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Data-Driven Prediction Models For Total Shear Strength of Reinforced Concrete Beams With Fiber Reinforced Polymers Using An Evolutionary Machine Learning Approach

Ataollah Taghipour Anvari [a], Saeed Babanajad [b], Amir H. Gandomi [c,d,*]

[a] *Lyles School of Civil Engineering, Purdue University, 550 W Stadium Ave, West Lafayette, IN 47907, United States*
[b] *Wiss Janney Elstner Associates (WJE) Inc, 330 Pfingsten Rd, Northbrook, IL 60062, United States*
[c] *Faculty of Engineering & IT, University of Technology Sydney, Sydney, NSW 2007, Australia*
[d] *University Research and Innovation Center (EKIK), Óbuda University, 1034 Budapest, Hungary*

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ABSTRACT

The strength of Reinforced Concrete (RC) structural elements may need to be improved due to building usage changes or damages that occurred after exposure to extreme loads. Fiber Reinforced Polymer (FRP) is commonly being used to enhance the performance of reinforced concrete beams due to several advantages such as having high strength and being lightweight. To perform the analysis and design of the members, there is a need for accurate models to determine the total shear strength of the structural elements strengthened with FRP sheets. In this paper, genetic programming has been successfully utilized to develop models to predict the total shear strength of the reinforced concrete beams. A strategy is adopted here to find a simple yet accurate formula to estimate the shear strength. These models can correlate the total shear strength of the beams reinforced with FRP sheets to the geometric and material properties of RC beams and FRP sheets, without the need for expensive laboratory tests. A compressive database of the total shear strength of the RC beams with FRP sheets was created from the literature. External validation and sensitivity analysis, using various statistical criteria, were conducted to assess the precision and validity of the proposed models. Based on 785 RC beams strengthened by externally bonded FRP sheets, tested between 1992 and 2022, two data-driven models were developed to predict the total shear strength of RC beams strengthened with FRP. The calculated correlations for Models I and II are 0.883 and 0.940, respectively. Superior performance was obtained compared to other models from the literature in accuracy. The proposed models can be utilized for design purposes and the development of structural solutions for existing structures.

1. Introduction

Reinforced Concrete (RC) structures are one of the common structural systems that have been used for past decades. Environmental effects, inappropriate design, and application, structure usage alteration, need for post-disaster (fire, earthquake, etc.) repair of the structures, and upgrading the structures based on new provisions produce the necessity for strengthening existing structures [1–4]. For past decades Fiber Reinforced Polymer (FRP) is being used widely as an effective material to improve RC structural elements. Corrosion resistance, high strength, low cost, lightweight, and simple application are some advantages of using FRP. These features led to the popularity of FRP utilization for rehabilitation and retrofitting purposes to prevent the demolition of existing structures [5,6]. Hence, various design methods were developed to estimate the shear strength of RC members with externally applied FRP [7–10], and some of them are utilized in provisions such as ACI 440R [141], and Canadian CSA-S806 [140].

In order to effectively design the RC members with FRP, it is important to understand the behavior of members to estimate the capacity. Many studies were conducted on beams strengthened by externally bonded FRP sheets. However, still there are some discussions on the shear strength contribution of FRP sheets to the total shear capacity of the members [11]. Most of the studies were performed on investigating the members induced to axial and flexural loading [12]. However, shear failure can be the dominated failure mode in some RC beams strengthened by externally bonded FRP sheets. Due to the brittle manner of the shear failure, most of the design methods in provisions prevent

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* Corresponding author at: Faculty of Engineering & IT, University of Technology Sydney, 15 Broadway, Ultimo, NSW 2007, Australia.
E-mail addresses: ataghipo@purdue.edu (A. Taghipour Anvari), sbabanajad@wje.com (S. Babanajad), gandomi@uts.edu.au (A.H. Gandomi).

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Nomenclature

a/d	Span-to-depth ratio
b_w	Minimum width of cross-section over the effective depth
d	Distance from top concrete fiber to centroid of steel rebar
d_f	The effective depth of FRP
f_c'	Compressive strength of concrete
f_{fe}	Tensile stress in FRP
$f_{max}(x_i)$	Maximum calculated strength over the ith input
$f_{min}(x_i)$	Minimum calculated strength over the ith input
f_y	Yielding strength of shear reinforcement
h	Height of a reinforced concrete beam
$\widehat{h}_i$	The average of the measured output
k_1	Modification factor for concrete strength
k_2	Modification factor based on the wrapping scheme
n	Number of samples
n	Number of FRP layers
n_T	Number of samples for training
n_V	Number of samples for validation
s_f	Spacing of FRP strips
t_f	Thickness of FRP
t_i	Estimated output
w_f	Width of FRP strips
w_T	Weight for training results
w_V	Weight for validation results
A_f	Effective area of FRP
E_f	Modulus of elasticity of FRP
L_e	Effective bonded length
N_i	Difference of the maximum and minimum calculated strength over the ith input
OBJ	Objective function
R	Correlation coefficient
R_f	FRP effective stress reduction factor
R_m	External indicator of predictability
R_O^2	Squared correlation coefficient between experimental and predicted values without intercept
$R_{O'}^2$	Squared correlation coefficient between predicted and experimental values without intercept
$RRMSE$	The root-mean-square error of prediction
S	Sensitivity
T	Training data
V	Validation data
V_f	Nominal shear strength of FRP
V_c	Nominal shear strength of concrete
V_s	Nominal shear strength of shear reinforcement
β	FRP orientation
$\varepsilon_{fk,e}$	Characteristic value of the effective FRP strain
ε_{fe}	Effective strain of FRP
ε_{fu}	Ultimate strain of FRP
κ_v	Bond-reduction coefficient
ρ	Performance index
ρ_f	FRP area fraction
ρ_s	Shear reinforcement ratio
ρ_T	Performance index for the training data
ρ_V	Performance index for the validation data
γ_{frp}	Partial safety factor

this type of failure mode [13].

The shear strength of RC beams with FRP application depends on various parameters which lead to complications in understanding the behavior and capacity of such beams under shear loads [9]. Studies had been performed on the beams strengthened by FRP sheets and, some methods have been proposed to calculate the shear strength capacity of reinforced concrete beams strengthened with FRP as a function of various parameters including beam size, mechanical properties of FRP and concrete, existing reinforcement, wrap shape, and configurations and available bond length [8,10,14,15].

Some models were proposed based on obtained data from the existing experimental studies in the literature to evaluate the shear strength contribution of externally bonded FRP sheets in RC beams. These models take into account the effect of various parameters such as dimensions of RC beams and material properties of concrete and FRP sheets [5,7,16]. In most of the existing studies, the total shear capacity of the beams with applied FRP is based on the superposition of shear strength contribution of concrete (V_c), shear reinforcement (stirrups) (V_s), and FRP sheets (V_f). The contribution of concrete and stirrups is defined clearly by ACI 318 [17]. The shear strength capacity of FRP is usually determined by experimentally investigating the additional shear strength of RC beams strengthened by FRP sheets compared to the conventional RC beams (so-called control specimen). However, the accuracy of experiments depends on various parameters such as limitations of laboratories that may not be considered during the testing procedure. In essence, most of the proposed models may rely on the results of a limited number of tests. Thus, the development of such models based on the gathered data points from a large number of experimental tests can result in models with a higher accuracy level for estimating the total shear strength of RC beams with FRP sheets.

Various techniques and algorithms have been developed to define models based on the relationships between the different parameters for hardened materials such as concrete and rocks [18,19]. Regression analysis, least median, and evolutionary optimization algorithm squares are examples of different techniques that have been used to solve civil engineering issues [18–20]. The mentioned methods can be utilized for design of structural components and the assessment of the existing structural components along with reliability analysis [20]. In order to use these methods, prior information about the parametersis required [21]. Some proposed methods may consider simple assumptions or use some approximations to reduce the complication of the issues; which can cause giant errors in the outcome results [22–24]. Genetic Programming (GP) and Artificial Neural Network (ANN) techniques can define relationships between the data in problems including a high variety of parameters exclusive of prior information about the general structure. This has made ANN and GP techniques among the complex techniques capable of classification and approximation problems for engineering issues [25,26]. Although the performance of GP and ANN techniques are similar, some issues with ANN techniques prohibit to generate data with enough accuracy [27]. The ANN systems do not provide the function to get the results by using the input values and the determination of ANN systems' parameter requires a trial-and-error procedure. However, these problems have been resolved in GP algorithms which provide the relationship between the parameters.

Other studies developed models to calculate the contribution of FRP sheets to the shear strength of RC beams based on the measured shear strength of the beams or analyzing the load paths within the sections. However, the goal of this study is to formulate the total shear strength of beams with FRP sheets. Gene Expression Programming (GEP), is an extension of GP proposed by Ferreira [28]. In particular, computer programs with various sizes and shapes are encoded in linear chromosomes of fixed length. To solve engineering problems and estimate the complex relationships between the given data and the obtained results (e.g., strength, displacement, etc.) researchers created methods using GEP to develop prediction models [29]. Therefore, the GEP technique is used in order to find an accurate yet simple model. To provide the data for the described technique for developing a model, the experimental data in the literature have been gathered. Then, the validity and accuracy of the developed models were calculated and compared with existing models.

2. Gene expression programming (GEP)

GP was introduced by Koza [30] as a useful prediction algorithm. By using GP, the relationships between the parameters for complex problems are estimated based on the Darwinian natural selection principle. A Genetic Algorithm (GA) can be utilized in GP. The generated results by GP are in the form of fixed-length binary strings. The results of GP in a computer code can also be presented in the form of a tree. The classical GP approach includes a hierarchically structured tree also known as tree-based GP [31].

GEP is an expansion of GP comprising five parts namely, (a) a function set, (b) a fitness set, (c) a terminal set, (d) control parameters, and (e) a terminal condition. For the presentation of the results, GEP uses fixed-length strings. The graphical representations of the GEP are the Expression Trees (ET). This genetic mechanism works at the chromosome level. The lack of sophistication in building diverse genetics and the multi-genic nature of GEP enables the users to develop programs with high nonlinearity [32].

GEP comprises several genes. Each gene has multiple arbitrary fixed-length symbols containing terminal sets. Chromosomes present a tree as a part of GEP. The developed language by Karva facilitates the reading of the information of chromosomes [21]. K-expression genes in Karva [28] language consists of letters presenting the considered problem's variables and constants. The mathematical and logical complexity of a gene can be obtained from the K-expressions presented in form of the tree.

To estimate the relationship for a problem, the GEP algorithm undergoes an iterative procedure until a solution is acquired. In the first step, the GEP algorithm generates random chromosomes with a fixed length for the initial population. In the next step, the k-expressions for each chromosome are generated. The fitness of the k-expressions is then evaluated. Chromosomes are revised and regenerated after being selected by roulette wheel sampling. The selection is conducted according to the fitness criteria. The selection based on these criteria results in the maintenance of the best chromosomes from the previous generations. The new generations go through the same procedure.

3. Existing models for estimating FRP contribution

The existing models in the literature mainly rely on the experimental results in order to predict the contribution of FRP sheets to the shear strength of RC beams. These models cannot be used to determine the total shear strength of RC beams. To calculate the total shear strength of RC beams, there is a need for separate analyses to estimate the shear strength contribution of bare concrete (V_c) and shear reinforcement (stirrups) (V_s). To compare the calculated shear strength of these models with the developed models in the current study, the contributions of concrete (V_c) and shear reinforcement (V_s) were added to the predicted shear strength of FRP sheets (V_f) using the existing models in the litrature. In the existing models, the contribution of FRP sheets to the shear strength is depending on factors such as the size of a beam or column, concrete strength, and wrapping configurations. A summary of the common prediction models developed in existing studies is as follows:

3.1. Triantafillou (1998)

The model developed by Triantafillou [14] is based on the effective strain of FRP, which depends mainly on the FRP development length. Triantafillou proposed Eq. (1) to estimate the contribution of FRP sheets to shear strength. The equation of shear strength contribution of FRP is analyzed by a semi-quantitative description of the problem. Enough development length of FRP avoids deboning before reaching FRP tensile fracture.

$$V_{f,d} = \frac{0.9}{\gamma_{frp}}\rho_f E_f \varepsilon_{fe} b_w d(1+cot\beta)sin\beta \tag{1}$$

where ε_{fe} is the effective strain of FRP and the partial safety factor (γ_{frp}) is equal to 1.15, 1.2, and 1.25 for CFRP, AFRP, and GFRP sheets, respectively.

$$\varepsilon_{fe} = \begin{cases} 0 \le \rho_f E_f \le 1 & 0.0119 - 0.0205(\rho_f E_f) + 0.0104(\rho_f E_f)^2 \\ \rho_f E_f \ge 1 & -0.00065(\rho_f E_f) + 0.00245 \end{cases} \tag{2}$$

3.2. Adhikary et al. (2004)

In the proposed model by Adhikary et al. [8], the behavior of FRP sheets was assumed similar to internal stirrups in that FRP sheets only carry normal stresses in principle directions. The effective strain at the ultimate state is assumed less than the tensile failure strain. The model is a function of the effective strain of FRP sheets as it is presented in Eq. (3) and the shear strength contribution of FRP can be computed using Eq. (4).

$$\frac{\varepsilon_{fe}}{\varepsilon_{fu}} = \frac{0.038(f'_c)^{1/3}}{\sqrt{\rho_f E_f}} \tag{3}$$

$$V_f = \rho_f E_f \varepsilon_{fe} d_f b_w (sin\beta + cos\beta) \tag{4}$$

3.3. ACI 440.2R-17

ACI 440.2R [141] uses Eq. (5) to predict the contribution of FRP to the shear strength of the RC beams. Eq. (5) is a function of five parameters namely, area, nominal strength, orientation, applied depth, and spacing of FRP laminates.

$$V_f = \frac{A_{fv} f_{fe}(sin\beta + cos\beta)d_f}{s_f} \tag{5}$$

The effective strain is equal to the maximum strain that can be achieved in FRP at the nominal strength. The effective strain for columns or beams for sections wrapped at four sides (fully wrapped) is limited to 0.004. Eq. (9) can be utilized to calculate the effective strain in U-wrapped sections. This equation is a function of the bond-reduction coefficient (κ_v). According to the prediction method recommended by ACI 440R, tensile strength in FRP (f_{fe}) and the effective area of FRP (A_{fv}) can be calculated using Eq. (6).

