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Shear Strength Prediction of Concrete Beams Reinforced with FRP Bars and Stirrups Using Gene Expression Programming

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Abstract: Existing reinforced concrete (RC) structures in humid regions suffer from deterioration due to the corrosion of ordinary reinforcement bars damaging the whole system. The deterioration of the transverse reinforcement leads to shear failure, which is one of the most dangerous failure modes. Therefore, researchers suggested using fiber-reinforced polymer (FRP) bars as a replacement for reinforcement bars in humid regions to integrate sustainability and improve their serviceability and durability. A simple model that can accurately estimate the shear strength of concrete beams designed with FRP longitudinal bars and stirrups is lacking. This research proposed a simplified Gene expression programming (GEP) based model to estimate the shear strength of FRP concrete beams. Seven parameters that principally dominate the shear behavior of FRP beams were utilized to create the GEP model. The parameters are the beam width, beam depth, concrete compressive strength, FRP tensile longitudinal reinforcement ratio, area of stirrups, spacing between the stirrups, and the ultimate FRP strength of stirrups. A comparison was made between the GEP and ACI-440 models; the R^2 values of the total database were 92% and 54% for the GEP and ACI models, respectively. The R^2 of the GEP model is considerably higher than that measured for the ACI model, and the errors of the GEP model are low, which affirms that the GEP is superior to the ACI model in estimating the shear strength of FRP beams. The trends of the GEP and ACI-440 models and the empirical results are similar, confirming the GEP model's consistency. Using the GEP model to estimate the shear strength of concrete beams designed with FRP longitudinal bars and stirrups is recommended.

Keywords: gene expression programming (GEP); shear strength; FRP bars; FRP stirrups; concrete beams

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1. Introduction

Conventional steel corrosion deteriorates reinforced concrete (RC) structures in humid regions. Therefore, researchers seek alternatives to steel bars with high tensile strength and corrosion resistance. The deterioration of the transverse reinforcement leads to shear failure, one of the most dangerous failure modes that can cause building collapse. The sustainability of RC structures in harsh environments is getting significant interest from various researchers to enhance existing structures' durability, strength, and serviceability. Therefore, researchers suggested using fiber-reinforced polymer (FRP) bars as a replacement for steel bars in humid areas to integrate sustainability and improve their serviceability and durability. Several kinds of sustainable FRP bars exist, such as carbon, basalt, glass, etc.

Several researchers have affirmed FRP bars' efficiency as a replacement for longitudinal and transverse steel reinforcement in concrete elements. Al-Hamrani et al. [1] applied basalt fiber-reinforced polymer (BFRP) longitudinal bars and BFRP stirrups to replace steel bars to investigate the shear behavior of concrete beams designed with BFRP reinforcement. They found that BFRP stirrups improved the shear strength of the concrete beams, and they reduced the crack width. By contrast, they showed that the shear strength was decreased in concrete beams with a higher shear-span-to-effective-depth (a/d) ratio. Duic et al. [2] investigated the shear and flexural behavior of concrete beams designed with BFRP bars.

They found that concrete beams designed with BFRP bars experienced more flexural and shear cracks than the conventional control beam. Nagajothi and Elavenil [3] studied the shear behavior of concrete beams prepared with BFRP and glass fiber-reinforced polymer (GFRP) bars and stirrups with various a/d ratios of 3.6, 3.9, and 4.3. They found that the shear strength of all tested beams was reduced by enlarging the a/d ratio. They also found that the shear strength of concrete beams prepared with BFRP and GFRP bars and stirrups is less than that measured with conventional steel bars. Issa et al. [4] performed an empirical program to investigate the shear behavior of concrete beams designed with BFRP bars with and without BFRP stirrups. They found that the shear strength of both types of basalt concrete beams enhanced for the same (a/d) ratio, while it reduced by enlarging the (a/d) ratio. Bentz et al. [5] performed an empirical test to study the shear behavior of concrete beams prepared with GFRP bars with and without GFRP stirrups. They showed that the shear behavior of concrete beams, designed with steel bars and stirrups, is similar to that prepared with GFRP bars and stirrups, whereas the latter's reinforcement is brittle.

Fan et al. [6] empirically and numerically studied the shear behavior of inorganic polymer concrete beams prepared with BFRP bars and stirrups. They showed that all tested beams failed in a brittle shear manner due to the rupture of BFRP stirrups and shear compression failure. Tomlinson and Fam [7] studied the shear and flexural behavior of concrete beams prepared with BFRP bars and stirrups. They showed that the beams' load-carrying capacity was improved by enhancing the flexural reinforcement ratio. They also found that beams without stirrups and those prepared with BFRP stirrups failed in shear. The BFRP beams designed with BFRP stirrups failed due to the rupture of stirrups at 90–96% of flexural capacity, while the beams without stirrups failed at 55–58% of ultimate flexural capacity. They also found that beams designed with steel transverse reinforcement failed in flexure. Lijuan et al. [8] studied the shear behavior of sea sand concrete beams with BFRP reinforcement. They showed that the shear strength of the beams improved with the increment of the concrete strength and stirrups ratio while it remained almost the same by changing the longitudinal reinforcement ratio. As previously discussed, several empirical programs were performed to investigate the shear behavior of concrete beams designed with FRP longitudinal and transverse reinforcement. Numerical and analytical studies were also performed to estimate the shear strength of concrete beams designed with FRP bars and stirrups, whereas most existing models are sophisticated. Lately, gene expression programming (GEP) and artificial neural networks (ANN) have been applied by several researchers [9–15] to create estimative models to estimate the behavior of structural elements, especially in cases where code formulations are lacking. GEP is more advanced than ANN since it creates simplified and precise estimative formulations using a comparatively limited database [16].

