Shear Design Equations for EB FRP-RC Beams Based on Data Fitting Approach

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Abstract - Based on a data fitting method applied to 490 experimental test data that are publicly available in the literature, this study provides simplistic and straightforward equations to determine the shear capacity of FRP bonded-RC beams. Complete wrap, U-wrap, and side wrap schemes pertaining to Carbon Fiber Reinforced Polymer (CFRP) were analyzed separately. Current design codes follow a customary approach where the nominal shear capacity is calculated by simply accumulating the shear contribution of concrete, transverse reinforcement, and FRP. The interaction between concrete, transverse reinforcement, and FRP is usually not taken into consideration. While the modulus of elasticity of FRP, longitudinal steel ratio, transverse steel ratio, and FRP ratio all have an inverse interaction with the effective strain of FRP, the concrete's compressive strength is positively linked with the effective FRP strain, i.e., when the concrete compressive strength increases, effective FRP increases. This investigation further showed that as transverse and longitudinal reinforcement are increased, the influence of FRP on shear contribution decreases. ACI 440.2R-17 and, CSA S806-02 are among the regularly used shear design methodologies in North America and they were used to compare the performance of the proposed equations. The obtained results show that the proposed equations predict the experimental results more accurately than ACI 440.2R-17 and CSA S806-02.

Keywords: Data fitting; Fiber reinforced polymers; Shear strength; RC beams; Curve fitting; Repair; Strengthening.

1. Introduction

Over the last three decades, numerous analytical and experimental studies have been conducted to analyze the behavior of Reinforced Concrete (RC) beams strengthened in shear using externally bonded fiber-reinforced polymer (FRP) sheets. Due to the high strength-to-weight ratio, non-corrosive characteristics, design flexibility, and extended service life, FRP is gaining popularity over traditional strengthening techniques [1]. While shear behavior is extremely complex and unprecedented, shear failure is comparatively brittle and can lead to sudden, catastrophic failure [2]. Bonding of FRP reinforcement orthogonal to the shear crack plane has been revealed to provide higher load-carrying capacities [3]. Therefore, with the growing demand for accurate predicting of shear, numerous analytical formulations have been derived to estimate the shear capacity of RC beams strengthened with FRP [1], [2], [4], [5], [6], [7], [8], [9]. However, most of these shear equations are semi-empirical and the experimental data available to study the shear behavior of RC structures strengthened using FRP is limited. Out of these, the prediction model developed by Triantafillou and Antonopoulos [4] is based on the assumption that FRP only carries normal stresses and therefore, develops an ultimate strain at the ultimate strength. This model is adopted by the current Eurocode. The model proposed by Khalifa [5] based on the FRP fiber orientation and an assumed crack pattern is the basis for the ACI 440.2R-17 [10]. In addition to that, the Canadian Standards Association (CSA-S806-02/CHBDC-2006), the Japan Society of Civil Engineers (JSCE 1997), the Norwegian Standard for Design of concrete structures (NS3473), and the Institution of Structural Engineers, UK (IStructE) have also developed design equations and guidelines for shear strengthening of RC structures using FRP. However, almost all these design equations are highly conservative which would potentially lead to costly and uneconomical designs. The National Cooperative Highway Research Program (NCHRP) report 678: Design of FRP systems for strengthening concrete girders in shear [11] summarizes all the design codes available.

Most previous studies have adopted non-linear statistical analyzes on limited experimental results to develop various design equations for RC elements strengthened with FRP in shear. Matthys [12] has derived equations to estimate the