$$A_{fv} = 2nt_f w_f \tag{6}$$

$$f_{fe} = \varepsilon_{fe} E_f \tag{7}$$

$$\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \tag{8}$$

$$\kappa_v = \frac{k_1 k_2 L_e}{11900\,\varepsilon_{fu}} \tag{9}$$

$$L_e = \frac{23300}{(n_f t_f E_f)^{0.58}} \tag{10}$$

$$k_1 = \left(\frac{f'_c}{27}\right)^{2/3} \tag{11}$$

$$k_2 = \begin{cases} \dfrac{d_f - L_e}{d_f}\, U - wraps \\ \dfrac{d_f - 2L_e}{d_f}\, Two\ sides \end{cases} \tag{12}$$

3.4. *Triantafillou and Antonopoulos (2000)*

The prediction model developed by Triantafillou and Antonopoulos [34] was established in Eurocode design format. This model is based on the assumption that FRP only carries normal stresses. Therefore, FRP develops an ultimate strain at ultimate strength similar to previously mentioned prediction models. The FRP contribution to the shear strength equation developed by Triantafillou and Antonopoulos is the same as the study by Triantafillou [14]. However, different equations are recommended to calculate the effective strain. Eqs. (15) and (16) were recommended to compute the amount of $\varepsilon_{f,e}$ for fully wrapped and U-shaped orsections with two-sided applied FRP laminates, respectively.

$$V_f = 0.9\frac{\varepsilon_{fk,e}}{\gamma_f}\rho_f E_f b_w d(1+cot\beta)sin\beta \tag{13}$$

$$\varepsilon_{fk,e} = \alpha\,\varepsilon_{fe} \le \varepsilon_{max} \tag{14}$$

where,

$\alpha = 0.8,\ \varepsilon_{max} = 0.005$

$$\varepsilon_{f,e} = 0.17\left(\frac{f_c^{2/3}}{E_f\rho_f}\right)^{0.3}\varepsilon_{fu} \tag{15}$$

$$\varepsilon_{f,e} = min\left[0.65\left(\frac{f_c^{2/3}}{E_f\rho_f}\right)^{0.56}\times 10^{-3},\ 0.17\left(\frac{f_c^{2/3}}{E_f\rho_f}\right)^{0.3}\varepsilon_{fu}\right] \tag{16}$$

To enhance the precision of the model predicting the FRP's shear strength contribution, it was recommended to limit $E_f\rho_f$ in RC sections where debonding is not prevented by mechanical anchorages. The limited value of $E_f\rho_f$ can be calculated using Eq. (17). Also, the FRP spacing should not exceed 0.8d in order to control the cracks [34].

$$(E_f\rho_f)_{lim} = \left(\frac{0.65\times 10^{-3}\alpha}{\varepsilon_{max}}\right)^{1/0.56} f_c^{2/3} = 0.018 f_c^{2/3} \tag{17}$$

3.5. *Khalifa et al. (1998)*

In the study conductedby Khalifa et al. [35] two models using different approaches were recommended to estimate the contribution of FRP to the shear strength of RC beams, as follows:

3.5.1. *Prediction model based on effective FRP stress*

In this method, the proposed model was developed based on the fracture propeties of FRP sheets. The ultimate stress within FRP was assumed in the vertical direction. The ultimate point of FRP was considered to control the design and it was assumed as the effective strain. The shear strength contribution of FRP sheets can be calculated using Eq. (18).

$$V_f = \rho_f E_f \varepsilon_{fe}\, b_w 0.9d(1+cot\beta)sin\beta \tag{18}$$

The effective strain of FRP sheets is a function of axial rigidity of FRP sheets and can be determined using Eqs. (19a) and (19b).

$$\varepsilon_{fe} = 0.0119 - 0.0205\left(\rho_f E_f\right) + 0.0104\left(\rho_f E_f\right)^2 0 \le \rho_f E_f \le 1\,GPa \tag{19a}$$

$$\varepsilon_{fe} = 0.00245 - 0.00065\left(\rho_f E_f\right)\rho_f E_f \ge 1\,GPa \tag{19b}$$

In addition, a modification was implemented to calculate the effective strain. According to the experimental results, a reduction factor for the ultimate strain was applied which can be computed using Eq. (20).

$$R_f = 0.5622\left(\rho_f E_f\right)^2 - 1.2188\left(\rho_f E_f\right) + 0.778\ \le 0.5 \tag{20}$$

3.5.2. *Prediction model based on bond mechanism*

Other than the fracture of FRP layers, bonding failure of FRP was considered because of the significant effect of the FRP bond on providing anchorage to a beam. Due to the application of shear forces, tensile stress develops in concrete in principle directions which results in the generation of inclined cracks. To transfer the tensile stress to both sides of the cracks sufficient bond strength is required. To address this issue a model was proposed by Khalifa et al. [35]. According to a study by Maeda et al. [36] on the bond mechanism of FRP sheets, empirical equations were proposed based on experimental results to compute the bond strength as a function of the bond effective length.

$$L_e = e^{6.134-0.58ln\left(t_f E_f\right)} \tag{21}$$

$$w_{fe} = \begin{cases} d_f - L_e U - wrapped \\ d_{\mathrm{f}} - 2L_e FRPappliedonsides \end{cases} \tag{22}$$

$$R_f = \frac{0.0042\,(f'_c)^{\frac{2}{3}}}{\left(E_f t_f\right)^{0.58}\varepsilon_{fu} d_f},\ R = 0.5\,if\,fully\,wrapped \tag{23}$$

$$f_{fe} = R_f f_{fu} \tag{24}$$

$$V_f = \frac{A_f f_{fe}(sin\alpha + cos\alpha)d_f}{s_f} \le \left(\frac{2\sqrt{f'_c}\,b_w d}{3} - V_s\right) \tag{25}$$

4. Shear strength of RC beam with FRP sheet

Two models were developed utilizing the GEP approach to realize the relationship between the shear strength of the beam considering the properties of applied FRP sheets and other variables affecting the shear strength capacity.

$$V_{T,GPI} = f\left(d, a/d, f'_c, b_w, f_y.\rho_s, E_f.\rho_f, \varepsilon_{fe}\right)$$

$$V_{T,\ GPII}(without\ shear\ reinforcement) = f\left(d, a/d, f'_c, b_w, E_f.\rho_f, \varepsilon_{fe}\right)$$

$$V_{T,\ GPII}(with\ shear\ reinforcement) = f\left(d, a/d, f'_c, b_w, f_y.\rho_s, E_f.\rho_f\right)$$

where,
d: Distance from top concrete fiber to centroid of rebar (mm)
a/d: Span to depth ratio
f'_c: Compressive strength of concrete (MPa)
b_w: Minimum width of cross-section over the effective depth (mm)
f_y: Yielding strength of shear reinforcement (MPa)
ρ_s: Shear reinforcement ratio
E_f: Modulus of elasticity of FRP (MPa)
ρ_f: FRP area fraction
ε_{fe} : $0.004 \le 0.75\varepsilon_{fu}$ for fully wrapped FRP
$\kappa_v\varepsilon_{fu} \le 00.004$ for U-shape and side FRP wrapping

4.1. *Experimental database*

The developed model to determine the total shear strength of reinforced concrete beams with FRP sheets is based on the results of more than 785 experiments obtained from the literature (excluding the reference beams). The contribution of the concrete and shear reinforcement to the shear strength of beams was calculated based on ACI provisions [17]. The range of material properties of FRP sheets and concrete, as well as the geometrical properties of some of the tests for each study, are presented in Table A1 in the appendix section. Table A2 presents the utilized parameters for some of the data points. The frequency histograms in Fig. 1 show the distribution of variables related to the properties of the RC beams. There are different types of variations in the distribution ranging from highly localized, and skewed, to highly distributed distributions. In general, the denser distribution with a more uniform shape results in better performance [37]. The gathered data consist of test data of RC beam specimens with rectangular (R) and T-shape (T) beams and various FRP wrapping shapes. A schematic drawing

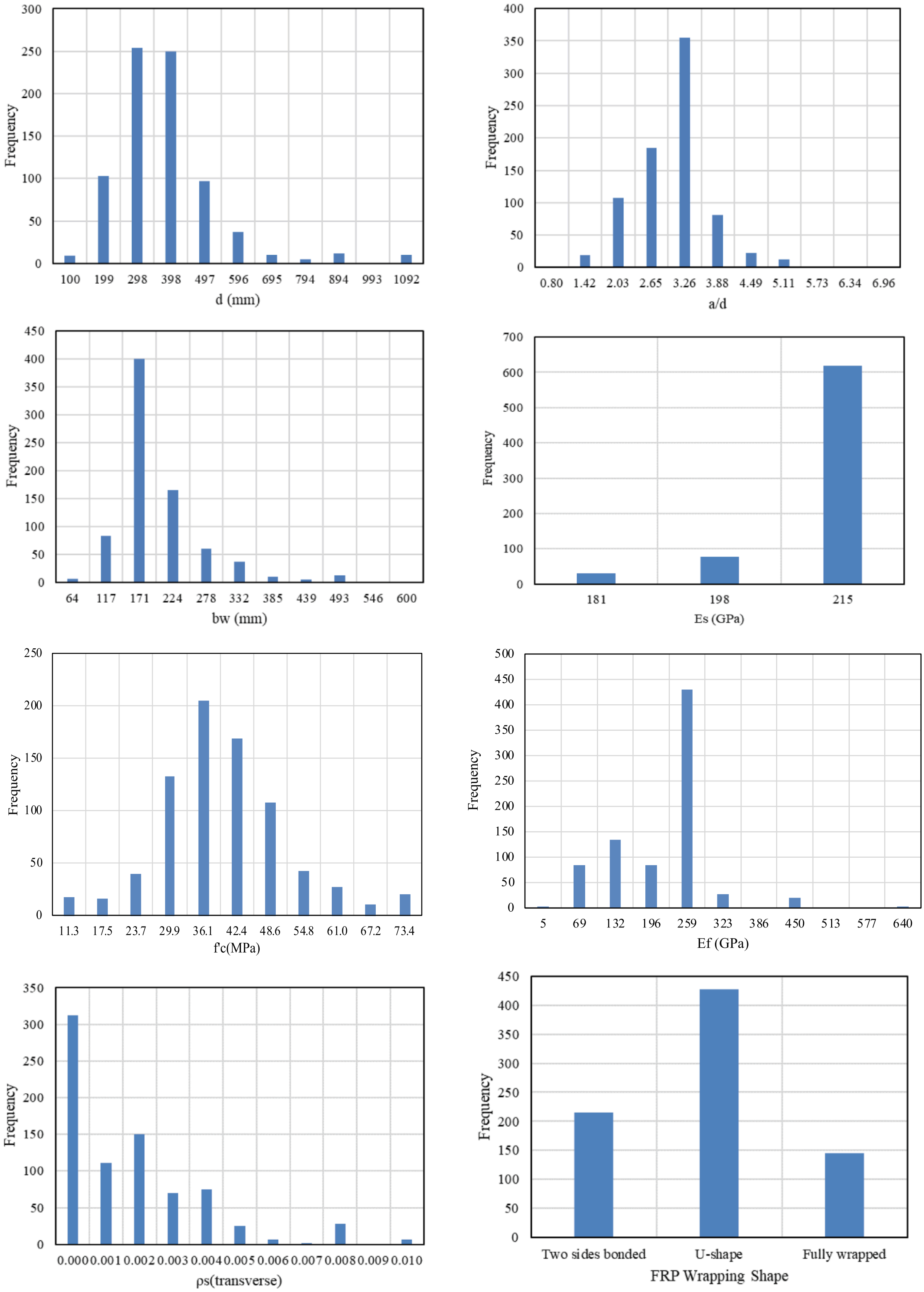


Fig. 1. The frequency distribution for the input variables

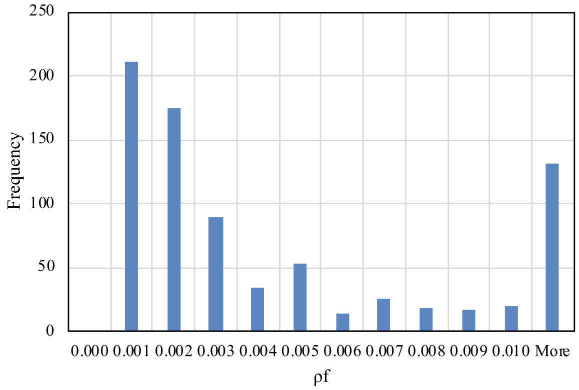


Fig. 1. (*continued*).

of RC rectangular and T-shape RC beams with three different FRP wrapping shapes is shown in Fig. 2.

One major challenge of generalized machine learning is overfitting [32,38]. To find a more accurate generalization, Banzhaf et al. [39] suggested to test the newly developed model based on a validation data set. Therefore, the data sets were categorized randomly as learning, validation, and testing subsets. Because learning and validation data are part of the modeling process, both data series are considered as one group namely "training data". Validation data were utilized to evaluate the performance capabilities of the proposed model in this study. The learning data were assigned for training purposes. The predictability performance of the ideal model was measured by utilizing the testing datasets. Multiple combinations of data categorizations including training and testing sets were checked to evaluate the consistency of data categorizations. In order to select the best combination, a threshold was determined based on the maximum, minimum, mean, and standard deviations. From a total of 785 datasets, 667 data vectors were assigned for the training process, which included 549 learning sets and 118 validation sets, while the remaining 118 vectors were employed to evaluate the derived model.

4.2. Performance measures

The two objectives of this study are the development of a simple model and identifying the best fitness values in the validation and learning steps to optimize modeling process. To achieve the best accuracy, an objective function is proposed [40], in which an estimate is acquired as a measure for comparing the model results with actual data. This objective function takes into account the influences of various data categories for the validation and training datasets. The finest GEP model can be derived using the multi-objective strategy [40,41] by minimizing the following function:

$$OBJ = w_T \cdot \rho_T + w_v \cdot \rho_V \tag{26}$$

$$w_T = \frac{n_T - n_V}{n} \; and \; w_V = 2\frac{n_V}{n} \tag{27}$$

where subscriptions of V and T are corresponding to the validation and training data, respectively. In Eq. (28), ρ represents the performance index which is calculated based on the relative root mean squared error (*RRMSE*). The correlation coefficient (R) can be calculated utilizing Eq. (30). The training and validation data are shown by T and V indices, respectively.

$$\rho = \frac{RRMSE}{1+R} \tag{28}$$

$$RRMSE = \frac{1}{|\overline{h_i}|}\sqrt{\frac{\sum_{i=1}^{n}(h_i - t_i)^2}{n}} \tag{29}$$

$$R = \frac{\sum_{i=1}^{n}(h_i - \overline{h_i})(t_i - \overline{t_i})}{\sqrt{\sum_{i=1}^{n}(h_i - \overline{h_i})^2 \sum_{i=1}^{n}(t_i - \overline{t_i})^2}} \tag{30}$$

where n is the number of samples, t_i is the estimated output, h_i is the measured (actual) outputs for i th output, and $\widehat{h_i}$ is the average of the measured output.

