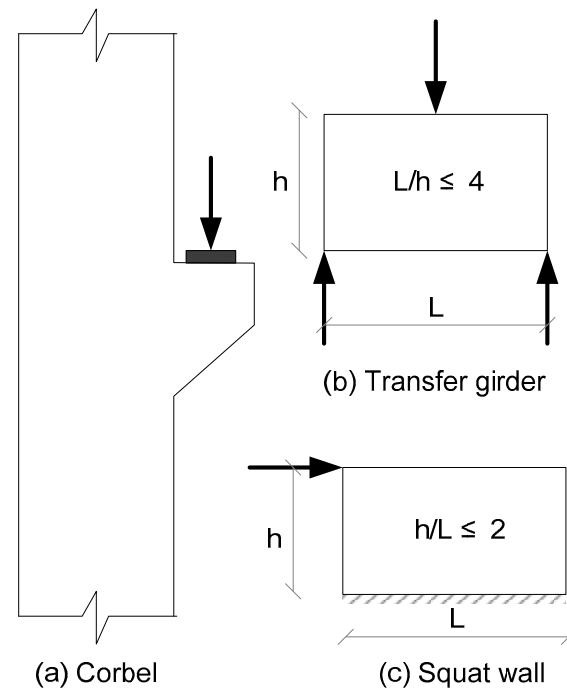


Figure 1. Applications of deep beams in reinforced concrete structures.

Recent advancements in concrete technology led to the addition of steel fibers to improve the tensile and shear strength of plain concrete. Therefore, the use of Steel Fibers Reinforced Concrete (SFRC) in deep beams is known to improve structural performance, delay shear cracking, and eliminate the use of minimum web steel reinforcements [4]. Over the last five decades, SFRC deep beams have been extensively investigated to eliminate shear reinforcement by adding steel fibers into the concrete. Many factors influence the structural behavior of SFRC deep beams, such as the steel fiber dosage, mechanical and geometrical properties of the steel fibers, shear span ratio, and longitudinal steel reinforcement.

For instance, Ashour et al. [5] evaluated eight specimens with a/d of 1.0 and 2.0, an effective depth of 215 mm, and concrete compressive strength of approximately 100 MPa. The test results revealed that adding a high amount of steel fibers can effectively increase the shear strength of beams with a low shear span-to-depth ratio ($a/d = 1$) and longitudinal steel reinforcement ratio of 2.85%. In contrast, minor shear strength improvement was observed for deep beams with $a/d = 2$ and a longitudinal steel reinforcement ratio of 0.37%. This can be justified as the addition of steel fibers into concrete improves its tensile strength and allows deep beams to carry additional shear forces. However, providing fewer longitudinal steel reinforcements reduces dowel stress and decreases the capacity of deep beams, which usually fail in flexure, (Ashour et al. [5], Li et al. [6], Mansur et al. [7]). Moreover, Cho and Kim [8] evaluated 12 SFRC deep beams with an effective depth of 165 mm, $a/d = 1.45$; the study explored various parameters, such as concrete compressive strength from 25 to 90 MPa, $\rho = 1.3$ or 2.9%, $V_f = 0.5$ or 1.0%. The study revealed that significant shear stress improvement was observed for high-strength concrete with a 0.5% steel fiber ratio. Although the shear strength of high-strength deep beams was also increased, the strength increase compared with high-strength beams with $V_f = 0.5\%$ was minor. This indicates that an optimum V_f of approximately 0.5% value is important to save materials cost. Also, the addition of steel fibers into brittle in nature, high-strength

concrete increases its tensile strength, thereby considerably improving the shear strength of SFRC deep beams.

On cylinder and beam samples reinforced with varied steel fiber content percentages, an Ultrasonic-Pulse Velocity (UPV) was performed [9]. The findings indicate that 2% is the ideal steel fiber content for beam sections. When assessing how the fibers affect the strength of the FRC, the fiber orientation must be considered. With the inclusion of steel fibers, the amplitude of UPV reduces for cylindrical samples. Wave speed is inexorably influenced by the cure time. The maximum UPV is seen for cylindrical samples 90 days after cure.

While the literature includes a bulk of tested SFRC deep beams, the current ACI-code version does not include predicting shear strength models to account for the added steel fibers. This discourages structural designers from adopting SFRC deep beams. Although five empirical equations were proposed to estimate the shear strength of SFRC deep beams, the models were derived based on a limited number of specimens, which makes these models unrepresentative and they may not be accurate if they are evaluated using a larger database. To fill this gap, the current study compiled a database of SFRC deep beams to build a data-driven model to forecast the shear strength of SFRC deep beams.

2. Shear Strength Models of SFRC Deep Beams

2.1. Background

The American Concrete Institute, ACI 318-19 [3], uses the strut-and-tie model (STM) to design RC deep beams, as shown in Figure 2. However, this model requires extensive efforts to design nodal joints, struts, and ties considering various requirements such as lowest dissipated energy (by reducing the number of ties), satisfying load path compatibility (ties in tension area and struts are in compression), and that load path shall follow the stiffest path. The internal forces in each component of the STM model can be determined by satisfying the force equilibrium at each node. To avoid concrete splitting of struts, secondary horizontal and vertical steel reinforcements are usually added to enhance the strength of the struts. Nevertheless, this option is considered cost-ineffective, as more steel rebars are needed, there are additional labor costs, and many trials are required to calculate the width of struts, ties, and nodes. Moreover, the STM (ACI 2019) methodology does not consider the improvement in shear strength if steel fibers are added to RC deep beams.

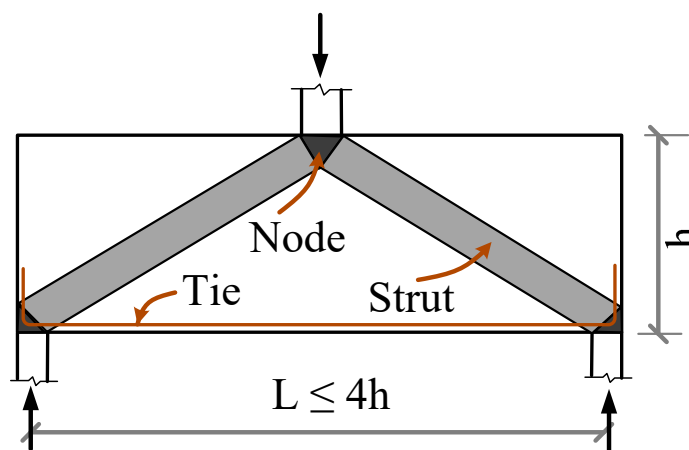


Figure 2. STM components in deep beams.