Existing RC structures located in harsh environments suffer from deterioration due to the corrosion of ordinary steel bars damaging the whole structure. The deterioration of the transverse reinforcement leads to shear failure, which is one of the most dangerous failure modes. Therefore, researchers suggested using FRP bars to replace steel bars in harsh environments to integrate sustainability and improve their serviceability and durability. Most existing models are sophisticated; hence, a simplified GEP model that can accurately estimate the shear strength of concrete beams designed with FRP bars and stirrups is lacking. Consequently, the current research applies GEP to create an estimative simplified GEP model that can estimate the shear strength of concrete beams designed with FRP longitudinal bars and stirrups. The GEP model will be established based on the parameters that principally dominate the shear strength of FRP beams. After thoroughly investigating the existing empirical, analytical, and numerical studies, seven parameters will be utilized to create the GEP model. A parametric analysis will then be performed to validate the proposed GEP model and check its efficiency. Moreover, the prediction obtained from the GEP model will be compared to that calculated using ACI-440.1-15 [17] guidelines.

2. Experimental Database

A comprehensive database of 83 data points was collected to create a GEP model to estimate the shear strength of concrete beams designed with FRP bars and stirrups. The database was gathered from various empirical programs [1–8,18–27], including concrete beams designed with GFRP and BFRP longitudinal bars and stirrups. The GEP model was created using seven parameters that principally dominate the shear strength of FRP beams. These parameters are beam width, beam depth, concrete compressive strength, FRP tensile longitudinal reinforcement ratio, area of stirrups, spacing between the stirrups, and the ultimate FRP strength of stirrups. For creating the GEP model, it should be trained and validated using the collected database, where 75% of the randomly chosen database was applied to train the model, and 25% of the randomly chosen database was applied to validate the model.

3. Analytical Background

The American Concrete Institute (ACI) proposed a model to estimate the shear strength of concrete beams designed with FRP. A comparison was performed between the GEP and the ACI-440.1-15 [17] predictions to check the efficiency of the GEP model. The shear strength of concrete beams designed with FRP bars and stirrups was estimated using the GEP and ACI-440.1-15 formulations. Figure 1 compares the experimental-to-predicted shear strength of concrete beams designed with FRP bars and stirrups to the beam depth. The empirical shear strength is collected from various empirical programs [1–8,18–27], including concrete beams prepared with GFRP and BFRP longitudinal bars and stirrups. Figure 1 shows the efficiency of the ACI PRC-440.1 model in estimating the shear strength of FRB beams. The comparison between the GEP and the ACI-440.1-15 estimations is shown in a later section. The ACI-440.1-15 model yielded reasonable estimations with an average (V_{EXP}/V_{ACI}) of 1.47. The procedures for estimating the shear strength of concrete beams designed with FRP bars and stirrups based on the ACI-440.1-15 are illustrated in Table 1.