In order to measure the accuracy of the model, it is notable that the R coefficient cannot be used. Because there will not be any changes in the R coefficient if all output values of the proposed model shift equally. Therefore, the objective function was developed to simultaneously consider the effect of changes of the R coefficient and *RRMSE* components. Lower *RRMSE* and a higher R produce a lower ρ and OBJ which presents a more accurate model. The closer values of ρ to zero indicate that the model computes actual values precisely [40].

The complexity of the model is quantified by using the expressional complexity proposed by Smits and Kotanchek [42] and it is used as the other objective asneeds to be reduced.

4.3. Model development using GEP

The developed GEP-based model was utilized for predicting the shear strength of RC beamsstrengthened with FRP sheets. d, a/d, f'_c, b_w, f_y, E_f, ρ_f, ρ_s , and ε_{fe} are the eight input parameters were used to develop the most proper formula given to their theoretical contribution to the shear strength of RC beams. The GEP predictive algorithm involves various parameter settings as presented in Table 1. These parameter settings were determined after extensive trial and error, accumulated experience in past projects, and previous settings used in the literature [43–45].

Two GEP models were developed using the numerous FRP input parameters including d, a/d, b_w ,f'_c, f_y ρ_s, E_f ρ_f, and $\varepsilon_{fe,}$ where each parameter is expected to have an influence on the shear strength of RC beams strengthened with FRP. Several runs were conducted to obtain accurate GEP models using R and *RRMSE* to control the accuracy of the models.

The architectural parameters of GEP are defined as the quantity of genes per chromosome and head size. For each model, the number of genes and the head size can be used to determine the structure of terms. A linking function was utilized to connect the encoded mathematical term function for the genes greater than 1. For each target parameter, the common mathematical functions were used to develop the GEP models. Two GEP models were generated based on three sets of data namely, RC beams (1) with and without shear reinforcement, (2) without transverse reinforcement, and (3) with shear reinforcement. The models with the highest R and lowest *RRMSE* were selected among the generated models for each data set.

The best GEP models for each dataset obtained based on the above-mentioned criteria. Fig. 3a, b, and c present the ETs for RC beams with and without shear reinforcement, RC beams without shear

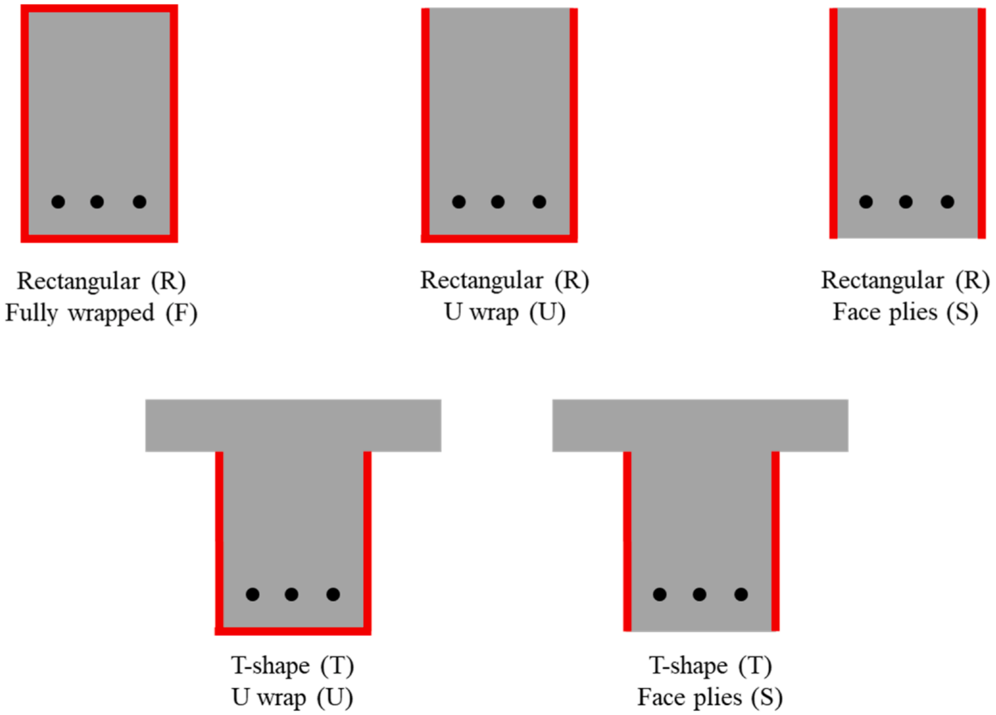


Fig. 2. Schematic drawings of the cross-section of RC beams and FRP wrapping shapes

reinforcement and RC beams with shear reinforcement, respectively.

Model I ($V_{T,GP\ I}$) is a generalized model which incorporated the geometric properties of RC beams as well as the material properties of concrete, shear reinforcement, and the FRP sheets. The developed GEP-based formulation of total shear strength of RC beams strengthened with FRP sheets (V_T) is a function of d, a/d, f'_c, b_w, $f_y\ \rho_f$, $E_f\ \rho_f$, and ε_{fe} . This model is developed based on the reported test data on RC beams with and without shear reinforcement.

The second model ($V_{T,GP\ II}$) takes a further step to determine the total shear strength of RC beams with FRP sheets without and with shear reinforcement with separate models. Model II is a function of d, a/d, f'_c, b_w, E_f, ρ_f, and ε_{fe} for RC beams without shear reinforcementand is a function of d, a/d, f'_c, b_w, $f_y\ \rho_s$, and $E_f\ \rho_f$ for RC beams with shear reinforcement. It should be noted that the FRP wrapping shape parameter (ε_{fe}) was considered during the process of the development of $V_{T,GP\ II}$ (with shear reinforcement). However, this parameter was eliminated from the GEP model for simplicitydue to the low importance of ε_{fe} among the other parameters (1%). The variable importance was calculated using commercially available software, GeneXproTools [46]. Table 2 shows the variable importance (%) for the two GEP models. The high importance level of the beam depth (d) for $V_{T,GP\ II}$ (with shear reinforcement) ,can be attributed to the size effect in shear strengthened RC beam with shear reinforcement [47,48].

$$V_{T,GPII} = \begin{cases} \text{A) Without shear reinforcement} \\ \left| d + (\varepsilon_{fe})^{\frac{1}{3}} (\varepsilon_{fe} - 3.75) \left(\left(\frac{a}{d} \right)^2 d f'_c \right)^{\frac{1}{2}} - 7505.95 \left(\left(\frac{a}{d} \right) b_w^2 (\varepsilon_{fe})^3 \right) - 6.49 \left(b_w^4 (E_f \rho_f) (\varepsilon_{fe})^5 \left(\left(\frac{a}{d} \right) - f'_c \right) \right) \right| \\ \text{B) With shear reinforcement} \\ \left| d - 62.87 \left(\frac{a}{d} \right) - \frac{11.94\, d}{(E_f \rho_f)} + 0.00177 (b_w (b_w - 153.55)) - (f_y \rho_s)^3 + 1.25 (f'_c (f_y \rho_s + 0.718)) \right| \end{cases} \tag{31b}$$

The GEP-based equations are given in Eq. (31a) and Eq. (31b). The constants used in the developed models are calculated as model outputs by on the gene expression programming to provide the best fit to the reported experimental data. The effective strain in FRP (ε_{fe}) can be calculated based on ACI 440.2R [141].

$$V_{T,GP\,I} = \left| d + b_w - 13.95 \left(\left(\frac{a}{d} \right)^3 d^2 \right)^{\frac{1}{5}} - 1.92 \left(\left(\frac{a}{d} \right) b_w^2 \right)^{\frac{1}{3}} + 0.867 f'_c (f_y \rho_s) + 1.1868 (d\, b_w^2 f'_c) (E_f \rho_f) (\varepsilon_{fe})^4 \right| \tag{31a}$$

where:

$\varepsilon_{fe} = 0.004 \leq 0.75\varepsilon_{fu}$ for fully wrapped FRP

$\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \leq 00.004$ for U-shape and side FRP wrapping

$$\kappa_v = \frac{k_1 k_2 L_e}{11900\varepsilon_{fu}} \leq 0.75$$

$$L_e = \frac{23300}{(n_f t_f E_f)^{0.58}}$$

Table 1
Parameter settings for the GEP algorithm

Parameter settings	Setting
Function set	$+$, -, $\times$, /, $\sqrt{}$, $\sqrt[3]{}$, $\sqrt[4]{}$, $\sqrt[5]{}$, ˆ2, ˆ3, exp, ln, mul3[a], mul4[b]
Population size	100-500 (200[c])
Number of generations	100,000-1,000,000
Maximum number of genes allowed in an individual (G_{max})	2-3
Maximum tree depth (D_{max})	5
Tournament size	10% of the population
Pareto Tournament	30% of tournaments
Crossover events	0.85
High-level crossover	0.2
Low-level crossover	0.8
Mutation events	12
Sub-tree mutation	9
Replacing input terminal with another random terminal	0.05
Gaussian perturbation of randomly selected constant	0.05
Direct reproduction	0.05
Ephemeral random constants	[-10,10]

[a] mul3 means the product of three factors.
[b] mul4 means the product of four factors.
[c] Bold set is the final set.

$$k_1 = \left(\frac{f'_c}{27}\right)^{2/3}$$

$$k_2 = \begin{cases} \dfrac{d_f - L_e}{d_f} U - wraps \\ \dfrac{d_f - 2L_e}{d_f} Two\ sides \end{cases}$$

A comparison of the predicted shear strength by GEP Models I and II with the experimental results is shown in Fig. 4. *RRMSE, R* and ρ were calculated for the proposed models in the current study. The obtained *RRMSE, R* and ρ for model one ($V_{T,GP\ I}$) were 0.453, 0.883, and 0.240, for model two ($V_{T,GP\ II}$) were 0.330, 0.940, and 0.170, respectively. The criteria for comparing the calculated metrics for the proposed models are discussed in the next section thoroughly. Comparing the calculated metrics for the proposed models indicates that the second models ($V_{T,GP\ II}$) estimates the total shear strength more accurately. The developed models in this research study are limited to the considered range of parameters. Further studies are recommended for the beams with properties out of the considered range of the parameters in this study and with special applications.

Figs. 5 to 7 demonstrate the experimental to the calculated shear strength ratio values against the considered parameters in Models I and Model II without and with shear reinforcement, respectively. It is anticipated that the accuracy of the models can be decreased due to the increase in the level of the scattering. As shown in Figs. 5 to 7, there is not any significant trend as the parameters scatter. The distribution decreases slightly as d, a/d, f'_c, b_w, and $E_f\rho_f$ increases for the models. Also, it should be noted that the properties of utilized RC beams for the experimental studies (used to develop the experimental studies) have a higher frequency for a certain range of parameters. For instance, RC beams with a beam depth (d) range of 100 mm to 400 mm have a higher frequency. More than 75% of the test data are obtained from testing of the slender beams with $a/h > 2$ [17]. Thus, the developed models can be used to estimate the shear strength of deep and slender beams with the stated accuracy. The obtained outcomes in the following sections confirm the accuracy of the developed models in the current study.

4.4. Model validity

The GEP models should have $R > 0.8$ to predict the values close to measured values accurately [49]. The excellent performance of the model was indicated by a ρ value closer to zero (e.g., less than 0.2). In Table 3, the validation criteria, and results from GEP models are presented. In the table, the R and ρ values for Models II are more and less than 0.8 and 0.2, respectively. Usually, the proposed models created by machine learning methods can be used for all datasets that were assessed for the model development. To further assess the validity of the model, the criteria developed by Golbraikh and Tropsha [50] were considered, which suggests that the minimum of the slope of one regression line (k or k') through the origin should be close to 1 and the performance indices of m and n should be less than 0.1. Roy and Roy [51] introduced a confirmation indicator (R_m) of the external predictability of models, whereby $R_m > 0.5$ satisfies the condition (indicates good predictability). Additionally, both the coefficient between predicted and experimental values (R_0^2) and the squared correlation coefficient between experimental and predicted values (R_0^2) should be close to 1 [31].

Table 4 presents the validity of the developed models, demonstrating that GEP Models I and II match the requirements. Also, the validation criteria such as R and $RRMSE$ are presented for the existing models in the literature [8,14,34,35,52,141] in Table 4. The calculated metrics indicate that Model II has the highest R and the lowest $RRMSE$ and ρ values. The remaining parameters are within (or close to) the recommended range.

4.5. Parametric study

A parametric study was conducted to assess the reliability of the designed equations (Model I and II). The tendency of the total shear strength RC beams strengthened with FRP sheets to the variation of design parameters namely d, a/d, f'_c, b_w, $E_f\rho_f$, and $f_y\rho_s$ are illustrated in Figs. 8 to 10, and for Model I and Model II without and with shear reinforcement, respectively.

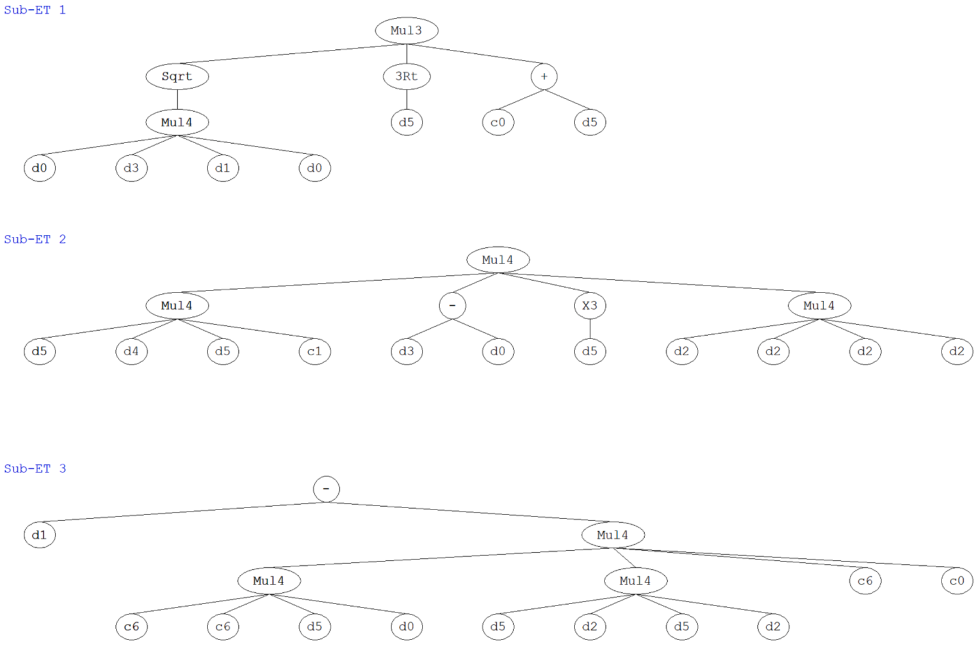
Reviewing all the results presneted in Fig. 8 to Fig. 10, the results are generally expected cases from a structural engineering standpoint. A similar trend was observed for the estimated total shear strength of RC beams strengthened with FRP sheets using Models I and II (Figs. 8 to 10, respectively). As shown in Figs. 8 to 10, the total shear strength predicted by Models I, and Model II (without and with shear reinforcement) increases by amplifying the values of d and b_w due to the increase in the area of the concrete. Similarly, the shear strength decreased at higher values of a/d ratios since beams are more flexural dominant. The shear strength of RC beams increased due to an increase in the compressive strength of concrete (f'_c). For $E_f\ \rho_f$ in Model II (with shear reinforcement), the shear strength of RC beams increased at lower values and remained almost constant at higher values. The lower shear strength change rate at higher values is due to the limitation of the experimental tests on the shear strength of the strengthened RC beams with higher f'_c, $E_f\rho_f$ and $f_y\rho_s$ to optimize the models. However, the shear strength raises by increasing the $E_f\ \rho_f$ in Model I and II. The shear strength of RC beams increased due to an increase in $f_y\ \rho_s$ for Models I and Model II (with shear reinforcement).

