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ORIGINAL ARTICLE

Proposal and evaluation of new models for predicting the FRP contribution to shear strength in reinforced concrete beams using gene expression programming

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Abstract

Fiber-reinforced polymers (FRP) have been widely used in shear strengthening applications of reinforced concrete (RC) beams. The accurate prediction of the FRP contribution to the shear strength of beams is essential for reliable design. Gene expression programming (GEP) has been widely utilized because it reliably expresses complex relationships between experimental variables. In this study, three new GEP models are proposed for three different strengthening configurations of FRP such as fully-wrapping, *U* wrapping, and side-bonding to predict the FRP contribution to shear strength. These models are developed using the most comprehensive database containing a total of 811 strengthened beams (350 fully-wrapped, 328 *U*-wrapped, and 133 side-bonded. Many variables have been considered in the proposed GEP models, including those that have been experimentally effective but are often neglected in existing literature equations, such as the shear span-to-effective depth ratio (a/d) and the stirrup ratio (ρ_w). Additionally, the reliability of existing equations in the literature and the proposed GEP models for predicting the FRP contribution to shear strength was statistically evaluated. As a result of this evaluation, the proposed GEP models for each strengthening configuration of FRP yielded the most accurate statistical results, with the lowest coefficient of variation (COV), and the highest coefficient of correlation (*R*).

Keywords FRP · Shear strength · Reinforced concrete · Beams · Gene expression programming

Abbreviations

COV	Coefficient of variation
ET	Expression tree
GEP	Gene expression programming
FEM	Finite element model
FRP	Fiber-reinforced polymers
M	Mean value
MAPE	Mean absolute percentage error
R	Coefficient of correlation
RC	Reinforced concrete
RMSE	Root-mean-square error
SD	Standard deviation

List of symbols

b_w	Beam width (mm)
f_c	Concrete compressive strength (MPa)
V_f	Contribution of FRP to the shear strength (kN)
d	Effective depth of beam (mm)
d_{fe}	Effective depth of FRP (mm)
ρ_f	FRP reinforcement ratio
t_f	FRP thickness (mm)
E_f	Modulus of elasticity (GPa)
a/d	Shear span-to-effective depth ratio
w_f/s_f	Shear strip width-to-spacing ratio
ρ_w	Stirrup ratio
ε_{fu}	Ultimate strain
f_{yw}	Yield strength of stirrups (MPa)

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1 Introduction

The strengthening of reinforced concrete (RC) structures to achieve the required performance is a widely preferred method. Recently, the strengthening method using fiber-reinforced polymer (FRP) has become popular in both academic studies and projects. FRP, an alternative composite material, is favored for strengthening structural elements such as columns, beams, and slabs due to its superior properties, including corrosion resistance, resistance to various chemicals, high strength-to-weight ratio, ease of application, and high tensile modulus. RC beams with insufficient shear strength could be strengthened using FRP by mainly four different strengthening configurations including fully-wrapped, *U*-wrapped with anchoraged, *U*-wrapped, and side-bonded.

Many previous experimental [1–137], analytical [3, 36, 82, 119, 123, 131, 138, 139], and statistical [140–144] studies were conducted on FRP-strengthened beams in shear. Li and Leung [6, 91] and Sengun and Arslan [35, 36] elaborately investigated the effect of a/d on the RC beams strengthened with various FRP configurations. Accordingly, it was stated that a/d affects the FRP contribution to shear strength by altering the angle of the shear crack and the load-carrying mechanism of beam. Therefore, a/d should be taken into account in the analytical equations. Bousselham and Chaallal [145] stated that the increase in shear capacity of the beams was limited by the increase in FRP reinforcement ratio (ρ_f) in slender beams. However, no significant increase in shear capacity was observed in deep beams. The size effect on the shear strength of beams strengthened with FRP was experimentally examined by Godat et al. [4] and Benzeguir et al. [146]. Godat et al. [4] concluded that the effect of FRP decreased as the effective depth of beam (d) and the beam width (b_w) increased. Benzeguir et al. [146] demonstrated that the size effect was more prominent in the FRP-strengthened beams without stirrups. The shear strip width-to-spacing ratio (w_f/s_f) was one of the important variables effective on the behavior of the FRP-strengthened beams studied by various researchers [1, 2, 35, 36, 82]. Akkaya et al. [1, 2], Sengun and Arslan [35, 36], and Mofidi and Chaallal [82] pointed out that the FRP contribution to the shear strength of the beam increased as the spacing between the FRP strips decreased. Mofidi and Chaallal [82] emphasized that variable (w_f/s_f) was not considered in the proposed equations. However, they suggested that it should be included. Additionally, several experimental studies indicated [16, 35–37, 121, 145] that the increase in the stirrups ratio (ρ_w) was inversely proportional to the increase in the FRP contribution to shear strength. It was stated by various researchers [74, 119, 147–152] that the contribution of FRP to the shear strength depended on (ρ_f), FRP thickness (t_f) and the concrete compressive strength (f_c).

The effect of FRP type on the shear behavior of beam was studied by Cao et al. [8] and Baggio et al. [57]. Chen and Teng [138, 139] expressed that there were mainly two different failure modes named as FRP debonding and rupture depending on the FRP strengthening configuration and proposed equations to calculate the FRP shear contribution for each of these failure modes considering effective FRP strain. The effects of different variables on the prediction accuracies of the equations were statistically analyzed by Kar and Biswal [140]; Kotynia et al. [141]; Lima and Barros [142]; Oller et al. [143]; Pellegrino and Vasic [144]. It was stated by Oller et al. [143] that the accuracies of the predicted equations were lower in the beams with stirrups. Kar and Biswal [140] concluded that (1) the experimental FRP shear contribution increased for the specimens without stirrups by the increase in beam depth; (2) the strengthening efficiency of the external strengthening system increased with an increase in *a*/*d* ratio, whereas the prediction accuracies of different design guidelines for the prediction of FRP shear contribution become lower with an increase in a/d ratio.

Researchers widely employ various computational methods [153, 154] and intelligent design techniques, such as utilizing origami structures [155–157], for solving engineering problems. In addition, the use of artificial intelligence for solving engineering problems is increasing day by day. With the rapid development of technology, it has become preferable to utilize artificial intelligence in the construction industry due to its advantage of easily learning complex datasets and making predictions with high accuracy. Machine learning is a subset of artificial intelligence that can be used in many different engineering fields. Machine learning has become a main topic in recent publications [158–160]. Various machine learning approaches such as gene expression programming, random forest, support vector regression, multiple expression programming, Gaussian process regression, artificial neural networks, and adaptive neuro-fuzzy interface system have been frequently applied in modeling complex problems in structural engineering [161–164].

Gene expression programming (GEP) is one of the widely used machine learning programs. GEP is a genetic algorithm using populations to derive analytical expressions, taking into account the complex relationships between the relevant variables. Model outputs are easier to interpret and analyze in GEP method compared to other machine learning and nonlinear regression methods due to the tractability and adaptability. In addition, unlike other machine learning methods, the GEP method derives an equation by considering the complex relationships among different variables in the dataset. There are studies providing different GEP models for the calculation of shear strength, deflection, and strains of different structural components/materials using the GEP method

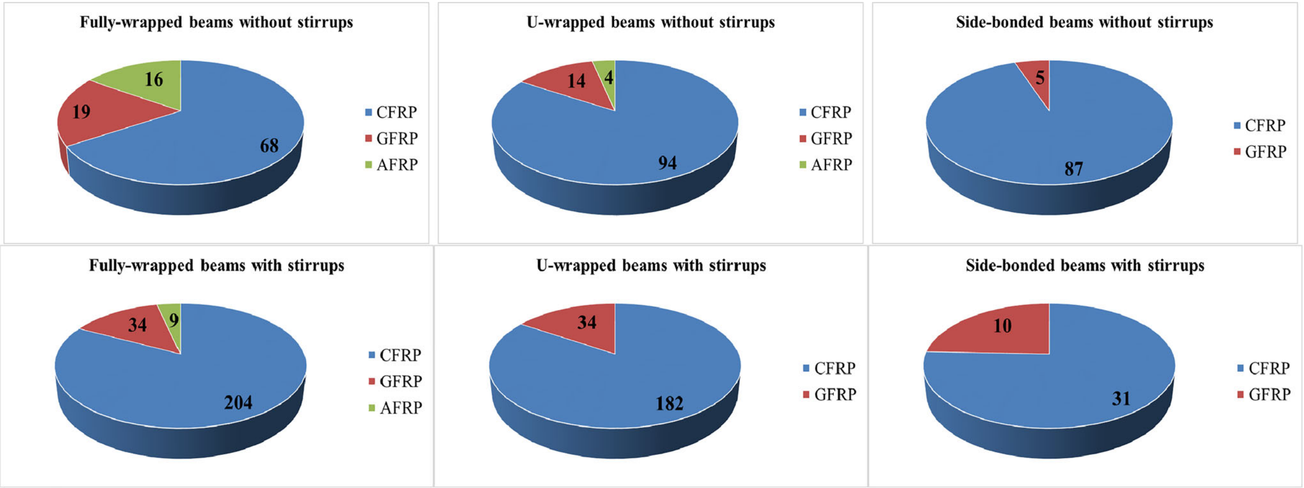


Fig. 1 The distribution of beams by FRP type

and examining the validity of these equations. Alshboul et al. [165], Gandomi et al. [166], and Kara [167] first determined the relevant input variables considering the previous experimental investigations conducted by various researchers on beams without stirrups and then gave an equation for the shear strength of beams without stirrups using the GEP method. Al-Ghrery et al. [168] dealt with the concrete cover separation on RC beams strengthened with FRP in flexure and proposed a model by using a total of 127 beams. Ism and Rabie [169] performed an experimental study to examine the flexural behavior of CFRP-strengthened beams and proposed an equation with the GEP method to calculate the rupture strain of FRP. Anvari et al. [170] gave a GEP model to calculate the total shear strength in RC beams strengthened with externally bonded FRP in shear and verified the validity of the model. The statistical results of the equations predicting the FRP contribution to shear strength carried out in the literature were discussed.

When previous experimental studies are evaluated, it could be expressed that the behavior of FRP-strengthened specimens varies significantly depending on many variables such as stirrups ratio (ρ_w), a/d, and the FRP reinforcement ratio (ρ_f). Furthermore, as the limited number of the statistical studies conducted using the limited number of the equations proposed to calculate the FRP contribution is analyzed, the predictions of the equations are not in good agreement with the experimental results. This is due to the fact that many important variables such as stirrups ratio (ρ_w) and a/d are not effectively taken into account in the proposed equations. Besides, the number of studies examining the FRP contribution using the extensive database by the GEP method is quite limited. The aim of this study is to propose equations that provide better predictions than those obtained using existing equations in the literature. Therefore, three different GEP models were proposed in this study using an extensive dataset containing a total of 811 specimens to determine the FRP contribution for each strengthening configuration. In the proposed models, a total of 12 variables whose effects have been shown experimentally have been tried to be effectively considered. The prediction accuracies of the different equations proposed in the literature to calculate the contribution of FRP to the shear strength were statistically evaluated and compared with the prediction results of the proposed GEP models.

2 Description of experimental database

Most of the experimental studies performed to date were attempted to be considered in collecting dataset. However, data quality is crucial for data mining projects. Some data may contain missing or incorrect values, which can negatively affect the accuracy and reliability of the model. Therefore, such corrupt or misleading data were removed from the datasets to increase the reliability of the models, their generalization ability, and the accuracies of the results. A database of 811 FRP reinforced beams with or without stirrups was considered in this study.