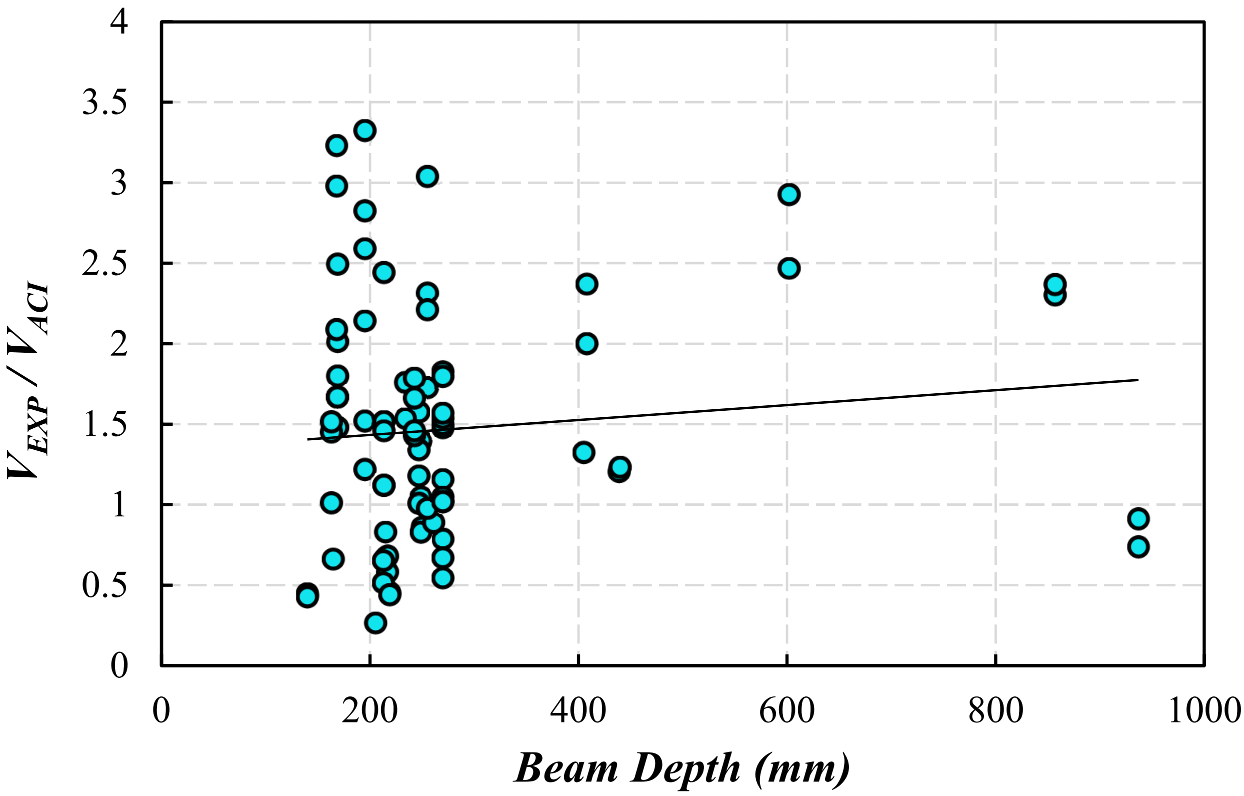


Figure 1. Ratios of experimental-to-predicted shear strength of concrete beams designed with FRP bars and stirrups.

Table 1. Procedures for shear strength calculation based on the ACI-440.1-15.

ACI-440.1-15
Concrete Shear Contribution $V_c = \frac{2}{5}\sqrt{f'_c}\, b_w\, c$ Where $c = kd,\ k = \sqrt{2\rho_l n + (\rho_l n)^2} - \rho_l n,$ and $n = E_l/E_c$
Stirrups Shear Contribution $V_{fv} = \frac{A_{fv}\, f_{fv}\, d}{s}$ Where $f_{fv} = 0.004\, E_{fv} \le f_{fb}$ and $f_{fb} = (0.05 r_b/d_b + 0.3) f_{fvu}$

4. Gene Expression Programming

4.1. Overview of Gene Expression Programming

Ferreira [28] was the first to propose Gene expression programming (GEP) for solving complex problems without needing a considerable database or predetermined equations. The GEP works by including or erasing several parameters to fit the input database, which can be either an empirical or numerical database. The GEP model is usually expressed by an expression tree (ET) or using several programming languages such as VBA, Matlab, C++, etc. The ET tree comprises genes and chromosomes with a fixed predefined length. The GEP expression consists of one or more genes, each with a head and tail. The head of the gene is presented by functions and terminal symbols (1, a, b, $\sqrt{}$, cos, *, $-$, /), whereas its tail comprises terminals such as constants and variables (1, a, b, c). The genes are linked by functions, including multiplication, subtraction, addition, and division. As the number of genes expanded, the accuracy of the GEP model enhanced, but it produced a complex model. Furthermore, expanding the number of chromosomes expends time. GEP is a competent program that can create estimative models, especially for cases lacking code formulations. Simplified procedures are adopted to create a GEP model, such as collecting a database, selecting the number of genes and chromosomes, determining the linking function, choosing the function sets, identifying the number of constants per gene, and specifying a fitness function. Selecting a simplified function set generates a simplified GEP model such as (+, *, $-$, /, x^n, $\sqrt{}$, etc.).

Several researchers have recently employed GEP to create estimative models that can solve sophisticated engineering problems. Murad and others created various GEP estimative models to solve complex problems in structural engineering, especially when guidelines are lacking. Murad [29] proposed a GEP model to estimate the biaxial shear strength of RC columns subjected to bidirectional cyclic loadings and a GEP model [30] to estimate the biaxial joint shear strength subjected to cyclic loading. Murad [31] also proposed a GEP model to estimate the compressive strength of concrete modified with nanomaterials where code guidelines are lacking in these three cases. Several researchers [10,14,32–41] have proved that GEP is a powerful tool for creating accurate models for solving various problems in the civil engineering field.

4.2. Model Development

The GEP model was created using GeneXproTools [42] to estimate the shear strength of concrete beams designed with FRP bars and stirrups. Many GEP models were created to select a GEP model that strongly complies with the collected empirical database. The parametric study was performed by changing the number of genes, linking function, head size, input parameters, and chromosomes to find the best GEP model. Table 2 shows the chosen parameters of the selected GEP model that best fit the empirical database. Seven parameters were chosen to create the GEP model; these parameters principally dominate the shear strength of FRP beams based on the observed, numerical, and analytical studies in the literature. The seven parameters are the beam width, beam depth, concrete compressive strength, FRP tensile longitudinal reinforcement ratio, area of stirrups, spacing between the stirrups, and the ultimate FRP strength of stirrups. Only two genes were chosen to create a simplified and practical GEP model. The linking function, the number of chromosomes, the head size, and the maximum number of constants per gene that best fit the empirical database are the subtraction, 30, 8, and 3, respectively. In addition, creating a simplified GEP model requires selecting a simple function set, which includes the following functions: multiplication, subtraction, addition, division, square root, inverse, square power x^2, power, x^3, and x^4. Eighty-three data points were utilized to create the GEP model, where the units of these parameters are Newton and mm. The training and validating database, which is needed for creating the GEP, was randomly chosen. The GEP model was trained using 75% of the database and validated using 25% of the database. The training data are the data utilized to create the GEP model, the validation data are the data needed to validate the created GEP model, and the entire data are the total database, including both the training and validation data. The seven parameters shown in Figure 2 that were chosen to create the GEP model were defined in the GeneXproTools as follows: d_0, d_1, d_2, d_3, d_4, d_5, and d_6, which refer to the beam width (b_w), beam depth (d), concrete compressive strength (f_c'), FRP tensile longitudinal reinforcement ratio (ρ_l), area of stirrups (A_{fv}), spacing between the stirrups (s), and the ultimate FRP strength of stirrups (f_{fv}), respectively. The proposed GEP model, which estimates the shear strength (V) of concrete beams designed with FRP bars and stirrups, is expressed in a mathematical equation and expression tree format, as shown in Equation (1) and Figure 2, respectively. Figure 2 demonstrates the expression tree of the created GEP model, which consists of two genes (Sub-ET 1 and Sub-ET 2). Each gene comprises input parameters, constants, and mathematical operators and can be read from left to right. The linking function between the two genes is subtraction. The constants of the first gene, shown in Figure 2, in the GEP model, C_1 and C_2, equal 45.18 and −26.44, respectively. While the constants of the second gene in the GEP model, C_1 and C_2, are −5.94 and 5.25, respectively.