4.6. Sensitivity analysis

Sensitivity analysis is a robust tool for weighing the contribution of each predictor variable in the developed models which determines how the total shear strength of RC beams is influenced based on the changes in other variables like beam depth, concrete compression strength, and span to beam depth ratio. By utilizing sensitivity analysis vital input variables can be selected. To assess the influence of each predictor variable on the total shear strength of RC beams strengthened with FRP sheets, the sensitivity analysis process offered by Gandomi et al. [53] was used. By using Eq. (32) and Eq. (33), the sensitivity of calculated strengths to each parameter was calculated.

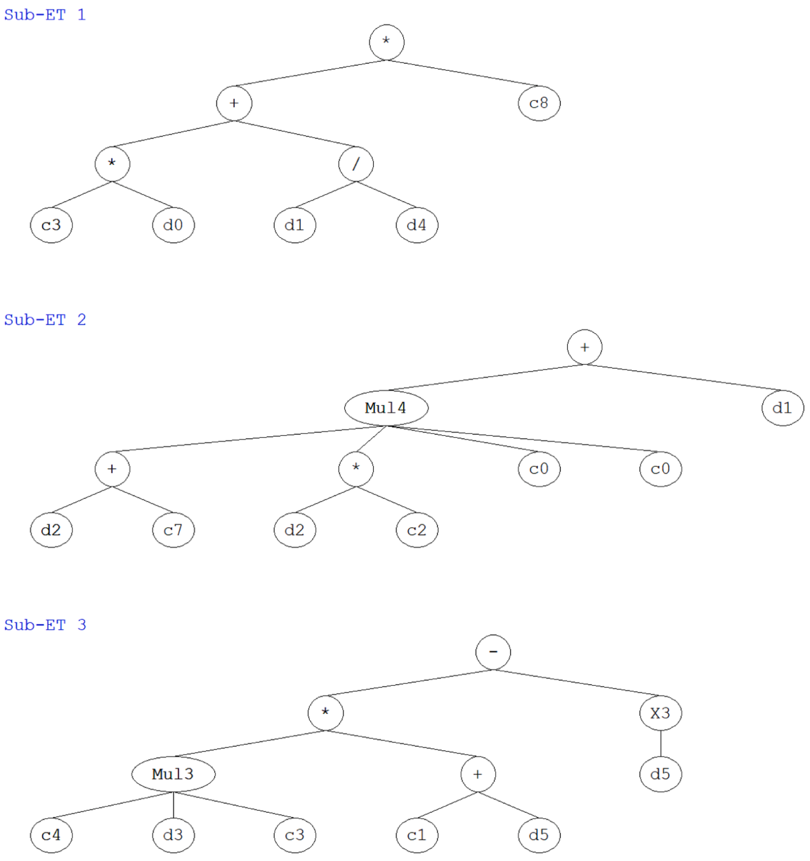
$$N_i = f_{max}(x_i) - f_{min}(x_i) \tag{32}$$

(a) Tree expression of Model I developed based on test results of RC beams with and without shear reinforcement. Note: d(0) = a/d, d(1)= d, d(2) = b_{web} , d(3) = f'c, d(4) = $E_f\ \rho_f$, d(5) = $f_y\ \rho_s$, d(6) = ε_{fe}, c = constants, 5Rt = 5th root, Mul4= multiplication of four terms, 3Rt = 3rd root



(b) Tree expression of Model II, without shear reinforcement developed based on test results of RC beams without shear reinforcement. Note: d(0) = a/d, d(1)= d, d(2) = b_{web} , d(3) = f'c, d(4) = $E_f\ \rho_f$, d(5) = ε_{fe}, c = constants, Mul3= multiplication of three terms Sqrt= 2nd root , 3Rt = 3rd root, Mul4= multiplication of four terms

Fig. 3. Best GEP models (for each dataset) tree representation for shear strength of RC beams with FRP sheets developed based on the RC beams' tests results (a) for Model I, (b) Model II without shear reinforcement, and (c) Model II with shear reinforcement.



(c) Tree expression of Model II, with shear reinfocement developed based on test results of RC beams with shear reinforcement. Note: d(0) = a/d, d(1)= d, d(2) = b_{web} , d(3) = f'c, d(4) = $E_f\ \rho_f$, d(5) = $f_y\ \rho_s$, d(6)= ε_{fe}, c = constants, Mul4= multiplication of four terms, Mul3= multiplication of three terms

Fig. 3. (*continued*).

Table 2
The variable importance for the generated GRP models

Variable	GEP Models		
	$V_{T,GP\ I}$	$V_{T,GP\ II}$ (without shear reinforcement)	$V_{T,GP\ II}$(with shear reinforcement)
a/d	3.35	3.65	8.49
d	24.30	12.33	61.74
b_w	13.28	27.30	20.58
f''_c	1.19	2.99	2.09
$E_f\rho_f$	28.41	24.57	2.89
$f_y\rho_s$	1.60	-	4.21
ε_{fe}	27.88	29.16	-

$$S_i = \frac{N_i}{\sum_{J=1}^{n} N_j} \times 100 \tag{33}$$

where $f_{min}(x_i)$ and $f_{max}(x_i)$ represent the minimum and maximum calculated strengths over the i^{th} input domain, and other variables are fixed at their mean values. The sensitivity of the parameters for the two models is shown in Fig. 11.

The sensitivity analysis results (shown in Fig. 11) indicated that the depth of RC beams and consequently the depth of FRP strip along the height of the beam have the highest influence (sensitivity > 40) on the total shear strength of the RC beams in the proposed models. Beam width (b_w) and span to beam depth ratio (a/d) ratio are the second and third most effective parameters in the total shear strength of RC beams. The shear reinforcement ($f_y\ \rho_s$) has a low sensitivity compared to d or b_w to the shear strength of the RC beams strengthened with FRP sheets. RC beams with shear reinforcement have the highest sensitivity to d (see Fig. 11c) which can be attributed to the size effect on the shear strength of RC beams.

4.7. Comparative study

The *RRMSE, R*, and ρ parameters for both experiment and proposed models are compared in Table 4. A model can deliver results with high accuracy with high R values and low *RRMSE*, in which the performance

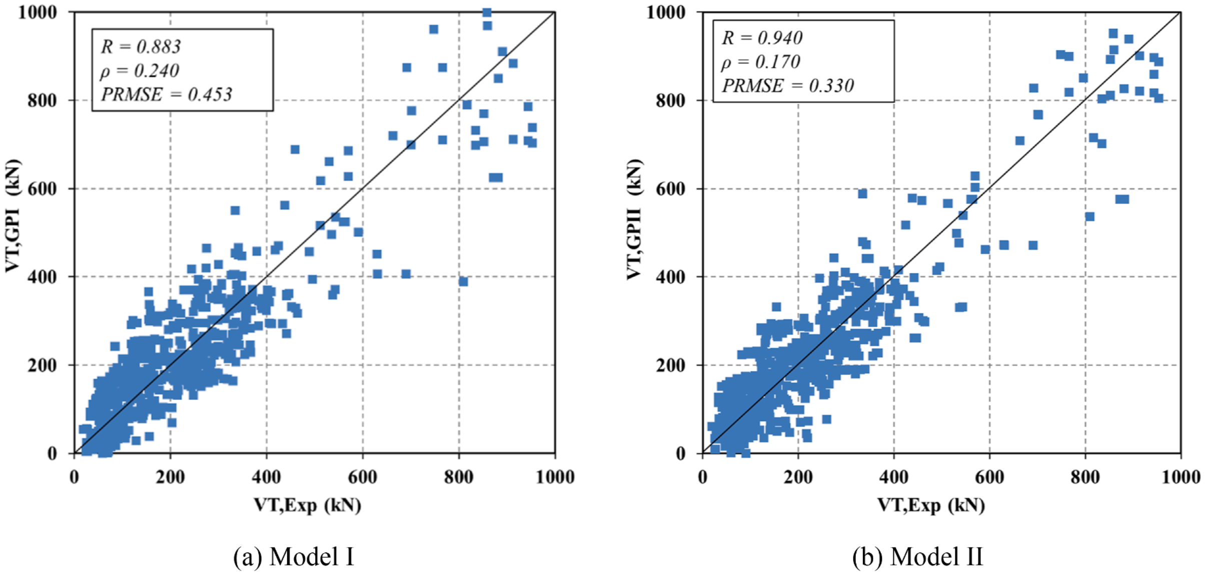


Fig. 4. Experimental against the calculated efficiency ratio using the GP prediction results for (a) Model I, and (b) Model II

index ρ involves both mentioned issues. As it is shown in Table 4, the GEP models outstand among other models. In calculating the total shear strength of the experimental data points using the existing models in the literature, if the models for the strength estimation of RC beams for concrete (V_c) and steel (V_s) were not available, the models recommended by ACI 318 [17] were utilized for the strength estimation. The performance levels for the proposed GEP models are superior to the other models.

Most of the advanced analytical models developed for the calculation of shear strength of RC beams with FRP sheets are listed in Table 4 are not utilized extensively in design codes. However, these models are developed in a format that their principal components are mathematically coupled. It is necessary to decouple these components in order to correlate the shear strength contribution of FRP and the main input variables.

For input parameters, the mechanical properties of concrete should be input into conventional models. Experimental tests are required to obtain the mechanical properties of concrete. These tests are time-consuming and expensive. The developed GEP models in the current study can predict the shear capacity contribution of FRP sheets without requiring conducting expensive experimental efforts. Moreover, the developed GEP models have the ability to obtain explicit relationships without assuming prior relations.

Lately, expert systems such as GEP have been introduced to carry out the design stages for civil engineering projects efficiently. For any experimental test or fieldwork usually, the properties of aimed output as intial estimations are inaccurate. Therefore having an accurate enough initial estimation of the outcome can be very helpful before conducting any task [21,54]. Since the models are developed based on data alone, it is suggested to use the proposed models for the first stages of design or as a supplement to common engineering software or design approaches. However, the sensitivity of GEP to parameter tuning is considered a limitation related to GEP. Utilizing the different forms of optimally controlling parameters of the run can develop its performance.

5. Conclusions

The application of FRP sheets is a common method to retrofit and improve the capacity of RC beams. Prediction models with a high level of accuracy are necessary to calculatethe capacity for the components of RC structures. To formulate the shear strength of reinforced concrete beams strengthened with FRP sheets, an evolutionary machine learning approach, called GEP, is suggested. The developed model can be used to obtain an accurate estimation of the shear strength for RC beams with FRP sheets. The models are developed based on the extensive database gathered from the literature. The models were validated through several validation phases in order to ensure the accuracy and performance. The comparative study indicated that the generated GEP models have higher accuracy compared to the existing models in the literature. Correlation coefficients (R) equal to 0.883 and 0.940 were obtained for the generated GEP models I and II, respectively. These models have performance indexes (ρ) of 0.240 and 0.170, respectively. A parametric study was conducted to evaluate the sensitivity of the variables to the total shear strength of the RC beams. The obtained results from the parametric study indicated that the RC beam depth (or FRP sheets' depth) has the most influence on the total shear strength of RC beams strengthened with FRP sheets. The estimated total shear strength using the proposed models increased with an increase in the beam depth. The developed models in this study deliver more accurate outcomes than the existing models in the literature. Moreover, unlike other conventional modeling methods, the GEP method can formulate the shear strength of RC beams without any assumptions or simplifications. Therefore, using the GEP models helps to avoid the experimental tests to estimate the shear strength of the RC beams with FRP sheets.