The database includes three different strengthening configurations such as fully-wrapped (350 beams), *U*-wrapped (328 beams), and side-bonded (133 beams). Since it is difficult to strengthen T-section RC beams with FRP due to the RC slabs, *U*-wrapped strengthening configuration with a proper anchoring system can be used in the strengthening applications. It is indicated in ACI 440.2R [171] that anchorage systems used in *U*-wrapped and side-bonded beams can result in higher FRP strains compared to *U*-wrapped and side-bonded configurations without anchorage. According to ACI 440.2R [171], the effective strain limits to account for the FRP contribution to shear

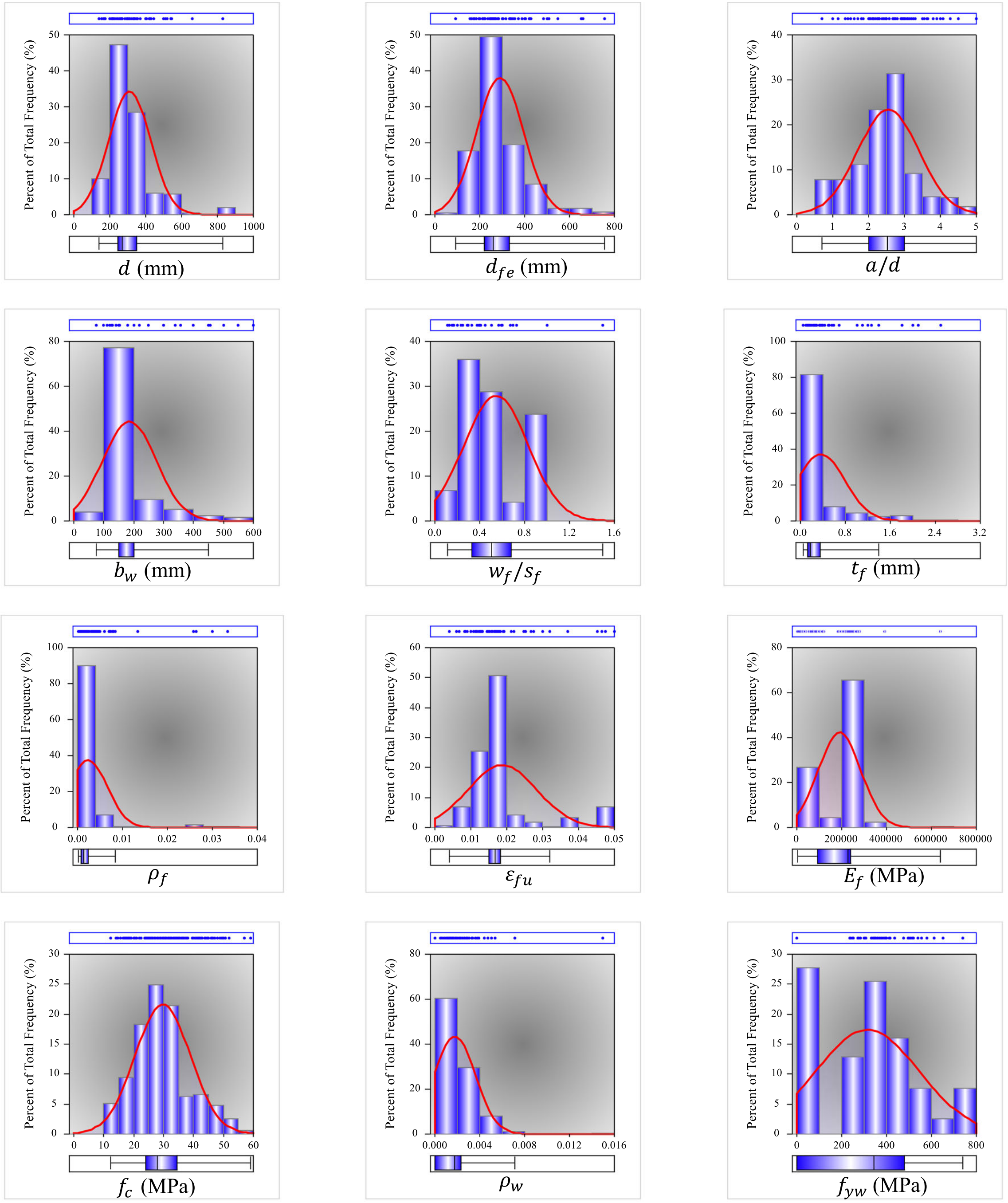


Fig. 2 Histograms of the input variables for fully-wrapped beams

strength in *U*-wrapped beams with anchored systems can be taken as the same as for fully-wrapped beams. In addition, fib TG 9.3 [172] has similar provisions regarding the calculation of the contribution of FRP to the shear strength for both fully-wrapped and anchored *U*-wrapped. Therefore, RC beams strengthened with anchored *U*-wrapped were considered as fully-wrapped beams to determine the contribution of FRP to the shear strength of the beam in this study. The number of beams in terms of FRP type in each strengthening configuration is given in Fig. 1. Test specimens where FRP strips were applied perpendicular to the beam axis were considered. Furthermore, 20 equations for fully-wrapped beams, 13 equations for *U*-wrapped beams, and 10 equations for side-bonded beams provided by various codes and researchers were statistically compared with the GEP equations.

The variables considered as input variables in GEP models are as follows: effective depth of beam (d), the

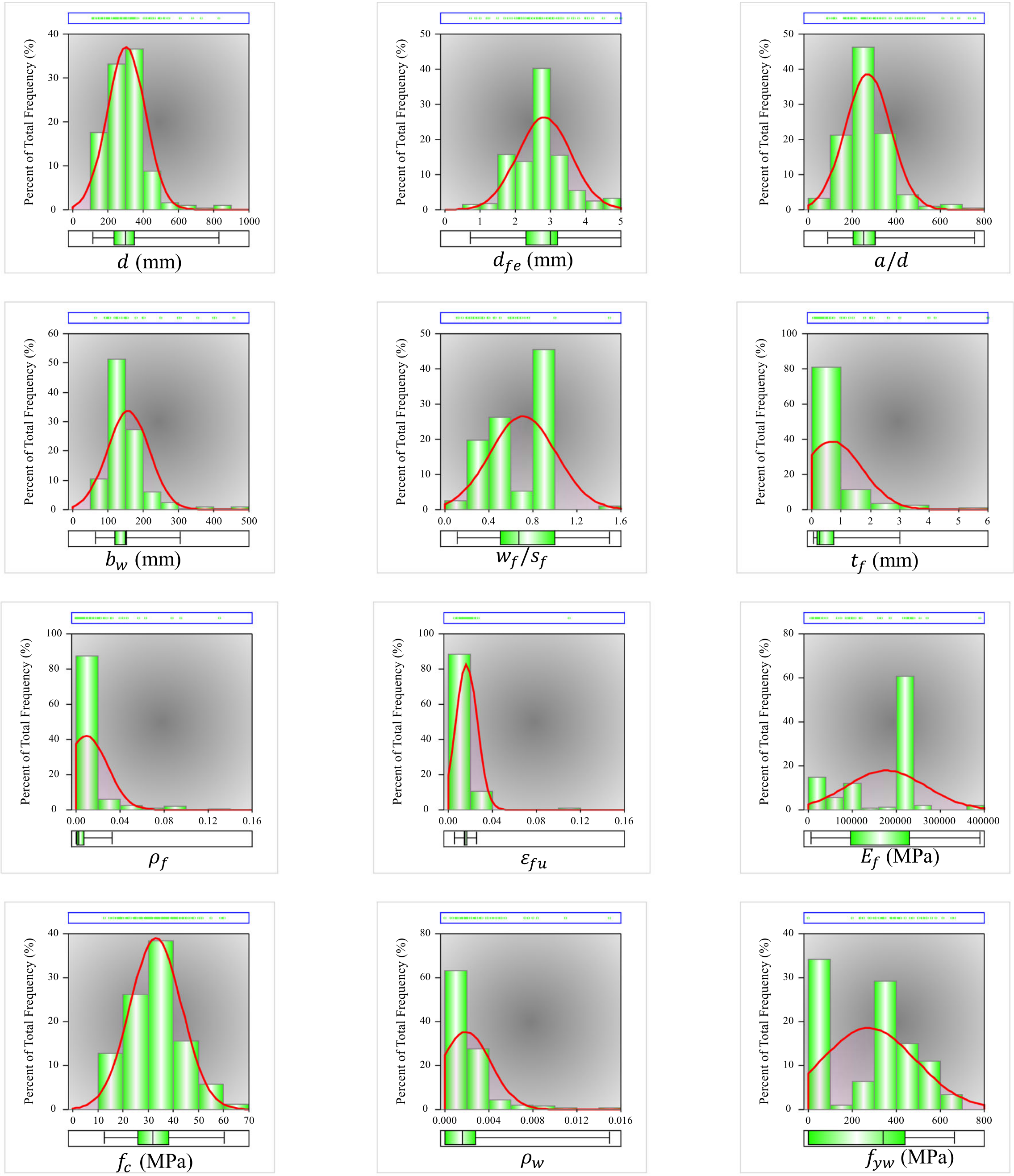


Fig. 3 Histograms of the input variables for *U*-wrapped beams

effective depth of FRP (d_{fe}), the shear span-to-effective depth ratio (a/d), the beam width (b_w), the FRP width-to-spacing ratio (w_f/s_f), the FRP thickness (t_f), the FRP reinforcement ratio (ρ_f), the ultimate strain ($\varepsilon_{\mathrm{fu}}$), the modulus of elasticity (E_f), the concrete compressive strength (f_c), the stirrups ratio (ρ_w), and the yield strength of stirrups (f_{yw}).

Within the scope of this study, the maximum and minimum values of each variable for references in the databases gathered to derive GEP models of three different strengthening configurations are given in Table A1-3. The histograms for all input variables were separately given for each strengthening configuration in Figs. 2, 3 and 4.

The rose diagrams of the input variables consisting of degrees of a circle to display the frequency of each class are presented in Fig. 5 for each strengthening configuration. Each spoke has a proportional length to indicate its quantity. θ, R bar, and v represent the mean direction, mean

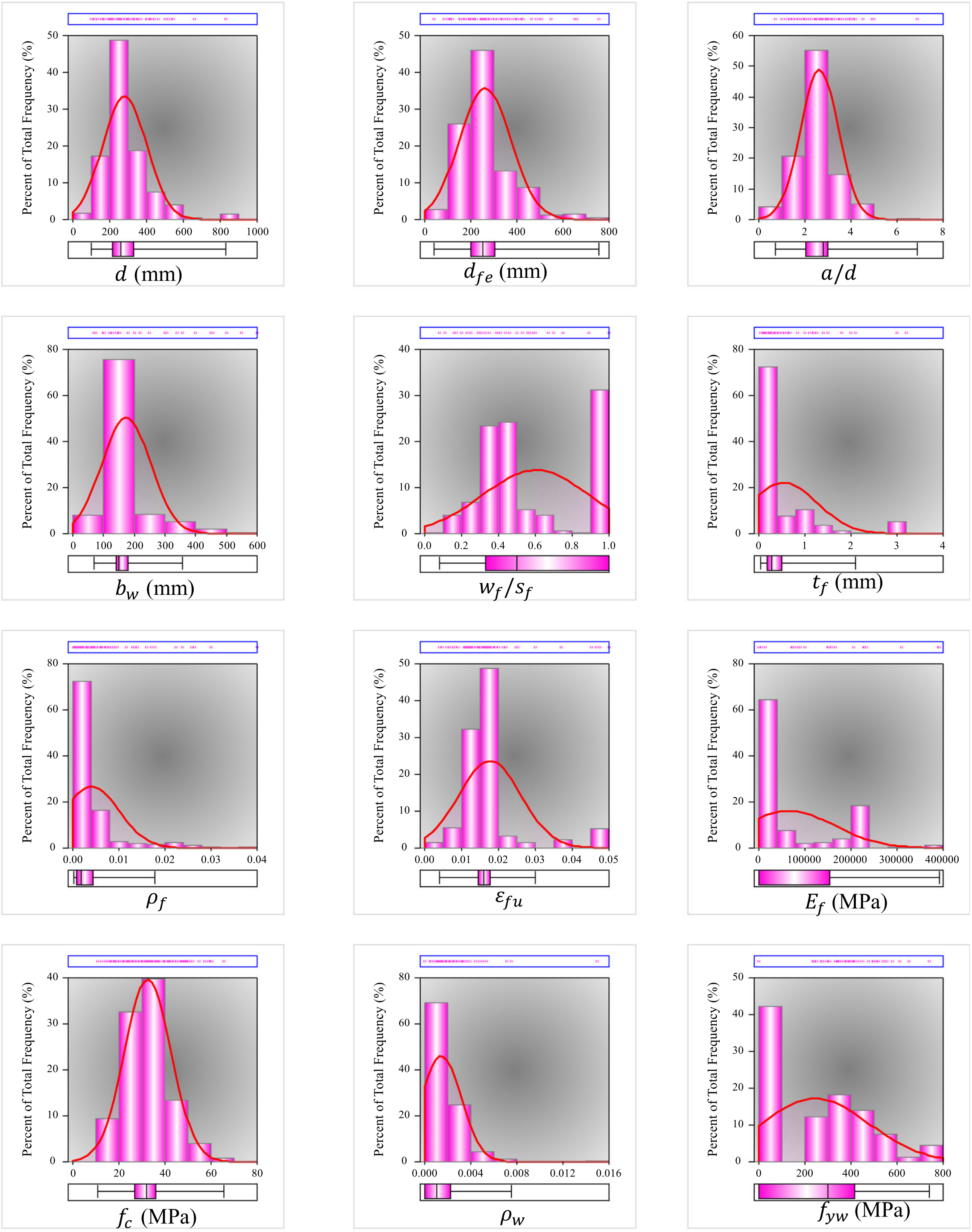
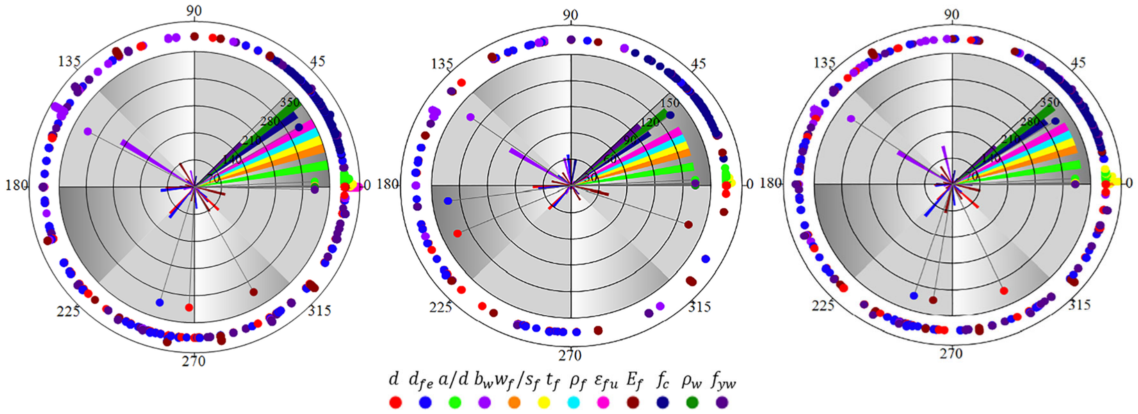


Fig. 4 Histograms of the input variables for the side-bonded beams

resultant length, and circular standard deviation in the rose diagrams. If the R bar is close to one, it indicates a high concentration. v also refers to the circular analog of the linear standard deviation. The summary of the statistical results of the rose diagrams is shown in Table 1 for each strengthening configuration separately.

