

Punching shear Prediction of Flat slabs Reinforced with FRP Bars

Zahir Noori M. TAKI^{1,*} Ahmed Faleh AL-BAYATI¹

¹ Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq.

* corresponding author: zahir.n.taki@nahrainuniv.edu.iq.

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Abstract

This paper presents three mathematical models to estimate the punching shear (PS) strength of fiber reinforced polymer (FRP) reinforced concrete (RC) slabs under concentric punching shear. These models were developed using symbolic regression (SR), extreme gradient Boosting (XGBoost), and random forest (RF). They account for the geometrical and mechanical properties of the FRP RC flat slabs at the internal column connections in the absence of moment transfer. A comprehensive database including the test results of 204 FRP RC flat slabs from the literature is used to develop these models. The proposed models achieved good agreements with the available test results. Comparisons with the existing design expressions evidenced the reliability of the proposed models.

Keywords

Reinforced Concrete; Punching Shear; Fiber Reinforced Polymer (FRP); Symbolic Regression; Extreme Gradient Boosting; Random Forest.

1. Introduction

Flat slabs are widely used in constructions owing to their architectural and economical advantages. They provide clear space and demand less formwork as they directly supported on columns. This would increase the number of stories for a given height of a building, ease the construction process, and reduce the time and construction cost. However, due to their configuration, the bending and shear stresses are concentrated at the column-slab connections leading to punching shear (PS) failure. The latter is a sudden local failure characterized by the formation of diagonal cracks forming a truncated cone around the column. Similar to steel reinforced flat slabs, those reinforced with fiber reinforced polymer (FRP) bars are also experience the PS failure. Various experimental studies were conducted to examine the key parameters influencing the PS strength of FRP flat slabs. These studies suggested that the concrete strength (f'_c), the FRP reinforcement ratio (ρ_f), the elastic modulus of FRP bars (E_f), the column size ($C1$, $C2$), and the effective depth of a slab (d) have pronounced influence of the PS strength of FRP reinforced concrete (RC) flat slabs. Various predictive models have been proposed to estimate the punching shear capacity of FRP-reinforced slabs. Among these, (Matthys and Taerwe, 2000) presented a PS design expression that allowed for the reduced stiffness of FRP rebars compared to steel ones. (El-Ghandour et al., 2003) presented a design expression for GFRP RC flat slabs. Their expression modified that of the British Standard BS8810 for RC steel slabs to account for the low stiffness and reduced bond characteristics of FRP reinforcement. (Ospina et al., 2003) suggested another PS expression that considered the axial stiffness and bond properties of FRP reinforcement. (Hemzah et al., 2019) proposed an empirical model that considered the effects of reinforcement characteristics, concrete compressive strength,

and column rectangularity. (Ju et al., 2021) presented a model based on the probabilistic–deterministic framework that considered the reduced stiffness of FRP bars and the ratio of the effective depth to the critical section. Recently, (Dinh et al., 2025) carried out theoretical and experimental investigations and found that the axial stiffness of FRP reinforcement affects the PS strength of FRP RC flat slabs. From this, they introduced an empirical model that agreed well with the test results.

The current design codes, such as (Institute, 2022), (ACI 440.11-22), (CAN/CSA S806-12), and (JSCE-97), provide empirical equations for designing FRP slabs against PS failure. Whereas the Eurocode (EN 1992-1-1 (2023)) adopts the crack sliding theory (CST) for the PS design of steel-reinforced flat slabs, allowing for the lower modulus of elasticity of FRP reinforcement. All these codes allow for a lower modulus of elasticity of FRP reinforcement than that of steel.

Therefore, the codes' PS equations provide different strength predictions and widely scattered. On the basis of the comprehensive literature review presented herein, it may be concluded that the punching shear capacity of interior flat slabs reinforced with FRP bars is governed by a number of critical parameters, namely the axial stiffness of the FRP reinforcement, slab thickness, concrete compressive strength, column dimensions, and column aspect ratio.

The development in computer programs, especially in the field of machine learning has provided accurate techniques to tackle various engineering problems such as symbolic regression (SR), artificial neural networks (ANN), extreme gradient Boosting (XGBoost), and random forest (RF). Unlike SR, the ANN, XGBoost, and RF do not require a predefined mathematical relationship between the input and output. However, these models generally operate as black-box models, lacking explicit mathematical formulations of the learned relationships. These methods are successfully implemented to tackle various structural concrete issues (Al-Bayati et al., 2025); (Taki & Al-Bayati, 2024); (Freiesleben et al., 2022); (Al-Bayati & Taki, 2024).

This paper presents three models for the calculations of the PS of FRP RC flat slabs. The proposed models are developed using SR, XGBoost, and RF techniques, and they are trained and tested using the test results of 204 FRP RC flat slabs from the literature. The strength predictions of the proposed models are compared with those of the existing ones for validation.

2. Existing Models

This section summarizes the PS expressions of the selected existing models along with those of the current American (ACI440.11-22), Japanese (JSCE-97), Canadian (CAN/CSA S806-12) and European (EN 1992-1-1 (2023)) design codes.

2.1 (Matthys & Taerwe, 2000)

$$V_c = \frac{1.36}{d^{1/4}} \left(100 \rho_f \frac{E_f}{E_s} f'_c \right)^{1/3} b_{0(1.5d)} d \quad (1)$$

Where:

V_c – Nominal punching shear [kN],

d – Effective depth of the slab [mm],

ρ_f – Tensile Reinforcement ratio [%],

E_f – Modulus of elasticity of FRP [GPa],

E_s – Modulus of elasticity of steel reinforcement [GPa],

f'_c – Ultimate compressive strength of concrete [MPa],

$b_{0(1.5d)}$ – Critical perimeter which is 1.5d away from the face of the column [mm]. It can be specified by the following equations:

$b_{0(0.5d)} = (2C_1 + 2C_2 + 4d)$ [mm], $b_{0(1.5d)} = (2C_1 + 2C_2 + 12d)$ [mm] for rectangular or square columns.

C_1, C_2 - Long and short dimensions of column cross-section [mm].

2.2 (Ospina et al., 2003)

$$V_c = 2.77(\rho_f f'_c)^{1/3} \left(\frac{E_f}{E_s}\right)^{1/2} b_{0(1.5d)} d \quad (2)$$

All parameters of this expression are explained earlier.

2.3 (El-Ghandour et al., 2003)

$$V_c = 0.79 \left[100 \rho_f \left(\frac{E_f}{E_s}\right) \left(\frac{0.0045}{\epsilon_y}\right) \right]^{1/3} \left(\frac{f_{cu}}{25}\right)^{1/3} \left(\frac{400}{d}\right)^{1/4} b_{0(1.5d)} d \quad (3)$$

In which, ϵ_y is the yield strain of steel reinforcement

2.4 (Jacobson et al., 2005)

$$V_c = 4.5 (\rho_f f'_c)^{1/3} \left(\frac{1}{d}\right)^{1/4} b_{0(1.5d)} d \quad (4)$$

All parameters of this expression are explained earlier.

2.5 (El-Gamal et al., 2005b)

$$V_c = V_{c,ACI\ 318-05} \times \alpha = 0.33 \sqrt{f'_c} b_{0(0.5d)} d \times \alpha \quad (5)$$

Where:

$$\alpha = 0.62 (\rho_f E_f)^{1/3} \left(1 + \frac{8d}{b_{0(0.5d)}}\right)$$

All parameters of this expression are explained earlier.

2.6 (Zhang et al., 2005)

$$V_c = \left(\frac{1}{d}\right)^{1/5} (f'_c)^{1/3} \left[0.25 + 1.10 \left(100 \rho_f \frac{E_f}{E_s}\right)^{1/2} \right] b_{0(1.5d)} d \quad (6)$$

All parameters of this expression are explained earlier.

2.7 (Nguyen-Minh & Rovňák, 2013)

$$V_c = \left(\frac{400}{d}\right)^{1/2} \left[\frac{0.8}{\frac{L_1 - C_1}{d}} \right] \left(\frac{\rho_f}{100} E_f\right)^{1/3} (f'_c) b_{cr,1} d \quad (7)$$

$$b_{cr,1} = \frac{2d}{\tan(\alpha)}; \alpha = 729 \left(\frac{L}{d}\right)^{-1.26}; 22.5^\circ \leq \alpha \leq 45^\circ$$

2.8 (Hemzah et al., 2019)

$$V_c = \frac{k_1}{3} (f'_c)^{1/2} \left[\left(\frac{E_f}{E_s}\right)^{1/3} (5\rho_f)^{0.39} \left(\frac{90}{f'_c}\right)^{1/3} \right]^{1/3} b_{0(0.5d)} d \quad (8)$$

Where (k_1) = 0.55 is regarded for all square and rectangular columns and 0.77 for all circular columns.

2.9 (Ju et al., 2021)

$$V_c = 2.3 \left(\sqrt[3]{100 \rho_f \frac{E_f}{E_s} f'_c} \right) \left(\frac{d}{b_{0(0.5d)}}\right)^{1/2} b_{0(0.5d)} d \quad (9)$$

2.10 ACI 440.11-22

ACI 440.11-22, section 22.5.5.1, estimates punching shear strength for concrete slabs reinforced with FRP by using the basic punching shear equation for steel-reinforced concrete slabs, which was adopted in ACI 318-19, multiplied by a reduction factor of 2.5k, which accounts for the effect of axial stiffness of FRP reinforcement bars on the contribution of concrete to the overall punching shear capacity.

$$V_c = 0.83\lambda_s k \sqrt{f'_c} b_{0(0.5d)} d \quad (10)$$

$$k = \sqrt{2\rho_f n + (\rho_f n)^2} - \rho_f n : n = \frac{E_f}{E_c} : \lambda_s = \sqrt{\frac{2}{1+0.004d}} < 1.0$$

$$V_c \text{ in equation must not less than } V_{cmin} = 0.13\lambda_s \sqrt{f'_c} b_{0(0.5d)} d \text{ [kN]}.$$

Due to minimal experimental data on the punching shear strength of high-strength concrete slabs, the $(\sqrt{f'_c})$ in the above equation is limited to $\sqrt{f'_c} \leq 8.3$ (MPa) and (k) represents the ratio between the cracked section neutral axis location and the reinforcement location.

2.11 JSCE-97

Nominal punching shear strength V_c according to (6.3.4) of the Japanese Society of civil Engineers (JSCE-97) standard code is given as:

$$V_c = \frac{\beta_d \beta_p \beta_r f_{bcd} b_{0(0.5d)} d}{\alpha} \quad (11)$$

$$\beta_d = \sqrt[4]{\frac{1}{d}} \leq 1.5 : \beta_p = \sqrt[3]{100\rho_f n} \leq 1.5 : n = \frac{E_f}{E_s} :$$

$$\beta_r = 1 + \frac{1}{1+0.25(\frac{u_0}{d})} : \alpha = 1 + 1.5 \left[\frac{(e_x + e_y)}{\sqrt{(b_x b_y)}} \right] : f_{pcd} = 0.2\sqrt{f'_c} \leq 1.2 \text{ [MPa]}$$

Where:

n – Modular ratio.

e_x – Eccentricity of load in x-direction [mm],

e_y – Eccentricity of load in y-direction [mm],

b_x – Dimensions of critical section in x-direction [mm],

b_y – Dimensions of critical section in y-direction [mm],

All other parameters of this expression are explained earlier.

2.12 CAN/CSA S806-12

According to CAN/CSA S806-12 code, article 8.7.2, the nominal punching shear strength V_c is the minimum value of the following:

$$V_c = \min \begin{cases} 0.028 \left(1 + \frac{2}{\beta_c} \right) (E_f \rho_f f'_c)^{1/3} b_{0(0.5d)} d \\ 0.147 \left(0.19 + \frac{\alpha_s d}{b_{0(0.5d)}} \right) (E_f \rho_f f'_c)^{1/3} b_{0(0.5d)} d \\ 0.056 (E_f \rho_f f'_c)^{1/3} b_{0(0.5d)} d \end{cases} \quad (12)$$

Where:

β_c – Ratio of long side to short side of column's cross section $\beta_c = \frac{\max(C_1, C_2)}{\min(C_1, C_2)}$,

α_s – specified according to column's type (4 for interior, 3 for edge, and 2 for corner column).

All other parameters of this expression are explained earlier.

According to Section 8.7.4 of the CSA S806-12, the value of f'_c shall not be taken greater than 60MPa. In addition, the value of V_c in the above equations must be multiplied by $(300/d)^{0.25}$ when the effective depth of the slab exceeds 300mm in which takes the effect of member's size into consideration.