CRediT authorship contribution statement

Ataollah Taghipour Anvari: Writing – original draft, Validation, Formal analysis, Investigation, Visualization. **Saeed Babanajad:** Validation, Investigation, Writing – review & editing, Supervision. **Amir H.**

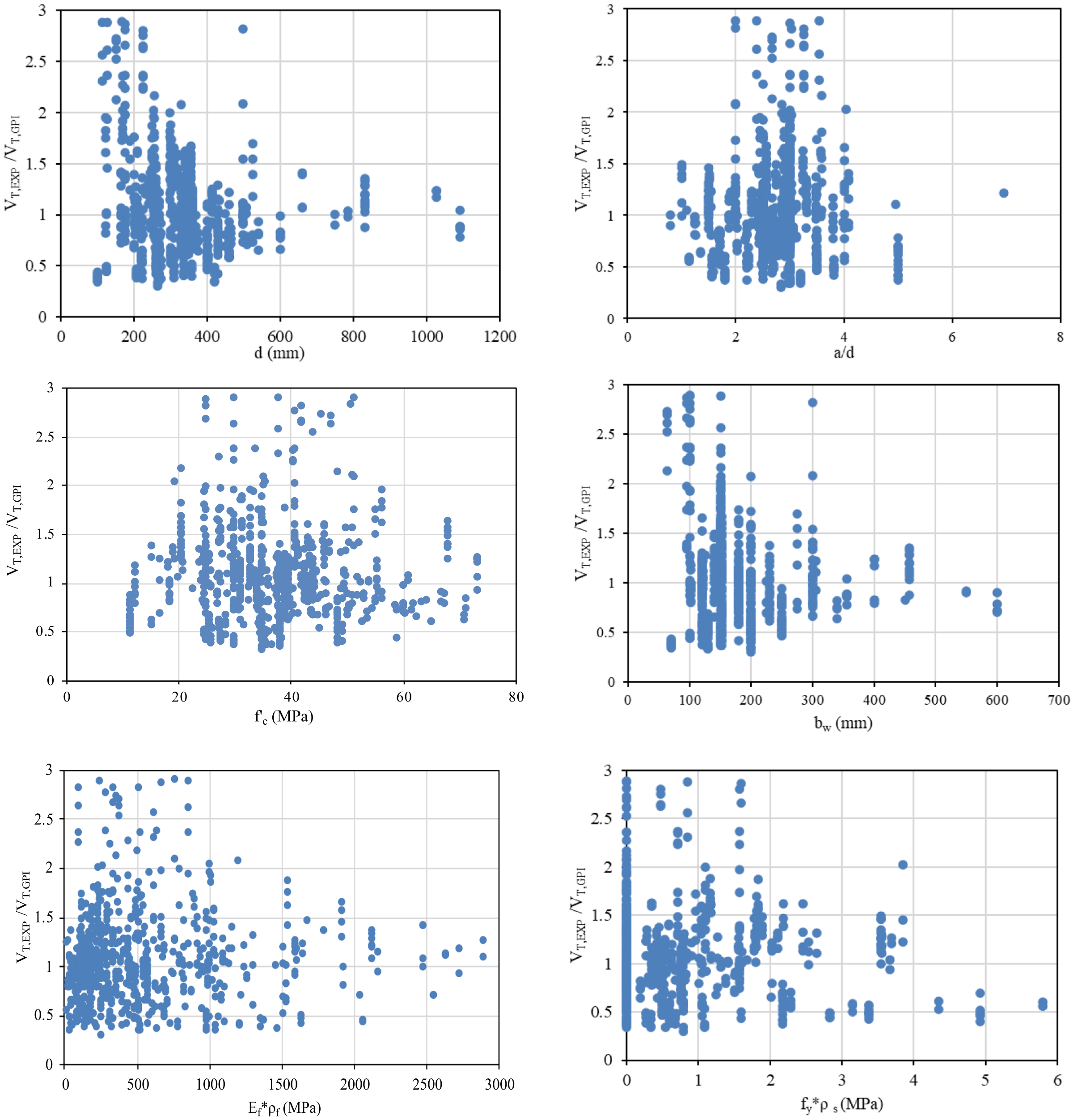


Fig. 5. The ratio between the calculated and experimental shear strengths with regard to all input parameters for Model I

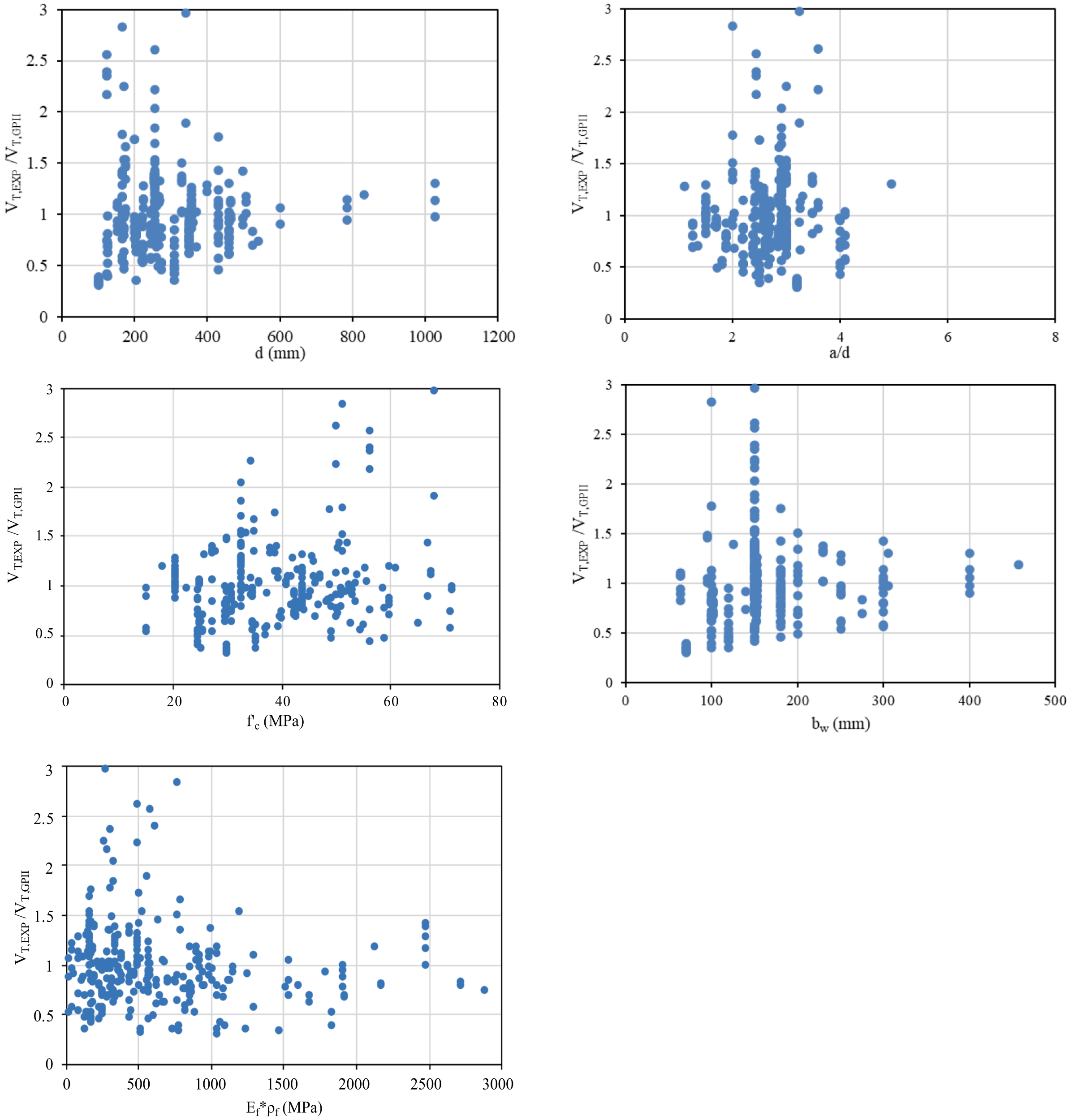


Fig. 6. The ratio between the calculated and experimental shear strengths with regard to all input parameters for Model II, without shear reinforcement

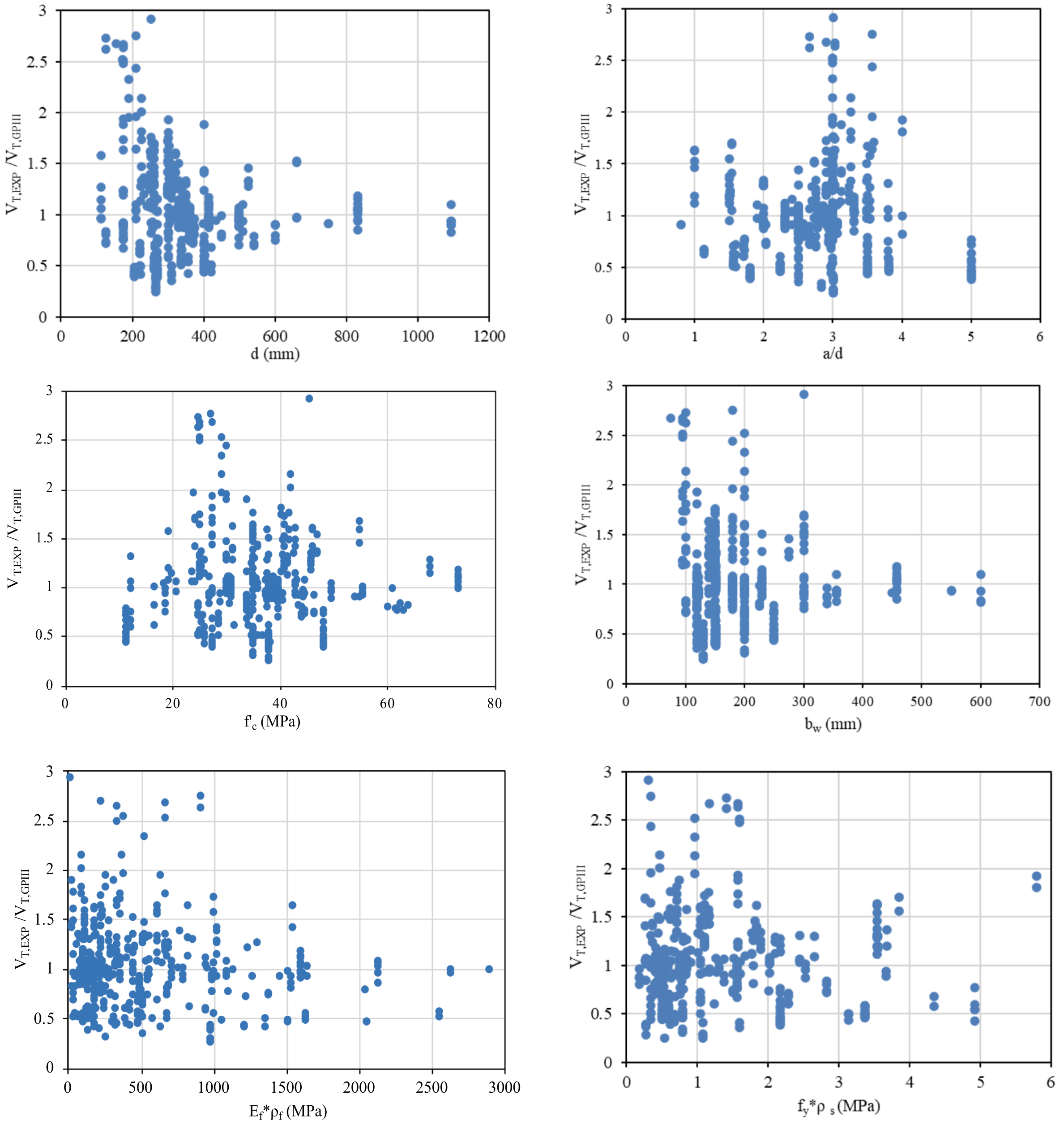


Fig. 7. The ratio between the calculated and experimental shear strengths with regard to all input parameters for Model II, with shear reinforcement

Table 3
Comparison of the validation criteria for the proposed models in the current study with the existing models’.

Item	Formula	Condition	Model I $V_{GP\ I}$	Model II $V_{GP\ II}$	Khalifa (1999) [52]	Triantafillou (1998) [14]	Triantafillou (2000) [34]	Khalifa (1998) (effective strain) [35]	Khalifa (1998) (bond mechanism) [35]	ACI 440.2R-17 [141]	Adhikary (2004) [8]
1	R	$R > 0.8$	0.883	0.940	0.497	0.794	0.743	0.449	0.754	0.793	0.747
2	RRMSE		0.453	0.330	2.041	0.597	0.858	2.818	0.646	0.598	0.669
4	ρ	$\rho < 0.2$	0.240	0.170	1.363	0.333	0.492	1.944	0.368	0.333	0.383
5	$k = \frac{\sum_{i=1}^{n} h_i \times t_i}{\sum_{i=1}^{n} h_i^2}$	$0.85 < k < 1.15$	0.884	0.956	1.241	0.768	0.426	1.418	0.777	0.792	0.767
6	$k' = \frac{\sum_{i=1}^{n} h_i \times t_i}{\sum_{i=1}^{n} t_i^2}$	$0.85 < k' < 1.15$	1.011	0.987	0.341	1.064	1.804	0.238	1.008	1.029	1.002
7	$R_m = R^2 \times (1 - \sqrt{\lvert R^2 - R_O^2\rvert})$	$R_m > 0.5$	0.442	0.588	0.044	0.315	0.282	0.047	0.246	0.298	0.236
8	$m = \frac{R^2 - R_O^2}{R^2}$	$\lvert m\rvert\langle 0.1$	-0.241	-0.127	-2.735	-0.397	0.433	-2.908	-0.565	-0.439	-0.597
9	$n = \frac{R^2 - R_{O'}^2}{R^2}$	$\lvert n\rvert\langle 0.1$	-0.282	-0.131	0.614	-0.573	1.634	2.028	-0.759	-0.588	-0.794
	where										
	$R_O^2 = 1 - \frac{\sum_{i=1}^{n}\left(t_i - h_i^o\right)^2}{\sum_{i=1}^{n}\left(t_i - \overline{t}\right)^2} h_i^o, h_i^o = k \times t_i$		0.968	0.996	0.924	0.880	0.313	0.789	0.890	0.905	0.890
	$R_{O'}^2 = 1 - \frac{\sum_{i=1}^{n}\left(h_i - t_i^o\right)^2}{\sum_{i=1}^{n}\left(h_i - \overline{h}\right)^2} t_i^o, t_i^o = k' \times h_i$		1.000	1.000	0.095	0.991	-0.350	-0.208	1.000	0.998	1.000

Table 4
Comparison of performance for variousmodels

ID	Researcher	*RRMSE*	*R*	*ρ*
1	Model I - $V_{GP\ 1}$	0.453	0.883	0.240
2	Model II - $V_{GP\ 1I}$	0.330	0.940	0.170
3	Khalifa (1999) [52]	2.041	0.497	1.363
4	Triantafillou (1998) [14]	0.597	0.794	0.333
5	Triantafillou (2000) [34]	0.858	0.743	0.492
6	Khalifa (1998) (effective strain) [35]	2.818	0.449	1.944
7	Khalifa (1998) (bond mechanism) [35]	0.646	0.754	0.368
8	ACI 440.2R-17 [141]	0.598	0.793	0.333
9	Adhikary (2004) [8]	0.669	0.747	0.383