effective FRP strain using the curve fitting method which can then be used to calculate the shear contribution of FRP. Colotti and Spadea [13] have developed equations using the truss model concept. Based on the equilibrium of forces in a cross-section of a beam at failure, Pellegrino and Moderna [14] have obtained a theoretical equation for effective FRP strain. Nehdi et al. [15], [16], and Kara [17] have taken a genetic algorithm approach whereas Hosseini and others [18], [19], [20], [21] have adopted machine learning and neural networks. Anvari et al. [22] have also used an evolutionary machine learning approach, named genetic expression programming. Shahnewaz and Alam [23] have proposed a genetic algorithm approach for predicting the shear strength of steel fiber RC (SFRC). These studies have proven to predict superior results as compared to the current design guidelines available. Furthermore, Lima and Barros [3], and Zhou et al. [24] have carried out reliability-based design analyzes of FRP shear-strengthened RC beams. Although there has been a lot of experimental and analytical research on this topic, it is still difficult to precisely determine the shear capacity of RC beams on their own. Therefore, the main objective of this study is to utilize a comprehensive database to develop a model that better predicts the shear strength of FRP-strengthened RC beams. Belarbi et al. [25] have developed a database summarizing 50 experiments that led to 375 experimental results that have been done from 1992 to 2009. This is an extension of that work which was originally presented by Triantafillou and Antonopoulos [4] and later updated by Bousselham and Chaallal [26]. The database was developed by reviewing 68 experimental studies resulting in 744 experimental data that were available in the literature.

2. Shear Design Guidelines

The current design code available in the United States for the shear strengthening of RC beams using FRP is the ACI 440.2R-17 [10]. The nominal share strength V_n of a member strengthened with FRP multiplied by a strength reduction factor ϕ should exceed the required shear strength, as per the Eqs. (1)-(2) given in ACI 318-19 [27]. The nominal shear strength is the accumulation of contributions from concrete, V_c, transverse steel reinforcement, V_s, and externally bonded, V_{frp}. Three types of techniques are considered in applying externally bonded FRP in the design code, namely complete wrap, U-wrap, and side-wrap. Depending on the technique used, the shear contribution from FRP, V_{frp} should further be multiplied by a strength reduction factor $\psi_f = 0.95$ for complete wrap members and $\psi_f = 0.85$ for U-wrap (3 sides) and side wrap (2 opposite sides) members. This method of direct addition or rather superposition of shear components is based on the truss model with a shear crack angle of 45 degrees. However, Colotti and Spadea [13] mentioned that this leads to an underestimation of the shear strength of RC beams:

$$\phi V_n \geq V_u \tag{1}$$
$$\phi V_n = \phi\left(V_c + V_s + \psi_f V_f\right) \tag{2}$$

where, V_n is the nominal shear strength of the beam, V_u is the required shear strength. Eq.(3) given in ACI 440.2R-17 for calculating the shear contribution from FRP is adopted from Khalifa et al.[5].

$$V_{frp} = \frac{A_{fv}E_f\epsilon_{fe}(\sin\alpha+\cos\alpha)d_{fv}}{s_f} \tag{3}$$

where, V_{frp} is the shear contribution from FRP, A_{fv} is the cross-section area of FRP, E_f is the modulus of elasticity of FRP, ϵ_{fe} is the FRP effective strain, α is the angle of orientation of FRP, d_{fv} and s_f are the effective depth and spacing of FRP, respectively. The most critical variable in estimating the shear contribution from FRP, V_{frp} is the effective strain, ϵ_{fe}. The failure mode of both the FRP system and the strengthened RC member determines the maximum strain that can be achieved in the FRP system at the nominal strength, which is known as the effective strain in FRP laminates, ϵ_{fe}. The effective strain, ϵ_{fe} is typically lower than the ultimate strain ϵ_{fu}, because of strain changes along the shear fracture, local debonding on either side along the shear crack, or potential bond failure. Generally, the experimental values obtained for ϵ_{fe} are only approximate. On the other hand, the interaction of the effective strain, ϵ_{fe} with concrete and transverse reinforcement, V_s cannot be neglected. Furthermore, when calculating the shear contribution from the

transverse reinforcement, it is assumed that they have yielded; however, in reality, this may not always be the case when additional FRP is applied, and the beam fails prematurely due to the debonding of FRP. The equations and the method provided in the ACI 440.2R-17 overestimate the shear contribution from transverse reinforcement, do not consider the interaction between the concrete, steel, and FRP, and therefore, underestimate the shear contribution from FRP [14].