2.2. Available Shear Strength Models

A limited number of equations are available to estimate the shear strength of SFRC deep beams. Narayanan and Darwish [10] used the results of 91 specimens to develop Equation (1) for estimating the shear stress (v_u , MPa) of SFRC deep beams, where $e = 1.0$ for $a/d > 2.8$, $e = 2.8(d/a)$ for $a/d \leq 2.8$, $\tau = 4.15$ MPa, $F = d_f V_f (l_f/d_f)$, $d_f = 0.5$ for round fibers, 0.75 for crimped or hooked fibers, and 1.0 for indented fibers. f_{spfc} is the splitting tensile

strength of SFRC, MPa, and can be estimated by $f_{spfc} = f_{cu} / (20 - \sqrt{F}) + 0.7 + \sqrt{F}$ (MPa), the parameter f_{cu} (MPa) is cube concrete compressive strength ($=1.25 f_{cm}$), where f_{cm} is the measured cylinder concrete compressive strength (MPa) and $v_b = 0.41 \tau F$

$$v_u = e \left[0.24 f_{spfc} + 80 \rho \frac{d}{a} \right] + v_b \quad (1)$$

Similarly, Ashour et al. [5] proposed Equation (2) to calculate the shear strength of SFRC beams (v_u , MPa) with $a/d \leq 2.5$, where f'_c is the concrete compressive strength (MPa), F and v_b are similar to the definition of Narayanan and Darwish [10]:

$$v_u = \frac{2.5}{a/d} \left[\left(2.11 \sqrt[3]{f'_c} + 7F \right) \left(\rho \frac{d}{a} \right)^{0.333} \right] + v_b (2.5 - a/d) \quad (2)$$

Kwak et al. [11] used Equation (3) to evaluate the shear strength of SFRC deep beams, where $e = 3.5(d/a)$ for $a/d \leq 3.5$

$$v_u = 3.7 e f_{spfc}^{2/3} \left(\rho \frac{d}{a} \right)^{0.333} + 0.8 v_b \quad (3)$$

Li et al. [6] estimated the shear strength of SFRC beams (f_v , MPa) with $a/d \leq 2.5$ using Equation (4), where f_f is the flexural strength of SFRC, MPa.

$$f_v = 9.16 \left[\left(f_f \right)^{2/3} (\rho)^{1/3} (d/a) \right] \quad (4)$$

Shahnewaz and Alam [12] used Equation (5) to calculate the shear strength of SFRC deep beams.

$$v_u = 3.2 + 0.072 f'_c + \rho V_f \left[1.26 - 0.25 \frac{a}{d} \right] - \frac{a}{d} \left[1.92 + 0.017 f'_c - 0.38 \frac{a}{d} \right] \quad (5)$$

3. Research Significance

This study assembled databases of tested RC and SFRC specimens from the literature to assess the shear strength of SFRC deep beams without stirrups. A nonlinear regression-based model was created to evaluate the shear strength of SFRC deep beams for assisting structural engineers with using these beams. As compared with other models in the literature, the proposed SFRC shear strength model performed better and had a lower root-mean-square error. The findings of this research provide practitioners with a solid foundation for developing accurate and practical estimations of shear strength in SFRC deep beams without stirrups.

4. Methodology

To forecast the shear strength of SFRC deep beams, this study attempts to provide an effective data-driven, nonlinear regression-based model. A model performance evaluation, data preprocessing, and feature selection and collection are all implemented. The performance of the suggested model and predictions' sensitivity to different parameters were assessed and contrasted with those of other models that were previously published. Figure 3 displays the methodology flowchart.