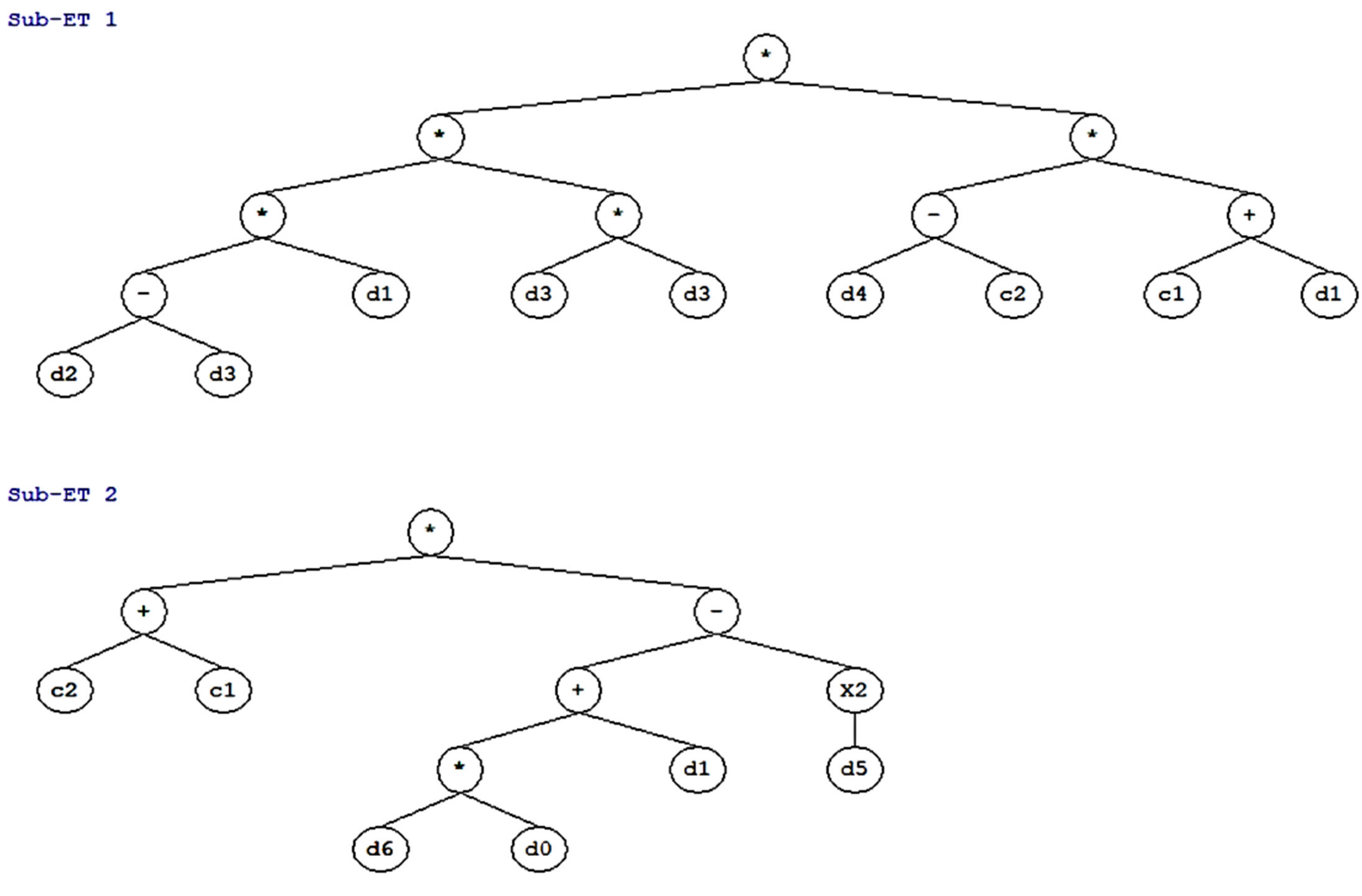


Figure 2. Expression tree of the proposed GEP model.

Table 2. GEP setting parameter.