2.12 EN 1992-1-1 (2023)

The PS design procedure for FRP-reinforced slabs follows the CST . The lower modulus of elasticity of FRP reinforcement is taken into account The PS strength of flat slab can be expressed as follows:

$$\tau_{Rd,c} = \min \left\{ \frac{0.6k_{pb} \left(100\rho_f \frac{E_f}{E_s} f_{ck} \frac{d_{dg}}{d_v} \right)^{1/3}}{0.5\sqrt{f_{ck}}}, \quad V_c = \tau_{Rd,c} b_{0(0.5d_v)} d_v \right\} \quad (13)$$

Where:

k_{pb} –Shear gradient enhancement coefficient for punching ($k_{pb} = 3.6 \sqrt{1 - \frac{b_0}{b_{0(0.5d)}}} : 1 \leq$

$k_{pb} \leq 2.5$),

f_{ck} – Characteristic compressive strength of cylinder ($f_{ck} \approx f'_c$),

d_{dg} –Equivalent aggregate size parameter accounting for the roughness of the punching shear crack and failure surface as influenced by the concrete type and aggregate characteristics,

b_0 –Length of control perimeter at face of column,

$b_{0(0.5d_v)}$ –Length of control perimeter at a distance of $0.5d_v$ from column face. $b_{0(0.5d_v)} = b_0 + \pi d_v$.

3. Experimental database

A total of 204 test results of FRP RC flat slabs subject to concentric PS are collected from the literature. The data base consists of (11, 12, 5, 3, 5, 6, 3, 4, 5, 5, 7, 6, 5, 2, 6, 5, 7, 5, 3, 8, 4, 7, 6, 4, 3, 6, 4, 3, 1, 3, 5, 3, 5, 1, 10, 1, 5, 4, 4, 3, and 9) reported by, (Louka, 1999), (Matthys & Taerwe, 2000), (Rahman et al., 2000), (Hassan et al., 2000), (El-Ghandour et al., 2003), (Zaghloul et al., 2003), (Ospina et al., 2003), (Hussein et al., 2004), (Jacobson et al., 2005), (El-Gamal et al., 2005a), (El-Gamal et al., 2005b), (Zhang et al., 2005), (El-Tom, 2007), (Zaghloul, 2007), (El-Gamal et al., 2007), (Lee et al., 2009), (Zhu et al., 2011), (Bouguerra et al., 2011), (Zhu et al., 2012), (Nguyen-Minh & Rovňák, 2013), (Dulude et al., 2013), (Hassan et al., 2013a), (Hassan et al., 2013b), (El-Gendy & El-Salakawy, 2015), (Tharmarajah et al., 2015), (Mostafa, 2016), (Elgabbas et al., 2016), (Gouda & El-Salakawy, 2016b), (Gouda & El-Salakawy, 2016a), (Oskouei et al., 2017), (Ju et al., 2018), (Al Ajami, 2018), (Hussein & El-Salakawy, 2018), (Hemzah et al., 2019), (Huang et al., 2020), (Gu, 2020), (Eladawy et al., 2020), (Salihi & Hamad, 2023), (Alkhattabi et al., 2024), (Elnady et al., 2024), (Khdir & Yaseen, 2024), and (Dinh et al., 2025) respectively. All these slabs were constructed without shear reinforcement and failed by the PS. It is randomly divided into two sets for training and testing. The training set includes 80% (163) slabs, and the remaining 20% (41) are for testing. The former set is used to form a relationship between the input parameters and the output to develop the models, and the latter is for unbiased evaluation of the developed models. The statistical descriptions of each parameter are summarized as illustrated in Table 1.

The frequency histograms and normal distribution curves are presented in Figure 1. The investigated variables are moderately asymmetrically distributed, but they are not symmetrically distributed in terms of normal distribution. The

majority of these parameters follow a bell-shaped trend but deviate from normality at varying levels of positive skewness. The majority are distributed around the middle ranges, and only a few approaches the extreme values. It should be noted that the histogram class intervals shown in Figure 1 were determined using the Freedman–Diaconis rule to obtain statistically optimal bin widths (Freedman & Diaconis, 1981). The calculated bin widths were subsequently rounded to practical engineering intervals to improve the readability of the graphical presentation without affecting the underlying statistical representation. Figure 2 presents the violin plots of the considered parameters. These plots show distribution of the data considering the region of concentration, dispersion, variability, skewness and potential outliers.

Table 1: Statistical description of the main parameters in the database

Variables	Mean	Standard deviation	Minimum	Maximum	Range
d [mm]	143.4	43.5	80.0	285.0	205.0
f'_c [MPa]	41.95	14.5	21.1	98.3	77.2
ρ_f [%]	0.93	0.54	0.15	3.76	3.6
E_f [GPa]	66.69	31.49	28.4	160.0	131.6
V_{test} [kN]	443.83	303.47	79.0	1600.0	1521.0

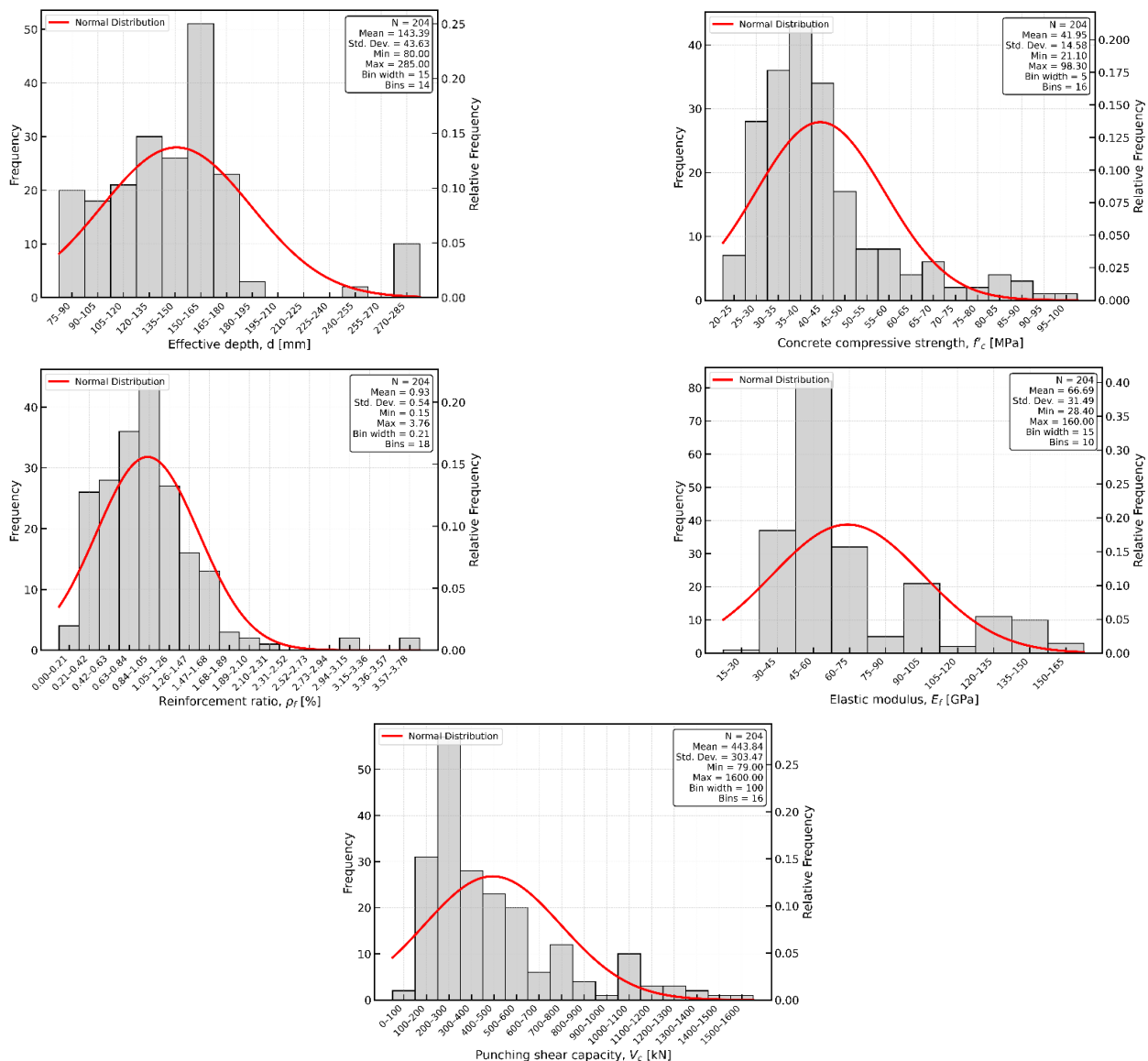


Figure 1: Frequency and normal distribution of the data

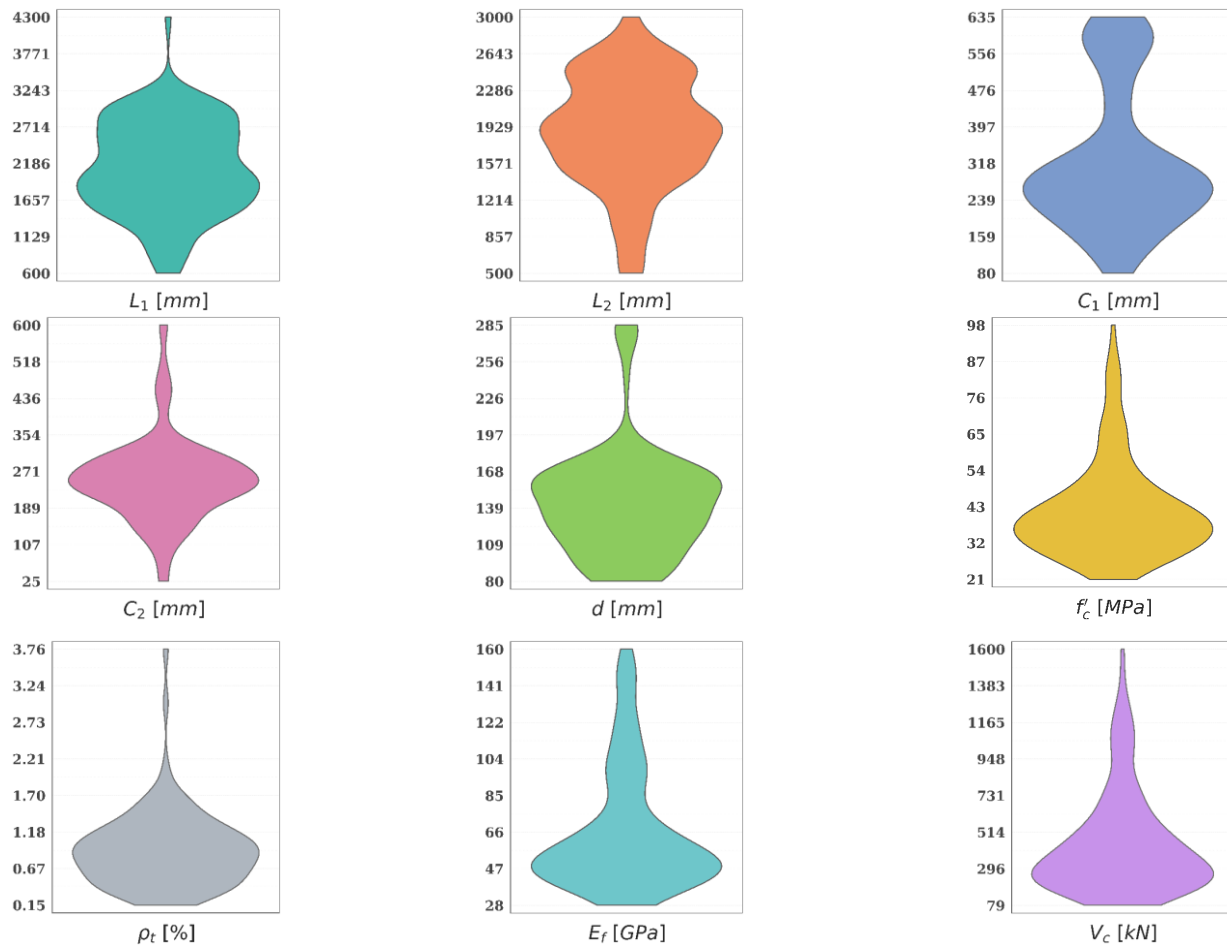


Figure 2: Violin plot distributions of the test parameters

4. Methodology

Three machine learning algorithms, namely eXtreme Gradient Boosting (XGBoost), Random Forest (RF), and Symbolic Regression (SR), were employed to develop the predictive models. These algorithms were selected due to their accuracy and consistency. The SR is regarded as a conventional machine learning approach, whereas XGBoost and R.F belong to the category of tree-based learning models. Among them, XGBoost has gained considerable attention because of its superior predictive performance and robustness across diverse datasets.