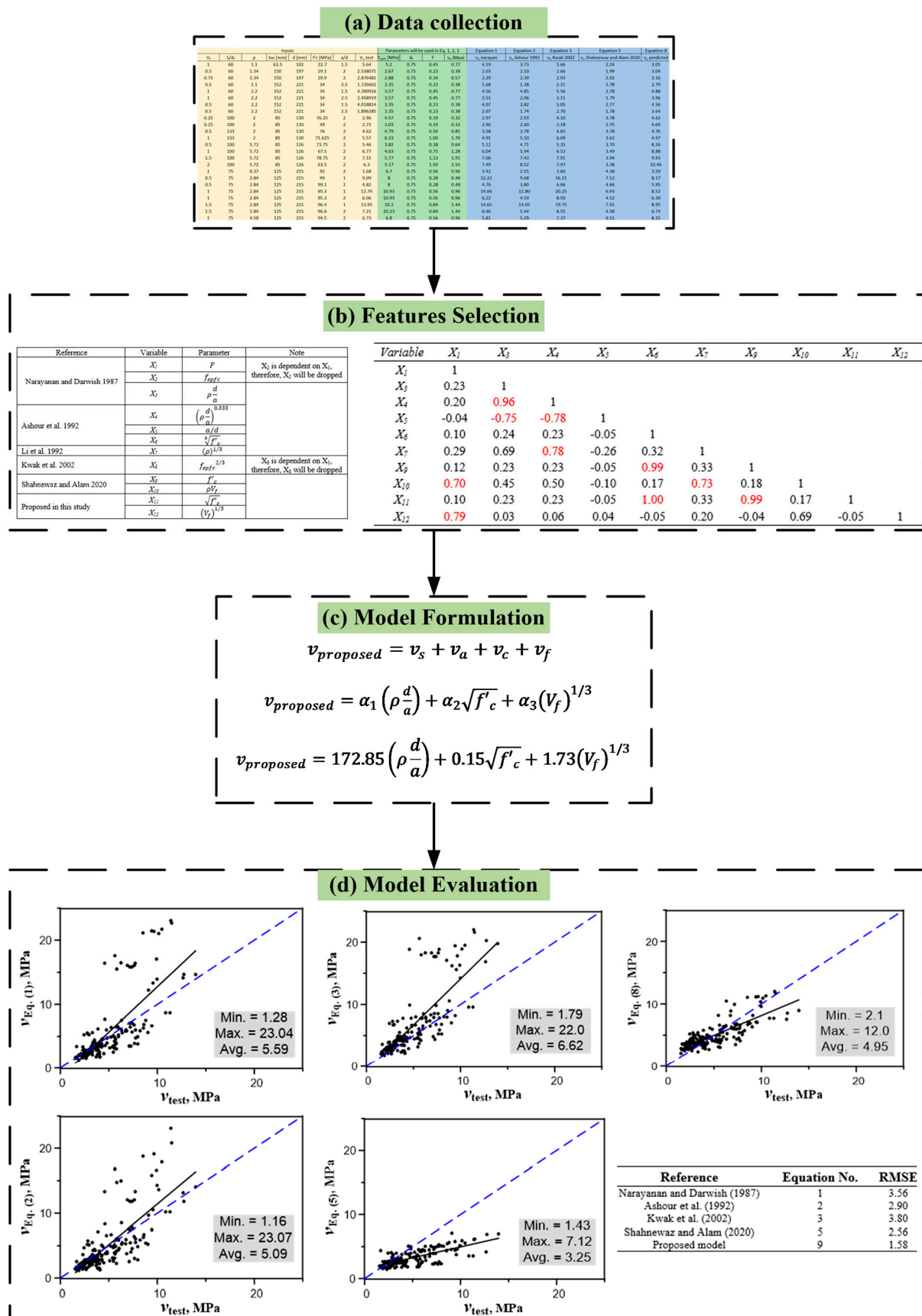


Figure 3. A flowchart outlining the study's methodology (refs. [5,6,10–12] are cited in (b) refs. [5,10–12] cited in (d)).

4.1. Available Experimental Database

A database of 172 evaluated SFRC deep beams was assembled and used to build a nonlinear, regression-based equation to forecast the shear strength of SFRC. Figure 4 and Table 1 demonstrate the database, including a wide range of parameters to give more insights into tested specimens and help improve the accuracy of the proposed model. Figure 4 shows that most of the collected dataset includes beams with an effective depth of less than 400 mm, concrete compressive strength of less than 70 MPa, longitudinal steel reinforcement ratio between 1 and 3%, steel fibers volume ratio from 0.25 to 1%, the shear span-to-depth ratio between 1.25 to 2.5, and steel fibers length-to-diameter ratio from 30 to 100. Table 1 summarizes key details of the references used to build the database, the number of specimens from each reference, and the range of investigated variables.

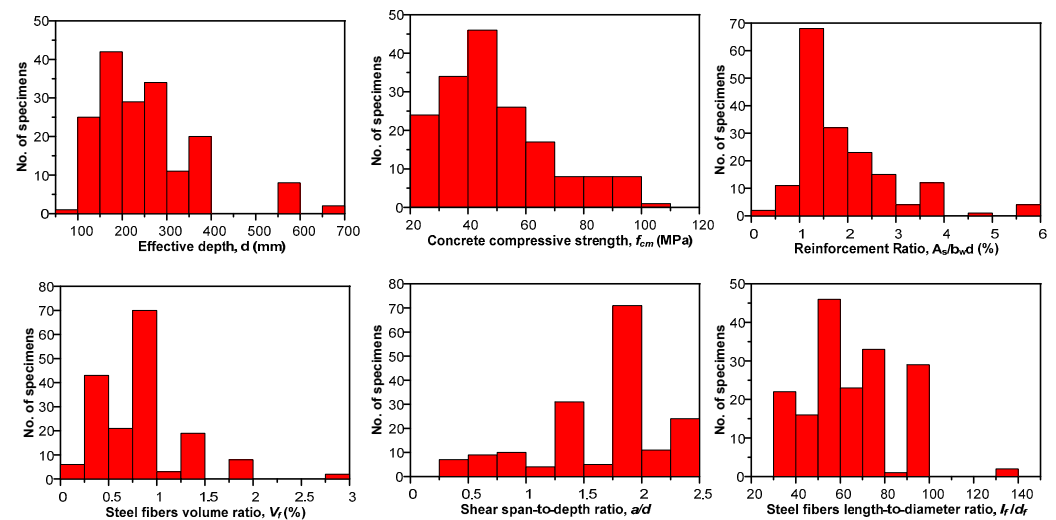


Figure 4. Database description.

Table 1. Database summary.

Reference	No. of Specimens	d (mm)	f'_c (MPa)	ρ (%)	V_f (%)	a/d	l_f/d_f
[6]	1	102	22.7	1.1	1.0	1.5	60
[7]	2	197	29.1;29.9	1.34	0.5; 0.75	2.0	60
[13]	5	221	34	1.1; 2.2	0.5; 1.0	1.5; 2.5	60
[10]	8	130; 126	49–78.8	2.0, 5.72	0.25–2.0	2.0	100;133
[5]	8	215	92–99.1	0.37–4.58	0.5–1.5	1.0;2.0	75
[14]	9	345	37.8–68.2	3.55	0.25–1.0	0.7–0.93	100
[15]	2	175	80	3.59	0.5; 1.0	2.0	100
[16]	4	186	23–26	1.2	0.5; 1.0	2.0	50;100
[17]	6	557	40.8–56.5	2.15	0.4–1.5	1.35	60;100
[11]	3	212	30.8–68.6	1.5	0.5;0.75	2.0	62.5
[18]	3	127	39.8	3.09	1.76	1.2;1.8	66.8
[19]	1	300	109.5	3.08	0.75	1.75	75
[20]	9	135	60–64.2	1.16	0.5;1.0	2.2	65;80
[21]	2	210	44.6;57.2	1.5	0.5	2.0	62.5
[22]	4	222	40.4–45.6	1.43	0.5;0.75	1.8;2.25	80
[23]	2	219	40.9;43.2	1.9	1.0;2.0	2.0	60
[24]	4	260	34.5–37.1	2.52	0.5–2.0	2.0	35
[25]	3	175	82–83.8	1.0	0.5–1.5	1.5	80
[26]	6	170	31.3;38.3	2.35	0.85;1.3	0.8–2.4	100
[27]	1	219	80	1.91	1.0	2.0	55
[28]	1	275	28.4	0.35	0.5	2.0	75
[8]	12	165	25.3–89.4	1.3;2.9	0.5;1.0	1.45	60

Table 1. Cont.