GEP Setting Parameter	
Function set	$+, -, *, /, \sqrt{x}, x^2, x^3, x^4$
Genes	2
Chromosomes	30
Head size	8
Linking function	Subtraction
Constant per gene	3
Mutation rate	0.05
Inversion rate	0.1
Transposition rate	0.1
One-point recombination rate	0.3
Two-point recombination rate	0.3
Gene recombination rate	0.1

The proposed GEP model is illustrated in Equation (1), whereas the procedures adopted to create the GEP model are demonstrated in detail in the Model development section. Equation (1) estimates the shear strength of concrete beams designed with FRP bars and stirrups:

$$V = \left[\left((\sqrt{f_c'} - \rho_l)d\,{\rho_l}^2\right)\left(A_{fv} + 26.44\right)(45.18 + d)\right] + \left[0.69\,\left(f_{fv}\,b_w + d - s^2\right)\right] \quad (1)$$

5. Results and Discussion

The proposed GEP model is estimated in this section using statistical parameters to check its efficiency. To further validate the GEP model, the sensitivity of the proposed GEP model to its seven parameters is checked by solely varying the values of each parameter and simultaneously fixing the other seven parameters. The sensitivity of the GEP model's shear strength to its seven parameters was estimated based on the data available from existing empirical, analytical, and numerical studies in the literature. Finally, a comparison is made between the GEP model and the previously proposed ACI-440.1-15 [17] code formulation.

5.1. Statistical Evaluation of the GEP Model

The GEP model is assessed in this section. Statistical analysis was performed to estimate the performance of the GEP model, which incorporates calculating the statistical parameters, R-squared (R^2), mean absolute error (MAE), and root mean square error (RMSE), which are illustrated in Equations (2)–(4). These equations are well-known equations in statistics that can be applied to estimate the performance of regression models. The R-Squared (R^2) is the coefficient of determination, a statistical measure in regression models that shows how well the data fit the regression model. The mean absolute error (MAE) is the average absolute error between actual and estimated values. The root mean square error (RMSE) is the standard deviation of the residuals (estimation errors).

$$R^2 = \frac{\left(\sum_{i=1}^{N}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)\right)^2}{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2 \sum_{i=1}^{N}\left(Y_i - \overline{Y}\right)^2} \quad (2)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|X_i - Y_i| \quad (3)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - Y_i)^2} \quad (4)$$

where

N The number of data points
X_i The actual output value
$\overline{X}$ Mean of the actual values
Y_i The estimated output value
$\overline{Y}$ Mean of the estimated values

The proposed GEP model was applied to estimate the shear strength of concrete beams designed with FRP bars and stirrups. The efficiency of the GEP model can be measured in Figure 3a–c, which demonstrates the relationship between the estimated and empirical shear strength that was plotted using the training database, validation database, and the entire database, respectively. It can be seen from Figure 3 that the R^2 values for the training, validation, and all data sets are 92%, 96%, and 92%, respectively, and the dispersion of points is nearly the ideal fit. This produces high R^2 values and low error values, where RMSE and MAE (error) for all data are 21% and 13%, respectively.

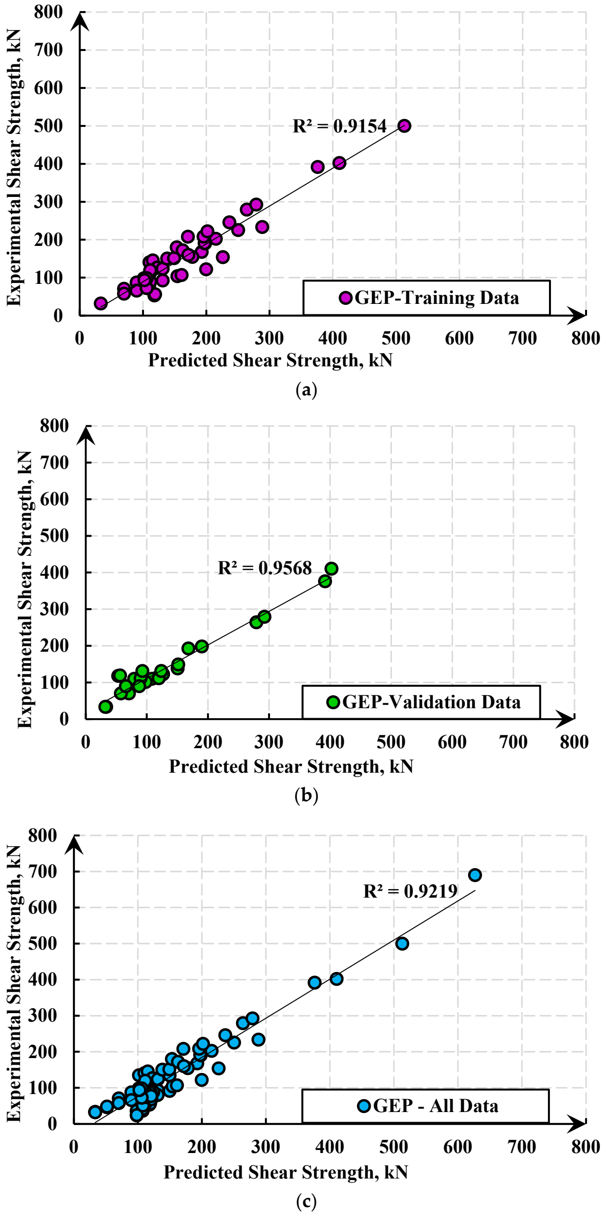


Figure 3. Comparison between the predicted and experimental shear strength using the GEP model (**a**) GEP training data, (**b**) GEP validation data, (**c**) GEP all data.