Additionally, the Pearson correlation coefficients matrices were given as heat map in Fig. 6 to measure the linear correlation between the two variables for each strengthening configuration. The correlation coefficient could be different values between -1 and 1 and indicate the relationship between two variables in terms of force and

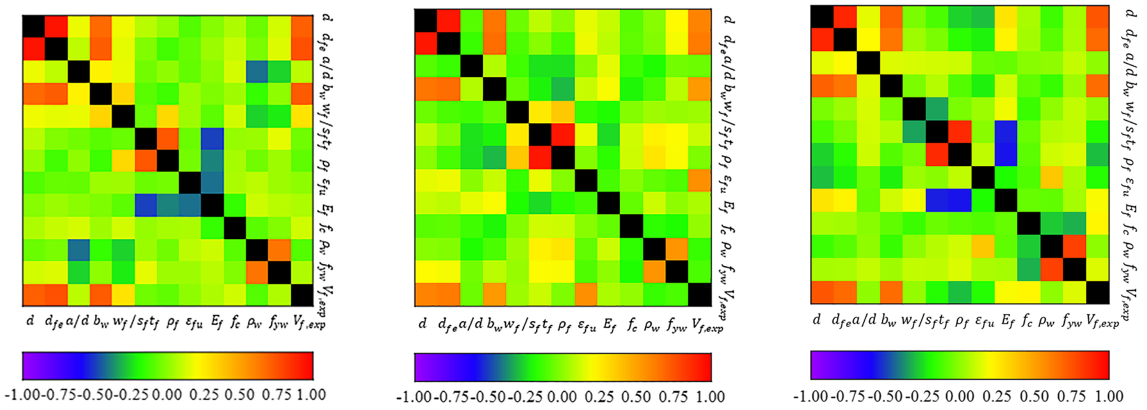


(a) Fully-wrapped (b) U-wrapped (c) Side-bonded

Fig. 5 Rose diagrams of the input variables

Table 1 Summary statistics of the rose diagrams

Statistics	Strengthening configuration	Variables											
		d	d_{fe}	a/d	b_{w}	w_f/s_f	t_f	ρ_f	$\varepsilon_{\mathrm{fu}}$	E_f	f_c	ρ_w	f_{yw}
Mean Direction (θ)	Fully-wrapped	267.44	253.21	2.550	152.52	0.55	0.36	0.0024	0.0201	299.48	29.71	0.0018	358.82
	U-wrapped	294.85	251.76	2.83	145.54	0.71	0.69	0.0094	0.0165	261.01	33.02	0.0019	0.0545
	Side-bonded	203.75	187.18	2.78	144.21	0.69	0.88	0.007	0.0160	340.89	37.03	0.0009	1.153
Mean Resultant Length (R bar)	Fully-wrapped	0.44	0.48	0.99	0.69	1	1	1	1	0.18	0.99	1	0.47
	U-wrapped	0.30	0.42	0.99	0.74	1	0.99	1	1	0.29	0.98	1	0.47
	Side-bonded	0.49	0.45	0.99	0.74	1	0.99	1	1	0.24	0.99	1	0.75
Circular Standard Deviation (v)	Fully-wrapped	72.96	69.76	0.85	49.42	0.29	0.43	0.0043	0.0103	105.59	9.19	0.0018	70.80
	U-wrapped	88.39	75.58	0.76	44.49	0.30	1.03	0.019	0.0097	90.69	10.19	0.0023	70.36
	Side-bonded	68.89	72.08	0.78	44.96	0.29	0.98	0.0073	0.0063	96.18	9.65	0.0016	43.81



Fully-wrapped beams U-wrapped beams Side-bonded beams

Fig. 6 Heat maps of the Pearson correlation matrix for each strengthening configuration

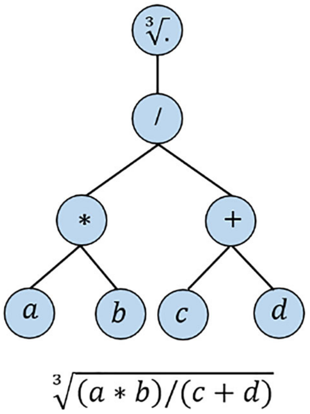


Fig. 7 The schematic representation of the expression tree of a chromosome [173]

direction. Positive values of correlation coefficients mean indicate a positive correlation between variables, and negative values indicate a negative correlation. In addition, the correlation coefficients close to zero demonstrate the poor relationship between the variables.

3 Derivation of equations with GEP

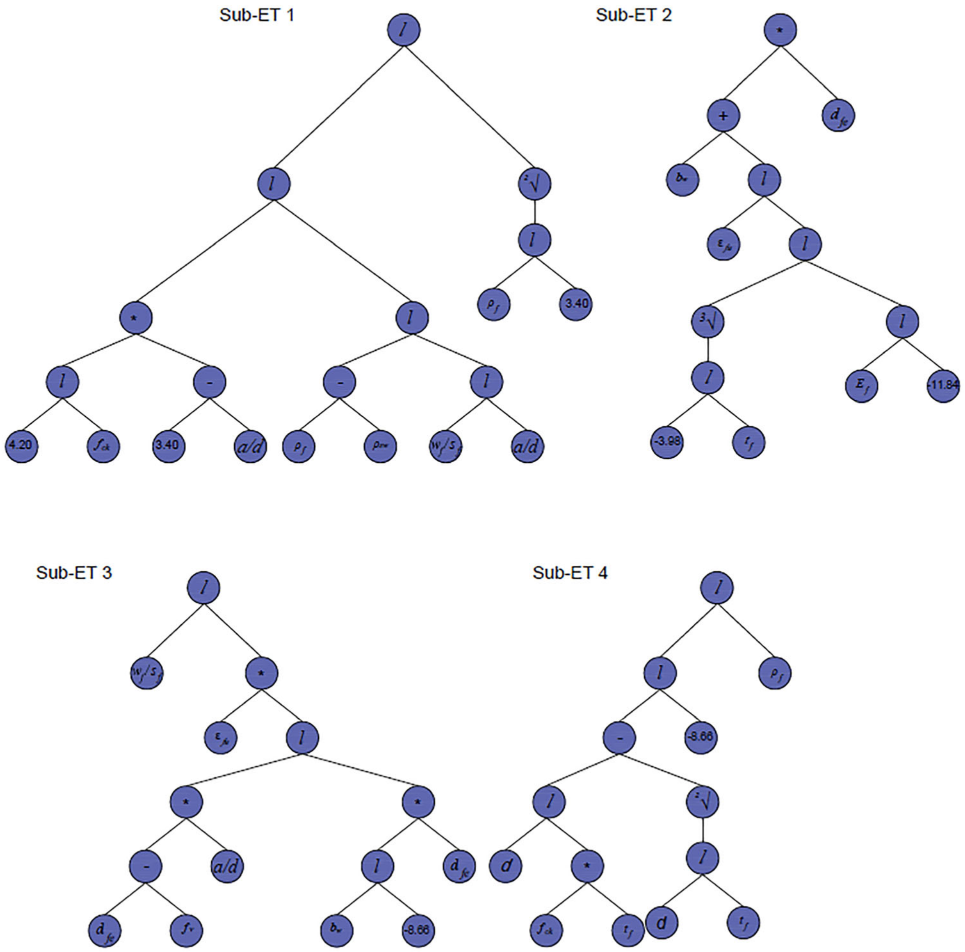
Gene expression programming (GEP) invented by Ferreira [173] is one of the machine learning tools frequently used to derive related prediction models for various engineering problems in recent years. The most important feature of gene expression programming is the generation of chromosomes representing any parse tree [173]. The GEP model consists of fixed length genes and chromosomes forming an expression tree (ET). The expression tree (ET) representation of a typical chromosome expressing the mathematical expression $\sqrt[3]{(a*b)/(c+d)}$ is presented in Fig. 7. ET consists of nonlinear entities of different sizes and shapes. A new language was created to read and express the information encoded in chromosomes. This reading of the expression tree is called the Karva language and is written in the format Q/* + abcd, where “Q” represents the cube root function of Fig. 7.

In this study, a computer program called GeneXproTools 5.0 [174] was used to derive the models for the prediction of the FRP contribution to the shear strength in fully-wrapped, *U*-wrapped, and side-bonded beams. The input variables such as $d, d_{fe}, b_w, t_f, E_f,$

Table 2 GEP variable settings

Definition	Values		
Strengthening configuration	Fully-wrapped	*U*-wrapped	Side-bonded
Input variables	d(mm), d_{fe}(mm), b_{w}(mm), t_f(mm), E_f(MPa), f_c(MPa), f_{yw}(MPa), a/d, w_f/s_f, ρ_f, ρ_w, ε_{fu}		
Output variable		V_f(N)	
Genes		4	
		4	
		4	
Function set		$+, -, *, /, \sqrt{\cdot}, \sqrt[3]{\cdot}$	
Chromosomes		30	
Head Size		10	
		10	
		10	
Linking function between ETs		Addition	
Mutation		0.00138	
Inversion rate		0.00546	
One point recombination rate		0.00277	
Two-point recombination rate		0.00277	
Gene recombination		0.00277	
Constants per gene		10	
Data type		Floating type	
Upper and lower bounds		± 10	
Training records	262	246	100
Validation records	88	82	33

Fig. 8 Expression trees (ETs) of the GEP model for fully-wrapped beams



f_c,f_{yw}, a/d, w_f/s_f, ρ_f, ρ_w, and ε_{fu} were used to obtain the output variable (V_f). Root-mean-square error (RMSE) was taken as a fitness function in the derivation of GEP models. The GEP variable settings are summarized in Table 2 by considering the previous studies [175–177].

The database was randomly divided into training (75%) and validation (25%) sets to overcome the problem of overfitting. For fully-wrapped, U-wrapped, and side-bonded beams, 262, 246, and 100 data points (75%) were used for the training sets, respectively, while the remaining 88, 82, and 33 data points (25%) were employed in the validation datasets. The proposed GEP model consisted of four different sub-expression trees linked by the linkage function for each strengthening configuration as shown in Figs. 8, 9 and 10. The GEP-based formulations for the contribution of FRP to the shear strength (V_f) were given in Eqs. (1)–(3) for fully-wrapped, U-wrapped, and side-bonded beams, respectively. The proposed models are valid for three different FRP types such as CFRP, GFRP, and AFRP whose properties are between the limit values in the databases.