Reference	No. of Specimens	d (mm)	f'_c (MPa)	ρ (%)	V_f (%)	a/d	l_f/d_f
[29]	11	260–305	26.5–50	0.93–1.64	0.25–0.75	1.54–2.48	45–80
[30]	4	127	20.7	2.0	1.0	2.0;2.4	62.5–100
[31]	6	360–657	33.5	1.06–1.78	1.0	0.46–1.11	60
[32]	9	275	24.9–31.2	0.63–2.47	1.0–3.0	1.5;2.0	60
[33]	18	362	38.4–47.4	1.11–2.32	0.4–1.2	1.0–2.0	37.5
[34]	9	170;178	52.5–54.6	1.23;1.35	0.5–1.5	1.97;2.35	80
[35]	4	250	53.1;55.4	0.53	0.5;1.0	2.4	50
[36]	8	270	40.4;43.2	1.21	0.26;0.51	0.5;1.5	50
[37]	7	80–280	45.8–51.5	2.0–3.54	0.75;1.5	2.0	60;67.7
Total	172						

To provide more insights about the overall information of each parameter, Figure 5 shows the trendline of various parameters with the measured shear stress. Figure 5A indicates that shear stresses are not influenced by the effective depth, as the relationship is a constant function. While Figure 5B–D, and Figure 5F reveal shear stresses are approximately correlated to f_{cm} , ρ , V_f , and l_f/d_f by square root, cubic root, cubic root, and linear functions, respectively. On the other hand, the shear stresses are inversely related to the shear span ratio, as shown in Figure 5E. Figure 5 presents valuable information to help select the regression model components and save the amount of time needed to find the most fitting function for each variable.

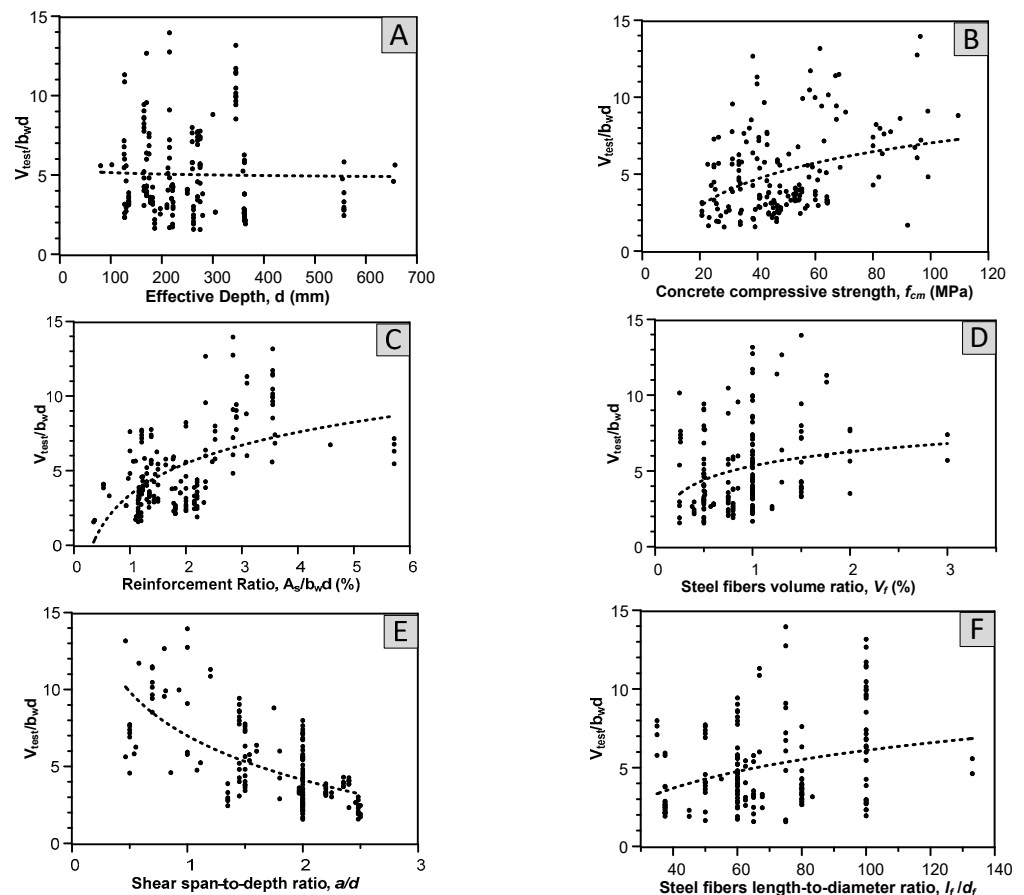


Figure 5. Effect of various variables on measured shear stress; (A) Effective depth, (B) Concrete compressive strength, (C) Longitudinal steel reinforcement ratio, (D) Steel fibers volume ratio, (E) Shear span-to-depth ratio, and (F) Steel fibers length-to-diameter ratio.

4.2. Comparison between RC and SFRC Databases

A database of 281 RC deep beams without stirrups was collected from the literature [38–70]. The average and standard deviation of beam depth, beam width, shear span-to-depth ratio, concrete compressive strength, longitudinal reinforcement ratio, and shear strength are 425 mm (234), 183 mm (64 mm), 1.35 (0.4), 33.5 MPa (16.7 MPa), 2.02% (1.1%), and 283.4 kN (206 kN), respectively. Further statistical measures such as median, mode, minimum, and maximum values in the database are summarized in Table 2.

Table 2. Statistical information of the collected database for RC deep beams without stirrups.

Statistical Measure	Features					
	d (mm)	b_w (mm)	a/d	f_{cm} (MPa)	ρ (%)	V_u (kN)
Mean	425	183	1.35	33.5	2.02	283.4
Median	356	178	1.36	27.9	1.82	220.8
Mode	305	178	1	31.4	1.13	192.7
Standard deviation	234	64	0.4	16.7	1.1	206
Minimum	132	51	0.5	11.3	0.26	20.7
Maximum	1559	460	2	87	5.04	1240
Count	281	281	281	281	281	281

Comparing SFRC deep beams with RC beams, Figure 6A shows that longitudinal steel reinforcement greatly increases shear strength. This is acceptable, since the steel fibers increase the ability of deep beams to bridge cracks, increasing their capacity to support loads. Although the shear stresses are inversely proportional to the span-to-depth ratio, Figure 6B revealed SFRC beams have higher shear stress than RC deep beams because, as the span-to-depth ratio of beams increases, the failure mode shifts from crushing of struts to diagonal shear failure. On the other hand, Figure 6C,D shows the concrete compressive strength and depth of beams have a minor effect on the performance of SFRC and RC beams, which can be justified as the shear strength of deep beams, is best simulated using the strut-and-tie model which mainly relies on the concrete compressive strength.