The high R^2 and the low error values proved a good correlation between the estimated and empirical shear strength values, which are close. The statistical evaluation affirmed the proposed GEP model's efficiency and proved that the GEP model can precisely estimate the shear strength of FRP beams with reasonable accuracy.

5.2. GEP Model Sensitivity

The sensitivity of the proposed GEP model to its seven parameters is checked in this section by solely varying each parameter's values and fixing the other seven parameters simultaneously. The variation of the GEP model to its parameters evaluates its efficiency. The sensitivity of the GEP model's shear strength to its seven parameters was estimated based on the data available from existing empirical, analytical, and numerical studies in the literature. The parametric analysis was performed using the following reference data to calibrate the GEP model, where the beam width = 200 mm, beam depth = 275 mm, concrete compressive strength = 40 MPa, FRP tensile longitudinal reinforcement ratio = 0.014, area of stirrups = 100 mm^2, spacing between the stirrups = 150 mm, and the ultimate FRP strength of stirrups = 1100 MPa.

The values of each parameter were varied, while the other seven parameters remained unchanged. Figure 4a–g demonstrates the variation in the shear strength of concrete beams designed with FRP bars and stirrups with the variation in the beam width, beam depth, concrete compressive strength, FRP tensile longitudinal reinforcement ratio, area of stirrups, spacing between the stirrups, and the ultimate FRP strength of stirrups, respectively.

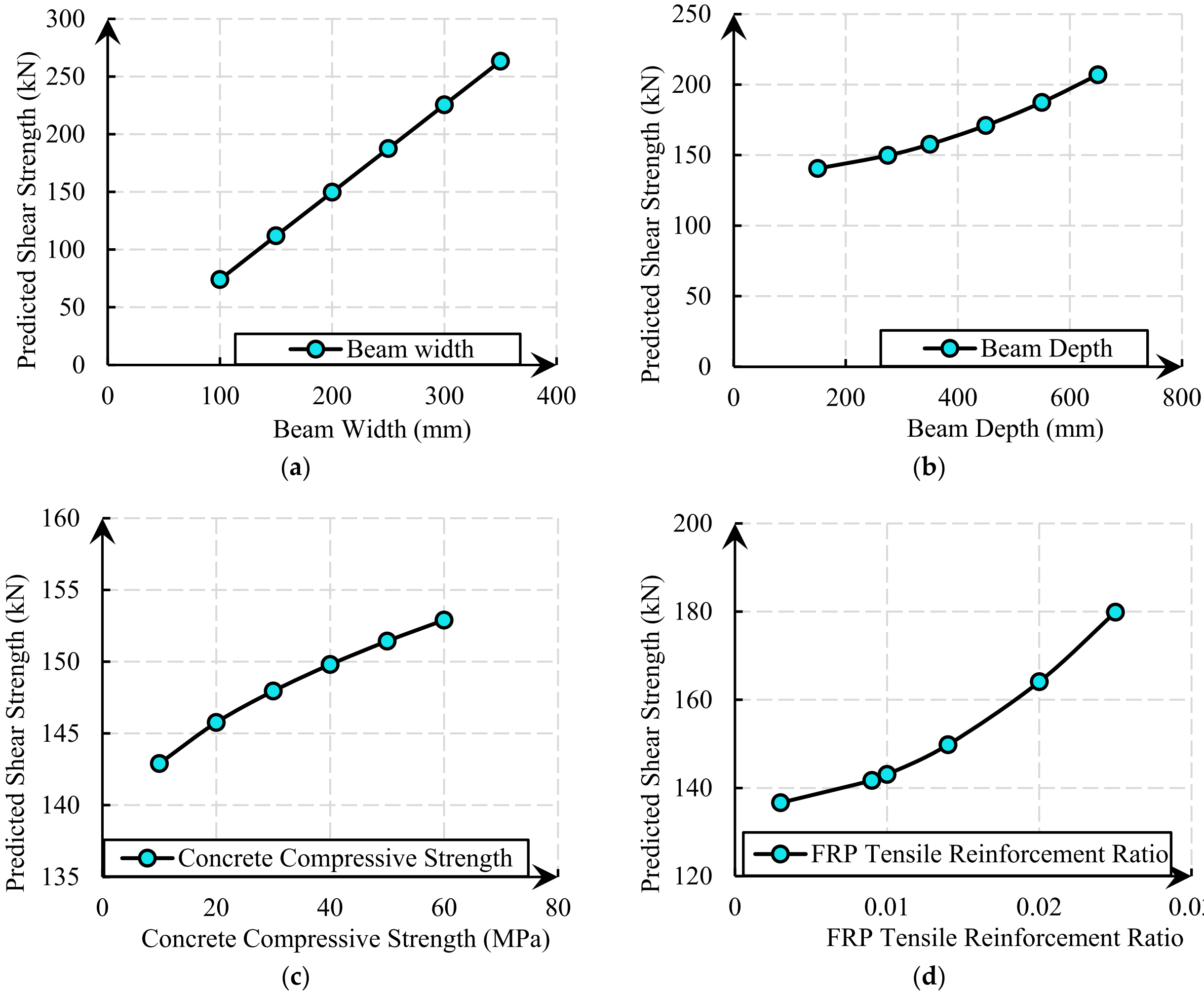
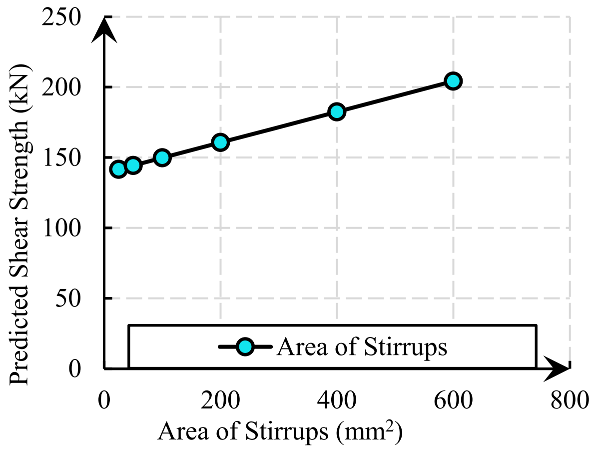