The ML models were developed using Python and the database is divided into training and testing sets. The performance of the proposed models is measured using the coefficient of determination (R^2), coefficient of variance (CV), mean absolute error (MAE), and root mean square error (RMSE). Figure 3 shows the general workflow for the proposed models and the evaluation of their performance

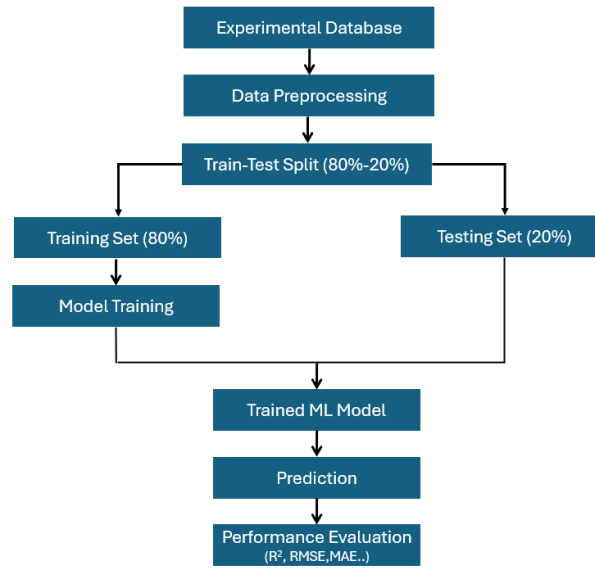


Figure 3: Workflow

diagram of the proposed machine

learning model development

$$R^2 = 1 - \frac{\sum_{i=1}^N (V_{test} - V_{Pred})^2}{\sum_{i=1}^N (V_{test} - \bar{V}_{test})^2} \quad (14)$$

$$C.O.V = \frac{\text{Standard deviation}}{\text{Mean}} \quad (15)$$

$$MAE = \frac{\sum_{i=1}^N |V_{Pred} - V_{test}|}{N} \quad (16)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (V_{Pred} - V_{test})^2}{N}} \quad (17)$$

Where:

 R^2 – Coefficient of determination [-], V_{test} – Experimental punching shear strength [kN], $V_{pred.}$ – Predicted punching shear strength [kN], N – No. of test results [-], $C.O.V$ – Coefficient of Variation [-], MAE – Mean absolute error [kN], $RMSE$ – Root mean square error [kN].

4.1 eXtreme Gradient Boosting (XGBoost)

Boosting (XGBoost) is an advanced ensemble predictive learning algorithm based on the Gradient Boosting framework. XGBoost supports parallel processing, enabling efficient model training on large datasets. The algorithm iteratively constructs a sequence of decision trees, with each subsequent tree developed to minimize the prediction errors of the preceding ones. The outputs of all individual trees are then assembled to produce the final prediction. Figure 4 shows a typical flowchart of the XGBoost algorithm technique. In this figure, the XGBoost algorithm utilizes an iterative procedure. Accordingly, the parameters in the subsequent step are updated using residual obtained from the previous step in order to optimize the objective function. Here x_i , ϕ and F_k shown in Figure 4, represent the i -th input variable, the trained parameters, and the prediction function of an individual tree, respectively (Nguyen et al., 2021).

The input variables used in the XGBoost model and the subsequent global feature contribution (SHAP) analysis were selected based on their physical significance and their established influence on the punching shear capacity of FRP-reinforced slab-column connections, as reported in previous experimental studies and design

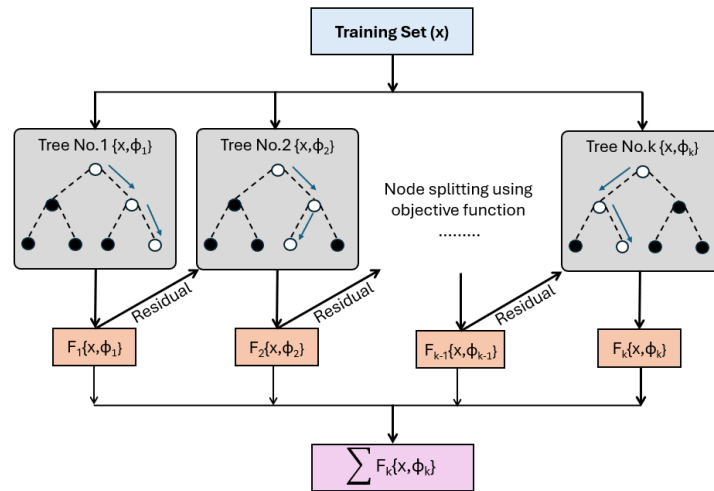


Figure 4: Flowchart of XGBoost algorithm

4.2 Random forest (RF)

RF is an ensemble learning algorithm that consists of a large number of decision trees to increase prediction accuracy and robustness. The RF algorithm is viewed as a variation of the bootstrap aggregation (bagging) method created to minimize variance and overfitting of decision trees by stabilizing them, improving their accuracy, or forcing extreme values. Each decision tree is built independently on a bootstrap subsample of the training dataset. The process employs a random subset of features at each split rather than considering all input variables. This increases diversity within the models and reduces correlation among individual trees. Every tree is constructed by taking a random subset of features and then just using a classical split-selection procedure. Then, the RF utilizes the predictions of many independent trees to improve performance and reduce overfitting (Mangalathu & Jeon, 2019). Figure 5 shows a typical flowchart of the RF algorithm technique.

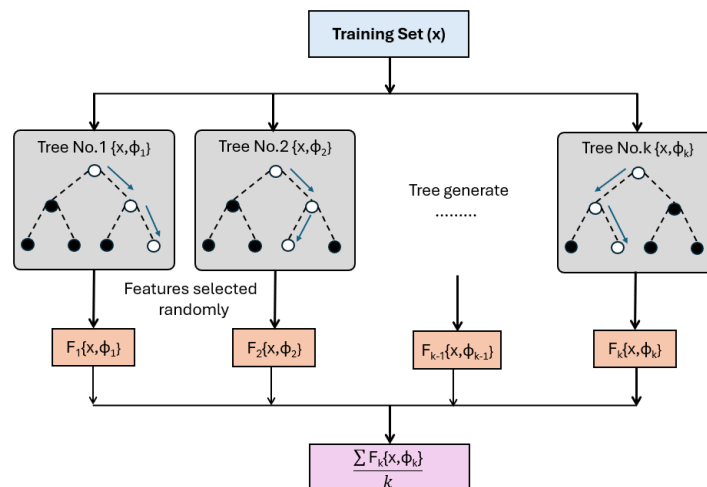


Figure 5: Flowchart of RF algorithm

4.3 Symbolic Regression technique (SR)

SR is a data-driven modeling technique that automatically discovers explicit mathematical relationships between input and output variables without assuming a predefined functional form. It can identify compact interpretable analytical models directly from experimental data by simultaneously optimizing the structure of an equation and its numerical coefficients. Unlike conventional machine learning methods, which often operate as black-box models, symbolic regression produces transparent equations that facilitate physical interpretation and engineering application (Makke & Chawla, 2024). SR provides a powerful framework for capturing these nonlinear interactions and deriving predictive equations that balance accuracy and interpretability. Consequently, it has emerged as a valuable tool for developing practical punching shear models and enhancing the understanding of the underlying mechanisms governing punching shear behavior.

4.4 SHAP Analysis

To examine the contribution of the most effective parameter to the PS strength to adopt in the SR model. This method examines all possible combinations of inputs to find the average effect of each one, and the more crucial input parameter achieves the higher SHAP value. Figure 6 plots the input parameters on the vertical axis and ranks them according to their relative importance. The SHAP values are plotted along the horizontal axis and show how much each variable contributes to the model prediction. Each dot represents a database instance, and the strength of each parameter is indicated by a color scale ranging from blue to red. The red-colored points represent higher parameter values, whereas the blue-colored points correspond to lower values. It should be noted that the parameters with positive SHAP values increase the predicted PS strength, and those with negative SHAP values reduce the predicted response. Furthermore, the broad horizontal spread of the SHAP values for the dominant variables indicates their substantial sensitivity and strong influence on the model prediction. The SHAP analysis indicates that the combined parameters $(\rho_f f'_c \beta)^{1/4}$ have the strongest influence on the PS strength. Therefore, it is adopted in the SR model, and the PS strength is calculated by multiplying the combined parameter by the shear area of the critical section ($b_0 d$).

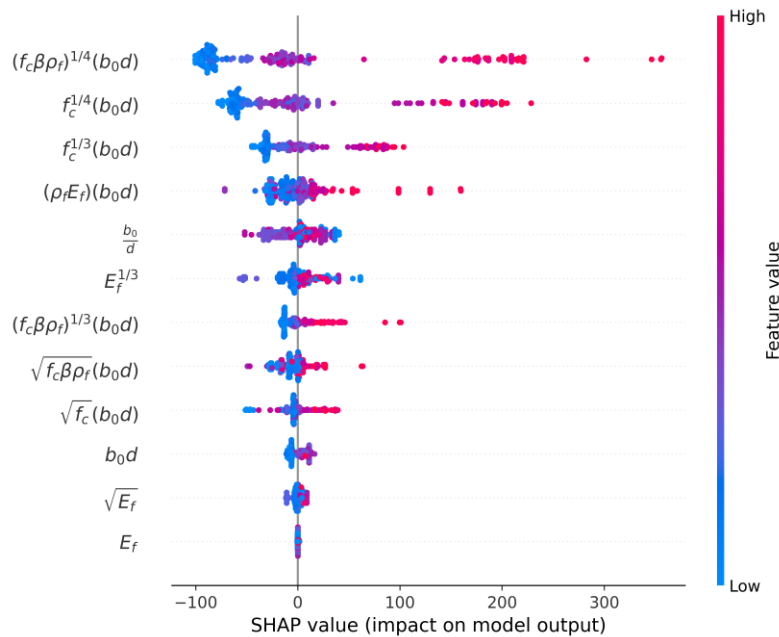


Figure 6: Global feature contribution analysis of the XGboosting model using SHAP values

Based on the SHAP analysis, the combined parameters $(\rho_f f'_c \beta)^{1/4}$ are found to have the strongest influence of the PS of FRP RC flat slabs. Hence, it is adopted in the proposed SR model, which takes the following form:

$$V_c = 0.3134(E_f)^{\frac{1}{3}}(\rho_f f'_c \beta_c)^{\frac{1}{4}} b_{0(1.5d)}. d \quad (18)$$

Where:

$$\beta_c = \text{Ratio of long side to short side of column's cross section } \beta_c = \frac{\max(C_1, C_2)}{\min(C_1, C_2)} [-].$$

All other parameters of this expression are explained earlier.

The above expression utilizes the influence of the mechanical properties of concrete and FRP reinforcement in the PS calculation. It combines the effects of reinforcement ratio, concrete compressive strength, column aspect ratio, and the effective shear-resisting area. It is hardly surprising since most existing models adopted the same parameters.

5. Statistical and Comparative Results

Figure 7 illustrates the Heatmap visualization comparing the PS predictions of the proposed and existing models. Among the empirical formulations, the equations proposed by (Hemzah et al., 2019), (Ospina et al., 2003), (El-Ghandour et al., 2003), and (El-Gamal et al., 2005) demonstrate the most satisfactory predictive performance among the conventional equations proposed by other researchers, exhibiting prediction ratios closest to unity with relatively lower variability. The equations proposed by (Matthys & Taerwe, 2000), (Jacobson et al., 2005), and (Ju et al., 2021), together with the provisions of (JSCE-97), (CSA S806-12) and EN 1992-1-1 (2023)) design codes, exhibit modest accuracy and widely scatter. In contrast, the provisions of ACI 440.11-22 design code show the least satisfactory performance, characterized by highly conservative predictions and significant variability relative to the experimental database. This behavior may be attributed to the inability of the existing formulations to adequately represent the interaction among concrete properties, reinforcement characteristics, slab geometry, and stiffness-related mechanisms governing the punching shear strength capacity.