4.3. Development of the Nonlinear Regression-Based Model and Features Selection

The response of concrete to shear stresses is complicated, and most current codes still rely on regression-based equations to predict the shear strength of RC beams [71]. However, adding steel fibers into concrete increases the complexity of estimating the shear strength of SFRC beams and predicting the failure mode, as steel fibers improve the shear response of SFRC beams. Therefore, nonlinear regression models are viable for forecasting SFRC deep beams' shear strength. In this study, parameters that were considered in previous models (which are reviewed in Equations (1)–(5)) are statistically evaluated in Table 3. The description of the considered parameters is summarized in Table 3, which includes 12 parameters (X_1 to X_{12}), where X_1 to X_3 , X_4 to X_6 , X_7 , X_8 , and X_9 to X_{10} were utilized in Equations (1)–(5), respectively. However, X_{11} and X_{12} are proposed in this study, where $X_{11} = \sqrt{f'_c}$ and $X_{12} = (V_f)^{1/3}$. These two parameters can be justified based on the information presented in Figure 5 which reveals the trendline between concrete compressive strength and shear stress is approximately a function of the square root of f'_c . Similarly, the steel fibers volume ratio is related to the shear stress with a function of almost cubic root of V_f . As $f_{spfc} = f_{cu} / (20 - \sqrt{F}) + 0.7 + \sqrt{F}$ (MPa), the value of $X_2 = f_{spfc}$ and $X_8 = (f_{spfc})^{2/3}$ are correlated to the parameter F , hence, X_2 and X_8 can be dropped out. Based on Table 4, X_{12} is selected as the first potential variable, since X_1 is significantly correlated ($R \geq 0.7$) to X_{10} and X_{12} . Similarly, X_3 is the second potential variable, as it is correlated to X_4 and X_5 . Moreover, X_{11} is the third potential variable, as X_6 is correlated to

X_9 and X_{11} . Therefore, the variables X_1 , X_4 , X_5 , X_6 , X_7 , and X_9 can be dropped out of the potential variables as they can be represented by X_3 , X_{11} , and X_{12} .

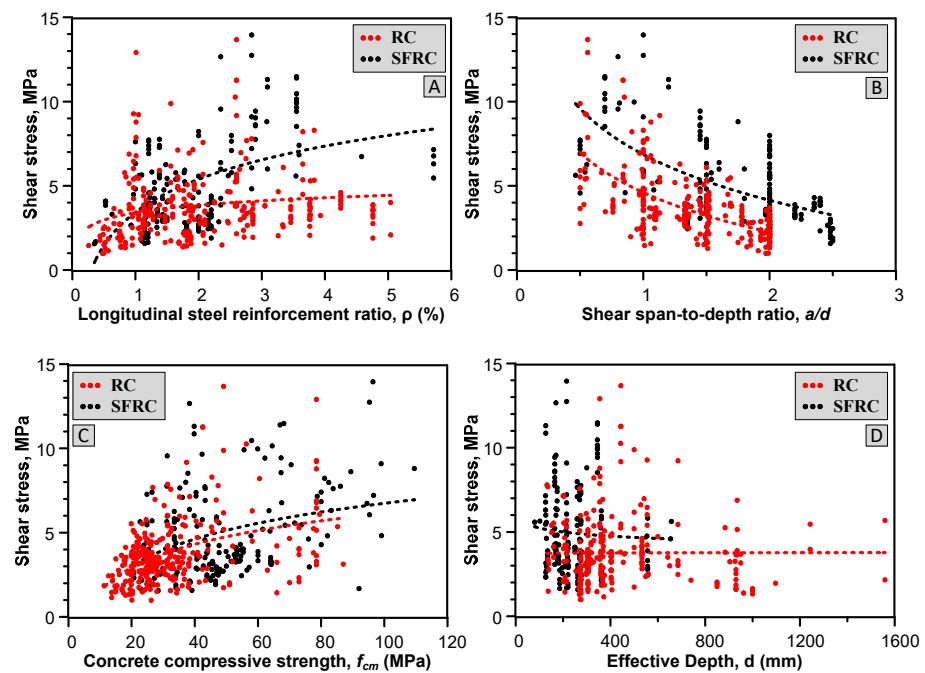


Figure 6. Effect of various parameters on the measured shear stresses for SFRC and RC deep beams; (A) Longitudinal steel reinforcement ratio, (B) Shear span-to-depth ratio, (C) Concrete compressive strength, and (D) Effective depth.

Table 3. Description of investigated variables to construct the nonlinear regression model.

Reference	Variable	Parameter	Note
[10]	X_1	F	X_2 is dependent on X_1 , therefore, X_2 will be dropped
	X_2	f_{spfc}	
	X_3	$\rho \frac{d}{a}$	
[5]	X_4	$\left(\rho \frac{d}{a}\right)^{0.333}$	
	X_5	a/d	
	X_6	$\sqrt[3]{f'_c}$	
[6]	X_7	$(\rho)^{1/3}$	
[11]	X_8	$f_{spfc}^{2/3}$	X_8 is dependent on X_1 , therefore, X_8 will be dropped
[12]	X_9	f'_c	
	X_{10}	ρV_f	
	X_{11}	$\sqrt{f'_c}$	
Proposed in this study	X_{12}	$(V_f)^{1/3}$	

Table 4. Correlation matrix of potential variables.

Variable	X ₁	X ₃	X ₄	X ₅	X ₆	X ₇	X ₉	X ₁₀	X ₁₁	X ₁₂
X ₁	1									
X ₃	0.23	1								
X ₄	0.20	0.96	1							
X ₅	−0.04	−0.75	−0.78	1						
X ₆	0.10	0.24	0.23	−0.05	1					
X ₇	0.29	0.69	0.78	−0.26	0.32	1				
X ₉	0.12	0.23	0.23	−0.05	0.99	0.33	1			
X ₁₀	0.70	0.45	0.50	−0.10	0.17	0.73	0.18	1		
X ₁₁	0.10	0.23	0.23	−0.05	1.00	0.33	0.99	0.17	1	
X ₁₂	0.79	0.03	0.06	0.04	−0.05	0.20	−0.04	0.69	−0.05	1

Note: The red numbers indicate that the variables are substantially connected, with a correlation coefficient of at least 0.7.