For fully-wrapped beams:

$$V_f = \frac{7.74[3.4-(a/d)](w_f/s_f)}{(a/d)f_c(\rho_f-\rho_w)\rho_f^{1/2}} + \left[b_w + \frac{\varepsilon_{fu}E_f t_f^{1/3}}{18.75}\right]d_{fe} - \left[\frac{0.12(w_f/s_f)b_w d_{fe}}{\varepsilon_{fu}(a/d)(d_{fe}-f_{yw})}\right] - \frac{0.13}{\rho_f}\left[\frac{d}{f_c t_f} - \left(\frac{d}{t_f}\right)^{1/2}\right] \tag{1}$$

For U-wrapped beams:

$$V_f = \frac{b_w[d+21.08(a/d)]}{[-0.93(w_f/s_f)f_c]^{1/3}} + \frac{9.42d_{fe}E_f^{1/3}[\rho_f+(w_f/s_f)]}{[0.87+3.31(w_f/s_f)]} + b_w\left[d_{fe} - \frac{4.16(\rho_w f_{yw})^{1/4}}{(t_f\varepsilon_{fu})^{1/2}}\right] + \left[\frac{-60.39\varepsilon_{fu}t_f d}{f_{yw} - \left(\frac{a/d}{E_f}\right)^{1/3}}\right] \tag{2}$$

For side-bonded beams:

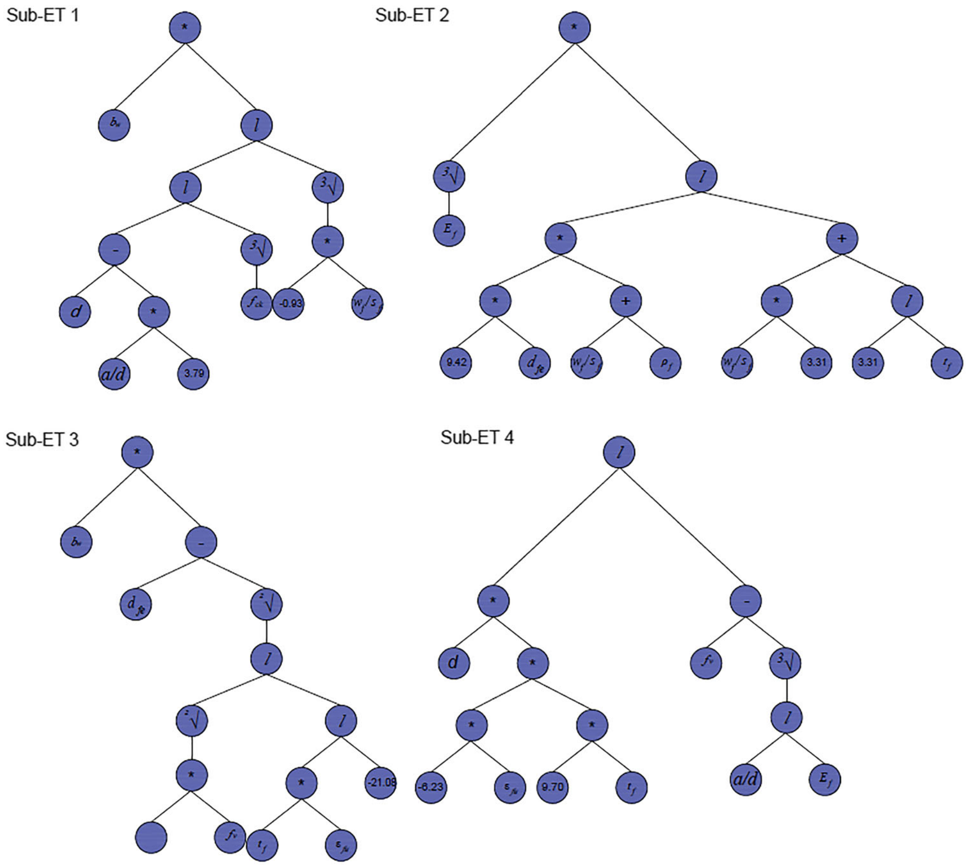


Fig. 9 Expression trees (ETs) of the GEP model for *U*-wrapped beams

$$
\begin{aligned}
V_f = & -30819.53 + f_c\left[9.9(d-9.9) + (0.88 - a/d)\left(f_{\mathrm{yw}} + d_{\mathrm{fe}}\right)\right] \\
& + \left[\left(d_{\mathrm{fe}} - \frac{d_{\mathrm{fe}}}{\varepsilon_{\mathrm{fu}}}\right) + \left(\frac{2431.7t_f}{w_f/s_f}\right)\right]\left(\sqrt{\rho_f} - \varepsilon_{\mathrm{fu}}b_w\right) \\
& + \left[\left(\frac{f_{\mathrm{yw}}^3\rho_w}{3.73}\right) - \left(\frac{(w_f/s_f)d_{\mathrm{fe}}^2}{2.63}\right) + \frac{(d_{\mathrm{fe}} - b_{\mathrm{w}}) + f_c}{\sqrt{\rho_f}}\right] \\
& - 44.19\left(\sqrt{E_f} - 9.98b_{\mathrm{w}}\right)
\end{aligned}
\tag{3}
$$

4 Results and discussion

The experimental FRP contribution (V_f) to the shear strength was calculated by subtracting the shear strength of the reference beams from the shear strength of the strengthened beams. The predicted FRP contribution (V_f) to shear strength was calculated by substituting the necessary variables (Tables A1-3) in both investigated equations and proposed GEP models. The accuracies of the considered equations were statistically interpreted by comparing the experimental (V_f) and predicted FRP contribution (V_f). Statistical variables such as the mean value (M), standard deviation (SD), mean absolute percentage error (MAPE), root-mean-square error (RMSE), coefficient of correlation (R), and coefficient of variation (COV) were considered in evaluation of the equations. The number of evaluated beams might differ due to the limitations of some equations to determine FRP contribution to shear strength as shown in Tables 3, 4 and 5. In order for the proposed models to be statistically in agreement with the experimental results, the MAPE, RMSE, and COV values should be low and the correlation coefficient (R) should be close to one value.

The Pearson correlation matrix (Fig. 6) shows that d_{fe} and b_{w} were the most effective variables for the experimental FRP contribution (V_f) of fully-wrapped beams, while f_c and w_f/s_f are less effective. In the proposed model for fully-wrapped beams, the same results related to the variables were obtained as shown in Fig. 11. For *U*-wrapped beams, d, d_{fe}, and b_{w} were highly effective on the experimental performance in contrast to f_c, ρ_f and ρ_w as shown in Fig. 6. However, d_{fe},t_f, f_{yw}, and $\varepsilon_{\mathrm{fu}}$ had a significant impact on the prediction accuracy of the proposed GEP model in *U*-wrapped beams (Fig. 11). In addition, for side-bonded beams, d, d_{fe}, and b_{w} were highly effective on the experimental performance in opposition to ρ_f,E_f,$\varepsilon_{\mathrm{fu}}$, and w_f/s_f. However, d and b_{w} had a strong effect on the

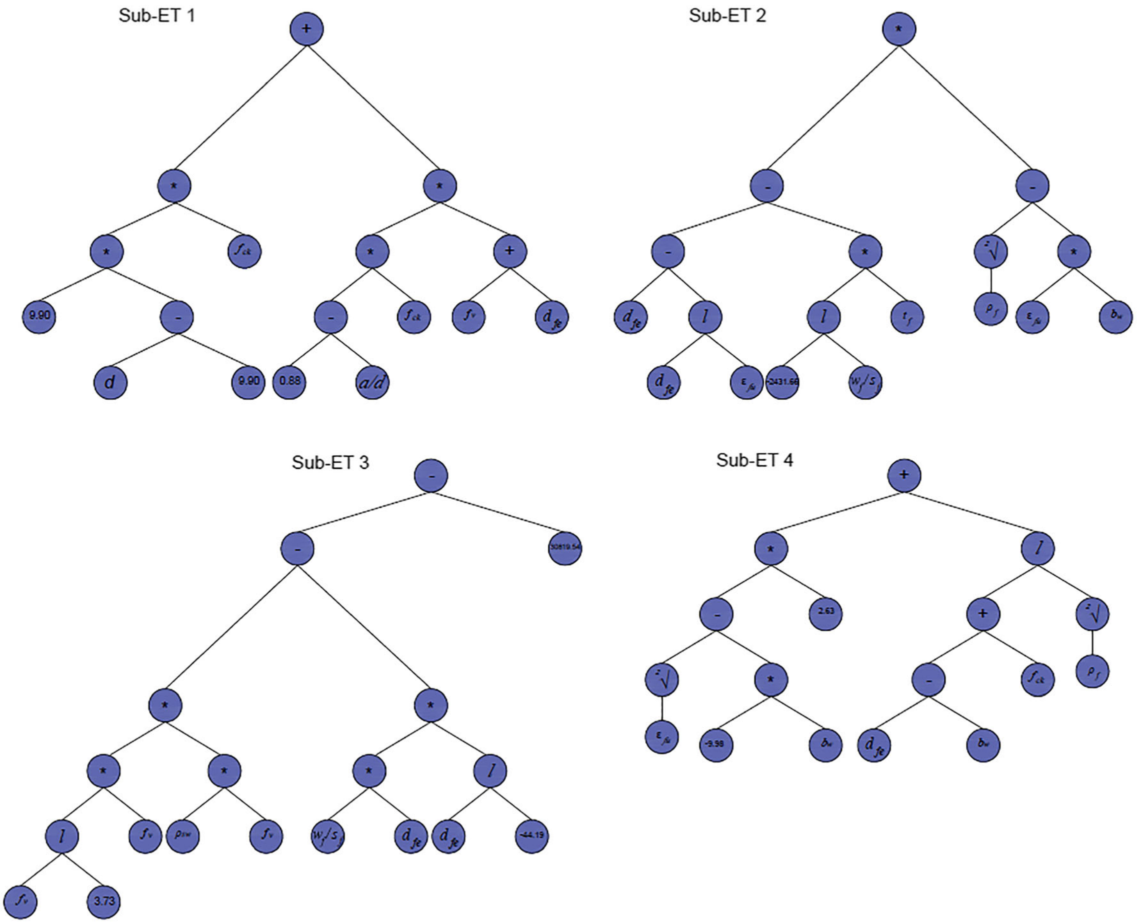


Fig. 10 Expression trees (ETs) of the GEP model for side-bonded beams

Table 3 Statistical values of each equation for the fully-wrapped beams

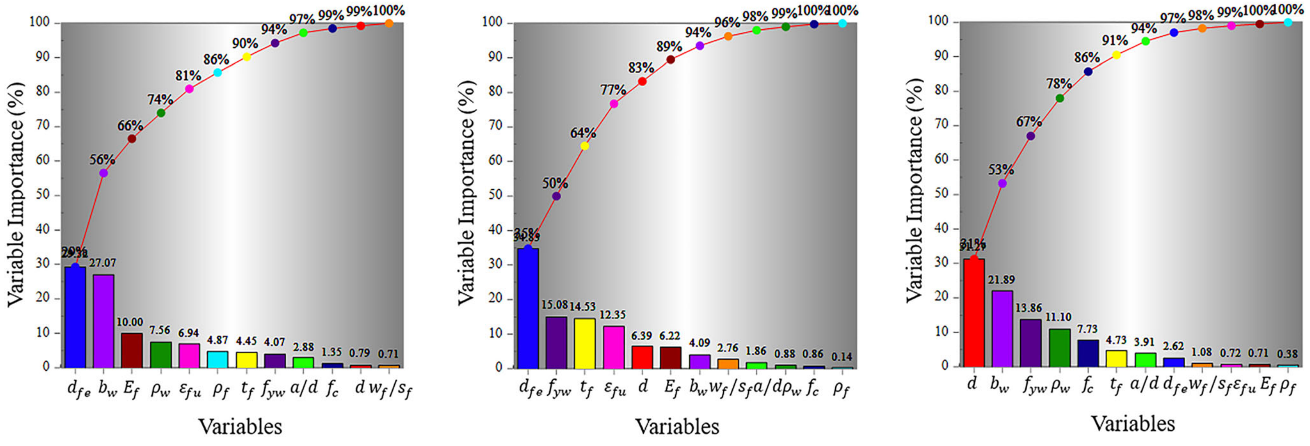
Equation	Number	*M*	SD	MAPE	RMSE	*R*	COV
Khalifa et al. [178]	347	1.214	0.788	50.251	58.421	0.738	0.649
Triantafillou and Antonopoulos [179]	350	0.664	0.475	50.893	68.240	0.645	0.715
Chen and Teng [139]	350	1.494	1.732	78.925	130.855	0.418	1.160
Bukhari et al. [131]	350	2.206	1.944	131.250	170.155	0.714	0.881
Zhang and Hsu [123]	350	0.937	0.623	44.018	53.835	0.747	0.665
ACI 440.2R [171]	350	0.838	0.956	61.661	86.568	0.433	1.141
CNR-DT 200 R1 [180]	350	0.475	0.379	59.552	84.278	0.527	0.798
fib TG 9.3 [172]	350	0.912	0.741	53.158	67.011	0.618	0.813
TR 55 [181]	350	0.678	0.567	54.642	73.030	0.570	0.836
DAfStf [182]	350	1.086	1.231	62.630	102.013	0.515	1.134
NCHRP Rep. No. 678 [183]	350	0.335	0.227	67.818	86.119	0.789	0.678
CSA-S806-12 [184]	350	1.269	1.456	76.861	110.987	0.431	1.148
CIDAR [185]	350	1.203	1.385	63.741	105.743	0.427	1.151
JSCE [186]	350	1.680	1.283	83.776	108.713	0.627	0.764
CECS 146 [187]	350	0.720	0.767	55.390	76.225	0.504	1.066
TEC-18 [188]	350	0.821	0.930	60.295	85.178	0.442	1.134
ISIS Manuel [189]	350	1.196	1.023	63.335	79.409	0.602	0.855
EN 1998–3 [190]	350	0.509	0.588	67.602	82.134	0.523	1.154
Sengun and Arslan [36]	350	1.159	0.684	44.221	47.186	0.811	0.590
Akkaya et al. [3]	350	1.052	0.685	44.659	50.846	0.764	0.651
Proposed GEP model	350	1.156	0.568	38.424	36.459	0.880	0.492