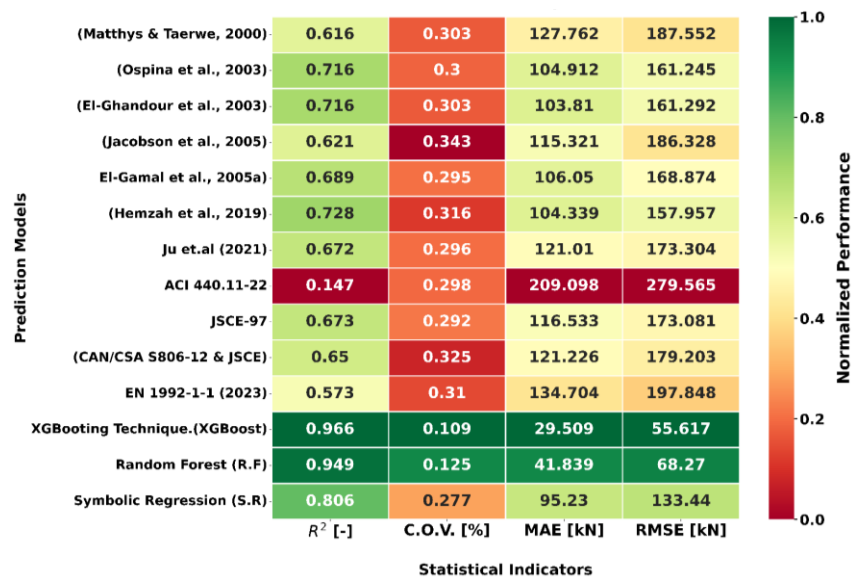


Figure 7: Heatmap visualization comparing the performance of punching shear prediction models based on the overall experimental database using R^2 , C.O.V., MAE, and RMSE

Furthermore, the proposed machine-learning-based models, particularly XGBoost and RF, significantly outperform the existing models by achieving substantially higher prediction accuracy, lower variability, and stronger agreement with the experimental results. Similarly, the proposed SR model demonstrates highly competitive predictive capability compared with the existing empirical equations, providing improved agreement with the experimental database while maintaining a simplified mathematical formulation. The enhanced predictive performance of the proposed XGBoost and Random Forest

(RF) models, together with the improved performance of the Symbolic Regression (SR) model, is attributed not merely to their data-driven nature, but rather to their ability to capture the interaction-controlled behavior governing punching shear resistance. Unlike conventional empirical equations and design-code provisions, which assume fixed functional relationships among the governing parameters, the proposed models identify the evolving interactions between concrete strength, reinforcement characteristics, slab geometry, stiffness, and critical shear perimeter directly from the experimental data. The SHAP analysis further confirms that punching shear resistance is governed primarily by coupled interaction terms rather than isolated variables. Consequently, the proposed models provide a more realistic representation of the underlying failure mechanism, resulting in substantially improved predictive accuracy and reduced scatter.

The performance evaluation metrics of the three proposed prediction models for both the training and testing stages are summarized in Table 2. Overall, all models demonstrate satisfactory predictive capability in estimating the punching shear strength of FRP-reinforced slabs. However, clear differences in prediction accuracy, stability, and generalization capability can be observed among the investigated approaches.

Table 2: Performance evaluation metrics of the proposed machine learning (ML) models for the training and testing datasets

Proposed Technique	Training						Testing					
	R2 [-]	Avg. [-]	STD. [-]	C.O.V [%]	MAE [kN]	RMSE [kN]	R ² [-]	Avg. [-]	STD. [-]	C.O.V [%]	MAE [kN]	RMSE [kN]
S.R	0.802	1.019	0.289	0.281	93.237	130.04	0.812	1.033	0.269	0.261	103.15	146.16
R.F	0.976	0.989	0.089	0.090	31.448	46.164	0.890	1.021	0.222	0.217	68.459	103.90
XGBoost	0.978	0.996	0.070	0.070	21.234	45.262	0.915	1.066	0.221	0.207	63.549	87.931

Figures 8 and 9 illustrate Box and violin plot comparisons of the punching shear strength ratio for existing design equations and ML models. The proposed ML models (XGBoost and RF) showed higher prediction accuracy than that of the SR model. That is, the coefficient of determination for the overall dataset obtained using XGBoost, RF, and SR are 0.966, 0.949, and 0.806, respectively. In general, a noticeable increase in data scatter is observed at higher load levels, as illustrated in Figure 10, with the dispersion starting to increase at approximately (150-200)kN and becoming significantly more pronounced beyond (250-300)kN. This behavior can be attributed to several interacting parameters. At elevated loads, the structural response transitions from a relatively stable, quasi-linear behavior to a highly nonlinear response characterized by crack localization, concrete softening, and potential shifts in failure mode (from flexural to punching shear or combined mechanisms) (Muttoni & Simões, 2023); (El-Gamal et al., 2005a). In addition, the bond degradation between concrete and reinforcement, particularly in the case of FRP bars, may reduce shear transfer efficiency. The system becomes increasingly sensitive to minor variations in material and geometric properties, amplifying prediction errors (Ospina et al., 2003). These factors, combined with the inherent limitations of empirical equations and possible experimental uncertainties, result in significantly higher dispersion at higher load levels.

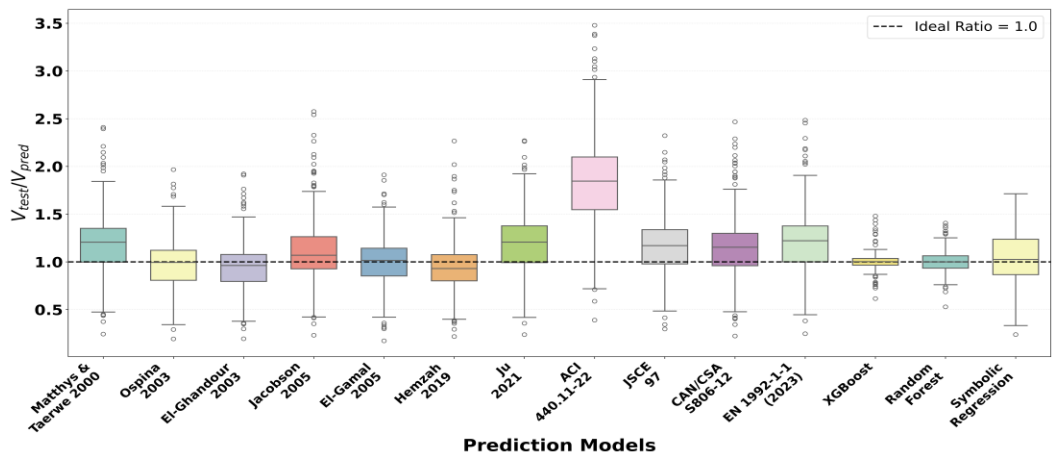


Figure 8: Box plot comparison of punching shear strength ratio for existing design equations and ML models

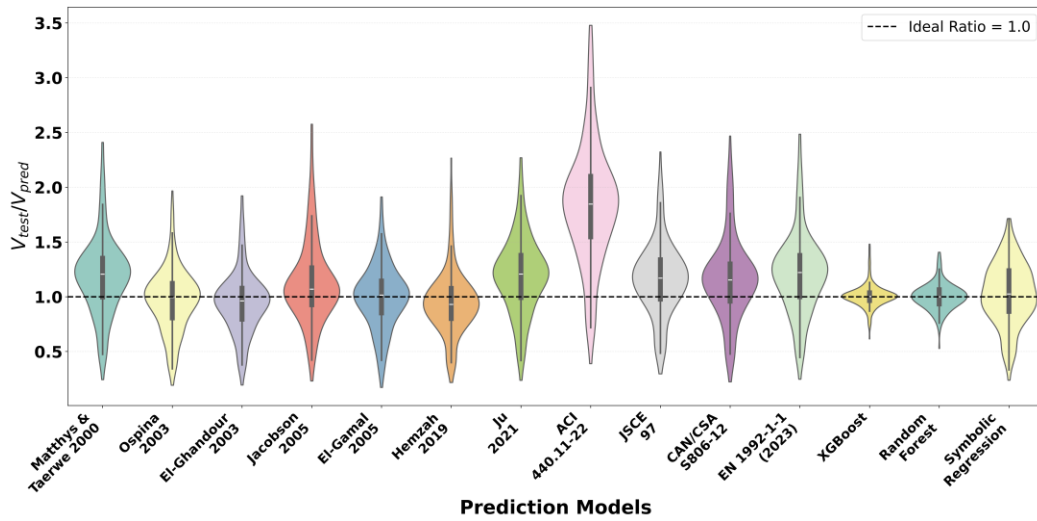
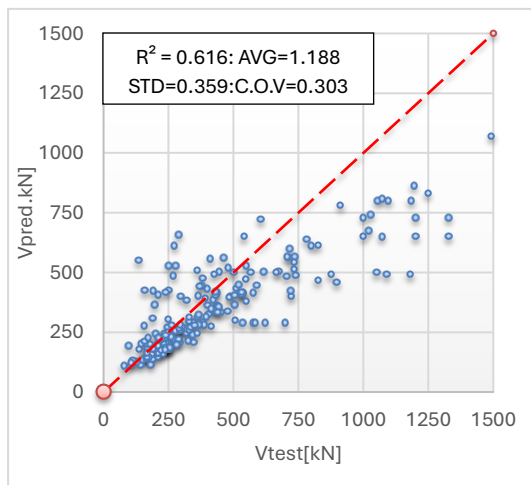
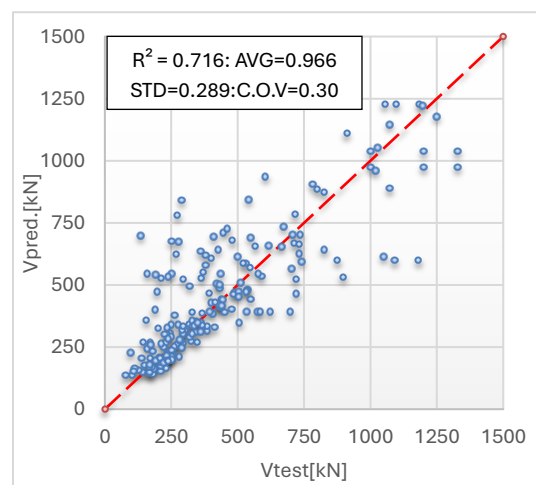


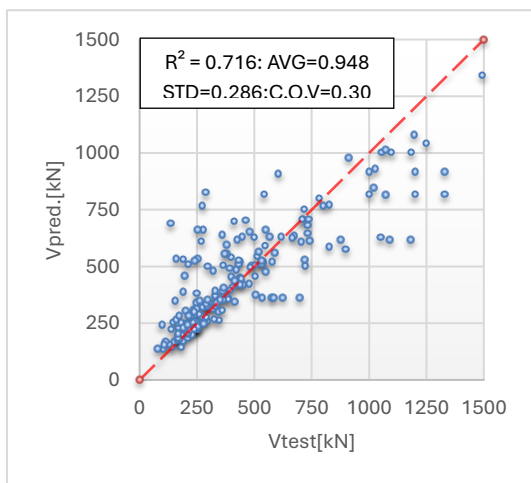
Figure 9: Violin plot comparison of punching shear strength ratio for existing design equations and ML models



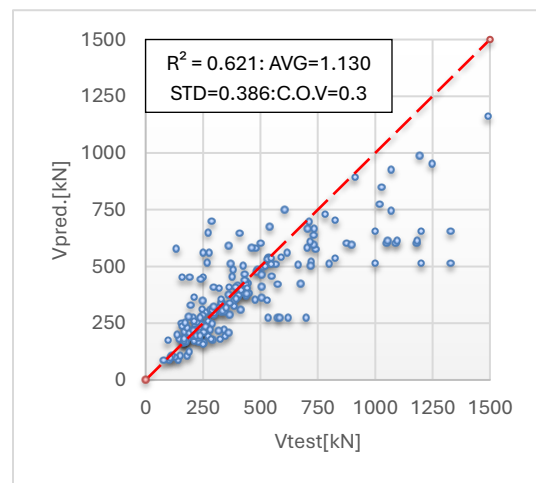
(a) Matthys & Taerwe (200)



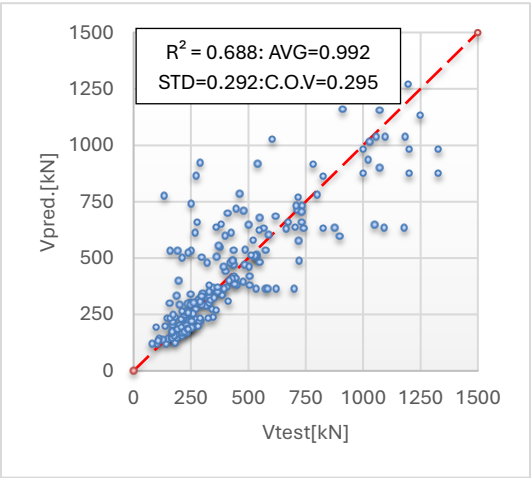
(b) Ospina (2003)