3. Database Used for this Study
3.1. Formation of the Database

The most significant aspect of this study is the database that was created to capture data on the shear strengthening of RC beams using FRP spanning from 1992 to 2022. This resulted in 744 test data. For each test data, experimental details were recorded under 25 categories: beam shape, span-to-depth ratio, FRP type, compressive strength of concrete, type of compressive strength test (cylinder/cube), width of the beam, the effective depth of the beam, area of longitudinal reinforcement, yield strength of transverse reinforcement, area of transverse reinforcement, spacing, and transverse reinforcement ratio. In relation to FRP, width, thickness, effective depth, number of wraps, spacing, reinforcement ratio, angle of primary fiber direction, modulus of elasticity, tensile strength, and wrapping scheme were recorded. In addition to that, the ultimate shear force at failure, the contribution of FRP to the overall shear strength, and the failure mode of each beam was recorded.

As in any data collection process, biases can be expected as well. Therefore, steps were taken to refine the database. There were few potential sources of bias in the dataset. To ensure that the dataset is free from sampling bias, beams that have FRP stirrups or FRP bars as longitudinal reinforcement were omitted as this study is only focused on externally bonded FRP for shear strengthening. Prestressed and post-tensioned beams were not considered. In addition, beams with circular holes/openings and inverted T beams were also removed. Beams that were constructed with fiber-mixed concrete and beams with FRP or mechanical anchorage were also omitted. Experiments that were carried out with impact loading in place of static loading were also removed. All these test data were underrepresented compared to the complete dataset. Moreover, in certain literature, key experimental data that was of interest in this study have not been recorded. In such cases, attempts were made to calculate missing data from the data that is already available. However, in cases where missing data were not able to be retrieved by any method, such test data were removed.

After a thorough process of refining the raw data, the final dataset comprised 490 test data. Out of these 490-test data, 119 were T-beams and the rest were rectangular beams. The shear strength of 333 beams was improved using FRP. The number of beams shear strengthened with AFRP, CFRP, and GFRP were 25, 285, and 23, respectively. The number of beams that were completely wrapped, U-wrapped, and side-wrapped were 66, 185, and 82, respectively, while 157 were control beams. Beams that were wrapped with novel techniques were not included in this study as they were underrepresented. As far as previous literature is concerned, this can be considered as one of the most thorough databases recorded.

3.2. Significance of the Database

Out of the 490-test data, 157 were pertaining to control beams with no FRP strengthening. The remaining 333 test data provided information on beams strengthened in shear with FRP. Three types of FRP were considered namely, Aramid, Glass, and Carbon. However, 285-test data pertaining to CFRP were only considered in this study. The data was further divided, depending on the wrapping scheme: completely wrapped, U-wrapped, and side-wrapped. Before performing detailed analyses, the data was further divided based on the provision of transverse reinforcement. A detailed overview of each set of data with FRP for shear strengthening is shown in Table 1.

Table 1: Detailed database of shear strengthening using FRP

Beam shape	Wrapping scheme	Provision of stirrups	Failure modes
Rectangular (223)	C (40)	WS (27)	R (16) and O (11)
		W/OS (13)	D (1), R (5), and O (7)
	U (112)	WS (57)	D (54) and O (3)
		W/OS (55)	D (30), R (8), and O (17)
	S (71)	WS (40)	D (29) and O (11)
		W/OS (31)	D (28), R (1), and O (2)
T-beam (62)	C (0)	WS (0)	-
		W/OS (0)	-
	U (60)	WS (38)	D (11), R (11), and O (16)
		W/OS (22)	D (10), R (7), and O (5)
	S (2)	WS (1)	D (1)
		W/OS (1)	D (1)

Note 1: C=complete wrap, U=U-wrap, and S=side wrap
Note 2: WS=with stirrup, W/OS = without stirrup
Note 3: D=Debonding, R=Rupture, and O=Shear and other modes of failure
Note 4: The number in parenthesis represents the number of beams in each category

The descriptive statistics of each category of data are presented in Table 2. Here, f_c' is the concrete compressive strength, t_f is the thickness of FRP, w_f is the width of FRP, d_f is the effective depth of FRP, s_f is the spacing of FRP, E_{frp} is the modulus of elasticity of FRP, f_{fu} is the tensile strength of FRP, ρ_f is the reinforcement ratio of FRP, ε_{fe} is the effective strain of FRP, b_w is the width of the concrete beam, d_{ef} is the effective depth of the beam, ρ_s is the longitudinal reinforcement ratio, $\frac{a}{d}$ is the shear span to effective depth ratio, f_{yv} is the yield strength of transverse reinforcement, A_v is the area of transverse reinforcement, s_v is the transverse reinforcement spacing, s_f is the transverse reinforcement ratio, α is the angle of primary fiber direction, V_u is the ultimate shear force, and V_{frp} is the shear contribution from FRP.