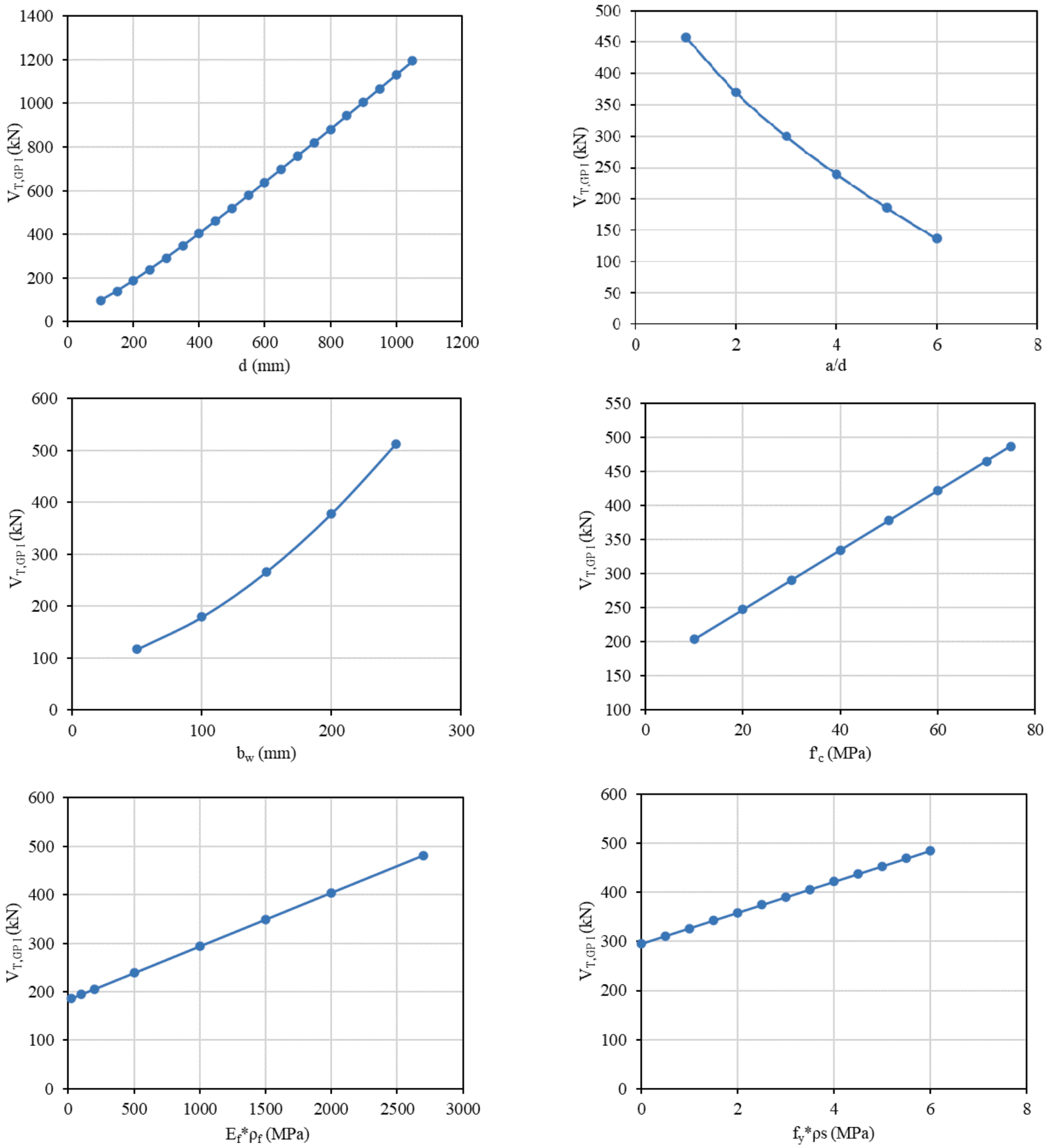


Fig. 8. Total shear strength of RC beams with FRP predicted using Mode I

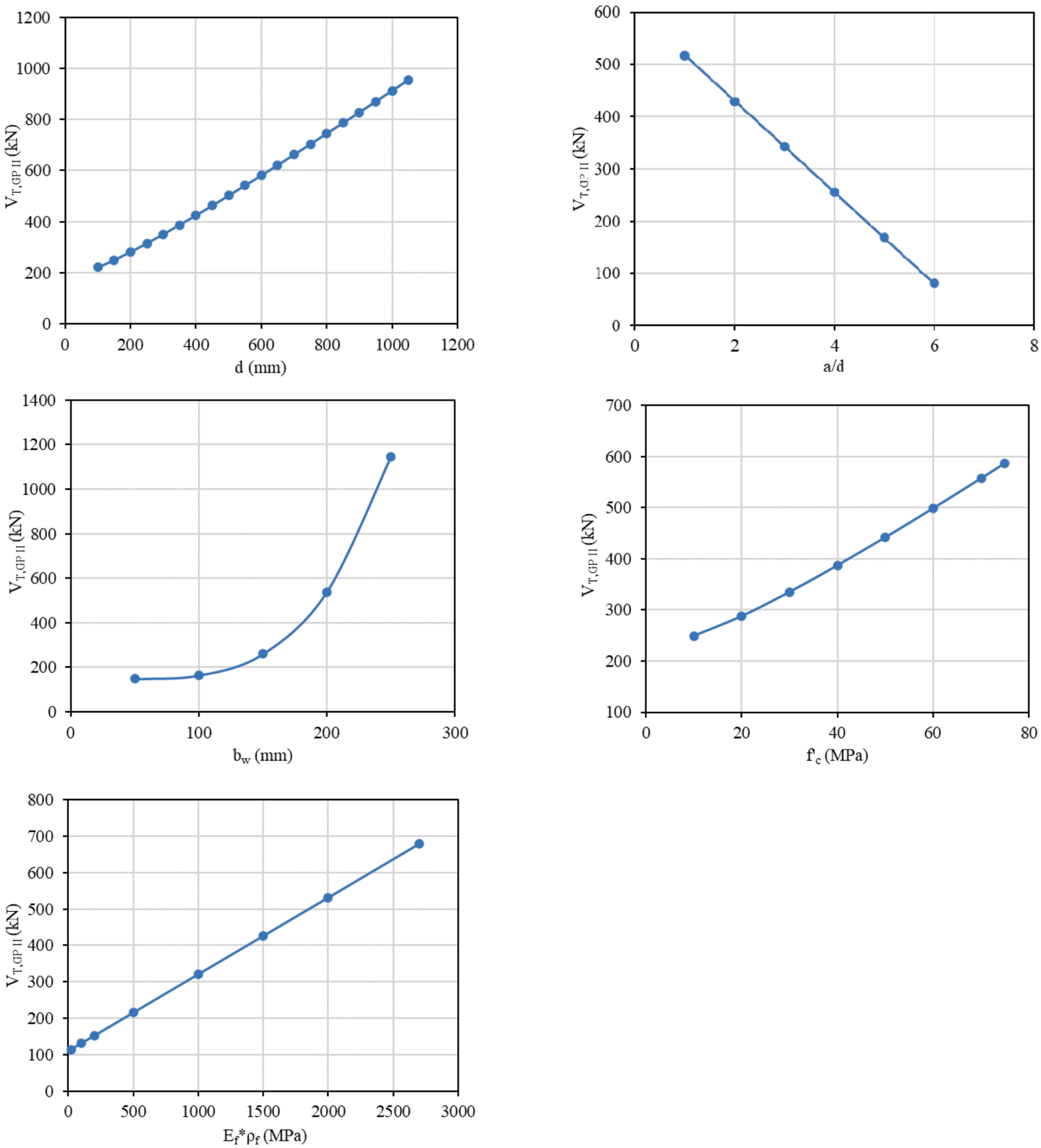


Fig. 9. Total shear strength of RC beams with FRP predicted by Mode II (without shear reinforcement)

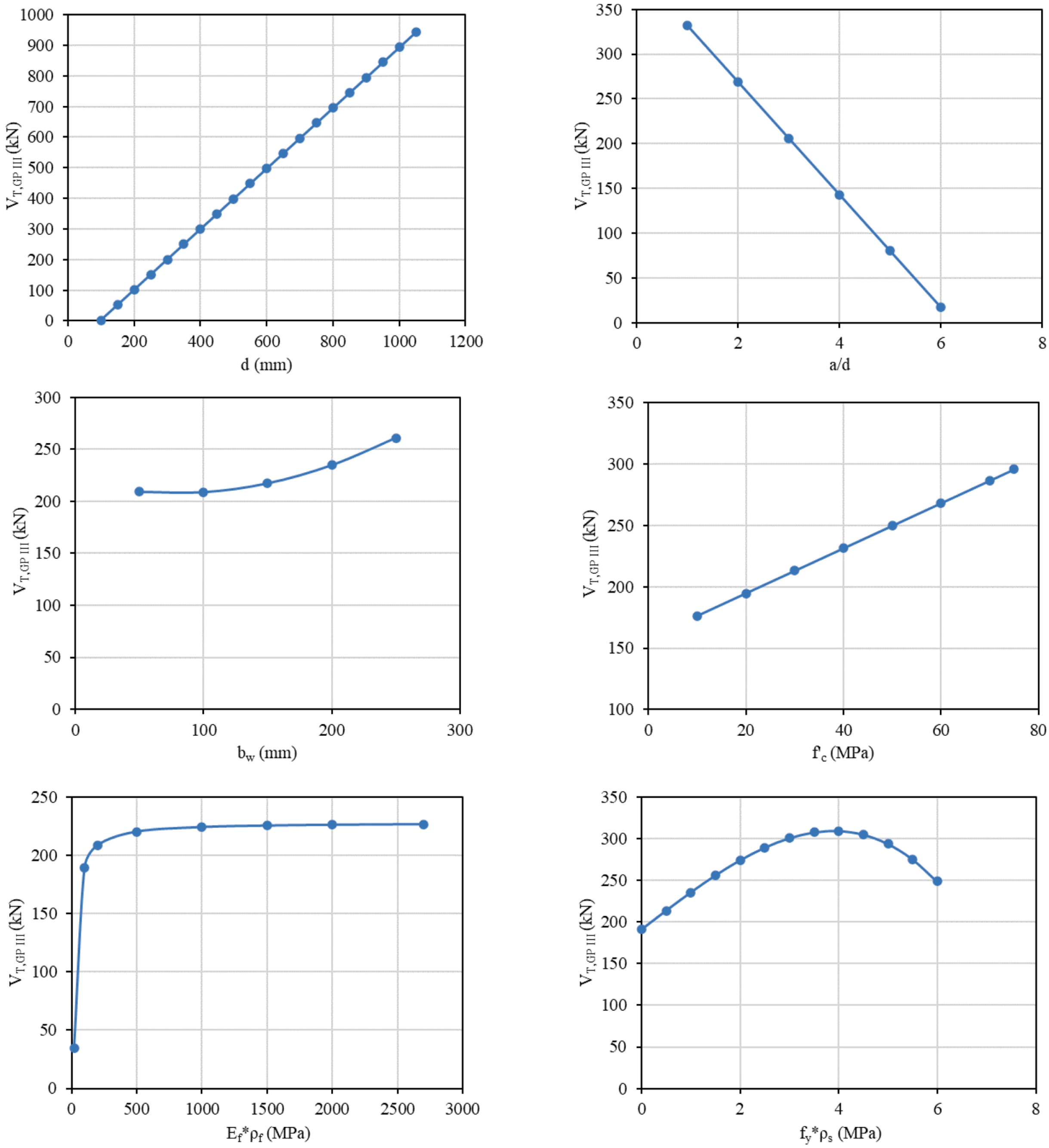
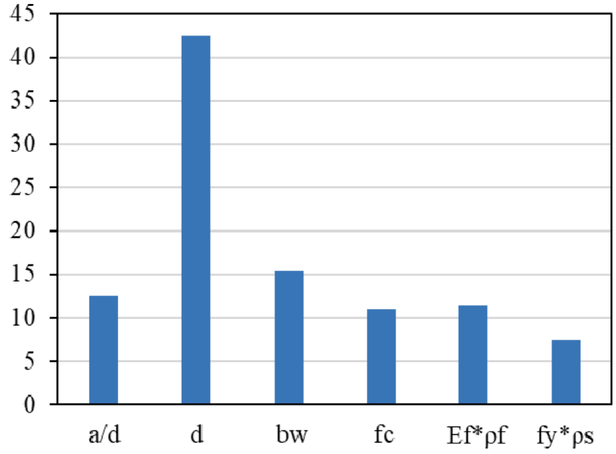
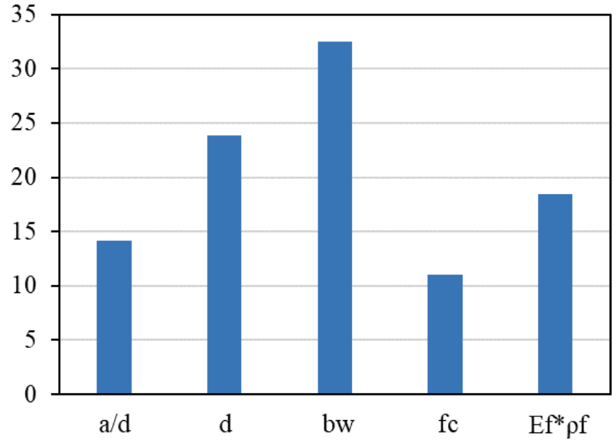


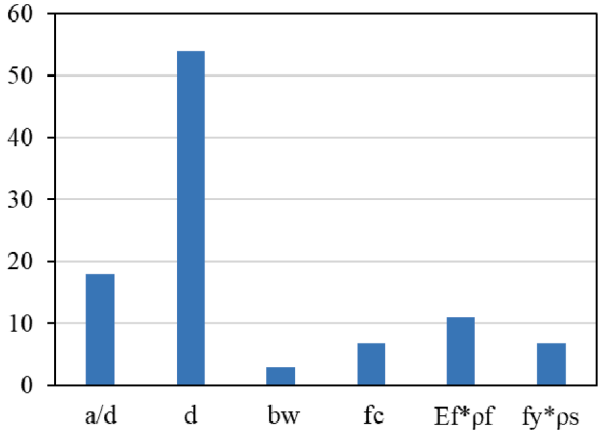
Fig. 10. Total shear strength of RC beams with FRP predicted by Mode II (with shear reinforcement)



(a) Model I



(b) Model II, without shear reinforcement



(c) Model II, with shear reinforcement

Fig. 11. Sensitivity of the parameters in (a) Model I, (b) Model II, without shear reinforcement and (c) Model II, with shear reinforcement

Gandomi: Conceptualization, Methodology, Supervision, Project administration.

Declaration of Competing 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.

Data availability

The developed database is being used for ongoing research projects and will be available upon completion.

Appendix

The range of the parameters for the experimental studies on strengthened RC beams with FRP sheets gathered from the existing studies is presented in Table A1 and Table A2.