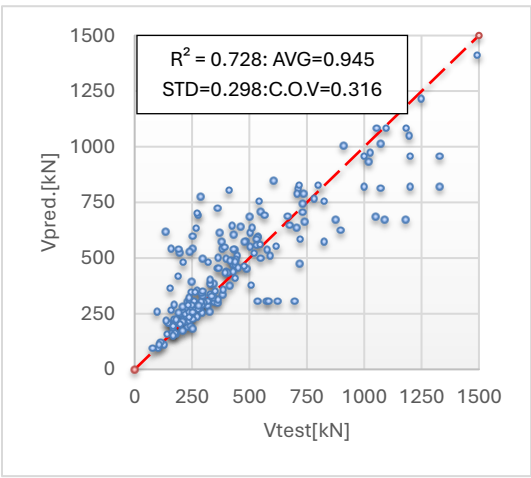
(c) El-Ghandour et al., (2003)



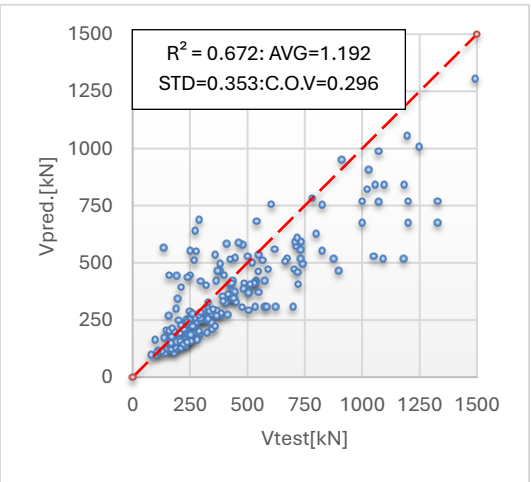
(d) Jacobson et al. (2005)



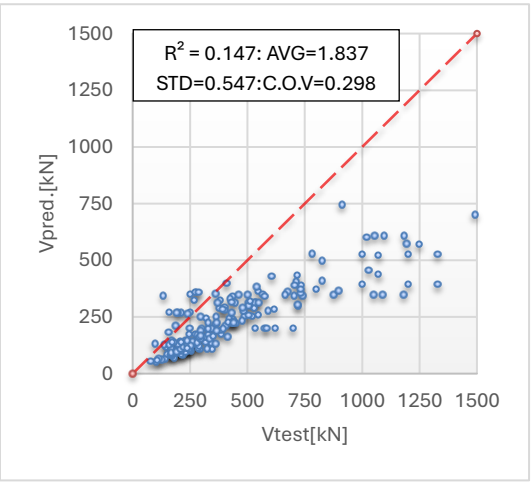
(e) El-Gamal et al. (2005)



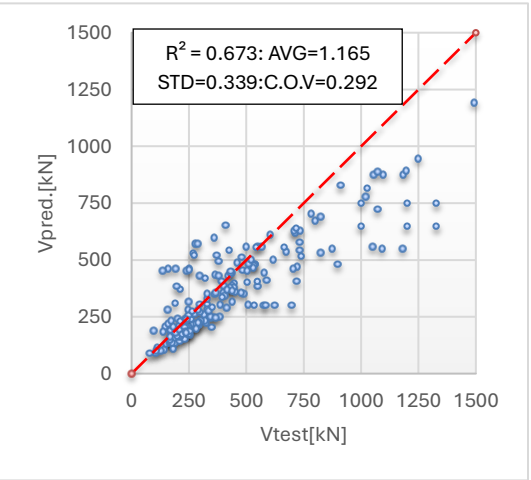
(f) Hemzah et al. (2019)



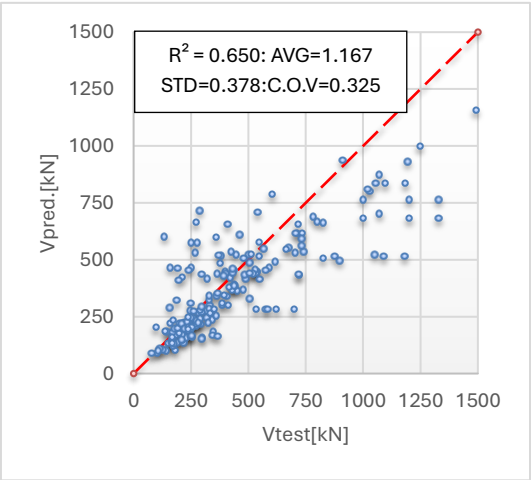
(g) Ju et al. (2021)



(h) ACI 440.11-22



(i) JSCE-97



(j) CAN/CSA S806-12

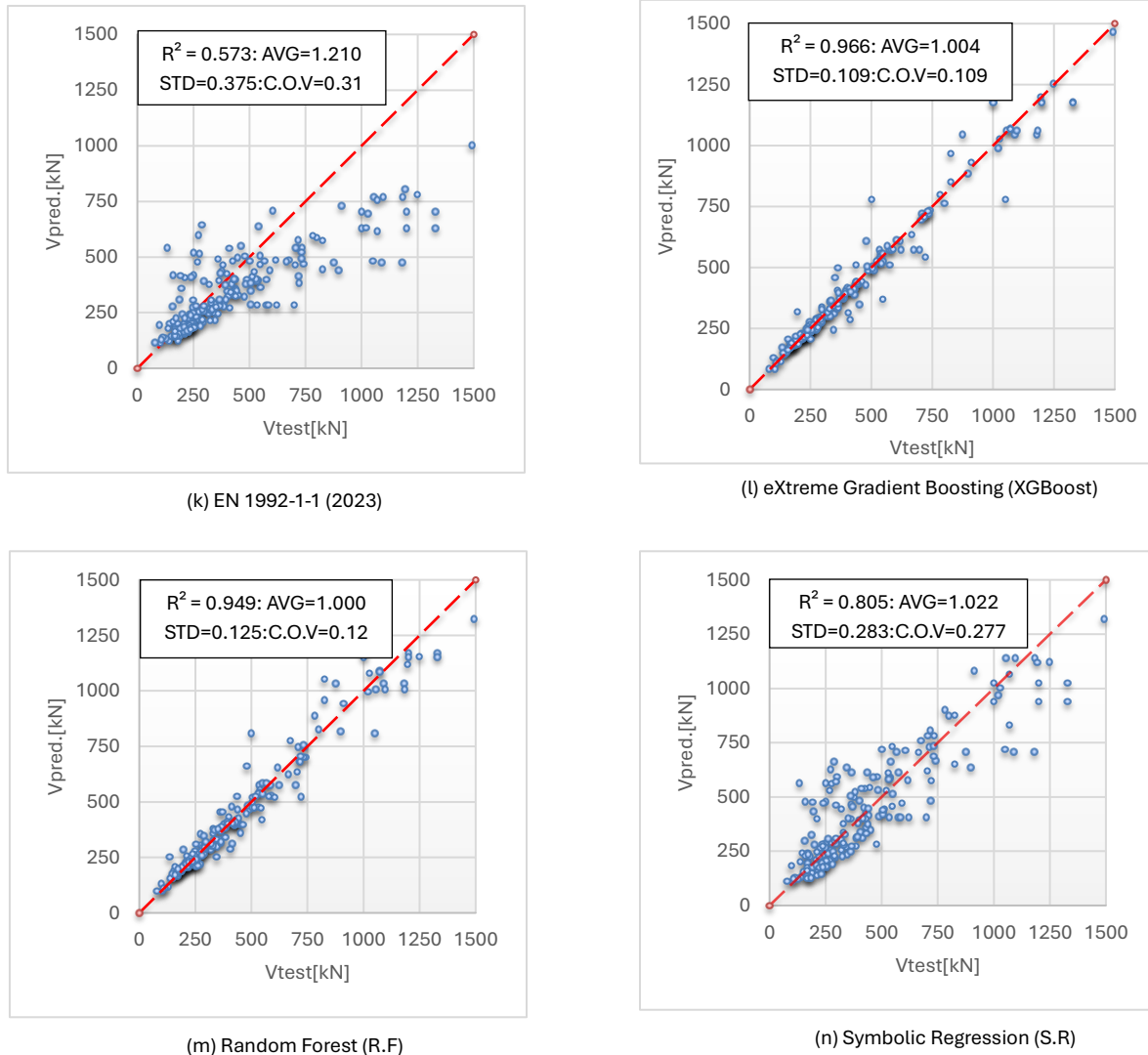


Figure 10: Test versus predicted punching shear capacity of flat slab reinforced with FRP bars for all investigated models

6. Conclusions

This paper has presented three empirical models developed based on the XGBoost, RF, and SR techniques to predict the PS of FRP RC slabs. A comprehensive database of slab columns with a wide range of test parameters was used to train and test the proposed models. The following can be reported:

1. The proposed ML models (XGBoost and RF) showed stronger agreement with the test results than the SR model. The coefficients of determination for the overall dataset obtained using XGBoost, RF, and SR are 0.966, 0.949, and 0.806. This higher predictive accuracy of XGBoost and Random Forest suggests that the PS strength of FRP-reinforced slabs is governed by multiple interacting mechanical mechanisms rather than a single global mathematical relationship, enabling ensemble-learning models to capture the underlying structural behavior more effectively than Symbolic Regression.
2. The proposed models were validated by comparing their punching shear predictions with the existing model (Hemzah et al., 2019), (Ospina et al., 2003), (El-Ghandour et al., 2003), and (El-Gamal et al., 2005). The comparisons revealed that the PS calculations of the proposed model overperformed those provided by the existing ones.

3. The SHAP analysis revealed that the combined parameters $(\rho_f f'_c \beta)^{1/4}$ and the effective shear-resisting area ($b_0 d$) as the dominant factors governing the punching shear capacity of FRP-reinforced slabs.
4. The provisions of ACI 440.11-22 show the poorest predictive performance, characterized by highly conservative predictions and considerably greater variability than the experimental database and the other international design codes, including the JSCE-97, CAN/CSA S806-12, and EN 1992-1-1 (2023).
5. Overall, most punching shear prediction equations proposed in the literature exhibited limited predictive accuracy, often yielding conservative estimates of experimental punching shear capacity, particularly at higher load levels and for large-scale flat slab specimens.

Author Contributions

Conceptualization, **Z.N.M.**; methodology, **Z.N.M.**; software, **Z.N.M.**; validation, **A.F.A.** and **Z.N.M.**; resources, **A.F.A.** and **Z.N.M.**; writing—original draft preparation, **Z.N.M.** and **A.F.A.**; writing—review and editing, **A.F.A.**; visualization, **A.F.A.**, and **Z.N.M.** All authors have read and agreed to the published version of the manuscript.

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Data availability

The data used to support the findings of this study are included within the article.

Conflict of interest

The authors have no conflict to declare.