Eq. (3) indicates that determining the effective FRP strain is crucial for predicting the shear contribution of the external FRP reinforcement. The crack opening along the shear crack, local FRP debonding on both sides of the shear crack, the development length of FRP, which depends on the bond at the FRP-concrete interface, and the axial rigidity of FRP all play a role in the estimation of this strain [16]. The effective strain, ϵ_{fe} is therefore calibrated using a function of $\frac{\rho_f E_f}{f_c'^{2/3}}$ which indicated a power function as shown in Figure 1 (inclusive of first and third quartiles). Initially, a correlation analysis was run for the full dataset which indicated that out of all 3 wrapping schemes considered, complete wrapping is the most efficient, while the two-side wrapping is the least efficient. Therefore, it was decided to analyze complete wrap, U-wrap, and side-wrap schemes separately. This analysis further indicated an inverse correlation between the shear contribution from FRP and the transverse steel ratio, which further supports the fact that as the transverse reinforcement is increased, the effect of FRP on shear contribution becomes less [15]. In particular, the dataset of beams strengthened using the u-wrap scheme, which was also reinforced with stirrups, was used to study the correlation in depth between the variables in consideration concerning the effective strain, ϵ_{fe} as it is the largest sample data set available.

Table 2: Descriptive statistics of the input parameters

Parameter	Min.	Max.	Mean
f_c' [MPa]	11	57	31
t_f [mm]	0.05	25	0.46
w_f [mm]	1	800	98.55
d_f [mm]	85	1028	289
s_f [mm]	1	800	141.73
E_{frp} [GPa]	5.3	390	196.3
f_{fu} [MPa]	106	4902	3152
ρ_f	0.000138	0.17	0.0053
ϵ_{fe} [mm/mm]	-0.00013	0.049	0.0053
b_w [mm]	63.5	600	181
d_{ef} [mm]	85	1028	317
ρ_s	0	18.72	3.03
f_{yv} [MPa]	0	653	240
A_v [mm^2]	0	142	40
s_v [mm]	0	800	148
ρ_v	0	0.011	0.0013
α	0	90	80
V_u [kN]	18.8	1584.5	226.1
V_{frp} [kN]	-0.98	492.9	74.5

The parameters which had the most significant correlation with the effective strain, ϵ_{fe} of FRP are shown in the correlation plot in Figure 2. The model error of current ACI 440.2R-17 concerning the experimental results obtained in terms of the shear contribution from FRP were measured using $\mu = \frac{V_{f,exp}}{Vf,ACI}$ which resulted in 1.5 for rectangular beams and 0.66 for T-beams respectively. The variation of model error is further shown in Figure 3.

4. Proposed Model

The correlation analysis in Figure 2 revealed that the compressive strength of concrete $f'^{2/3}_c$ has a positive correlation with effective strain, ϵ_{fe} while longitudinal steel ratio ρ_s, transverse steel ratio ρ_v, FRP ratio ρ_f, and modulus of elasticity of FRP, all have a negative correlation with ϵ_{fe}. With the scatter plots obtained for effective strain, ϵ_{fe} along with the variables in consideration that indicated a power function, it was evident that the data calls for a non-linear regression analysis. With the influence of the studies done by Pellegrino and Modena [14] and Nehdi and Nikopour [16], since the distribution of the data was generally known, it was decided to derive a custom equation based on experimental data fitting in the form of Eq. (4) to find the coefficients that provide the best fit. The coefficients C$_1$ and C$_2$ are unknown. An exponential curve fitting method in the commercially available software MATLAB 2023 version was used for this purpose. A similar approach was taken for the side wrapping and complete wrapping schemes as well. For beams without transverse reinforcement, Eq. (5) was considered:

$$\epsilon_{fe} = C_1 \left(\frac{f'^{2/3}_c \frac{a}{d}}{\rho_s \rho_v \rho_f E_f} \right)^{C_2} \tag{4}$$

$$\epsilon_{fe} = C_1 \left(\frac{f'^{2/3}_c \frac{a}{d}}{\rho_s \rho_v E_f} \right)^{C_2} \tag{5}$$