Figure 4. *Cont.*



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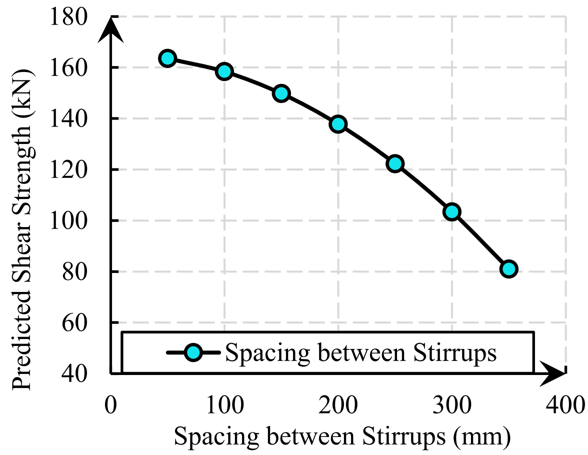
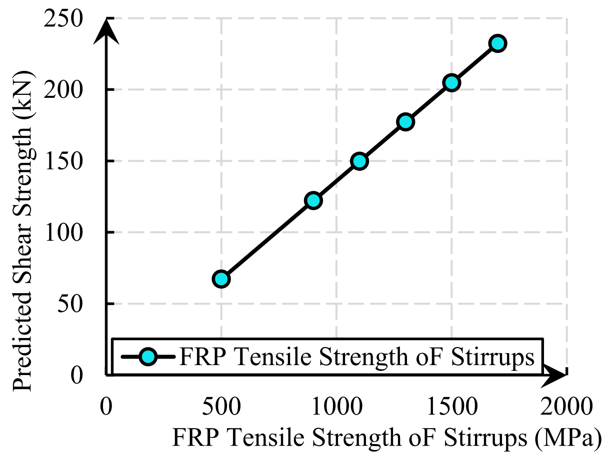


(**f**)



(**g**)

Figure 4. Effect of all input parameters on the predicted shear strength according to the GEP model (**a**) beam width (**b**) beam depth (**c**) concrete compressive strength, (**d**) FRP tensile reinforcement ratio, (**e**) Area of stirrups, (**f**) spacing between stirrups, (**g**) FRP tensile strength of stirrups.

It can be seen in Figure 4a–g that the shear strength of concrete beams designed with FRP bars and stirrups decreases when enlarging the spacing between the stirrups. In contrast, it enhances when enlarging the beam width, beam depth, concrete compressive strength, FRP tensile longitudinal reinforcement ratio, stirrups area, and stirrups' ultimate FRP strength. The GEP model is sensitive to its parameters since the trend of the model conforms with the trend of the ACI guidelines and the empirical studies in the literature, which were discussed earlier.

5.3. Comparison between the GEP Model and the ACI-440.1-15 Formulation

A statistical comparison is made in this section between the GEP model and the ACI-440.1-15 [17] formulation. The relation between the empirical and estimated shear strength values of concrete beams designed with FRP bars and stirrups is shown in Figure 5 for the GEP and ACI-440 models. The R^2 value of the GEP model is 92%, while it is 54% in the ACI model for the entire database. The R^2 value of the GEP model is considerably higher than that estimated for the ACI model, and the errors of the GEP model are low, which affirms that the GEP is superior to the ACI model in estimating the shear strength of FRP beams. Moreover, the GEP model is more practical and straightforward than the ACI model. The trends of the GEP and ACI-440 models coincide with the empirical results, which affirms the sensitivity and efficiency of the proposed GEP model.