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Appendix A

See Tables A.1 and A.2 in Appendix-A

Table A.1: Details of Flat slab test data from literature

No.	Source	Type	ID	Length(L1)	Width (L2)	Loading area		d	f _c '	ρ _f	E	V _{test}
			Specif.	[mm]	[mm]	C1 [mm]	C2 [mm]	[mm]	MPa	[%]	[GPa]	[kN]
1	(Louka, 1999[	GFRP	1	3000	1800	575	225	175	43	1	41.3	500
2		GFRP	2	3000	1800	575	225	175	43	1	41.3	1050
3		GFRP	3	3000	1800	575	225	175	43	1	39.3	875
4		GFRP	4	3000	1800	575	225	175	43	1	39.3	1090
5		GFRP	5	3000	1800	575	225	175	43	1	39.3	1180
6		CFRP	C1	3000	1800	575	225	175	55	1	100	1000
7		CFRP	C2	3000	1800	575	225	175	55	1	100	1200
8		CFRP	C3	3000	1800	575	225	175	55	1	100	1328
9		CFRP	H2	3000	1800	575	225	175	45	1	160	1055
10		CFRP	H4	3000	1800	575	225	175	45	1	160	1096
11		CFRP	H4	3000	1800	575	225	175	45	1	160	1183
12	(Matthys & Taerwe, 2000)	CFRP	C1	1000	1000	150	150	96	36.7	0.27	91.8	181
13		CFRP	C1'	1000	1000	230	230	96	37.3	0.27	91.8	189
14		CFRP	C2	1000	1000	150	150	95	35.7	1.05	95	255
15		CFRP	C2'	1000	1000	230	230	95	36.3	1.05	95	273
16		CFRP	C3	1000	1000	150	150	126	33.8	0.52	92	347
17		CFRP	C3'	1000	1000	230	230	126	34.3	0.52	92	343
18		CFRP	CS	1000	1000	150	150	95	32.6	0.19	148	142
19		CFRP	CS'	1000	1000	230	230	95	33.2	0.19	148	150
20		C&G	H2	1000	1000	150	150	89	35.8	3.76	40.7	231
21		C&G	H2'	1000	1000	80	80	89	35.9	3.76	40.7	171
22		C&G	H3	1000	1000	150	150	122	32.1	1.22	44.8	237
23		C&G	H3'	1000	1000	80	80	122	32.1	1.22	44.8	217
24	(Rahman et al., 2000)	GFRP	1	2000	2500	250	150	162	42	0.28	85	622
25		GFRP	2	2000	2500	250	150	162	42	0.28	85	698
26		GFRP	3	2000	2500	250	150	162	42	0.28	85	575
27		GFRP	4	2000	2500	250	150	162	42	0.28	85	534
28		GFRP	5	2000	2500	250	150	162	42	0.28	85	584
29	(Hassan et al., 2000)	GFRP	1	1800	3000	575	225	165	59	0.57	147	1000
30		GFRP	2	1800	3000	575	225	165	59	0.57	147	1200
31		GFRP	3	1800	3000	575	225	165	59	0.57	147	1328
32	(El-Ghandour et al., 2003)	GFRP	SG1	2000	2000	200	200	142	32	0.18	45	170
33		CFRP	SC1	2000	2000	200	200	142	32.8	0.15	110	229
34		GFRP	SG2	2000	2000	200	200	142	46.4	0.38	45	271
35		GFRP	SG3	2000	2000	200	200	142	30.4	0.38	45	237
36		CFRP	SC2	2000	2000	200	200	142	29.6	0.35	110	317
37	(Zaghloul et al., 2003)	GFRP	F1	1500	1500	200	200	82	37.4	1.1	46	165
38		GFRP	F2	1500	1500	200	200	112	33	0.81	46	170
39		GFRP	F3	1500	1500	200	200	82	38.2	1.29	46	210
40		GFRP	F4	1500	1500	200	200	82	39.7	1.54	46	230
41		GFRP	F5	1500	1500	200	300	82	30.3	1.1	46	168
42		GFRP	F6	1500	1500	200	400	82	29.4	1.1	46	185
43	(Ospina et al., 2003)	GFRP	GFR-1	2150	2150	250	250	120	29.5	0.73	34	217
44		GFRP	GFR-2	2150	2150	250	250	120	28.9	1.46	34	260
45		GFRP	NEF-1	2150	2150	250	250	120	37.5	0.87	28.4	206
46	(Hussein et al., 2004)	GFRP	G-S1	1830	1830	250	250	100	40	1.18	42	249
47		GFRP	G-S2	1830	1830	250	250	100	35	1.05	42	218
48		GFRP	G-S3	1830	1830	250	250	100	29	1.67	42	240
49		GFRP	G-S4	1830	1830	250	250	100	26	0.95	42	210
50	(Jacobson et al., 2005)	GFRP	1	2300	2000	635	250	161	38	0.98	33	537
51		GFRP	2	2300	2000	635	250	161	37	0.98	33	536
52		GFRP	3	2300	2000	635	250	161	37	0.95	33	531
53		GFRP	7	4300	2000	635	250	161	34	0.98	33	721
54		GFRP	8	4300	2000	635	250	161	51	0.98	33	897
55		GFRP	G-S1	3000	2500	600	250	159	49.6	1	44.6	740

No.	Source	Type	ID	Length(L1)	Width (L2)	Loading area		d	f _c '	ρ _t	E	V _{test}
			Specif.	[mm]	[mm]	C1 [mm]	C2 [mm]	[mm]	MPa	[%]	[GPa]	[kN]
56	(El-Gamal et al., 2005a)	GFRP	G-S2	3000	2500	600	250	159	44.3	1.99	38.5	712
57		GFRP	G-S3	3000	2500	600	250	156	49.2	1.21	46.5	732
58		CFRP	C-S1	3000	2500	600	250	165	49.6	0.35	122.5	674
59		CFRP	C-S2	3000	2500	600	250	165	44.3	0.69	122.5	799
60	(Zhang et al., 2005)	CFRP	CS1	1900	1900	250	250	100	31	0.41	120	251
61		CFRP	CS2	1900	1900	250	250	100	33	0.54	120	293
62		CFRP	CS3	1900	1900	250	250	100	25.7	0.75	120	285
63		CFRP	CSHD1	1900	1900	250	250	100	35.9	0.54	120	325
64		CFRP	CSHD2	1900	1900	250	250	100	38.6	0.75	120	360
65		CFRP	CSHS1	1900	1900	250	250	150	85.6	0.36	120	399
66		CFRP	CHSHS2	1900	1900	250	250	150	98.3	0.5	120	446
67	(El-Tom, 2007)	GFRP	1	1900	1900	250	250	110	66.8	1	41	282
68		GFRP	2	1900	1900	250	250	110	62	1.2	41	319
69		GFRP	3	1900	1900	250	250	110	64	1.5	41	384
70		GFRP	4	1900	1900	250	250	160	64	1.2	41	589
71		GFRP	5	1900	1900	250	250	145	70.1	1.2	41	487
72		GFRP	6	1900	1900	250	250	135	67.6	1.2	41	437
73	(Zaghloul, 2007)	CFRP	ZJEF1	1760	1760	250	250	120	25	1.37	100	188.3
74		CFRP	ZJEF2	1760	1760	250	250	120	26.2	0.94	100	155.9
75		CFRP	ZJEF3	1760	1760	250	250	120	56.8	1.37	100	210.9
76		CFRP	ZJEF5	1760	1760	250	250	81	28.4	1.37	100	97.1
77		CFRP	ZJEF7	1760	1760	420	250	120	27.8	1.37	100	196.2
78	(El-Gamal et al., 2007)	GFRP	G-S4	3000	2500	600	250	175	44.1	1.2	44.5	707
79		GFRP	G-S5	3000	2500	600	250	175	44.1	1.2	44.5	735
80	(Lee et al., 2009)	GFRP	GFU1	2300	2300	225	225	110	36.3	1.17	48.2	222
81		GFRP	GFB2	2300	2300	225	225	110	36.3	2.14	48.2	246
82		GFRP	GFB3	2300	2300	225	225	110	36.3	3	48.2	248
83		GFRP	GFBF3	2300	2300	225	225	110	33.8	3	48.2	330
84		BFRP	S3	1500	1500	150	150	135	33.5	0.29	100	145
85		BFRP	S4	1500	1500	150	150	135	35.6	0.55	100	275
86	(Zhu et al., 2011)	BFRP	S5	1500	1500	150	150	135	32.8	0.42	100	235
87		BFRP	S6	1500	1500	150	150	135	32.5	0.42	100	225
88		BFRP	S7	1500	1500	150	150	135	22.6	0.42	100	170
89		BFRP	S8	1500	1500	150	150	135	41.8	0.42	100	235
90		BFRP	S9	1500	1500	150	150	135	40.6	0.42	100	200
91	(Bouguerra et al., 2011)	GFRP	G-200-N	3000	2500	600	250	165	49.1	1.2	44.5	732
92		GFRP	G-175-Na	3000	2000	600	250	143	35.2	1.2	41.6	484
93		GFRP	G-150-N	3000	2000	600	250	118	35.2	1.2	41.6	362
94		GFRP	G-175-H	3000	2000	600	250	143	64.8	1.2	41.6	704
95		GFRP	G-175-N-0.7	3000	2000	600	250	143	53.1	0.7	41.6	549
96		GFRP	G-175-N-0.35	3000	2000	600	250	143	53.1	0.35	41	506
97		CFRP	C-175-N	3000	2000	600	250	145	40.3	0.4	122	530
98	(Zhu et al., 2012)	GFRP	A	1500	1500	150	150	130	22.2	0.42	45.6	176
99		GFRP	B-2	1500	1500	150	150	130	32.5	0.42	45.6	209
100		GFRP	B-3	1500	1500	150	150	130	32.4	0.55	45.6	245
101		GFRP	B-4	1500	1500	150	150	130	32.8	0.29	45.6	167
102		GFRP	C	1500	1500	150	150	130	44.4	0.42	45.6	252
103	(Nguyen-Minh & Rovňák, 2013)	GFRP	GSL-PUNC-0.4	2200	2200	200	200	129	39	0.48	48	180
104		GFRP	GSL-PUNC-0.6	2200	2200	200	200	129	39	0.68	48	212
105		GFRP	GSL-PUNC-0.8	2200	2200	200	200	129	39	0.92	48	248
106	(Dulude et al., 2013)	GFRP	G (0.7) 30/20	2500	2500	300	300	130	34.3	0.71	48.2	329
107		GFRP	G (1.6) 30/20	2500	2500	300	300	130	38.6	1.56	48.1	431
108		GFRP	G (0.7) 45/20	2500	2500	450	450	135	44.9	0.71	48.2	400
109		GFRP	G (1.6) 45/20	2500	2500	450	450	130	32.4	1.56	48.1	504
110		GFRP	G (0.3) 30/35	2500	2500	300	300	285	34.3	0.34	48.2	825
111		GFRP	G (0.7) 30/35	2500	2500	300	300	280	39.4	0.73	48.1	1071
112		GFRP	G (0.3) 45/35	2500	2500	450	450	285	48.6	0.34	48.2	911
113		GFRP	G (0.7) 45/35	2500	2500	450	450	280	29.6	0.73	48.1	1248
114	(Hassan et al., 2013a)	GFRP	G (1.6) 30/20-H	2500	2500	300	300	131	75.8	1.56	57.4	547
115		GFRP	G (1.2) 30/20	2500	2500	300	300	131	37.5	1.21	64.9	438