Table 4 Statistical values of each equation for the *U*-wrapped beams

Equation	Number	*M*	SD	MAPE	RMSE	*R*	COV
ACI 440.2R [171]	312	2.016	2.067	131.754	95.797	0.279	1.025
Triantafillou [119]	308	2.217	1.775	130.756	53.118	0.670	0.801
fib TG 9.3 [172]	328	1.650	1.401	93.725	55.647	0.486	0.849
Khalifa et al. [178]	273	1.399	1.002	72.721	42.227	0.619	0.716
Khalifa and Nanni [74]	212	1.436	1.024	74.174	32.797	0.662	0.713
Mofidi and Chaallal [82]	328	1.925	1.215	101.699	45.978	0.607	0.631
Bukhari et al. [32]	328	1.533	1.393	94.367	57.442	0.421	0.909
Chen and Teng [138, 139]	328	1.084	0.813	59.521	42.964	0.531	0.750
CNR-DT 200 [191]	328	1.574	1.376	92.690	54.037	0.402	0.874
Sengun and Arslan [36]	328	1.904	1.437	101.999	46.245	0.695	0.755
CAN/CSA [192]	328	3.951	8.391	327.305	444.009	0.115	2.124
JSCE [186]	162	4.705	3.587	372.683	158.419	0.591	0.762
CNR-DT 200 R1 [180]	328	1.291	1.184	76.856	50.775	0.413	0.918
Proposed GEP model	328	1.182	0.702	47.875	23.281	0.882	0.594

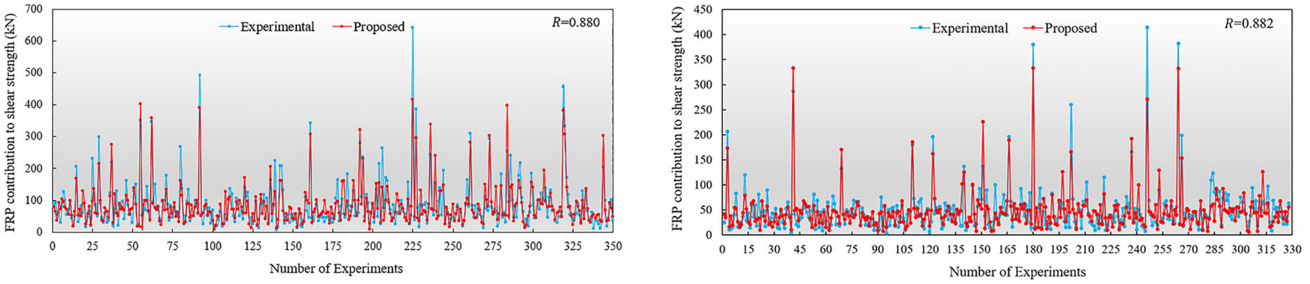
Table 5 Statistical values of each equation for the side-bonded beams

Equation	Number	*M*	SD	MAPE	RMSE	*R*	COV
ACI 440.2R [171]	112	0.644	0.550	54.207	77.180	0.437	0.855
Triantafillou [119]	133	0.683	0.319	38.688	64.377	0.609	0.467
fib TG 9.3 [172]	133	0.616	0.379	46.169	71.837	0.561	0.615
Khalifa et al. [178]	77	0.401	0.267	61.749	90.871	0.515	0.666
Mofidi and Chaallal [82]	129	0.466	0.298	58.080	78.161	0.663	0.639
Bukhari et al. [32]	129	0.299	0.168	70.089	92.814	0.589	0.561
Chen and Teng [138, 139]	133	0.282	0.168	71.801	93.590	0.609	0.596
CNR-DT 200 [191]	133	0.172	0.191	82.765	99.597	0.542	1.111
Sengun and Arslan [36]	133	0.631	0.295	40.782	65.365	0.667	0.468
CAN/CSA [192]	133	0.675	0.707	58.450	81.088	0.315	1.047
Proposed GEP model	133	1.079	0.441	29.499	24.515	0.922	0.381

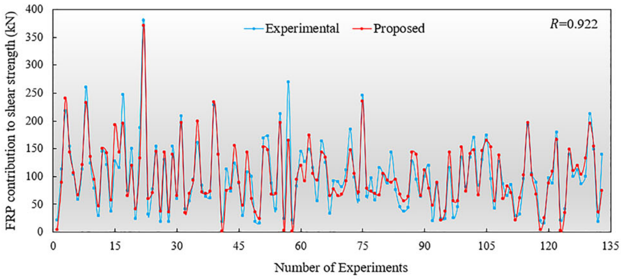


(a) Fully-wrapped (b) U-wrapped (c) Side-bonded

Fig. 11 The contribution of each input variable in GEP models for different strengthening configurations

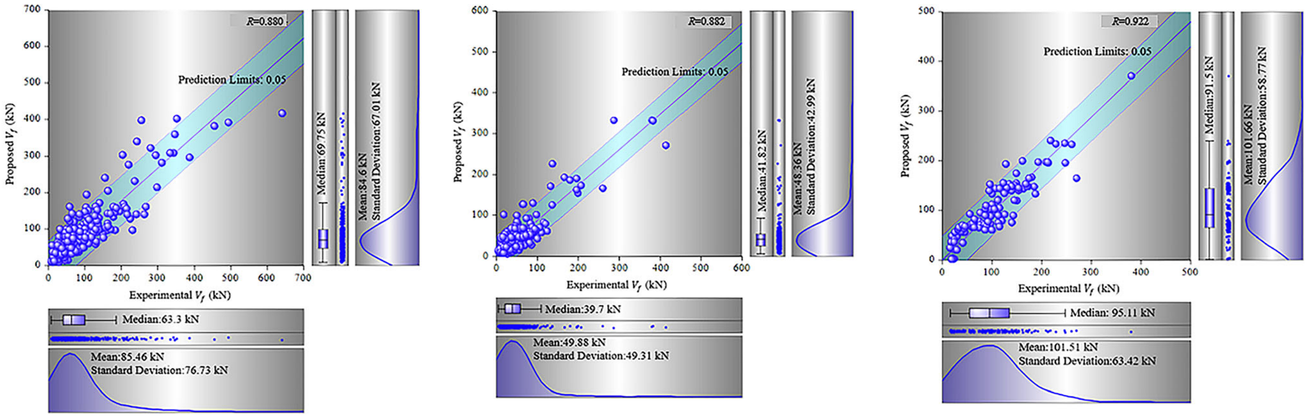


Fully-wrapped U-wrapped



Side-bonded

Fig. 12 The comparison of experimental results versus GEP models



Fully-wrapped U-wrapped Side-bonded

Fig. 13 The illustration of experimental and predicted values of FRP contribution to the shear strength

prediction accuracy of the proposed GEP model in side-bonded beams (Fig. 11). To summarize, it was evaluated that the geometric dimensions such as d, d_{fe}, and b_w are more effective on the FRP contribution to the shear strength and these variables were effectively considered in the proposed GEP models.

The comparisons between FRP contribution to shear strength calculated by the proposed GEP models and experimental results were given for each FRP strengthening configuration in Figs. 12 and 13. As a result of this comparison, it was seen that the density of the distribution between the predicted and the experimental results of V_f was in the prediction limit of the 5%. As shown in Table 3 for fully-wrapped beams, compared to the other equations, the GEP model was the most reliable with COV and R values of 0.492 and 0.880, respectively. It was seen that the equations given the statistically closest predictions to the GEP model in terms of COV and R values were Sengun and Arslan [36], Akkaya et al. [3], Khalifa et al. [178], Zhang and Hsu [123] and NCHRP Rep. No. 678 [183]. On the contrary, it was also seen that the COV and R values of the Chen and Teng [139], ACI 440.2R [171], DAfStf [182], CSA-S806-12 [184], CIDAR [185], EN 1998-3 [190], CECS 146 [187], and TEC-18 [188] equations were between 1.060–1.160 and 0.418–0.527, respectively. Thus, it was understood that the prediction accuracies of these equations were low. The predictions by NCHRP Project No. 678 and CNR-DT 200 R1 for fully-wrapped beams were not economical due to the lowest mean values.

For *U*-wrapped beams shown in Table 4, the GEP model was the most reliable as fully-wrapped beams with COV and R values of 0.594 and 0.882, respectively, whereas the CAN/CSA [192] was the worst result with COV and R values of 2.124 and 0.115, respectively. In accordance with COV and R values, the equations given the closest predictions to the GEP model were Khalifa et al. [178], Khalifa and Nanni [74], Mofidi and Chaallal [82] and Sengun and Arslan [36]. However, it was also seen that the COV and R values of the ACI 440.2R [171], fib TG 9.3 [172], Bukhari et al. [32], CNR-DT 200 [191], and CNR-DT 200 R1 [180] equations were between 0.849–1.025 and 0.279–0.486, respectively. Thus, it was understood that the prediction accuracies of these equations were low.

As for side-bonded beams as shown in Table 5, the GEP model had the best prediction accuracy with COV and R values of 0.381 and 0.922, respectively. The equation by Sengun and Arslan [36], with a COV value of 0.468 and an R value of 0.667, had the closest predictions to the GEP model statistically. Contrary, the COV and R values of the CAN/CSA [192] equation were 1.047 and 0.315, respectively. Therefore, it was understood that the prediction accuracy of CAN/CSA [192] equation was incompatible for side-bonded beams. Considering the COV and R values among the three models derived by the GEP method, it was seen that the model with the highest predictive accuracy was for side-bonded beams. The predictions by Bukhari et al. [32], Chen and Teng [138, 139], and CNR-DT 200 R1/2013 for side-bonded beams were not economical due to the lowest mean values.

5 Conclusions

In this study, three different GEP models were proposed to assess the FRP contribution to the shear strength of the RC beams for each strengthening configuration. The prediction accuracies of the GEP models proposed and the existing equations commonly used in the literature were compared utilizing a comprehensive dataset with a total of 811 RC beams strengthened with FRP. Furthermore, the relative contribution of each input variable in GEP models proposed for different strengthening configurations was investigated. The main results obtained were as follows:

The effects of 12 experimental variables on the shear behavior of RC beams strengthened with FRP were considered to propose GEP models. Experimental variables with the most influence in the proposed GEP models were d_{fe} and b_{w} for fully-wrapped beams, d_{fe} and f_{yw} for *U*-wrapped beams, d and b_{w} for side-bonded beams.

The proposed GEP models outperformed equations commonly used in the literature, exhibiting higher R values and lower COV values. These models incorporated variables such as a/d and ρ_w, which significantly influence shear behavior. Among the derived GEP models, it was observed that the model yielding the best statistical results was for side-bonded beams.

The GEP models proposed in this study are valid for beams where the shear failure occurs, effective depth of beam greater than 100 mm, and a/d ratio greater than 0.71. Strengthened with carbon, glass and aramid strips was applied perpendicular to the beam axis. In future research, it is recommended to derive equations with higher accuracy by gathering a wider data set, including beams strengthened with different inclined type of FRP strips such as carbon, glass, aramid, and basalt.

Finally, this study proved that GEP models can be used effectively and reliably in various scientific fields, thanks to their robustness and ability to adapt to different conditions and problems. With these features, it can be said that GEP models have the potential to make significant contributions to research studies.

Source codes of the GEP

Side-bonded.gep U-wrapped.gep Fully-wrapped.gep Side-bonded.py U-wrapped.py Fully-wrapped.py

Appendix A

See Tables 6, 7 and 8.