4.4. Derivation and Evaluation of the Nonlinear Regression Model

It is of great interest to build a simple and accurate model to estimate the shear strength of SFRC deep beams. Equation (6) includes the main contributors to the shear strength of SFRC deep beams, such as the longitudinal steel reinforcement (or dowel action), mechanical properties of concrete, shear span-to-depth ratio, and steel fiber dosage.

$$v_{proposed} = v_s + v_a + v_c + v_f \quad (6)$$

where v_s , v_a , v_c , and v_f are the shear stress contribution of the longitudinal steel reinforcement, shear span-to-depth ratio, concrete, and steel fibers, respectively. Based on the analysis conducted in the section of selecting the features, the three variables $\left(\rho \frac{d}{a}\right)$, $\sqrt{f'_c}$, and $\left(V_f\right)^{1/3}$ are found to be representative of the other parameters. The v_s and v_a components in Equation (6) can be correlated to the variable $\left(\rho \frac{d}{a}\right)$, while v_c and v_f can be related to $\sqrt{f'_c}$ and $\left(V_f\right)^{1/3}$, respectively. The general form of the proposed shear strength of SFRC deep beams is shown in Equation (7), where α_1 , α_2 , and α_3 are correlation constants determined by conducting the nonlinear regression analysis.

$$v_{proposed} = \alpha_1 \left(\rho \frac{d}{a}\right) + \alpha_2 \sqrt{f'_c} + \alpha_3 \left(V_f\right)^{1/3} \quad (7)$$

Based on the assembled dataset of 172 tested SFRC deep beams, a nonlinear regression analysis was performed, where the values of the regression constants are $\alpha_1 = 172.85$, $\alpha_2 = 0.15$, and $\alpha_3 = 1.73$. The final version of the proposed shear strength ($v_{proposed}$, MPa) is listed in Equation (8).

$$v_{proposed} = 172.85 \left(\rho \frac{d}{a}\right) + 0.15 \sqrt{f'_c} + 1.73 \left(V_f\right)^{1/3} \quad (8)$$

5. Results and Discussions

5.1. Performance of the Proposed Model

The constants α_1 , α_2 , and α_3 in Equations (7) and (8) were calibrated to attain the minimum value of Root Mean Square Error (RMSE), Equation (9), where N is the total number of specimens (172), v_{test} and v_p are the experimental shear stress and predicted shear strength, respectively. The RMSE is calculated to the predicted shear stress using Equations (1)–(3), and (5) and compared with the proposed equation. Table 5 reveals that the proposed model can predict the shear strength of SFRC deep beams with the least RMSE, which indicates the high accuracy of the forecasting model, while Equation (3) has the lowest RMSE with high scatteredness in predicting the shear stresses. Figure 7

shows the comparison of the experimental results of shear stresses with the predicted shear stresses using Equations (1)–(3), (5), and (8).

$$RMSE = \sqrt{\frac{1}{N} \sum_{k=1}^N (v_{test} - v_p)^2} \quad (9)$$

Table 5. RMSE summary of the investigated equations.

Reference	Equation No.	RMSE
[10]	1	3.56
[5]	2	2.90
[11]	3	3.80
[12]	5	2.56
Proposed model	8	1.58