No.	Source	Type	ID	Length(L1)	Width (L2)	Loading area		d	f _c	ρ _t	E	V _{test}
			Specif.	[mm]	[mm]	C1 [mm]	C2 [mm]	[mm]	MPa	[%]	[GPa]	[kN]
116	(Hassan et al., 2013b)	GFRP	G (1.6) 30/35	2500	2500	300	300	275	38.2	1.61	56.7	1492
117		GFRP	G (1.6) 30/35-H	2500	2500	300	300	275	75.8	1.61	56.7	1600
118		GFRP	G (0.7) 30/20-B	2500	2500	300	300	134	39	0.71	48.2	386
119		GFRP	G (1.6) 30/20-B	2500	2500	300	300	131	32	1.56	48.1	451
120		GFRP	G (1.6) 45/20-B	2500	2500	450	450	131	39	1.56	48.1	511
121		GFRP	G (0.3) 30/35-B	2500	2500	300	300	284	39	0.34	48.2	782
122		GFRP	G (0.7) 30/35-B-1	2500	2500	300	300	281	30	0.73	48.1	1027
123		GFRP	G (0.7) 30/35-B-2	2500	2500	300	300	281	47	0.73	48.1	1195
124		GFRP	G (0.3) 45/35-B	2500	2500	450	450	284	32	0.34	48.2	1020
125	(El-Gendy & El-Salakawy, 2015)	GFRP	GSC-0.9-XX-0.4	2800	1500	300	300	160	41	0.9	60.5	251
126		GFRP	GSC-1.35-XX-0.4	2800	1500	300	300	160	41	1.35	60.5	268
127		GFRP	GSC-1.8-XX-0.4	2800	1500	300	300	160	41	1.7	60.5	277
128		GFRP	GSC-0.9-XX-0.2	2800	1500	300	300	160	41	0.85	60.5	239
129		GFRP	GSC-0.9-XX-0.3	2800	1500	300	300	160	41	0.9	60.5	159
130		GFRP	GRD-0.9-XX-0.4	2800	1500	300	300	160	41	0.9	59.9	191
131	(Tharmarajah et al., 2015)	GFRP	G-0.6%-12-125 T&B	1425	500	500	25	119	68.1	0.6	67.4	344
132		GFRP	G-0.6%-16-300 T&B	1425	500	500	25	117	65.7	0.6	67.4	365
133		GFRP	B-0.6%-12-125 T&B	1425	500	500	25	119	69.3	0.6	54	300
134		GFRP	B-0.6%-16-300 T&B	1425	500	500	25	117	66.1	0.6	54	295
135	(Mostafa, 2016)	GFRP	GSC-0.9-XX-0.4	2600	1450	300	300	160	81	0.87	60.5	251
136		GFRP	GSC-1.35-XX-0.5	2600	1450	300	300	160	85	1.28	60.5	272
137		GFRP	GSC-1.8-XX-0.4	2600	1450	300	300	160	80	1.7	60.5	288
138	(Elgabbas et al., 2016)	BFRP	S2-B	3000	2000	600	250	160	48.8	0.8	69.3	548
139		BFRP	S3-B	3000	2000	600	250	160	42.2	0.79	69.3	665
140		BFRP	S4-B	3000	2000	600	250	160	42.2	0.8	69.3	566
141		BFRP	S5-B	3000	2000	600	250	160	47.9	1.2	69.3	716
142		BFRP	S6-B	3000	2000	600	250	160	47.9	0.4	69.3	576
143		BFRP	S7-B	3000	2000	600	250	160	47.9	0.4	69.3	436
144	(Gouda & El-Salakawy, 2016a)	GFRP	GN-0.65	2600	2600	300	300	160	42	0.65	69.3	363
145		GFRP	GN-0.98	2600	2600	300	300	160	38	0.98	68	378
146		GFRP	GN-1.30	2600	2600	300	300	160	39	1.3	68	425
147		GFRP	GH-0.65	2600	2600	300	300	160	70	0.65	68	380
148	(Gouda & El-Salakawy, 2016b)	GFRP	G-00-XX	2600	2600	300	300	160	38	0.65	68	421
149		GFRP	G-30-XX	2600	2600	300	300	160	42	0.65	68	296
150		GFRP	R-15-XX	2600	2600	300	300	160	40	0.65	63.1	320
151	(Oskouei et al., 2017)	GFRP	NW59	800	800	250	250	176	59	0.7	43	719
152	(Ju et al., 2018)	GFS1	GFRP	3000	2400	300	500	171	36.7	1.57	46.7	410
153		GFS2	GFRP	3000	2400	300	500	171	36.7	1.2	46.7	360
154		GFS3	GFRP	3000	2400	300	500	171	36.7	0.79	46.7	370
155	Al Ajami, 2018	GFRP	G150(200)47	1700	1700	200	200	94	47	0.96	52.5	199
156		GFRP	G250(160)52	1700	1700	200	200	191	52	0.93	52.5	617.2
157		GFRP	G250(100)53	1700	1700	200	200	191	53	1.01	52.5	479.3
158		GFRP	G150(200)35	1700	1700	200	200	94	35	0.96	52.5	167.8
159		GFRP	G250(160)37	1700	1700	200	200	191	37	0.93	52.5	520
160	(Hussein & El-Salakawy, 2018)	GFRP	H-1.0-XX	2800	2800	300	300	160	80	0.98	65	461
161		GFRP	H-1.5-XX	2800	2800	300	300	160	84	1.46	65	541
162		GFRP	H-2.0-XX	2800	2800	300	300	160	87	1.93	65	604
163	(Hemzah et al., 2019)	CFRP	C-F-S-10-4	600	600	100	100	80	51	0.3	144	103
164		CFRP	C-F-S-10-6	600	600	100	100	80	52	0.45	144	127
165		CFRP	S-F-D-10-4	600	600	100	100	80	46	0.6	144	112
166		CFRP	S-F-S-10-4	600	600	100	100	80	52	0.3	144	79
167		CFRP	S-F-S-10-6	600	600	100	100	80	48	0.45	144	107
168	(Huang et al., 2020)	CFRP	F1	1600	1600	200	200	125	25	0.89	123	262

No.	Source	Type	ID	Length(L1)	Width (L2)	Loading area		d	f _c '	ρ _t	E	V _{test}
			Specif.	[mm]	[mm]	C1 [mm]	C2 [mm]	[mm]	MPa	[%]	[GPa]	[kN]
	(Gu, 2020)											
169	(Gu, 2020)	A30-1	GFRP	1500	1500	300	300	88	27.4	1.28	51.1	191
170		A30-2	GFRP	1500	1500	300	300	108	27.3	1.05	51.1	289
171		A30-3	GFRP	1500	1500	300	300	138	26.2	0.82	51.1	413
172		A30-4	GFRP	1500	1500	350	350	86	26.8	1.31	51.1	209
173		A40-1	GFRP	1500	1500	350	350	88	28.2	1.28	51.1	232
174		A40-2	GFRP	1500	1500	350	350	88	26.4	0.89	51.1	221
175		A40-3	GFRP	1500	1500	300	300	88	28.6	1.28	51.1	236
176		A50-1	GFRP	1500	1500	300	300	88	29.2	1.28	51.1	253
177		A50-2	GFRP	1500	1500	300	300	90	32.2	0.87	54.1	237
178		A50-3	GFRP	1500	1500	350	350	88	26.7	1.28	51.1	280
179	(Eladawy et al., 2020)	G4(1.06)-H	GFRP	2500	2500	300	300	151	92	1.06	62.6	134
180	(Salihi & Hamad, 2023)	B16(0.88)	Basalt	2000	2000	250	250	134	29.8	0.88	48.3	295.5
181		B16(1.77)	Basalt	2000	2000	250	250	134	29.8	1.77	48.3	405.2
182		B12(0.88)	Basalt	2000	2000	250	250	138	29.8	0.88	48	290.1
183		B12(0.88)-C35	Basalt	2000	2000	250	250	138	34.6	0.88	48	295.8
184		B12(0.88)-C25	Basalt	2000	2000	250	250	138	21.1	0.88	48	238.1
185	(Alkhattabi et al., 2024)	G-0.20-0.70	GFRP	2500	2500	300	300	144	34.3	0.7	48.1	329
186		G-0.20-1.60	GFRP	2500	2500	300	300	144	38.6	1.6	48.1	431
187		G-0.35-0.30	GFRP	2500	2500	300	300	244	34.3	0.3	48.1	825
188		G-0.35-0.70	GFRP	2500	2500	300	300	244	39.4	0.7	48.1	1071
189	(Elnady et al., 2024)	6-G-S1	GFRP	1500	1500	250	600	117	38	0.83	63.7	365.6
190		9-G-S1	GFRP	1500	1500	250	600	117	44.9	1.25	63.7	391.6
191		12-G-S1	GFRP	1500	1500	250	600	117	41.4	1.67	63.7	431.6
192		6-G-S2	GFRP	1500	1500	250	600	117	43.1	0.83	63.7	477.1
193	(Khdir & Yaseen, 2024)	BR1.5E0	Basalt	2000	1200	250	250	118	30.9	0.44	51.6	137.2
194		BR2.5E0	Basalt	2000	1200	250	250	118	30.9	0.733	51.6	158.8
195		BR3.5E0	Basalt	2000	1200	250	250	114	30.9	1.026	51.6	172.3
196	(Dinh et al., 2025)	GFRP	F-S80	2000	2000	300	300	162	25.2	0.98	50	443.2
197		GFRP	F-S120	2000	2000	300	300	162	32.6	0.65	50	429
198		GFRP	F-S150	2000	2000	300	300	162	32.6	0.52	50	328.4
199		GFRP	F-S120-B16	2000	2000	300	300	159	24.1	1.04	50	415.2
200		GFRP	F-S80-L2	2000	2000	300	300	162	24.1	0.72	50	393.9
201		GFRP	F-S120-C20	2000	2000	200	200	162	25.2	0.65	50	334.7
202		GFRP	F-S120-C45	2000	2000	450	450	162	24.1	0.65	50	504.3
203		GFRP	F-S120-A2.0	2000	2000	300	150	162	25.2	0.65	50	350
204		GFRP	F-S120-A1.5	2000	2000	450	300	162	24.1	0.65	50	438.8

Table A.2: Experimental punching shear capacities and corresponding V_{test}/V_{pred} ratios for the empirical equations and machine learning models

No.	V _{test} [kN]	$\frac{V_{test}}{V_{Eq.1}}$	$\frac{V_{test}}{V_{Eq.2}}$	$\frac{V_{test}}{V_{Eq.3}}$	$\frac{V_{test}}{V_{Eq.4}}$	$\frac{V_{test}}{V_{Eq.5}}$	$\frac{V_{test}}{V_{Eq.8}}$	$\frac{V_{test}}{V_{Eq.9}}$	$\frac{V_{test}}{V_{Eq.10}}$	$\frac{V_{test}}{V_{Eq.11}}$	$\frac{V_{test}}{V_{Eq.12}}$	$\frac{V_{test}}{V_{Eq.13}}$	$\frac{V_{test}}{V_{XGB}}$	$\frac{V_{test}}{V_{RF}}$	$\frac{V_{test}}{V_{Eq.18}}$
1	500.0	1.00	0.81	0.80	0.83	0.77	0.73	0.95	1.44	0.90	0.95	1.04	0.64	0.62	0.70
2	1050.0	2.09	1.71	1.67	1.74	1.62	1.53	1.99	3.01	1.88	2.00	2.17	1.35	1.30	1.46
3	875.0	1.77	1.46	1.42	1.45	1.38	1.30	1.68	2.51	1.59	1.70	1.84	0.84	0.85	1.24
4	1090.0	2.21	1.82	1.76	1.80	1.71	1.62	2.10	3.13	1.98	2.11	2.29	1.04	1.05	1.54
5	1180.0	2.39	1.97	1.91	1.95	1.85	1.75	2.27	3.39	2.15	2.29	2.48	1.13	1.14	1.67
6	1000.0	1.37	0.96	1.09	1.52	1.02	1.04	1.30	1.90	1.33	1.31	1.42	0.85	0.86	0.98
7	1200.0	1.64	1.16	1.31	1.83	1.22	1.25	1.56	2.28	1.60	1.57	1.70	1.02	1.03	1.17
8	1328.0	1.82	1.28	1.45	2.02	1.35	1.39	1.72	2.52	1.77	1.74	1.89	1.13	1.14	1.30
9	1055.0	1.32	0.86	1.05	1.72	1.02	0.97	1.25	1.73	1.20	1.26	1.37	0.99	1.05	0.93
10	1096.0	1.37	0.89	1.09	1.79	1.05	1.01	1.30	1.80	1.25	1.31	1.42	1.03	1.09	0.96
11	1183.0	1.48	0.96	1.18	1.93	1.14	1.09	1.40	1.94	1.35	1.42	1.54	1.11	1.17	1.04