While the preceding formulae for effective strain, ϵ_{fe} do not explicitly consider the strain distribution along the shear fracture and the FRP bond behavior, they have the advantage of avoiding complicated expressions that would otherwise be provided by methods such as genetic algorithms or machine learning. The results for ϵ_{fe} obtained from the above equations were used to calculate the shear contribution from FRP as given in Eq. (6). Moreover, it is interesting to note the dependency of the effective strain of FRP, ϵ_{fe} on transverse steel ratio and longitudinal steel ratio and not just on the stiffness of FRP, $\rho_f E_f$ (refer to Figure 2). This prevails the importance of considering the interaction of FRP
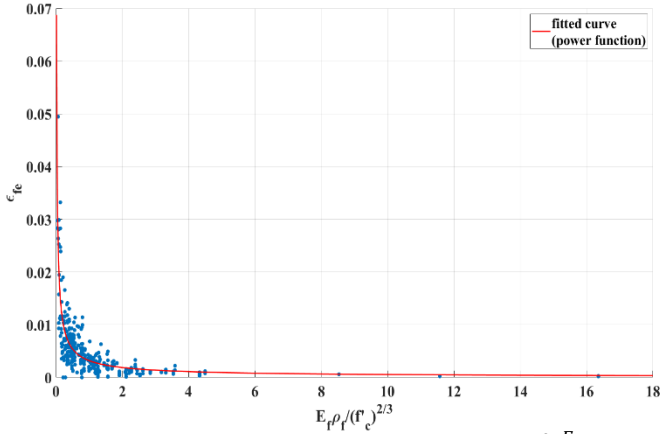

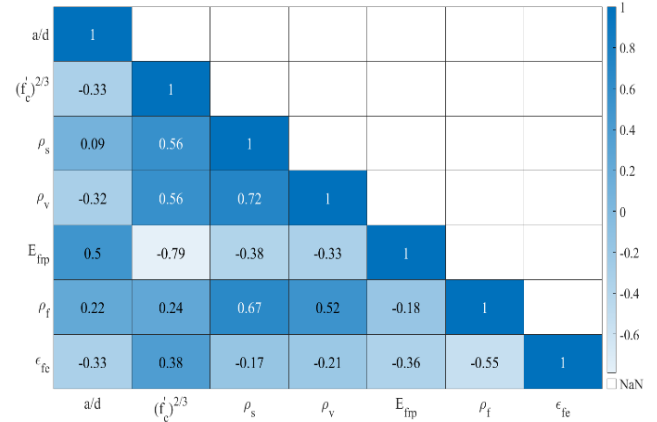Fig. 1: Power function variation of ϵ_{fe} vs. $\frac{\rho_f E_f}{f'^{2/3}_c}$

Fig. 2: Correlation between input parameters in beams shear strengthened using CFRP (U-wrap)

with concrete, longitudinal, and transverse reinforcement when investigating the behavior of shear. The estimated new effective strain values were then used to calculate the shear contribution of FRP as shown in Eq. (6).

$$V_{frp} = \frac{A_{fv}E_f\epsilon_{fe,estimated}(sin\alpha+cos\alpha)d_{fv}}{s_f} \tag{6}$$