Table A1
FRP sheets and concrete material properties and beams’ geometrical properties

	Reference	Type^{1}	a/d	d	bw	fy	ρ_s	f'_c	E_f	FRP Configuration^{2}		t_f	w_f	s_f	ρ_f
			-	mm	mm	MPa	$\times10^{-3}$	MPa	GPa			mm	mm	mm	$\times10^{-3}$
1	Berset (1992) [55]	R	3.81	79	114	400	0-5.51	42.9	16.80	S	C	0.64-1.60	0	0	11.2-28.1
2	Uji (1992) [56]	R	2.50	170	100	-	0	24.6-27.4	230	W-S	C	0.10-0.19	0	0	1.9-3.9
3	Al-Suleimani et al. (1994) [57]	R	3.54	113	150	450	1.88	37.7	15.4	S-U	C- D	3.00	0-20	0-50	16.0-40.0
4	Chajes et al. (1995) [58]	T	2.67	152	63.5	-	0	41.8-61.9	11.00-21.00	U	C	0.46-1.04	0	0	14.5-32.8
5	Sato (1996) [59]	R	2.70	260	200	-	0	37.5-45.2	230	S-U	C-D	0.11	0-30	0-60	0.55-1.10
6	Araki et al. (1997) [60]	R	1.56	336	200	366	1.64-13.09	21.0-26.1	87-230	F	C-D	0.11-0.22	0-120	0-180	0.24-1.44
7	Funakawa et al. (1997) [61]	R	2.50	510	600	400	1.30	30.7	240	W	C	0.167-0.501	0	0	0.56-1.67
8	Miyauchi et al. (1997) [62]	R	2.00-3.00	165	125	-	0	32.4-39.1	230	W	D	0.111	50	100-250	0.36-0.89
9	One et al. (1997) [63]	R	1.54	260	300	358	0.75	24.3	230-248	W	C	0.11-0.22	0	0	0.73-1.47
10	Kamiharako et al. (1997) [64]	R	1.67-2.50	400-600	250-400	-	0	32.6-34.6	90-244	W	D	0.11-0.169	40	100	0.22-0.54
11	Sato (1997) [65]	T	2.50	240	150	396	6.70	35.3-35.9	230	U	C	0.111	0	0	1.48
12	Täljsten (1997) [66]	R	2.17-3.48	460	180	-	0	48.50-65.20	65.60-100.60	S	C-D	0.8-2	0-50	0-100	6.29-22.22
13	Taerwe et al. (1997) [67]	R	2.98	420	200	486	0.71-1.41	35-38.40	280	U-W	C-D	0.11	0-50	0-400	0.14-1.10
14	Umezu et al. (1997) [68]	R	2.94-3.11	253-499	150-1100	-	0-4.76	38-45.60	73-244	F	C-D	0.044-0.288	0-100	0-200	0.29-1.92
15	Adey et al. (1998) [69]	R	2.03	370	200	400	0-3.77	46.4	230	S-F	C	0.13	0	0	1.30
16	Chaallal et al. (1998) [70]	R	2.73-2.86	210-220	150	400	1.88-7.54	35	150	S	D	1.00	50	100-150	6.29-6.67
17	Khalifa et al. (1999) [52]	R	3.59	255	150	460	0-8.38	20.5-50	228	U-F	C-D	0.17-0.33	0-50	0-125	0.88-4.40
18	Mitsui et al. (1998) [71]	R	1.14-1.59	220	150	400	2.62	28.5	230	F	C	0.17	0	0	2.23
19	Triantafillou (1998) [14]	R	3.20	100	70	-	0	30	235	S	D	0.16	30-60	60	2.21-6.26
20	Grace et al. (1999) [72]	R	5.00	270	152	500	4.35	48.26	12.5-230	S-U	C	0.5-3.9	0	0	6.58-52.63
21	Khalifa and Nanni (2000) [73]	T	3.00	357	150	470	10.47	35	228	S-U	C-D	0.17-0.33	0-50	0-125	1.76-4.40
22	Matthys (2000) [74]	R	3.13	400	200	530	0.71-1.41	33.80-37.50	233	U-F	D	0.111	50	200-400	0.14-0.28
23	Täljsten and Elfgren (2000) [75]	R	2.17-3.48	460	180	-	0	50.3-65.2	65.6-100.6	U	C	0.80-2.00	0-50	0-141.42	4.44-22.20
24	Annaiah et al. (2001) [76]	T	2.57	355.6	152.4	-	0	20.68	117-228	U	C	0.165-0.6	0	0	2.17-7.87
25	Deniaud and Cheng (2001) [77]	T	2.75-2.90	360-540	140	400	0-2.02	37.4-44.1	8.1-230	U	C-D	0.11-2.10	0-100	0-100	0.79-30
26	Park et al. (2001) [78]	R-T	2.50-3.50	204-231.4	100	-	0-7.54	25.4	155-240	S-U	C-D	0.16-1.20	0-25	0-75	3.20-8.00
27	Wong (2001) [79]	R	3.98-6.96	460	305	-	0	22.6-43.5	99.09	S	D	0.84	200	300	3.67
28	Chaallal et al. (2002) [80]	T	2.00	343	122	443	1.90-8.29	37.9	231	U	C	0.15-0.44	0	0	2.37-7.12
29	Khalifa and Nanni (2002) [81]	R	3.00-4.03	253	150	460	0-8.38	19.3-27.5	228	U	C-D	0.17-0.33	0-75	0-125	0.88-4.40
30	Li et al. (2002) [82]	R	3.01	266	130	500	0.54-4.35	38	42.4	S	C	1.50	0	0	23.08
31	Micelli et al. (2002) [83]	T	2.57	356	152	-	0	20.7	117-228	U	C	0.17-0.60	0	0	2.17-7.89
32	Moren (2002) [84]	R	1.25-1.88	203	102	-	0	42.58	165	S	D	1.2	50	100.8	11.67-16.51

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Table A1 (*continued*)

	Reference	Type[1]	a/d	d	bw	fy	ρ_s	f'_c	E_f	FRP Configuration[2]		t_f	w_f	s_f	ρ_f
			-	mm	mm	MPa	$\times10^{-3}$	MPa	GPa			mm	mm	mm	$\times10^{-3}$
33	Pellegrino and Modena (2002) [85]	R	3.00	250	150	534	0-3.35	27.5-31.4	234	S	C	0.17-0.50	0	0	2.20-6.60
34	Alagusundaramoorthy et al. (2003) [86]	R	2.77	330	230	414	1.84	39	228	F	C	0.18-0.36	0	0	1.57-3.13
35	Allam and Ebeido (2003) [87]	R	1.71-2.57	175	120	400	0-3.93	34	230	S-U	C-D	0.26	0-50	0-100	2.17-4.30
36	Abdel-Jaber et al. (2003) [88]	R	2.42	165	150	-	0	43.3-61.1	155-230	S-U	C-D	0.27-1.20	0-20	0-60	3.60-16
37	Beber (2003) [89]	R	2.90	255	150	-	0	32.8	230	U-F	C-D	0.09-1.40	0-50	0-141.4	0.74-9.33
38	Diagana et al. (2003) [90]	R	2.23	403	130	550	1.45	38.0	105	U-F	D	0.43	40	200-350	1.06-1.32
39	Täljsten (2003) [91]	R	2.69	465	180	-	0	58.7-71.4	234	S	C	0.07-0.165	0	0	0.78-1.83
40	Adhikary et al. (2004) [8]	R	4.08	245	300	-	0	37.2-43.9	120-230	U-F	C	0.17-0.29	0	0	1.11-1.91
41	Adhikary and Mutsuyoshi (2004) [92]	R	3.00	170	150	-	0	30.5-35.4	120-230	S-U	C	0.17-0.33	0	0	2.23-4.40
42	Ianniruberto and Imbimbo (2004) [93]	R	3.00	300	150	495	2.36	35	75.9	F	C	0.12-0.36	0	0	1.60-4.80
43	Song et al. (2004) [94]	R	2.90	298	150	395	2.79	40.8	235	U	C-D	0.22-0.44	0-40	0-120	0.98-2.93
44	Zhang et al. (2004) [95]	R	1.25-1.88	203.2	101.6	-	0	42.54	73.1-165	S-U	C-D	0.33-1.20	0-40	0-101.6	6.50-13.2
45	Cao et al. (2005) [96]	R	1.80-2.92	222.5	150	361	0-1.88	15.13-25.93	20.5-249	F	D	0.167-1.20	25-30	40-100	0.67-8.47
46	Carolin and Täljsten (2005) [97]	R	2.91-3.03	330-430	180	515	0-1.57	46-71	234	S	C	0.07-0.5	0	0	0.78-5.56
47	Islam et al. (2005) [98]	R	0.80	750	120	500	2.09	37.8	165-230	S-U	C-D	0.33-1.20	0-50	0-160	5.50-8.84
48	Miyajima et al. (2005) [99]	R	2.93	375	340	382	0.49	37.8	253	F	D	0.11	50-100	150	0.22-0.43
49	Qu et al. (2005) [100]	R	2.00	166-498	100-300	-	0	49.7-51.2	235	U	D	0.11-0.33	30-90	50-150	1.33
50	Zhang and Hsu (2005) [101]	R	2.67-4.19	200	152.4	-	0	43.8	73.1-165	S	C-D	0.33-1.2	0-40	0-127	4.33-7.01
51	Bousselham and Chaallal (2006) [10]	T	1.51-3.03	175-350	95	420	3.75	25	243	U	C	0.07-0.13	0	0	1.39-2.78
52	De Lorenzis and Rizzo (2006) [102]	R	3.00	173	200	545	1.77	29.30	230	U	C	0.165	0	0	1.65
53	Guadagnini et al. (2006) [103]	R	1.10-3.30	224	150	-	0	42.16-43.44	65	F	D	1.00	2.81-5.15	50-100	0.37-1.37
54	Pellegrino and Modena (2006) [5]	R	3.00	250	150	534	3.35-3.94	41.4	234	U	C-D	0.17-0.33	0	0	2.20-4.40
55	Saafan (2006) [104]	R	2.38	126	100	330	0-8.70	29.8	21.0-21.5	U-F	C	2.00-4.00	0	0	40-80
56	Teng et al. (2006) [105]	R	2.41	270	150	300	0-5.36	36.80-45.73	266	F	D	0.11	20	50	0.59
57	Barros et al. (2007) [106]	R	2.20-2.44	123-273	150	464	0-5.03	49.2-56.2	166-390	S-F	D	0.334-1.40	10-25	40-300	0.59-3.73
58	Dias et al. (2007) [107]	T	2.50	360	180	450	1.05-1.75	18.6	174.3	S	D	1.40	9.5	114-275	0.76-1.33
59	Monti and Liota (2007) [108]	R	3.50	400	250	500	1.01	11.3	390	S-U-F	C-D	0.22	0-150	0-300	0.83-1.76
60	Mosallam and Banerjee (2007) [109]	R	1.80-2.96	206	150	400	1.55	27.54	24.2-151.7	S-U	C-D	1.19-4.20	0-50.8	0-101	7.98-56.00
61	Leung et al. (2007) [110]	R	2.73-2.90	155-660	75-300	420	1.40-2.79	27.4	235	U-F	D	0.11-0.44	20-80	60-240	0.98
62	Dias and Barros (2008) [111]	T	2.50	356	180	444	1.05-2.42	31.1	166.6	S	D	1.4	10	100-367	0.58-1.59
63	Jayaprakash et al. (2008) [112]	T	2.50-4.00	300-310	120	311-554	3.99-10.47	16.70-27.40	230	U	D	0.09	80	150-200	0.60-1.13
64	Yalim et al (2008) [113]	T	3.81	260	152	414	8.14	35	70.52	U	C-D	1.02	0-102	0-305	4.49-23.20
65	Rizzo and De Lorenzis (2009) [114]	R	3.00	190	200	545	1.77	29.3	121.5-230	U	C-D	0.17-2.00	0-16	0-146	1.65-4.38
66	Siddiqui (2009) [115]	R	2.83	265	200	420	1.88	35	77.28	S	D	1.00	50	150	3.33-6.67
67	Sundarraja and Rajamohan (2009) [116]	R	2.66	125	100	375	0-7.54	24.8	73	S-U	D	1.00	15-40	45	9.43-21.14
68	Bukhari et al. (2010) [117]	R	2.85	267	152	-	0	60	234.5	S-F	C-D	0.34	0-305	0-455	3.00-4.47
69	Godat et al. (2010)	R	2.00	166-498	100-300	-	0	49.7-51.2	230	U-F	C-D	0.111-0.333	30-90	20-60	2.22-3.33

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Table A1 (*continued*)

	Reference	Type^1	a/d	d	bw	fy	ρ_s	f'$_c$	E$_f$	FRP Configuration^2		t$_f$	w$_f$	s$_f$	ρ_f
			-	mm	mm	MPa	$\times10^{-3}$	MPa	GPa			mm	mm	mm	$\times10^{-3}$
70	Dias and Barros (2011) [118]	T	2.50	360	180	447-450	1.05-1.75	39.7	171-218.4	S-U	D	0.176-1.4	9.5-60	80-275	0.65-2.06
71	Belarbi et al. (2011) [12]	T	3.30-3.31	830.58	457.2	414	1.02-1.53	18.27-30.48	228	U	D	254	254	381	0.48
72	Mofidi and Chaallal (2011) [119]	T	3.00	350	152	540	3.67	31	230	U	C-D	0.11	0-87.5	0-175	0.72-1.45
73	Panda et al. (2011) [120]	T	3.26	225	100	252	0-2.83	39.53-42.67	13.18	S	C	0.36-1.08	0	0	7.20-21.60
74	Belarbi et al. (2012) [121]	T	3.30	830.58	457.2	276	0-1.53	18.27-30.47	228	U	D	3.20	254	381	9.33
75	Ozden et al. (2013) [122]	T	3.80	339.50	120	249	1.39	12.4	73-640	U	D	0.131-0.14	20	120	61.3-82.6
76	Panda et al. (2013) [123]	T	3.26	225	100	252	0-2.83	39.58-42.67	13.18	S-U	C	0.36	0	0	7.20
77	Kim et al. (2015) [124]	T	3.07	1092	356	476	0.97-3.53	27	102	U	C-D	0.28	0-365	0-508	0.79-1.57
78	Li and Leung (2015) [125]	R	1.00-3.50	303	180	310	2.30	47	235	F	D	0.11	60	150	0.49
79	Chen et al. (2016) [126]	T	3.00	320	200	416	2.51	43-46.1	226	U	D	0.167	50	100	0.84
80	Foster et al. (2017) [127]	T	3.00	300-600	150-300	434-510	0.93	54.1-65.4	230	U	C	0.50-2.00	0	0	6.67-13.33
81	Keskin et al. (2017) [128]	R	2.50	200	150	-	0	39	230	F	D	0.166	10	10	2.21
82	Nguyen-Minh et al. (2018) [129]	T	1.50-2.30	413	120	342	1.57	38.3-73.4	26.10-95.80	U	C-D	1.00-2.00	0-75	0-150	8.33-21.67
83	Benzeguir et al. (2019) [47]	T	3.00	175-525	95-275	420-650	0-4.13	30	231	U	C	0.066-0.334	0	0	1.39-2.82
84	Karzad et al. (2019) [130]	R	3.48	330	230	370-450	0-2.91	28-36	230	U	D	0.167-0.334	100	150	0.97-1.94
85	Oller et al. (2019) [131]	T	2.97	498	200	646	1.18	38.5-62.6	263	U	D	0.17-1.00	0-100	0-240	0.35-10
86	Benzeguir et al (2020) [132]	T	3.00	350-525	152-275	440-650	3.78-4.13	30	90	U	D	2.00	30	100-175	5.82-6.02
87	Chalioris et al. (2020) [133]	T	2.86	175	150	-	0	35.15	230	U	C	0.26-0.39	0	0	3.47-5.20
88	Mhanna et al. (2020) [134]	T	2.75	309	150	460	4.12	45.9	73.77	U	D	1.02	100	150	9.07
89	Moradi et al. (2020) [135]	R	2.67	300	200	352	3.93	35	238	S-U-F	D	0.131	80	200	0.52
90	Ibrahim et al. (2021) [136]	T	3.24	340	150	559	0-3.90	68	230	U	D	0.166-0.332	50	90-170	0.65-1.30
91	Samb et al. (2021) [137]	T	3.00	350	152	614	0-2.54	30	56.50-115.70	U	D	0.38-1.90	0	0	5.00-26.84
92	Tran et al. (2021) [138]	R	1.70	264	200	810	0-283	31.6-36.2	82-120	U	C-D	0.51-1.02	0-50	0-50	5.10-1-.20
93	Akkaya et al. (2022) [139]	R	1.00-2.00	260	140	740	4.78	35	70-255	F	D	0.34-0.68	50	100-150	1.62-3.24
94	Jin et al. (2022) [48]	R	1.50	245-1027	100-400	-	0	44	232	U	D	0.167-0.501	50-600	200-800	0.63-2.51

^{1} Beam type: R = Rectangular , T = T-beam ^{2} FRP configuration: S = Bonded face plies, U = Bonded U wraps, F = Fully wrapped, C = Continuous, D = Discrete

Table A2
Detailed information on the obtained data from experiments (gathered from the literature) conducted on RC beams with FRP sheets.