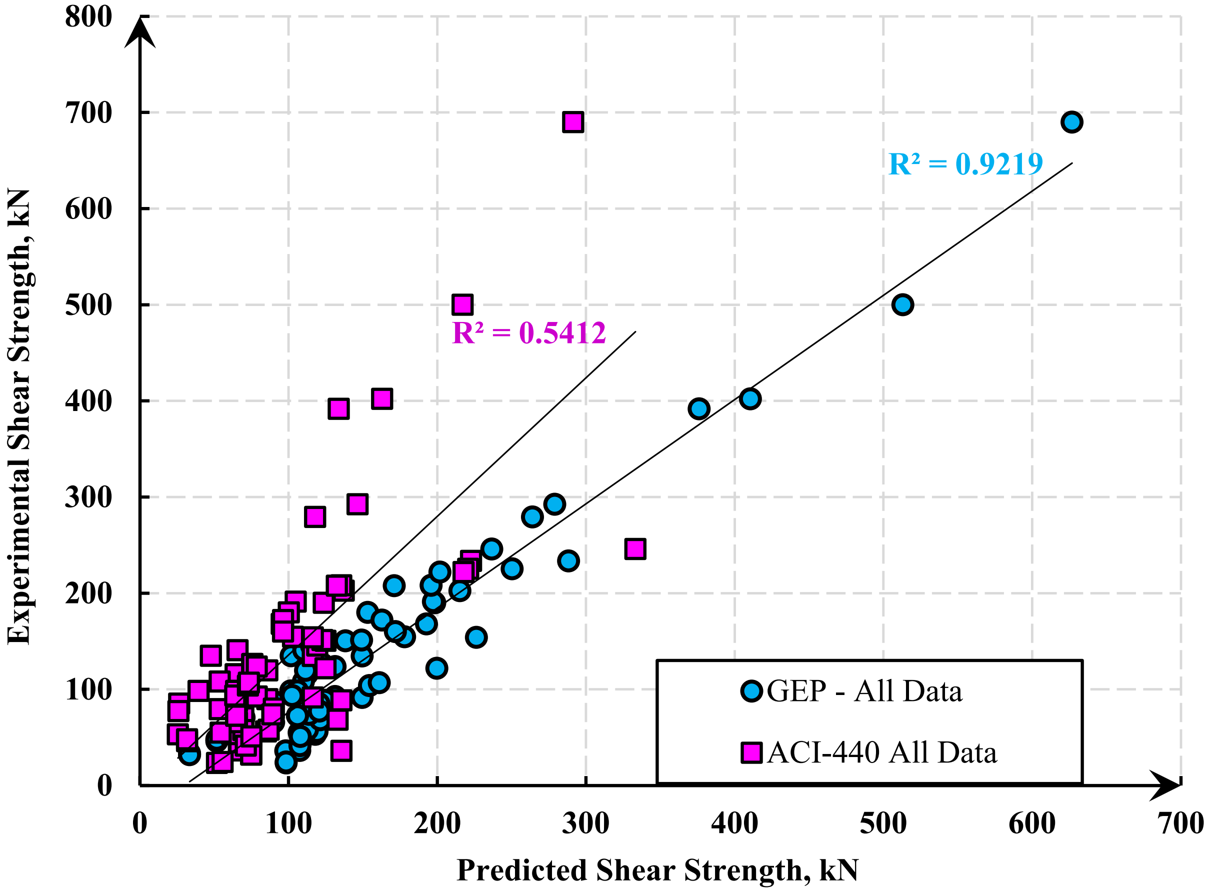


Figure 5. Comparison between the ACI-440 and GEP models.

6. Conclusions

A simplified and accurate GEP model is proposed in this research to estimate the shear strength of FRP concrete beams. The GEP model was created using seven parameters that principally dominate the shear behavior of FRP beams. These parameters are beam width, beam depth, concrete compressive strength, FRP tensile longitudinal reinforcement ratio, area of stirrups, spacing between the stirrups, and the ultimate FRP strength of stirrups. The GEP model was created using a considerable database that consists of 83 data points, where the GEP was randomly trained and validated using 75% and 25% of the database, respectively. The following points summarize the research outcomes.

1. The GEP model was compared to the ACI-440 formulation, and it was found that the R^2 values of the GEP and ACI models are 92% and 54%, respectively, for the entire database.
2. The R^2 value of the GEP model is significantly higher than that estimated for the ACI model, which affirms that the GEP is superior to the ACI model in estimating the shear strength of FRP beams. Moreover, the GEP model is more practical and straightforward than the ACI model.
3. The trends of the GEP coincide with the ACI-440.1-15 model and the empirical results, which affirm the sensitivity and efficiency of the proposed GEP model, where the shear strength of FRP beams decreases when enlarging the spacing between the stirrups. In contrast, it is enhanced when enlarging the beam width, beam depth, concrete compressive strength, FRP tensile longitudinal reinforcement ratio, stirrups area, and stirrups' ultimate FRP strength.
4. Using the simplified GEP model to estimate the shear strength of concrete beams designed with FRP longitudinal bars and stirrups is recommended.

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Abbreviations

f_c'	Concrete cylinder compressive strength (MPa)
V_c	Concrete shear contribution (N)
V_{fv}	Stirrups shear contribution (N)
A_{fv}	Area of transverse FRP reinforcement (mm^2)
b_w	Width of beam (mm)
C	Distance from extreme compression fiber to the neutral axis of the member (mm)
D	Effective depth of beam (mm)
E_c	Concrete elastic modulus (MPa)
E_l	Modulus of elasticity of longitudinal FRP bar (MPa)
ρ_l	longitudinal reinforcement ratio
f_{fv}	Tensile stress in FRP transverse reinforcement at failure (MPa)
f_{fvu}	Ultimate tensile strength of FRP transverse reinforcement bars (MPa)
f_{fb}	Tensile stress in FRP transverse reinforcement at failure at the bent portion MPa)
r_b	Internal radius of bend in FRP reinforcement
E_{fv}	Modulus of elasticity of shear FRP bars (MPa)
d_b	Diameter of reinforcing bar (mm)
S	Spacing between stirrups (mm)

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