Table 6 The minimum and maximum values of the variables for fully-wrapped references

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Akkaya et al. [1]	11	260/260	260/260	1/2	140/140	0.33/0.5	0.34/0.68	0.002/0.003	0.017/0.05	70/255	28/28	0/0	0/0	29.58/96.63
Akkaya et al. [2]	11	260/260	260/260	1/2	140/140	0.33/0.5	0.34/0.68	0.002/0.003	0.017/0.05	70/255	28/28	0.005/0.005	740/740	28.37/99.74
Akkaya et al. [3]	16	260/260	260/260	1/1	140/140	0.33/0.5	0.34/0.68	0.002/0.003	0.017/0.05	70/255	28/28	0.004/0.007	740/740	63.54/150.57
Godat et al. [4]	1	498/498	498/498	2/2	300/300	1.5/1.5	0.33/0.33	0.003/0.003	0.015/0.015	237/237	43/43	0/0	0/0	297.5/297.5
Diagana et al. [5]	2	425/425	425/425	2.12/2.12	130/130	0.16/0.2	0.43/0.43	0.001/0.001	0.013/0.013	105/105	38/38	0.001/0.001	240/240	45/67.5
Li and Leung [6]	6	303/303	303/303	1/3.5	180/180	0.4/0.4	0.11/0.11	0/0	0.018/0.018	235/235	38/44	0.002/0.002	310/310	57/123
Araki et al. [7]	8	336/336	336/336	1.5/1.5	200/200	0.23/1	0.11/0.44	0/0.004	0.015/0.03	82/230	17/18	0.002/0.002	344/344	35/206
Cao et al. [8]	12	223/223	223/223	1.35/2.92	150/150	0.2/0.6	0.17/1.27	0/0.008	0.013/0.021	5/249	14/25	0/0.002	0/303	11/70
Moradi et al. [9]	1	300/300	300/300	2.67/2.67	200/200	0.4/0.4	0.13/0.13	0.001/0.001	0.018/0.018	238/238	28/28	0.004/0.004	352/352	74.52/74.52
Leung et al. [10]	6	155/660	155/660	2.73/2.95	75/300	0.33/0.33	0.11/0.44	0.001/0.001	0.018/0.018	235/235	27/27	0.003/0.003	310/310	25.35/343.15
Funakawa et al. [11]	5	400/510	400/510	2.5/2.5	250/600	0.4/1	0.11/0.5	0/0.002	0.016/0.032	90/244	25/27	0/0.001	0/340	55/493.5
Umezu et al. [12]	15	253/499	253/499	2.9/3	150/600	0.5/1	0.04/0.29	0/0.001	0.018/0.037	73/244	32/38	0/0	0/0	26/387
Beber [13]	8	253/261	253/261	2.8/2.92	150/150	0.5/1	0.11/0.11	0.001/0.001	0.015/0.015	230/230	25/33	0/0	0/0	45.9/88.57
Ianniruberto and Imbimbo [14]	6	300/300	300/300	3/3	150/150	1/1	0.12/0.36	0.002/0.005	0.047/0.047	76/76	33/33	0.002/0.002	495/495	73/149
Miyajima et al. [15]	4	243/243	243/243	4.5/4.5	340/340	0.33/0.67	0.11/0.11	0/0	0.019/0.019	253/253	30/30	0/0	500/500	81.3/162.6
Grande et al. [16]	8	405/420	405/420	3/4	250/250	1/1	0.19/0.19	0.002/0.002	0.006/0.007	392/392	21/21	0.001/0.002	476/500	65/170
Zhang et al. [17]	2	255/255	255/255	3.9/3.9	220/220	1/1	0.19/0.19	0.002/0.002	0.018/0.018	118/188	35/35	0.002/0.002	500/500	47.45/49.35
Alzate et al. [18]	6	355/355	355/355	3/3.55	250/250	0.6/0.6	0.17/0.29	0.001/0.001	0.016/0.017	240/240	15/17	0.001/0.001	500/500	118.38/216.04
Uji [19]	1	170/170	170/170	2.5/2.5	100/100	1/1	0.1/0.1	0.002/0.002	0.012/0.012	230/230	25/25	0/0	0/0	34.5/34.5

Table 6 (continued)

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Al-Tersawy [20]	2	175/175	175/175	2/2	100/100	0.57/0.57	0.13/0.26	0.001/0.003	0.017/0.017	200/200	21/21	0.005/0.005	240/240	35.1/37
Miyauchi et al. [21]	3	165/165	165/165	2/3	125/125	0.2/0.5	0.11/0.11	0/0.001	0.015/0.015	230/230	32/35	0/0	0/0	18.75/34.6
Adey and Brühwiler [22]	1	370/370	370/370	2.03/2.03	200/200	1/1	0.13/0.13	0.001/0.001	0.015/0.015	230/230	46/46	0/0	0/0	135/135
Taerwe et al. [23]	1	420/420	420/420	2.98/2.98	200/200	0.25/0.25	0.11/0.11	0/0	0.013/0.013	280/280	28/28	0.001/0.001	300/300	98.9/98.9
Mitsui et al. [24]	6	220/220	220/220	1.14/1.59	150/150	1/1	0.17/0.17	0.002/0.002	0.015/0.015	230/230	29/29	0.003/0.003	300/500	18/55.4
Khalifa thesis [25]	1	253/253	253/253	3.62/3.62	150/150	1/1	0.17/0.17	0.002/0.002	0.015/0.015	228/228	52/52	0/0	0/0	47/47
Zhao and Xie [26]	8	200/200	200/200	2.27/3.64	150/150	0.25/0.5	0.12/0.24	0/0.001	0.008/0.008	220/220	14/21	0.001/0.002	300/558	12.5/20
Matthys and Taerwe [27]	1	370/370	370/370	3.2/3.2	200/200	0.25/0.25	0.11/0.11	0/0	0.015/0.015	230/230	35/35	0.001/0.001	300/300	98.9/98.9
Adhikary et al. [28]	5	245/245	245/245	4.08/4.08	300/300	1/1	0.17/0.29	0.001/0.002	0.015/0.017	120/230	41/44	0/0	0/0	88/138
Carolin and Täljsten [29]	2	430/430	430/430	2.91/2.91	180/180	1/1	0.22/0.22	0.002/0.002	0.019/0.019	234/234	46/52	0/0	0/0	241/263
Zhou and Li [30]	14	350/350	350/350	1.43/3	150/150	0.33/1	0.17/0.5	0.001/0.002	0.018/0.018	237/237	41/51	0.002/0.004	367/367	60.27/133.77
Teng et al. [31]	6	260/260	260/260	2.5/2.5	150/150	0.4/0.4	0.11/0.11	0.001/0.001	0.015/0.015	266/266	36/43	0/0.005	0/342	52.4/85.6
Bukhari et al. [32]	1	267/267	267/267	3.14/3.14	152/152	1/1	0.34/0.34	0.004/0.004	0.015/0.015	235/235	36/36	0/0	0/0	60.6/60.6
Colalillo and Sheikh [33]	3	546/546	506/546	3.07/3.07	400/400	0.5/1	1/1	0.003/0.005	0.011/0.011	94/94	48/48	0.001/0.001	501/501	103/236.5
Li [34]	4	210/420	210/420	0.71/1.71	100/200	0.5/0.5	0.17/0.33	0.002/0.002	0.015/0.015	240/240	19/24	0.003/0.003	434/434	24.3/194.8
Sengun and Arslan [35, 36]	15	200/200	200/200	2.5/4.5	150/150	0.33/0.5	0.34/0.36	0.002/0.005	0.017/0.045	73/255	34/34	0/0.004	0/610	9.8/93.14
Khalifa and Nanni [37]	1	357/357	257/257	3/3	150/150	1/1	0.17/0.17	0.002/0.002	0.017/0.017	228/228	35/35	0/0	0/0	131/131
Gang et al. [38]	7	264/264	264/264	1.5/3.1	150/150	0.39/1	0.11/0.33	0.001/0.002	0.015/0.015	235/235	31/31	0.002/0.004	393/393	20.5/55.5
Annaiah et al. [39]	8	356/356	280/280	2.57/4.28	152/152	1/1	0.17/0.6	0.002/0.008	0.013/0.017	117/228	24/24	0/0	0/0	26.18/81.44

Table 6 (continued)

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Deniaud et al. [40]	1	540/540	390/390	2.74/2.74	140/140	0.5/0.5	0.11/0.11	0.001/0.001	0.015/0.015	230/230	44/44	0.001/0.001	520/520	85.3/85.3
Cui [41]	4	220/220	220/220	2.27/2.27	150/150	0.15/0.33	0.17/0.33	0/0.001	0.015/0.015	235/235	25/26	0.002/0.002	346/346	20/40
Zhiping and Haobo [42]	5	200/220	170/200	2.5/2.75	100/110	0.5/0.5	0.11/0.11	0.001/0.001	0.011/0.011	230/230	24/24	0/0	0/0	25.7/50.8
Xuesong and Zhongfan [43]	4	300/300	300/300	1.7/2.9	150/150	0.33/0.33	0.22/0.22	0.001/0.001	0.018/0.018	235/235	20/20	0.003/0.003	395/395	54/72
Danying et al. [44]	8	210/214	210/214	2.3/3.5	150/150	0.5/0.5	0.11/0.11	0.001/0.001	0.017/0.017	212/212	32/40	0.002/0.002	300/300	38.99/96.8
Altin et al. [45]	6	330/330	255/255	5/5	120/120	0.25/0.4	0.12/0.12	0.001/0.001	0.018/0.018	231/231	25/25	0/0.001	0/275	35.49/38.17
Gamino et al. [46]	2	265/265	185/185	2.74/2.74	120/120	0.29/0.33	0.11/0.17	0.001/0.001	0.013/0.015	218/235	57/59	0.001/0.001	517/517	65/80
Luo [47]	7	272/272	196.5/196.5	2.2/2.2	150/150	0.25/0.5	0.17/0.33	0.001/0.001	0.015/0.015	230/230	17/17	0.002/0.002	340/340	35/75
Belarbi et al. [48]	4	831/831	653/653	3.3/3.3	457/457	0.67/0.67	0.13/0.13	0/0	0.017/0.017	228/228	18/30	0.001/0.002	276/276	203.4/310.96
Tang [49]	6	270/270	195/195	2.2/2.2	150/150	0.13/0.5	0.17/0.17	0/0.001	0.015/0.015	230/230	24/31	0.002/0.002	333/333	28.5/82.5
Koutas and Triantafillou [50]	3	245/245	165/165	2.04/2.04	140/140	1/1	0.23/0.23	0.003/0.003	0.016/0.016	230/230	18/18	0/0	0/0	37/84
Manos et al. [51]	2	330/330	330/330	2.73/2.73	120/120	0.5/0.67	0.13/0.13	0.001/0.001	0.009/0.009	42/42	22/22	0/0	0/0	75.7/83.6
Ozden et al.[52]	6	320/320	245/245	3.8/3.8	120/120	0.17/0.17	0.13/0.16	0/0	0.004/0.047	73/640	12/12	0.001/0.001	249/249	7.3/28.1
Deniaud and Cheng [53]	6	350/540	200/390	2.74/3.03	140/140	1/1	1.8/2.1	0.026/0.03	0.006/0.015	8/18	30/44	0/0.002	0/520	24.4/129.2
Zhuang and Lieping [54]	1	215/215	215/215	2.16/2.16	150/150	0.5/0.5	0.17/0.17	0.001/0.001	0.027/0.027	102/102	32/32	0.002/0.002	377/377	38/38
Haidong [55]	7	318/318	318/318	2.2/2.2	150/150	0.17/0.5	1.1/1.1	0.002/0.007	0.025/0.025	22/22	33/33	0.002/0.002	362/362	24/46.5
Panda et al. [56]	3	225/225	165/165	3.26/3.26	100/100	1/1	0.36/0.36	0.007/0.007	0.012/0.012	13/13	40/42	0/0.003	0/252	18/25.5
Baggio et al. [57]	5	285/310	235/285	2.9/3.2	150/150	0.5/0.73	0.4/0.51	0.003/0.004	0.009/0.022	26/67	50/50	0.001/0.001	384/384	43.5/83.6
Panigrahi et al. [58]	2	140/140	90/90	2.38/2.38	150/150	1/1	1/2.5	0.013/0.033	0.025/0.027	7/8	18/19	0/0	0/0	45/53

Table 6 (continued)