5. Results and Discussion

Since the database contained different types of FRP sheets, initially, the ratio $R = \frac{\epsilon_{fe}}{\epsilon_{fu}}$ was considered to examine the percentage of effective strain, ϵ_{fe} with respect to the ultimate strain of FRP, ϵ_{fu} which should ideally be ≤ 1, assuming any unrealistic data has been omitted already during the database refining process. The resulting ratios obtained are shown in Table 3. For both U-wrap and side-wrap schemes, the results indicate that beams with stirrups have reached a lesser effective strain compared to beams without stirrups. As mentioned before, this provides more evidence that the impact of FRP on shear contribution decreases as transverse reinforcement is increased. However, for the complete wrap scheme, beams with stirrups have reached a higher effective strain as compared to beams without stirrups. This could be due to the fact that the complete wrap scheme has a higher force transfer zone on either side of the shear crack, which is the development length of FRP and, therefore, precedes stirrups in shear resistance. Moreover, complete wrapping schemes indicate higher effective strain, ϵ_{fe} overall. It is apparent that FRP wrapping configuration significantly influences the shear strengthening and closed-shaped/complete wrapping schemes are likely to provide higher failure loads. The coefficients C_1 and C_2 found for each CFRP-wrapping scheme are given in Table 3. It is important to note that the results obtained from this analysis are based on U.S. customary units. The available data on AFRP and GFRP were insufficient to perform the analyses. The final strain level in the FRP sheets corresponds to the coefficients C_1 and C_2. For beams with transverse reinforcement strengthened using CFRP, evidently, the complete wrap scheme has the highest C_1 and lowest C_2 whereas the side wrap scheme has the lowest C_1 and highest C_2. This means that the complete wrap scheme reaches closer to its ultimate strain therefore, ultimate capacity provides better efficiency compared to the U-wrap and side wrap bond applications. However, this is not the case for beams without transverse reinforcement

strengthened using CFRP. Complete wrap application has the lowest C_1 and C_2 whereas side wrap application has the highest C_1 and C_2. It is also interesting to note that the C_2 coefficient for the complete wrap scheme indicates an inverse relationship. On average, the proposed model for ϵ_{fe} well agrees with the experimental results for all the wrapping schemes of rectangular beams and U-wrapping schemes of T-beams respectively. With the new estimated effective FRP strains, the new shear contribution from FRP, V_{frp} was calculated and compared against the experimental values, which indicated a similar variation as the estimated effective FRP strain, ϵ_{fe}. The stirrups' ability to yield or not, however, could not be determined because the shear contribution from transverse reinforcement was not available. This prevented a comparison of the experimental and estimated ultimate shear forces, which are the result of the sum of the shear contributions from the concrete, transverse reinforcement, and FRP.

Table 3: Values for R, C1, and C2 obtained to estimate ϵ_{fe}

			$R=\dfrac{\epsilon_{fe}}{\epsilon_{fu}}$	C_1	C_2
Rectangular beams	C	WS	52 %	0.27	0.10
		W/OS	41 %	0.41	-0.04
	U	WS	26 %	0.04	0.32
		W/OS	30 %	0.40	0.56
	S	WS	15 %	0.002	0.71
		W/OS	16 %	0.32	0.69
T-Beams	U	WS	22 %	0.07	0.22
		W/OS	32 %	0.32	-0.02

Note 1: C=complete wrap, U=U-wrap, and S=side wrap
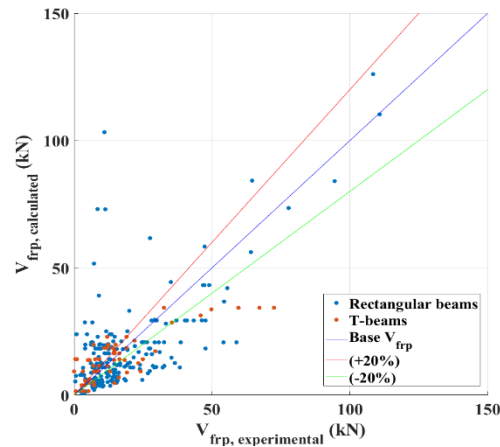Note 2: WS=with stirrup, W/OS = without stirrup

Fig. 3: Calculated V_{frp} (ACI 440.2R-17) vs. experimental V_{frp}

Furthermore, these new results were compared against the design codes available to investigate the applicability of the proposed equations (see Table 4). For each wrapping scheme, the mean, and the standard deviation between the ratio of $\dfrac{V_{frp,exp}}{V_{frp,calc}}$ were calculated and tabulated in Table 4. As far as design codes are concerned, the ACI 440.2R-17 and, Canadian Standards Association (CSA-S806-02/CHBDC-2006) [28] were considered in this analysis. Both codes don't consider the interaction between RC, transverse reinforcement, and FRP when estimating the shear contribution of FRP. Compared to the ACI 440.2R-17, the proposed equations based on data fitting provide comparatively better results. The deviation of the results is also relatively low in the proposed method as compared to the ACI 440.2R-17. Especially for the complete wrap scheme, this is significantly low, while for the side wrap scheme, this may not be the case.