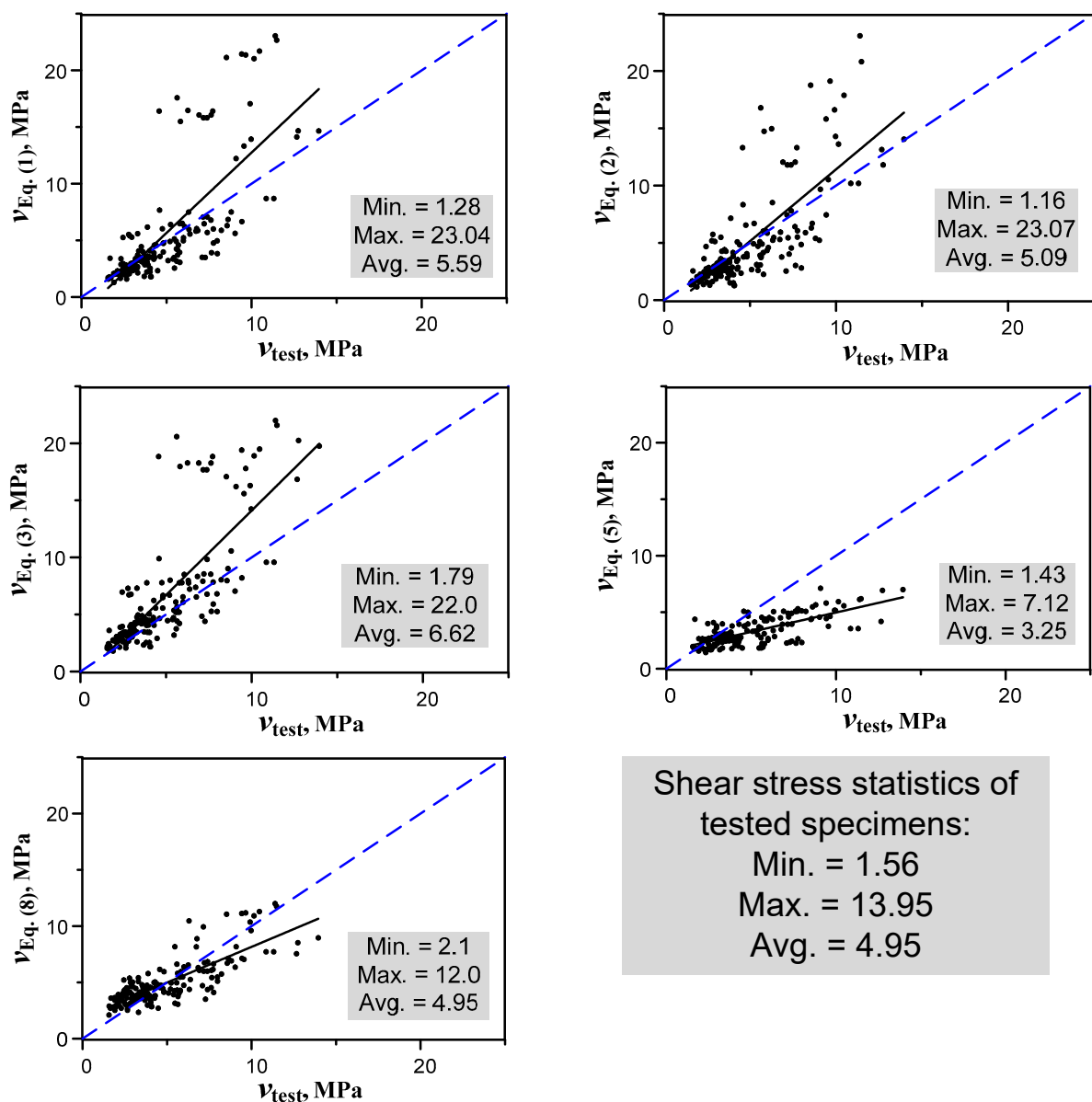


Figure 7. Statistical information for tested and predicted shear stresses using Equations (1)–(3), (5), and (8).

Figure 7 shows that the predicted shear stresses using Equations (1)–(3) overestimate the shear strength of SFRC deep beams, while Equation (5) significantly underestimates the shear strength. The minimum (v_{min}), maximum (v_{max}), and average (v_{avg}) of the experimental shear stresses in the database are 1.56, 13.95, and 4.95, respectively. The maximum predicted shear stress using Equations (1)–(3) are approximately 65% more than v_{max} , while Equations (5) and (8) have maximum forecasted shear stresses of nearly 50% and 14% less than v_{max} , respectively. The average of the predicted shear stresses using Equation (8) matches the average of tested specimens of 4.95 MPa. However, the average of shear stresses using Equations (1)–(3) are 5.59, 5.09, and 6.62 MPa which are higher than v_{avg} , but Equation (5) has average shear stress (3.25 MPa) lower than v_{avg} . The highest accuracy of the proposed equation (Equation (8)) can be explained by the fact it has the lowest RMSE value (Table 5). Figure 7 shows predictions using Equation (8) have the lowest scatteredness around the blue dashed line (this refers to the perfect prediction).

5.2. Importance of Key Parameters

Figure 8 displays the outcomes of the feature importance research. The parameters of d , b_w , a/d , ρ , l_f/d_f , f_{cm} , and V_f are indicated as crucial variables. The shear strength of SFRC deep beams without stirrups is most significantly affected by the parameters d and b_w , with significance values of 90% and 78%, respectively. This is because the shear strength is greatly influenced by the size of the beam. Additionally, the compression strength of the concrete and the ratio of steel reinforcement have an important factor of approximately 75%. This is because these two factors are extremely important in resisting the applied shear forces through the dowel action and compression zone contribution on the beam. The shear span-to-depth ratio, steel fiber volume ratio, and steel fiber length-to-diameter ratio all have lower significance values than the shear span-to-depth ratio (64%, 48%, and 43%, respectively), but the designer should still consider their contributions, because doing so can make it more difficult to predict the shear strength. As a result, when developing the suggested regression-based model for this study, the contribution of these seven factors was considered.

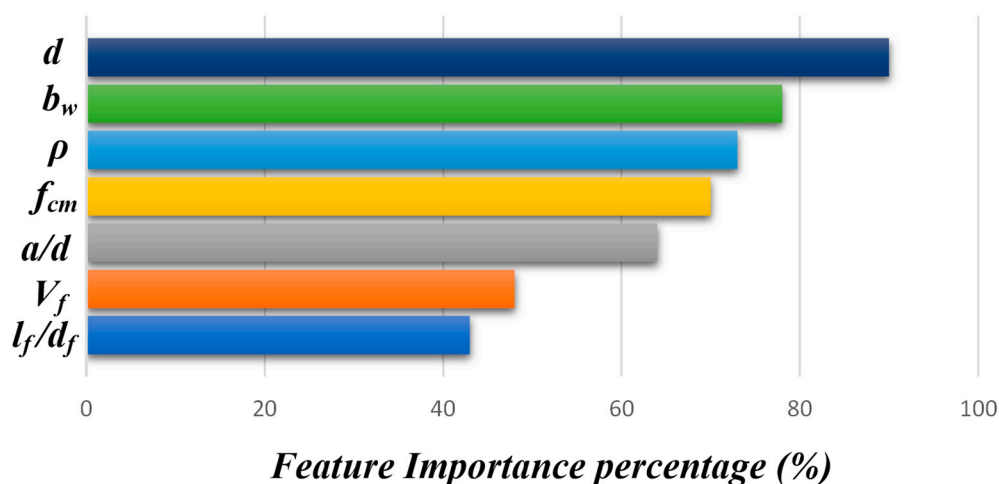


Figure 8. Features importance percentage of the key influencing parameters.

5.3. Effect of Selected Parameters on the Proposed Model

As Equation (5) has the lowest RMSE value (Table 5) among the other evaluated equations, except for the proposed model (Equation (8)), this section further investigates these two equations to examine the sensitivity of various variables. Hence, Figure 9 shows the performance of the predicted shear stresses using Equations (5) and (8). The figure reveals the trendlines of a/d , ρ , and f_{cm} versus the predicted shear stresses using Equation (8) match the test results in terms of the average fitting line and the scatteredness of data. However, these trendlines significantly diverge away from the experimental

trendline for the predictions using Equation (5). This reveals the outperformance of the proposed model considering the most important features that influence the shear strength of SFRC deep beams with stirrups.