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Zhen and Ruixing [59]	6	215/215	215/215	1.86/2.79	150/150	0.2/0.6	0.17/0.17	0/0.001	0.015/0.015	249/249	24/24	0.002/0.002	300/300	19/45
Mofidi and Chaallal [60]	3	350/350	248/248	3/3	152/152	0.23/1	2/2	0.006/0.026	0.015/0.015	90/230	34/34	0.004/0.004	650/650	59.2/84.1
Zhouhong et al. [61]	1	330/330	330/330	2.42/2.42	180/180	0.45/0.45	1.4/1.4	0.007/0.007	0.015/0.015	185/185	35/35	0.002/0.002	350/350	70.05/70.05
Guangfu et al. [62]	2	295/295	250/250	2/2	180/180	0.4/0.4	0.11/0.11	0/0	0.015/0.015	235/235	16/16	0.015/0.015	285/285	12.99/15.67
Chaoyang et al. [63]	7	210/443	210/420	1/2.26	100/250	0.3/0.67	0.17/0.33	0.001/0.002	0.013/0.015	230/270	19/32	0/0.003	0/400	45.4/455
Bae and Belarbi [64]	3	831/831	756/756	3.3/3.3	457/457	0.67/0.67	0.17/0.17	0/0	0/0	228/228	27/43	0.001/0.001	414/414	255/641
Chen et al.[65]	7	320/320	300/300	3/3	200/200	0.5/0.5	0.17/0.17	0.001/0.001	0/0	226/226	43/46	0/0.003	416/416	49.9/170.5
Kim et al. [66]	11	521/521	483/483	1.5/3	356/356	0.5/1	0.17/0.56	0.001/0.002	0/0	57/228	27/27	0.002/0.004	476/476	58/267
Bourget et al. [67]	6	350/350	304/304	3/3	152/152	0.11/0.11	1.4/2	0.002/0.003	0/0	90/120	28/28	0/0.004	540/540	45/120
El-Saikaly et al. [68]	3	350/350	304/304	3/3	152/152	0.11/1	0.38/2	0.003/0.005	0/0	65/90	28/28	0.003/0.003	580/580	58/87
Frederick et al. [69]	1	234/234	200/200	3.2/3.2	130/130	1/1	0.15/0.15	0.002/0.002	0.012/0.012	119/119	31/31	0.002/0.002	415/415	34.8/34.8

Table 7 The minimum and maximum values of the variables for *U*-wrapped references

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Chajes et al. [70]	9	152/153	89/89	2.65/2.7	64/64	1/1	0.46/1.04	0.014/0.033	0.009/0.023	11/21	42/48	0/0	0/0	11.2/26.53
Norris et al. [71]	2	167/167	167/167	2.74/2.74	127/127	1/1	1/1	0.016/0.016	0.011/0.012	33/34	37/37	0.002/0.002	420/420	15/17
Khalifa Thesis [25]	16	253/357	253/257	3/4.03	150/150	0.4/1	0.17/0.34	0.001/0.005	0.015/0.017	228/228	19/50	0/0.008	0/200	26/92.5
Gang-Wu et al. [38]	3	264/264	264/264	2.2/2.2	150/150	0.39/1	0.11/0.11	0.001/0.001	0.015/0.015	235/235	31/31	0.002/0.002	393/393	35.5/75.5
Matthys [72]	4	370/370	370/370	3.2/3.2	200/200	0.13/1	0.11/0.11	0/0.001	0.015/0.015	230/230	34/38	0.001/0.001	560/560	30.1/115.4
Chaallal et.al [73]	10	343/343	254/254	2/2	92/92	1/1	2/6	0.043/0.13	0.016/0.016	231/231	38/38	0.003/0.011	441/441	31.15/84.55
Khalifa and Nanni [74]	8	255/255	255/255	3/4	150/150	0.4/1	0.17/0.33	0.001/0.004	0.017/0.017	228/228	19/28	0/0.008	0/350	50.5/92.5
Zhuang and Lieping [54]	7	215/215	215/215	1.5/2.8	150/150	0.5/1	0.11/0.17	0.001/0.002	0.015/0.027	102/235	25/32	0.002/0.004	307/377	16.8/53.7
Abdel-Jaber et al. [75]	2	165/165	165/165	2.42/2.42	150/150	1/1	0.27/0.54	0.004/0.007	0.015/0.015	230/230	50/51	0/0	0/0	35/41.9
Allam and Ebeido [76]	8	175/175	175/175	1.71/2.57	120/120	0.5/1	0.26/0.26	0.002/0.004	0.015/0.015	230/230	32/32	0.004/0.004	380/380	22.5/52.5
Diagana et al. [5]	2	425/425	425/425	2.12/2.12	130/130	0.16/0.2	0.43/0.43	0.001/0.001	0.013/0.013	105/105	30/30	0.002/0.002	240/240	20/32.5
Zhang et al. [77]	2	203/203	203/203	0.88/1.25	102/102	1/1	0.33/0.33	0.006/0.006	0.013/0.013	73/73	43/43	0/0	0/0	40.05/52.96
Adhikary et al. [28]	4	170/245	120/245	3/4.08	150/300	1/1	0.17/0.29	0.001/0.002	0.015/0.017	120/230	26/40	0/0	0/0	29.3/53
Xuesong and Zhongfan [43]	8	300/300	300/300	1.7/2.9	150/150	0.33/1	0.22/0.44	0.001/0.003	0.018/0.018	235/235	20/20	0.003/0.003	395/395	35/76.25
Islam et al. [78]	1	730/730	730/730	0.72/0.72	120/120	1/1	0.33/0.33	0.006/0.006	0.015/0.015	230/230	38/38	0.002/0.002	533/533	199/199
Beber and Filho [13]	5	253/253	253/253	2.92/2.92	150/150	0.5/1	0.11/0.11	0.001/0.001	0.015/0.015	230/230	33/33	0/0	0/0	36/81.5
Dias and Barros [79]	4	123/273	123/273	2.2/4.88	150/150	0.13/0.63	0.33/0.33	0.001/0.003	0.008/0.008	390/390	41/48	0/0	0/0	10.8/33.7
Teng et al. [80]	1	173/173	163/163	3/3	200/200	1/1	0.17/0.17	0.002/0.002	0.015/0.015	230/230	29/29	0.002/0.002	665/665	19.3/19.3
Qu Zhe [81]	3	166/498	166/498	1.51/1.51	100/300	0.6/0.6	0.11/0.33	0.001/0.001	0.015/0.015	235/235	41/41	0/0	0/0	21.85/195.95

Table 7 (continued)

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Altin et al. [45]	3	330/330	255/255	5/5	120/120	0.25/0.4	0.12/0.12	0.001/0.001	0.018/0.018	231/231	25/25	0.001/0.001	275/275	19.53/33.04
Gamino et al. [46]	2	265/265	185/185	2.74/2.74	120/120	0.33/0.34	0.11/0.11	0.001/0.001	0.012/0.015	221/235	60/60	0.001/0.001	517/517	37.5/49
Mofidi and Chaallal [82]	14	350/350	248/304	3/3	152/152	0.23/1	0.06/2	0.001/0.006	0.013/0.015	90/230	31/34	0/0.004	0/650	10.1/77.8
El-Ghandour [83]	3	245/245	205/205	3.67/3.67	120/120	0.27/0.27	0.18/0.18	0.001/0.001	0.016/0.016	240/240	40/40	0.002/0.002	400/400	25/55
Colalillo and Sheikh [33]	1	546/546	506/506	3.07/3.07	400/400	1/1	1/1	0.005/0.005	0.011/0.011	94/94	48/48	0.001/0.001	501/501	207/207
Belarbi et al. [48]	2	831/831	653/653	3.3/3.3	457/457	0.67/0.67	0.13/0.13	0/0	0.017/0.017	228/228	21/29	0.001/0.002	276/276	132.38/166.17
Bae et al. 2012 [84]	3	305/610	305/610	3/3	203/406	0.33/0.66	0.17/0.17	0.001/0.001	0.015/0.015	228/228	25/32	0/0	0/0	46.7/137
Koutas and Triantafillou [50]	1	245/245	165/165	2.04/2.04	140/140	1/1	0.23/0.23	0.003/0.003	0.016/0.016	230/230	18/18	0/0	0/0	29/29
Godat and Chaallal [85]	10	343/343	253/253	2/2	127/127	1/1	2/6	0.032/0.095	0.016/0.016	231/231	38/38	0.002/0.008	441/441	26.4/72.4
Manos et al. [51]	2	330/330	330/330	2.73/2.73	120/120	0.5/0.67	0.13/0.13	0.001/0.001	0.009/0.009	42/42	22/22	0/0	0/0	58.4/61.6
Mofidi and Chaallal [60]	17	350/350	248/248	3/3	152/152	0.35/1	0.11/0.22	0.001/0.003	0.015/0.015	230/230	27/35	0/0.004	0/650	14.5/69.4
Ebead and Saeed [86]	1	119/119	119/119	4.2/4.2	100/100	1/1	0.17/0.17	0.003/0.003	0.016/0.016	165/165	50/50	0/0	0/0	18.35/18.35
Al-Sulaimani et al. [87]	1	114/114	114/114	3.51/3.51	150/150	1/1	3/3	0.04/0.04	0.015/0.015	13/13	38/38	0.002/0.002	300/300	15.6/15.6
Mosallam and Banerjee [88]	2	206/206	106/106	1.8/1.8	150/150	1/1	2.1/2.1	0.028/0.028	0.021/0.021	24/24	28/28	0.002/0.002	300/300	10.83/18
Panda et al. [56]	6	225/225	165/200	3.26/3.3	100/100	0.5/1	0.36/0.36	0.004/0.007	0.012/0.012	13/160	38/42	0/0.003	0/252	11.5/19.5
Baggio et al. [57]	5	285/310	260/310	2.9/3.2	150/150	0.5/0.73	0.4/0.51	0.003/0.004	0.022/0.022	26/67	50/50	0.001/0.001	384/384	40.4/75.2
Panigrahi et al. [58]	4	140/140	90/125	2.38/2.4	150/150	0.5/1	1/1	0.007/0.013	0.025/0.025	7/7	19/19	0/0	0/0	26.5/34
Zhouhong et al. [61]	2	330/330	330/330	2.42/3.03	180/180	0.45/0.45	1.4/1.4	0.007/0.007	0.015/0.015	185/185	35/35	0.002/0.002	350/350	93.5/124
Guangfu et al. [62]	2	295/295	250/250	2/2	180/180	0.4/0.4	0.11/0.11	0/0	0.015/0.015	235/235	16/16	0.015/0.015	285/285	14.01/39.83

Table 7 (continued)

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Nguyen-Minh and Rovňák [89]	12	175/682	175/682	1.7/2	100/300	1/1	1/1.3	0.007/0.026	0.01/0.022	26/96	23/25	0.002/0.002	350/350	17.5/260
Al-Rousan et al. [90]	1	120/120	120/120	4.2/4.2	100/100	1/1	0.2/0.2	0.003/0.003	0.016/0.016	165/165	50/50	0.005/0.005	420/420	9.2/9.2
Chaoyang et al. [63]	2	340/443	340/373	2/2.26	200/250	0.3/0.67	0.17/0.17	0.001/0.001	0.014/0.015	230/270	22/32	0.001/0.002	235/400	83/100.15
Li and Leung [91]	6	303/303	303/303	1/3.5	180/180	0.4/0.4	0.11/0.11	0/0	0.018/0.018	235/235	38/44	0.002/0.002	310/310	10/68
Panigrahi et al. [92]	3	225/225	165/165	3.26/3.26	180/180	1/1	0.62/4.2	0.007/0.047	0.01/0.015	19/24	42/42	0/0	0/0	38.75/45.02
Peng [93]	10	300/300	300/300	1/3	180/180	0.33/0.33	0.17/0.17	0.001/0.001	0.015/0.015	235/235	32/32	0.003/0.007	325/380	12.19/49.04
Al-Lebban and Mackie [94]	4	235/235	171/171	3/4	152/152	0.46/0.46	0.66/0.66	0.004/0.004	0.011/0.012	87/216	60/60	0/0	0/0	22.3/86.1
Gonzalez-Libreros et al. [95]	2	250/250	250/250	3/3	150/150	1/1	0.17/0.17	0.002/0.002	0.008/0.008	390/390	25/25	0.002/0.003	527/527	39.6/53
Pham and Hao [96]	1	210/210	210/210	2.62/2.62	150/150	0.5/0.5	0.45/0.45	0.003/0.003	0.017/0.017	89/89	47/47	0/0	0/0	26/26
Al-Rousan et al. [97]	4	185/417	185/417	1.2/2.7	150/150	0.5/0.5	0.17/0.17	0.001/0.001	0.019/0.019	231/231	55/55	0/0	0/0	19.1/73.4
Huo et al. [98]	1	267/267	217/217	3.36/3.36	150/150	0.5/0.5	0.17/0.17	0.001/0.001	0.015/0.015	236/236	28/28	0/0	0/0	48/48
Sengun and Arslan [35]	6	200/200	200/200	2.5/4.5	150/150	0.33/0.33	0.34/0.34	0.002/0.002	0.017/0.017	255/255	43/43	0/0.004	0/610	8.59/19.87
El-Saikaly et al. [99]	6	350/350	304/304	3/3	152/152	0.11/1	0.38/1.4	0.002/0.005	0.013/0.019	65/120	28/28	0/0.004	0/580	5/39
Galal and Mofidi [100]	1	242/242	200/200	2.4/2.4	155/155	1/1	0.27/0.27	0.003/0.003	0.011/0.011	87/87	43/43	0.005/0.005	465/465	13.5/13.5
Randl and Harsányi [101]	3	489/489	450/450	3.2/3.2	200/200	0.26/0.26	2.6/2.6	0.007/0.007	0.11/0.11	100/100	34/37	0/0	0/0	286.8/382.4
Qin et al. [102]	3	295/295	260/260	3.1/3.1	125/125	1/1	1/1	0.016/0.016	0.01/0.01	96/96	29/34	0.003/0.003	542/542	19/39
Bae and Belarbi [64]	1	831/831	756/756	3.3/3.3	457/457	0.67/0.67	0.16/0.16	0/0	0.017/0.017	228/228	42/42	0.001/0.001	414/414	414/414
Altin et al. [45]	3	330/330	285/285	5/5	120/120	0.25/0.4	0.12/0.12	0.001/0.001	0.017/0.017	231/231	25/25	0.002/0.002	275/275	9.8/16.5
Oller et al. [103]	1	493/493	400/400	3/3	200/200	0.21/0.21	0.17/0.17	0/0	0.015/0.015	230/230	43/43	0.001/0.001	500/500	40/40