Reference	Specimen	Type	d	a/d	bw	f'$_c$	fy	ρ_s	E$_f$	ρ_f	ε_{fe}	V$_{total}$
		R-T^1	mm	-	mm	MPa	MPa	-	MPa	-	-	kN
Berset (1992)	3	R	78.65	3.81	114	42.9	-	0.0000	16800	0.0112	0.0000	31
Uji (1992)	3	R	170	2.50	100	24.6	-	0.0000	230000	0.0019	0.0040	60
Al-Suleimani et al. (1994)	SO	R	113	3.54	150	37.7	450	0.0019	15400	0.0160	0.0019	42
Chajes et al. (1995)	A1	T	152	2.67	63.5	45.4	-	0.0000	11000	0.0328	0.0023	39
Sato (1996)	S2	R	260	2.70	200	45.2	-	0.0000	230000	0.0006	0.0040	80
Araki et al. (1997)	CF045	R	336	1.56	200	24.8	366	0.0016	230000	0.0002	0.0040	118
Funakawa et al. (1997)	S2	R	510	2.50	600	30.7	400	0.0013	240000	0.0006	0.0040	691
Miyauchi et al. (1997)	1/5 Z-3	R	165	3.00	125	35.1	-	0.0000	230000	0.0004	0.0040	75
One et al. (1997)	SB2	R	260	1.54	300	24.3	358	0.0008	248000	0.0007	0.0040	267
Kamiharako et al. (1997)	2	R	400	2.50	250	32.6	-	0.0000	244000	0.0004	0.0040	285
Sato (1997)	2	T	240	2.50	150	35.7	396	0.0067	230000	0.0015	0.0040	223
Täljsten (1997)	S1	R	460	2.17	180	50.3	-	0.0000	65600	0.0133	0.0037	341
Taerwe et al. (1997)	BS2	R	420	2.98	200	36.2	486.1	0.0014	280000	0.0001	0.0040	124

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Table A2 (*continued*)

Reference	Specimen	Type	d	a/d	bw	f'_c	fy	ρ_s	E_f	ρ_f	ε_{fe}	V_{total}
Umezu et al. (1997)	AS1	R	257	3.11	150	43	1720	0.0006	73000	0.0006	0.0040	91
Adey et al. (1998)	2	R	370	2.03	200	46.4	-	0.0000	230000	0.0013	0.0039	211
Chaallal et al. (1998)	RS90a	R	210	2.86	150	35.0	400	0.0019	150000	0.0067	0.0019	88
Khalifa et al. (1999)	CW2	R	255	3.59	150	27.5	460	0.0084	228000	0.0044	0.0026	214
Mitsui et al. (1998)	A0	R	220	1.14	150	28.5	400	0.0026	230000	0.0022	0.0040	134
Triantafillou (1998)	S1A	R	100	3.20	70	30.0	-	0.0000	235000	0.0022	0.0002	22
Grace et al. (1999)	CF-I	R	270	5.00	152	48.26	500	0.0044	230000	0.0066	0.0013	52
Khalifa and Nanni (2000)	BT2	T	357	3.00	150	35.0	470	0.0105	228000	0.0022	0.0040	155
Matthys (2000)	BS2	R	400	3.13	200	33.8	530	0.0014	233000	0.0001	0.0040	252
Täljsten and Elfgren (2000)	S1	R	460	2.61	180	50.3	-	0.0000	65600	0.0133	0.0040	341
Annaiah et al. (2001)	JS2A	T	355	2.57	152	20.68	-	0.0000	228000	0.0022	0.0030	237
Deniaud and Cheng (2001)	T6NS-C45	T	540	2.75	140	44.1	-	0.0000	230000	0.0011	0.0040	214
Park et al. (2001)	2	R	204	2.50	100	25.4	-	0.0000	240000	0.0032	0.0033	65
Wong (2001)	RWOA-1	R	460	3.98	305	22.6	-	0.0000	99091	0.0037	0.0022	247
Chaallal et al. (2002)	G5.5_1L	T	343	2.00	122	37.9	443	0.0083	231000	0.0024	0.0040	320
Khalifa and Nanni (2002)	SW3-2	R	253	3.00	150	19.3	460	0.0084	228000	0.0044	0.0021	177
Li et al. (2002)	B80_1	R	266	3.01	130	38.0	500	0.0005	42400	0.0231	0.0020	33
Micelli et al. (2002)	JS2A	T	356	2.57	152	20.7	-	0.0000	228000	0.0022	0.0030	236
Moren (2002)	13	R	203	1.88	102	42.58	-	0.0000	165000	0.0117	0.0019	84
Pellegrino and Modena (2002)	TR30C2	R	250	3.00	150	27.5	-	0.0000	234000	0.0022	0.0029	120
Alagusundaramoorthy et al. (2003)	SB3-90	R	330	2.77	230	39	414	0.0018	228000	0.0016	0.0040	232
Allam and Ebeido (2003)	S-2	R	175	2.57	120	34.0	400	0.0039	230000	0.0022	0.0023	83
Beber (2003)	V9_A	R	255	2.90	150	32.8	-	0.0000	230000	0.0007	0.0035	98
Diagana et al. (2003)	PU2	R	403	2.23	130	38.0	550	0.0014	105000	0.0011	0.0040	130
Täljsten (2003)	RC1	R	465	2.69	180	67.4	-	0.0000	234000	0.0012	0.0040	306
Adhikary et al. (2004)	C1	R	245	4.08	300	37.2	-	0.0000	230000	0.0011	0.0040	165
Adhikary and Mutsuyoshi (2004)	B-2	R	170	3.00	150	35.4	-	0.0000	230000	0.0022	0.0000	51
Ianniruberto and Imbimbo (2004)	ST1b	R	300	3.00	150	35.0	495	0.0024	75900	0.0016	0.0040	242
Song et al. (2004)	SB1_3	R	298	2.90	150	40.8	395	0.0028	235000	0.0029	0.0040	240
Zhang et al. (2004)	Z11-S90	R	203	1.88	101.6	42.54	-	0.0000	165000	0.0093	0.0019	85
Cao et al. (2005)	A2	R	222	2.70	150	25.925	361	0.0019	249000	0.0007	0.0040	93
Carolin and Täljsten (2005)	A145	R	430	2.91	180	67.0	-	0.0000	234000	0.0008	0.0040	247
Islam et al. (2005)	B1	R	750	0.80	120	37.8	500	0.0021	230000	0.0055	0.0035	701
Miyajima et al. (2005)	case 2	R	375	2.93	340	37.8	382	0.0005	253000	0.0002	0.0040	212
Qu et al. (2005)	U4	R	166	2.00	100	51.2	-	0.0000	235000	0.0013	0.0040	101
Zhang and Hsu (2005)	Z4-90	R	200	2.67	152	43.8	-	0.0000	165000	0.0050	0.0019	74
Bousselham and Chaallal (2006)	DBS01L	T	175	1.51	95	25.0	420	0.0037	243000	0.0014	0.0033	162
De Lorenzis and Rizzo (2006)	UW90	R	173	3.00	200	29.3	545	0.0018	230000	0.0017	0.0034	142
Guadagnini et al. (2006)	SB40R	R	224	3.30	150	43.44	-	0.0000	65000	0.0004	0.0040	58
Pellegrino and Modena (2006)	A-U1-C-17	R	250	3.00	150	41.4	534	0.0039	234000	0.0022	0.0040	238
Saafan (2006)	S8FP	R	126	2.38	100	29.8	-	0.0000	21500	0.0400	0.0029	32
Teng et al. (2006)	UBF-00	R	270	2.41	150	38.93	-	0.0000	266000	0.0006	0.0040	155
Barros et al. (2007)	A10-M	R	273	2.20	150	49.2	-	0.0000	390000	0.0006	0.0040	61
Dias et al. (2007)	2s-7LV	T	360	2.50	180	18.6	450	0.0010	174300	0.0013	0.0010	164
Monti and Liota (2007)	SS90*	R	400	3.50	250	11.3	500	0.0010	390000	0.0009	0.0013	100
Mosallam and Banerjee (2007)	B21R	R	206	1.80	150	27.54	400	0.0015	24200	0.0560	0.0020	54
Leung et al. (2007)	SB-U1	R	155	2.90	75	27.4	420	0.0028	235000	0.0010	0.0035	65
Dias and Barros (2008)	2s-3LV	T	356	2.50	180	31.1	444	0.0010	166600	0.0006	0.0015	190
Jayaprakash et al (2008)	TT1-1	T	310	2.50	120	38	400	0.0079	230000	0.0008	0.0040	121
Yalim et al. (2008)	W-CSP(1)-4	T	260	3.81	152	35	414	0.0081	70522	0.0045	0.0030	71
Rizzo and Lorenzis (2009)	UW90	R	190	3.00	200	29.3	545	0.0018	230000	0.0017	0.0034	142
Siddiqui (2009)	BSS-1	R	265	2.83	200	35	420	0.0019	77280	0.0033	0.0026	48
Sundarraja and Rajamohan (2009)	RF2	R	125	2.66	100	24.8	375	0.0075	73000	0.0094	0.0015	27
Bukhari et al. (2010)	C2	R	267	2.85	152	60.0	-	0.0000	234500	0.0030	0.0037	115
Godat et al. (2010)	U4	R	166	2.00	100	51.2	-	0.0000	230000	0.0033	0.0040	203
Dias and Barros (2011)	2S-4LV	T	360	2.50	180	39.7	447	0.0010	171000	0.0008	0.0017	202
Belarbi et al. (2011)	RC8-S90-DMA	T	830	3.31	457.2	23.8	414	0.0015	228000	0.0005	0.0035	943
Mofidi and Chaallal (2011)	S0-0.12R	T	350	3.00	152	31	540	-	230000	0.0005	0.0040	121
Panda et al. (2011)	S0-1L-CT-S-90	T	225	3.26	100	40.1	-	0.0000	13180	0.0072	0.0000	66
Belardi et al. (2012)	RC-8-S90-NA	T	830	3.30	457.2	20.68428	276	0.0015	228000	0.0093	0.0006	851
Ozden et al. (2013)	FBwoA-CFRP	T	339	3.80	120	12.4	249	0.0014	238000	0.0004	0.0023	62
Panda et al. (2013)	S0-1L-SZ-S-90	T	225	3.26	100	39.58	-	0.0000	13180	0.0072	0.0000	65
Kim et al. (2015)	L-S	T	1092	3.07	356	27	476	0.0010	102000	0.0008	0.0040	747
Li and Leung (2015)	B1W	R	303	1.00	180	47	310	0.0023	235000	0.0005	0.0040	460
Foster et al. (2017)	LB0.7UA	T	600	3.00	300	55	510	0.0009	230000	0.0067	0.0024	512
Keskin et al. (2017)	A2.5RC10/10	R	200	2.50	150	39	-	0.0000	230000	0.0022	0.0040	180
Nguyen-Minh et al. (2018)	P-A1-2.3-C	T	413	2.30	120	38.3	342	0.0016	95800	0.0083	0.0030	276
Benzeguir et al. (2019)	S.S0.1L	T	175	3.00	95	30	-	0.0000	231000	0.0014	0.0037	62
Karzad et al. (2019)	RS-0-1L-28	R	330	3.48	230	36	-	0.0000	230000	0.0010	0.0040	155
Oller et al. (2019)	M1-a	T	498	2.97	200	42.8	646	0.0012	263000	0.0004	0.0040	349
Benzeguir et al (2020)	M.S1.Str	T	350	3.00	152	30	650	0.0038	90000	0.0060	0.0018	275
Chalioris et al. (2020)	T2J	T	175	2.86	150	35.15	-	0.0000	230000	0.0035	0.0029	82

(*continued on next page*)

Table A2 (*continued*)

Reference	Specimen	Type	d	a/d	bw	f'_c	fy	ρ_s	E_f	ρ_f	ε_{fe}	V_{total}
Mhanna et al. (2020)	BSU	T	309	2.75	150	45.9	460	0.0041	73770	0.0091	0.0036	317
Moradi et al. (2020)	EXW	R	300	2.67	200	35	352	0.0039	238000	0.0005	0.0040	223
Ibrahim et al. (2021)	NoSt-1LFRP@90	T	340	3.24	150	68	-	0.0000	230000	0.0012	0.0040	220
Samb et al. (2021)	EBS-S0-1L200	T	350	3.00	152	30	-	-	74700	0.0050	0.0040	120
Tran et al. (2021)	FRP.1-1.7	R	264	1.70	200	31.6	810	0.0028	82000	0.0051	0.0038	166
Akkaya et al. (2022)	SDB1-46-C1-10	R	260	1.00	140	35	740	0.0048	255000	0.0016	0.0040	391
Jin et al. (2022)	S-0.0835%	R	245	1.50	100	44	-	0.0000	232000	0.0008	0.0040	124

[1] Beam type: R = Rectangular, T = T-beam

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