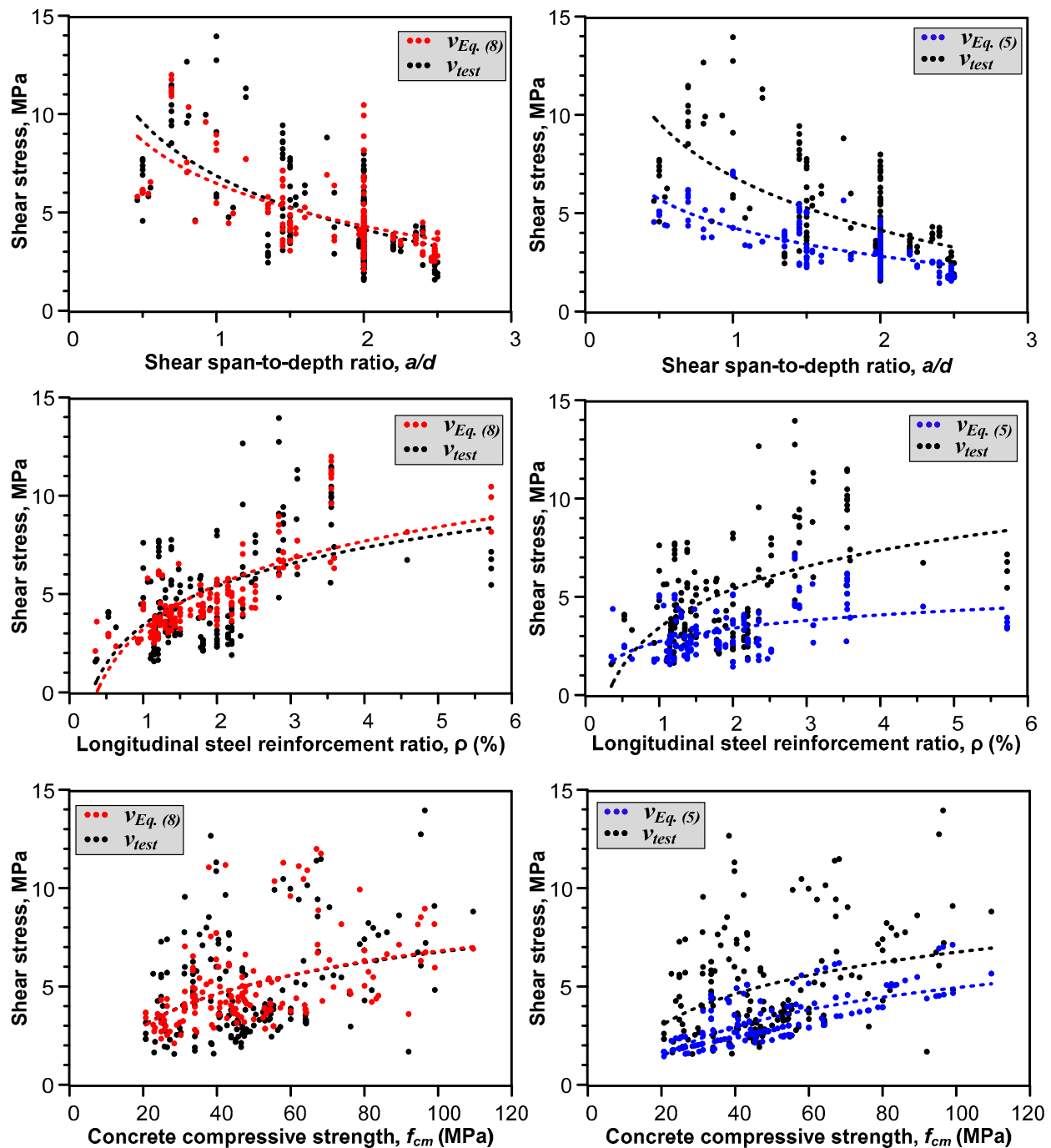


Figure 9. Effect of various parameters on the predicted shear stresses using Equations (5) and (8).

6. Summary and Conclusions

Most modern codes still rely on regression-based models to forecast the shear strength of RC beams because of how intricate concrete's response to shear pressures is. However, since steel fibers enhance the SFRC beams' shear response, adding steel to concrete makes it more difficult to determine the shear strength and anticipate the mode of failure. To fill this gap, the experimental databases of RC and SFRC deep beams without stirrups that is currently available in the literature was used in this study to create a nonlinear

regression-based model. The choice of features, data preprocessing, and model derivation are explained. The model's performance was assessed and compared with other models that were found in the literature. The inferences that can be made are as follows:

1. Longitudinal steel reinforcement significantly boosts the shear strength of SFRC deep beams without stirrups. This can be justified, as the steel fibers improve deep beams' capacity to carry loads by helping them bridge cracks.
2. Even though the shear stresses are inversely related to the span-to-depth ratio, SFRC deep beams experience higher shear loads than RC deep beams because when the span-to-depth ratio of beams rises, the failure mode shifts from crushing of struts to diagonal shear failure.
3. The results also show that the concrete compressive strength and depth of beams have only a small impact on the performance of SFRC and RC beams, which is understandable given that the strut-and-tie model, which primarily relies on the concrete compressive strength, provides the most accurate simulation of the shear strength of deep beams.
4. A survey was conducted to explore the input parameters of the available shear strength models in literatures, and the investigation revealed the three variables $\left(\rho \frac{d}{a}\right)$, $\sqrt{f'_c}$, and $\left(V_f\right)^{1/3}$ are significant to quantify the shear strength contribution of steel reinforcement, concrete, and steel fibers ratio. Therefore, these three variables were utilized to build the proposed shear strength model for SFRC deep beams without stirrups.
5. The proposed model outperformed the other equations in the literature, since it was able to anticipate the shear strength of SFRC deep beams with the lowest RMSE (=1.58) and lowest scatteredness, demonstrating the model's high accuracy.
6. The shear stresses predictions using the proposed model revealed that the trendlines of a/d , ρ , and f_{cm} versus the predicted shear stresses match the test results in terms of the average fitting line and the scatteredness of data. This demonstrates the suggested model's superior performance when considering various crucial factors that affect the shear strength of SFRC deep beams without stirrups.

The goal of the current study is to determine whether it is possible to use SFRC deep beams without stirrups in place of the minimum shear reinforcement in RC deep beams. The study does not advise, however, that deep beams with stirrups be replaced with SFRC deep beams if the shear loads are greater than the minimum shear stresses. This work is restricted to SFRC deep beams without stirrups; however, additional research is required for SFRC deep beams with stirrups because they have complex shear force transfer that must be quantified. Furthermore, research into deep beams without stirrups reinforced with synthetic fibers is advised because these fibers play a crucial role in preventing corrosion on RC structures. Furthermore, advanced machine learning algorithms are advised to improve the prediction accuracy of shear strength.

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