Table 7 (continued)

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Nguyen-Minh et al. [104]	15	406/406	400/400	2.3/2.3	120/120	0.5/1	1/2	0.008/0.022	0.01/0.022	26/96	31/59	0.002/0.002	342/342	15/87.5
Chen et al. [65]	2	320/320	300/300	3/3	200/200	0.5/0.5	0.17/0.17	0.001/0.001	0.019/0.019	226/226	43/46	0/0.003	0/416	29.7/39.7
Kim et al. [66]	2	521/521	483/483	1.5/3	356/356	0.5/0.5	0.28/0.28	0.001/0.001	0.016/0.016	87/87	27/27	0.002/0.004	476/476	18/98
Altin et al. [105]	3	330/330	285/285	5/5	120/120	0.25/0.4	0.12/0.12	0.001/0.001	0.017/0.017	231/231	25/25	0.002/0.002	310/310	11.3/19.6
Panda et al. [106]	3	225/225	200/200	3.3/3.3	100/100	0.5/0.5	0.36/0.36	0.004/0.004	0.012/0.012	160/160	38/40	0/0.003	0/252	11.5/13
El-Maaddawy and Chekfeh [107]	5	200/200	190/190	3/3	120/120	0.58/0.58	0.38/1.14	0.004/0.011	0.013/0.013	65/65	32/32	0.003/0.003	344/344	7.2/27.2
Mofidi and Chaallal [108]	1	350/350	304/304	3/3	152/152	1/1	0.11/0.11	0.001/0.001	0.014/0.014	231/231	34/34	0.003/0.003	540/540	48.5/48.5
Samir et al. [109]	4	215/295	165/245	3.8/3.8	105/105	1/1	3/3	0.057/0.057	0.013/0.013	28/28	19/26	0.002/0.002	580/580	4.3/26.5
El-Maaddawy and Chekfeh [110]	6	200/200	190/190	3/3	120/120	0.58/0.58	0.38/0.76	0.004/0.007	0.013/0.013	65/65	20/20	0.003/0.003	344/344	9/44
Frederick et al. [69]	2	235/235	200/200	3.2/3.2	130/130	1/1	0.15/0.15	0.002/0.002	0.012/0.012	119/119	27/27	0.002/0.002	415/415	18/58.8
Chaallal et al. [111]	3	350/350	304/304	3/3	152/152	1/1	0.13/0.13	0.002/0.002	0.014/0.014	231/231	25/35	0/0.004	0/650	18.5/38.7
Farghal [112]	2	280/280	250/250	2.5/2.5	150/150	0.5/0.5	0.13/0.13	0.001/0.001	0.015/0.015	230/230	26/27	0/0.003	0/240	20.5/31.5
Sato et al. [113]	2	260/260	260/260	2.7/2.7	200/200	0.5/1	0.11/0.11	0.001/0.001	0.015/0.015	230/230	33/41	0/0	0/0	106.1/110
Park et al. [114]	1	186/186	186/186	2.7/2.7	100/100	1/1	0.16/0.16	0.003/0.003	0.014/0.014	240/240	17/17	0/0	0/0	38.6/38.6
Täljsten [115]	1	466/466	466/466	2.7/2.7	180/180	1/1	0.11/0.11	0.001/0.001	0.019/0.019	234/234	51/51	0/0	0/0	136.55/136.55
Godat et al. [4]	3	166/498	166/498	2/2.1	100/300	1.5/1.5	0.11/0.33	0.003/0.003	0.015/0.015	237/237	43/43	0/0	0/0	22/196
Alzate et al. [18]	18	361/362	320/320	3.5/3.5	250/250	0.6/1	0.17/0.29	0.001/0.002	0.016/0.017	240/240	13/29	0.001/0.001	500/500	21.01/97.75
Pellegrino and Modena [116]	4	250/250	250/250	3/3	150/150	1/1	0.17/0.33	0.002/0.004	0.015/0.015	230/230	38/38	0.004/0.005	534/534	11.7/36.3
Deniaud and Cheng [117]	2	357/357	305/305	3/3	150/150	0.4/1	0.17/0.17	0.001/0.002	0.017/0.017	228/228	27/27	0/0	0/0	65/72
Deniaud and Cheng [53]	2	361/361	250/250	3/3	140/140	1/1	1.8/1.8	0.026/0.026	0.006/0.006	18/18	22/22	0.001/0.002	520/520	24.35/48.65

Table 8 The minimum and maximum values of the variables for side-bonded references

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Chaallal et al. [118]	2	215/215	215/215	2.79/2.79	150/150	0.5/0.5	1/1	0.007/0.007	0.016/0.016	150/150	35/35	0.002/0.002	400/400	87.5/95
Triantafillou [119]	6	100/100	100/100	3.2/3.2	70/70	0.5/1	0.16/0.16	0.002/0.005	0.014/0.014	235/235	30/30	0/0	0/0	18.75/24.05
Kachlakec and Bames [120]	3	101/101	101/101	1.5/1.5	152/152	1/1	0.11/0.33	0.001/0.004	0.015/0.015	230/230	28/28	0/0	0/0	19.4/29.7
Khalifa thesis [25]	1	357/357	257/257	3/3	150/150	0.4/0.4	0.34/0.34	0.002/0.002	0.017/0.017	228/228	35/35	0/0	0/0	121.5/121.5
Gang-Wu et al. [38]	1	264/264	264/264	2.2/2.2	150/150	0.35/0.35	0.11/0.11	0.001/0.001	0.015/0.015	235/235	31/31	0.002/0.002	300/300	150/150
Pellegrino and Modena [121]	9	250/250	250/250	3/3	150/150	1/1	0.17/0.5	0.002/0.007	0.019/0.019	234/234	28/31	0/0.003	0/548	112.8/247.5
Abdel-Jaber et al. [75]	2	165/165	165/165	2.42/2.42	150/150	0.4/1	0.27/0.27	0.001/0.004	0.015/0.015	230/230	47/48	0/0	0/0	55.5/97.5
Allam and Ebeido [76]	8	175/175	175/175	1.71/2.57	120/120	0.5/1	0.26/0.26	0.002/0.004	0.015/0.015	230/230	32/32	0.004/0.004	250/380	76.25/115
Täljsten [115]	1	430/430	430/430	2.91/2.91	180/180	1/1	0.11/0.11	0.001/0.001	0.019/0.019	234/234	59/59	0/0	0/0	260.6/260.6
Wong and Vecchio [122]	3	465/465	465/465	3.94/6.88	305/305	0.67/0.67	0.84/0.84	0.004/0.004	0.011/0.011	99/99	23/44	0/0	0/0	218/246.5
Adhikary et al. [28]	4	170/170	120/170	3/3	150/150	1/1	0.17/0.33	0.002/0.004	0.015/0.015	230/230	31/34	0/0	0/0	58.6/80.8
Beber and Filho [13]	7	253/253	253/253	2.92/2.92	150/150	0.35/1	0.11/1.4	0.001/0.007	0.012/0.015	205/230	33/33	0/0	0/0	98.12/142.91
Carolin and Täljsten [29]	4	330/430	330/430	2.8/3	180/180	1/1	0.22/0.51	0.002/0.006	0.019/0.019	234/234	37/47	0/0.002	0/515	128/149
Zhang and Hsu [123]	2	195/195	195/195	2.74/2.74	152/152	0.31/0.31	1.5/1.5	0.006/0.006	0.017/0.017	165/165	44/44	0/0	0/0	63.9/73.7
Monti and Liotta [124]	2	402/402	252/252	3.48/3.48	250/250	0.5/1	0.22/0.22	0.001/0.002	0.008/0.008	390/390	11/11	0.001/0.001	300/300	100/112.5
Mosallam and Banerjee [88]	2	206/206	106/106	1.8/1.8	150/150	0.5/0.5	1.19/1.19	0.008/0.008	0.019/0.019	152/152	28/28	0.002/0.002	300/300	55.47/56.95
Grande et al. [125]	2	405/405	405/405	3/4	250/250	1/1	0.19/0.19	0.002/0.002	0.006/0.006	392/392	21/21	0.001/0.001	500/500	180/185
heKim et al. [126]	6	220/220	220/220	1.7/2.2	250/250	0.5/1	1.2/1.2	0.005/0.01	0.015/0.02	158/235	35/35	0/0	0/0	94.5/173
Siddiqui [127]	1	265/265	265/265	2.83/2.83	200/200	0.33/0.33	1/1	0.003/0.003	0.011/0.011	77/77	35/35	0.002/0.002	420/420	95.97/95.97

Table 8 (continued)

References	Number	d(mm) min/max	d_{fe}(mm) min/max	a/d min/max	b_w(mm) min/max	w_f/s_f min/max	t_f(mm) min/max	ρ_f min/max	ε_{fu} min/max	E_f(GPa) min/max	f_c(MPa) min/max	ρ_v min/max	f_{yv}(MPa) min/max	V_f(kN) min/max
Gamino et al. [46]	1	265/265	185/185	2.74/2.74	120/120	0.33/0.33	1.4/1.4	0.008/0.008	0.004/0.004	310/310	55/55	0.001/0.001	300/300	103.5/103.5
Bukhari et al. [32]	3	267/267	267/267	3.14/3.14	152/152	1/1	0.34/0.34	0.004/0.004	0.015/0.015	235/235	60/60	0/0	0/0	115.4/127
Lim [128]	3	272/272	272/272	3.07/3.07	200/200	0.2/0.4	1.2/1.2	0.002/0.005	0.017/0.017	165/165	40/40	0/0	0/0	111.8/126.6
Ebead and Saeed [129]	14	217/217	217/217	3/3	150/150	0.4/0.56	3.2/3.2	0.017/0.024	0.014/0.014	72/72	33/37	0/0.004	0/410	57.77/100.05
Al-Rousan et al. [90]	7	119/120	119/120	4.17/4.2	100/100	0.5/1	0.17/1.4	0.003/0.014	0.016/0.017	165/230	50/50	0/0	0/0	15.85/18.95
Sundarraja et al. [130]	4	120/120	120/120	2.8/2.8	100/100	0.33/0.89	1/1	0.007/0.018	0.047/0.047	73/73	29/29	0/0.008	0/300	24.05/29.5
Al-Sulaimani et al. [87]	4	114/114	84/114	3.51/3.51	150/150	0.4/1	3/3	0.016/0.04	0.015/0.015	13/13	38/38	0.002/0.002	450/450	41.2/45.2
Panda et al. [56]	3	225/225	165/165	3.26/3.26	100/100	1/1	0.36/0.36	0.007/0.007	0.012/0.012	13/13	40/42	0/0.003	0/300	65/92
Bukhari et al. [131]	11	262/262	112/262	2/2	150/150	0.08/1	0.34/0.34	0/0.005	0.015/0.015	235/235	48/51	0/0	0/0	125/187.55
Panigrahi et al. [58]	2	135/135	41/41	3/3	150/150	0.5/1	0.17/0.33	0.001/0.004	0.025/0.025	7/7	24/25	0/0	0/0	86/100
Ebead and Saeed [86]	2	225/225	152/152	2.18/3	150/180	0.4/0.4	0.11/0.33	0/0.002	0.005/0.005	72/72	34/35	0/0.003	0/410	105/123
Al-Lebban and Mackie [94]	3	235/362	171/362	2/2.22	152/305	0.46/0.46	0.33/0.33	0.001/0.002	0.012/0.012	87/87	60/66	0/0	0/0	174.7/380.5
Pham and Hao [96]	1	210/210	210/210	2.9/2.9	150/150	0.5/0.5	0.11/0.11	0.001/0.001	0.017/0.017	89/89	47/47	0/0	0/0	145/145
Moren Thesis [132]	2	197/197	197/197	1.3/1.9	102/102	0.5/0.5	1.2/1.2	0.012/0.012	0.017/0.017	165/165	35/35	0/0	0/0	31.6/36.76
Zhang et al. [77]	7	203/203	203/203	1.3/1.9	102/102	0.39/1	0.33/1.2	0.006/0.013	0.013/0.017	73/165	35/35	0/0	0/0	32.04/64.25

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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