Evidently, the side wrap scheme should be further investigated, and the design equations provided in the ACI 440.2R-17 ought to be revised. Both ACI 440.2R-17 and CSA-S806-02 underestimate the contribution from FRP in the complete wrap scheme.

Table 4: The study's performance considerations for the shear design equations

Method	Complete wrap				U-Wrap				Side wrap			
	With transverse reinforcement		Without transverse reinforcement		With transverse reinforcement		Without transverse reinforcement		With transverse reinforcement		Without transverse reinforcement	
	$\dfrac{V_{frp,exp}}{V_{frp,calc}}$		$\dfrac{V_{frp,exp}}{V_{frp,calc}}$		$\dfrac{V_{frp,exp}}{V_{frp,calc}}$		$\dfrac{V_{frp,exp}}{V_{frp,calc}}$		$\dfrac{V_{frp,exp}}{V_{frp,calc}}$		$\dfrac{V_{frp,exp}}{V_{frp,calc}}$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Proposed Equations	1.00	0.41	1.00	0.44	1.02	0.48	1.01	0.45	1.11	0.97	1.01	0.59
ACI 440.2R-17	2.01	0.86	1.65	0.80	1.29	0.60	1.20	0.93	0.98	0.97	-0.06	4.78
CSA S806-02	1.63	1.21	1.66	0.86	0.66	0.47	0.82	0.47	0.92	0.98	0.45	0.35

For the side wrap scheme, both codes overestimate the results with a higher scatter of results for beams with transverse reinforcement. In contrast, beams without transverse reinforcement are greatly overestimated. Perceptibly, beams shear reinforced using the side wrap scheme need much more investigation. In the U-wrap scheme, ACI 440.2R-17 underestimates results by about 20%-30%, and CSA-S806-02 overestimates this by a similar percentage.

7. Conclusion
Based on the data fitting method, this study developed shear design equations for FRP-RC beams with and without FRP stirrups. Results for shear strength computed using the suggested equations are in good agreement with the experimental findings in the database considered. When compared to the majority of research, which has developed complex equations utilizing various statistical methodologies, such as machine learning, etc., these equations are significantly more straightforward and simplistic. Conclusively, the following summary can be made:
1. Through this study, an extensive repository containing 490 test data relevant to RC beams shear strengthened utilizing FRP was created. This database underwent a rigorous refining process. When compared to preceding publications, this could be regarded as one of the most comprehensive databases yet created.
2. The two-sided wrapping is the least efficient, according to the correlation study carried out using the database, while the complete wrapping is the most efficient.
3. This analysis also revealed an inverse relationship between the shear contribution from FRP and the transverse steel ratio, further demonstrating that the effect of FRP on shear contribution decreases as transverse and longitudinal reinforcement are increased. On the other hand, completely wrapped shear-strengthened beams without stirrups showed higher effective strain than beams with transverse reinforcement. This may be taken into account given that transverse reinforcement is preceded in shear resistance by the complete wrap FRP-strengthening design, since it has a higher force transfer zone on each side of the shear crack. Complete wrapping methods, however, generally show higher effective strain and are hence likely to produce higher failure loads.
4. To optimize the equations for the shear design of FRP-RC beams, the curve fitting approach can be a useful tool. The results obtained from the analysis are in good agreement with experimental results.
5. The suggested equation shows how the FRP effective strain, ϵ_{fe} is dependent on the compressive strength of the RC, the FRP's axial stiffness, the transverse reinforcement, and the longitudinal reinforcement. The ACI 440.2R-17, however, does not consider this. When assessing the performance of RC beams shear enhanced using FRP, it is crucial to take this interaction between the parts into account.
6. The current ACI 440.2R-17 code exhibited poor performance compared to the equations proposed in this study developed using the curve fitting method. However, the proposed technique should be further examined for the side wrap scheme in beams with transverse reinforcement because it greatly increased the standard deviation of the results

for the predicted shear contribution of FRP. The Canadian standard (CSA-S806-02/CHBDC-2006) investigated in this study behaves in a similar manner.

7. It is recommended that AFRP and GFRP be added to the database of experimental findings for shear strengthening utilizing CFRP in order to conduct a more thorough analysis and produce optimized equations.

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