No.	V_{test} [kN]	$\frac{V_{test}}{V_{Eq.1}}$	$\frac{V_{test}}{V_{Eq.2}}$	$\frac{V_{test}}{V_{Eq.3}}$	$\frac{V_{test}}{V_{Eq.4}}$	$\frac{V_{test}}{V_{Eq.5}}$	$\frac{V_{test}}{V_{Eq.8}}$	$\frac{V_{test}}{V_{Eq.9}}$	$\frac{V_{test}}{V_{Eq.10}}$	$\frac{V_{test}}{V_{Eq.11}}$	$\frac{V_{test}}{V_{Eq.12}}$	$\frac{V_{test}}{V_{Eq.13}}$	$\frac{V_{test}}{V_{XGB}}$	$\frac{V_{test}}{V_{RF}}$	$\frac{V_{test}}{V_{Eq.18}}$
12	181.0	1.56	1.29	1.24	1.68	1.44	1.13	1.67	2.57	1.65	1.76	1.46	1.01	0.99	1.41
13	189.0	1.38	1.15	1.10	1.50	1.28	0.90	1.51	2.04	1.41	1.40	1.30	1.02	1.01	1.26
14	255.0	1.41	1.17	1.13	1.55	1.31	0.95	1.52	2.54	1.49	1.60	1.32	1.02	1.09	1.44
15	273.0	1.29	1.06	1.02	1.41	1.19	0.77	1.41	2.07	1.30	1.30	1.21	1.11	1.25	1.31
16	347.0	1.65	1.28	1.32	1.79	1.45	1.15	1.65	3.23	1.69	1.88	1.60	1.11	1.16	1.47
17	343.0	1.43	1.11	1.14	1.55	1.25	0.89	1.44	2.50	1.40	1.45	1.37	1.40	1.36	1.27
18	142.0	1.24	0.95	0.99	1.57	1.17	0.90	1.33	2.18	1.33	1.40	1.16	0.98	0.90	1.08
19	150.0	1.11	0.85	0.88	1.41	1.05	0.72	1.22	1.74	1.14	1.12	1.04	1.00	0.94	0.97
20	231.0	1.22	1.18	0.97	1.00	1.15	0.76	1.33	2.10	1.30	1.37	1.13	1.02	1.06	1.40
21	171.0	1.06	1.03	0.85	0.88	1.01	0.78	1.16	2.16	1.20	1.41	1.01	0.92	1.02	1.22
22	237.0	1.15	1.02	0.92	0.98	1.03	0.76	1.16	2.21	1.19	1.31	1.11	1.02	0.99	1.11
23	217.0	1.21	1.06	0.96	1.03	1.07	0.91	1.22	2.68	1.30	1.58	1.28	0.97	0.97	1.16
24	622.0	2.15	1.58	1.71	2.26	1.70	2.02	2.02	3.10	2.07	2.20	2.19	1.09	1.08	1.53
25	698.0	2.41	1.78	1.92	2.54	1.91	2.27	2.26	3.48	2.32	2.47	2.45	1.22	1.21	1.71
26	575.0	1.99	1.46	1.58	2.09	1.57	1.87	1.86	2.87	1.91	2.03	2.02	1.00	1.00	1.41
27	534.0	1.84	1.36	1.47	1.94	1.46	1.73	1.73	2.66	1.78	1.89	1.88	0.93	0.93	1.31
28	584.0	2.02	1.49	1.61	2.13	1.60	1.90	1.89	2.91	1.94	2.06	2.05	1.02	1.02	1.43
29	1000.0	1.53	1.03	1.22	1.94	1.14	1.22	1.48	2.54	1.54	1.46	1.59	0.85	0.87	1.06
30	1200.0	1.84	1.23	1.47	2.33	1.37	1.46	1.78	3.05	1.85	1.76	1.91	1.02	1.04	1.28
31	1328.0	2.03	1.36	1.62	2.58	1.52	1.62	1.97	3.37	2.05	1.94	2.11	1.13	1.15	1.41
32	170.0	1.11	0.94	0.89	0.95	0.96	1.02	1.08	1.17	1.06	1.14	1.12	0.98	0.86	0.88
33	229.0	1.17	0.86	0.94	1.35	1.00	1.10	1.14	1.56	1.11	1.20	1.18	1.05	0.98	0.91
34	271.0	1.22	1.03	0.97	1.04	0.99	1.15	1.19	1.55	1.24	1.25	1.23	0.93	0.89	1.06
35	237.0	1.23	1.04	0.98	1.05	1.07	1.08	1.20	1.68	1.18	1.26	1.24	1.03	1.01	1.03
36	317.0	1.27	0.92	1.01	1.46	1.10	1.11	1.23	2.27	1.22	1.30	1.28	1.03	1.11	1.05
37	165.0	1.18	1.14	0.94	1.01	1.13	1.00	1.36	2.06	1.21	1.20	1.16	0.85	0.85	1.25
38	170.0	0.92	0.83	0.74	0.80	0.84	0.78	0.96	1.60	0.91	0.94	0.92	0.90	0.88	0.88
39	210.0	1.41	1.37	1.13	1.22	1.35	1.19	1.63	2.42	1.47	1.43	1.38	1.03	1.01	1.53
40	230.0	1.44	1.39	1.15	1.24	1.37	1.21	1.66	2.43	1.51	1.46	1.41	1.04	1.05	1.58
41	168.0	1.16	1.12	0.92	1.00	1.15	0.89	1.37	1.88	1.19	1.11	1.16	0.96	0.97	1.34
42	185.0	1.17	1.13	0.93	1.01	1.17	0.86	1.42	1.82	1.18	1.07	1.20	1.01	0.99	1.45
43	217.0	1.17	1.08	0.93	0.91	1.06	0.92	1.21	1.70	1.14	1.12	1.17	1.05	1.06	1.07
44	260.0	1.12	1.04	0.89	0.87	1.02	0.85	1.16	1.83	1.09	1.08	1.12	1.01	1.10	1.09
45	206.0	1.03	0.98	0.82	0.75	0.90	0.83	1.06	1.44	0.98	0.99	1.03	1.01	1.01	0.97
46	249.0	1.23	1.15	0.98	1.02	1.11	0.99	1.35	2.03	1.22	1.17	1.22	1.04	0.89	1.25
47	218.0	1.17	1.09	0.93	0.97	1.08	0.92	1.28	1.95	1.13	1.12	1.16	0.96	0.90	1.17
48	240.0	1.17	1.09	0.93	0.98	1.11	0.88	1.29	1.83	1.17	1.12	1.17	0.93	0.95	1.20
49	210.0	1.28	1.20	1.02	1.07	1.24	0.97	1.41	2.13	1.31	1.23	1.28	0.94	0.91	1.24
50	537.0	1.29	1.11	1.03	0.99	1.04	0.90	1.27	1.70	1.11	1.20	1.35	0.96	0.97	0.91
51	536.0	1.30	1.12	1.04	1.00	1.05	0.90	1.28	1.72	1.11	1.21	1.36	0.98	0.99	0.91
52	531.0	1.30	1.12	1.04	1.00	1.05	0.91	1.28	1.70	1.11	1.21	1.36	1.00	0.99	0.91
53	721.0	1.80	1.55	1.43	1.38	1.48	1.23	1.77	2.41	1.54	1.67	1.88	1.33	1.38	1.26
54	897.0	1.95	1.69	1.56	1.50	1.50	1.43	1.92	2.45	1.86	1.81	2.04	1.01	1.10	1.41
55	740.0	1.51	1.25	1.21	1.29	1.17	1.11	1.49	2.14	1.44	1.38	1.57	1.01	1.06	1.11
56	712.0	1.26	1.07	1.01	1.02	1.00	0.88	1.24	1.75	1.15	1.15	1.31	0.99	1.04	0.97
57	732.0	1.42	1.17	1.13	1.23	1.11	1.04	1.41	2.06	1.35	1.30	1.48	1.02	1.04	1.07
58	674.0	1.33	0.92	1.06	1.59	1.02	1.04	1.29	1.86	1.26	1.22	1.39	1.18	0.87	0.89
59	799.0	1.31	0.90	1.04	1.56	1.02	0.97	1.27	2.14	1.19	1.20	1.36	1.05	0.97	0.91
60	251.0	1.35	1.06	1.08	1.60	1.27	1.10	1.48	2.44	1.33	1.29	1.34	0.99	1.01	1.24
61	293.0	1.41	1.10	1.12	1.66	1.31	1.15	1.55	2.74	1.38	1.35	1.40	1.00	1.04	1.33
62	285.0	1.33	1.05	1.06	1.58	1.29	1.02	1.46	2.51	1.36	1.28	1.33	0.97	1.06	1.27
63	325.0	1.52	1.19	1.21	1.79	1.39	1.25	1.67	2.94	1.46	1.45	1.51	1.06	1.07	1.44
64	360.0	1.47	1.15	1.17	1.74	1.33	1.21	1.62	2.74	1.45	1.41	1.46	1.08	1.09	1.44
65	399.0	0.92	0.66	0.74	1.09	0.66	0.91	0.89	1.36	1.12	0.89	0.94	0.97	0.96	0.83

No.	V_{test} [kN]	$\frac{V_{test}}{V_{Eq.1}}$	$\frac{V_{test}}{V_{Eq.2}}$	$\frac{V_{test}}{V_{Eq.3}}$	$\frac{V_{test}}{V_{Eq.4}}$	$\frac{V_{test}}{V_{Eq.5}}$	$\frac{V_{test}}{V_{Eq.8}}$	$\frac{V_{test}}{V_{Eq.9}}$	$\frac{V_{test}}{V_{Eq.10}}$	$\frac{V_{test}}{V_{Eq.11}}$	$\frac{V_{test}}{V_{Eq.12}}$	$\frac{V_{test}}{V_{Eq.13}}$	$\frac{V_{test}}{V_{XGB}}$	$\frac{V_{test}}{V_{RF}}$	$\frac{V_{test}}{V_{Eq.18}}$
66	446.0	0.88	0.63	0.71	1.05	0.62	0.87	0.85	1.42	1.12	0.85	0.90	1.03	1.12	0.82
67	282.0	1.10	1.01	0.88	0.91	0.89	0.97	1.17	1.65	1.29	1.06	1.10	0.97	0.96	1.13
68	319.0	1.20	1.10	0.96	0.99	0.98	1.04	1.28	1.94	1.37	1.15	1.20	1.07	1.06	1.25
69	384.0	1.33	1.22	1.06	1.10	1.08	1.14	1.41	2.21	1.53	1.27	1.33	1.04	1.13	1.41
70	589.0	1.32	1.10	1.05	1.09	0.98	1.15	1.25	2.13	1.43	1.27	1.34	1.02	1.12	1.25
71	487.0	1.21	1.04	0.97	1.00	0.91	1.07	1.18	1.92	1.38	1.17	1.22	1.00	1.05	1.18
72	437.0	1.21	1.06	0.97	1.00	0.93	1.07	1.21	1.94	1.38	1.17	1.22	0.99	1.08	1.21
73	188.3	0.61	0.47	0.48	0.68	0.57	0.45	0.63	0.89	0.61	0.58	0.61	1.01	0.94	0.58
74	155.9	0.56	0.43	0.45	0.63	0.52	0.43	0.58	0.85	0.56	0.54	0.56	0.94	0.82	0.52
75	210.9	0.52	0.40	0.41	0.58	0.42	0.44	0.54	0.78	0.57	0.50	0.52	0.91	0.82	0.53
76	97.1	0.50	0.43	0.40	0.56	0.50	0.38	0.59	0.73	0.52	0.48	0.50	0.74	0.74	0.53
77	196.2	0.54	0.41	0.43	0.60	0.49	0.37	0.57	0.73	0.51	0.48	0.55	0.62	0.69	0.45
78	707.0	1.25	1.01	1.00	1.06	0.96	0.89	1.19	1.81	1.12	1.14	1.30	0.98	0.95	0.90
79	735.0	1.30	1.05	1.04	1.10	1.00	0.93	1.24	1.88	1.17	1.19	1.35	1.02	0.98	0.94
80	222.0	1.00	0.89	0.80	0.87	0.89	0.81	1.05	1.67	0.96	0.98	0.99	1.00	0.93	0.99
81	246.0	0.90	0.81	0.72	0.79	0.81	0.71	0.95	1.42	0.87	0.89	0.90	0.89	0.95	0.94
82	248.0	0.81	0.73	0.65	0.71	0.73	0.63	0.86	1.23	0.78	0.80	0.81	0.93	0.96	0.87
83	330.0	1.11	0.99	0.88	0.97	1.01	0.85	1.17	1.68	1.08	1.09	1.10	1.10	1.09	1.18
84	145.0	0.72	0.54	0.57	0.80	0.62	0.70	0.70	1.23	0.70	0.79	0.72	0.89	0.83	0.60
85	275.0	1.08	0.81	0.86	1.20	0.92	1.02	1.06	2.01	1.04	1.18	1.08	1.11	1.07	0.95
86	235.0	1.03	0.78	0.82	1.15	0.89	0.98	1.01	1.99	1.02	1.14	1.04	1.01	1.03	0.89
87	225.0	0.99	0.74	0.79	1.10	0.86	0.94	0.97	1.91	0.98	1.09	1.00	0.98	1.00	0.85
88	170.0	0.85	0.64	0.68	0.94	0.78	0.75	0.83	1.59	0.88	0.93	0.85	0.94	0.89	0.70
89	235.0	0.95	0.72	0.76	1.06	0.79	0.94	0.94	1.79	0.97	1.05	0.96	1.07	1.03	0.83
90	200.0	0.82	0.61	0.65	0.91	0.68	0.81	0.80	1.55	0.82	0.90	0.82	0.93	0.92	0.71
91	732.0	1.35	1.10	1.07	1.15	1.04	0.98	1.31	1.96	1.27	1.23	1.40	1.00	0.97	1.00
92	484.0	1.22	1.05	0.97	1.02	1.03	0.84	1.25	1.76	1.06	1.12	1.27	0.96	1.00	0.91
93	362.0	1.16	1.04	0.92	0.96	1.02	0.80	1.28	1.67	1.04	1.06	1.21	0.73	0.99	0.90
94	704.0	1.45	1.24	1.16	1.20	1.10	1.10	1.49	2.04	1.53	1.33	1.51	1.01	1.11	1.14
95	549.0	1.45	1.24	1.15	1.20	1.14	1.10	1.48	1.76	1.43	1.32	1.51	1.05	1.02	1.07
96	506.0	1.69	1.45	1.35	1.40	1.33	1.33	1.73	1.62	1.66	1.54	1.76	1.00	0.97	1.17
97	530.0	1.27	0.90	1.01	1.51	1.04	0.95	1.29	1.84	1.14	1.16	1.32	1.01	1.11	0.87
98	176.0	1.21	1.05	0.97	1.04	1.13	1.08	1.20	1.94	1.28	1.33	1.21	0.98	0.95	1.01
99	209.0	1.27	1.09	1.01	1.09	1.11	1.20	1.26	1.91	1.25	1.39	1.27	0.96	0.99	1.09
100	245.0	1.36	1.17	1.08	1.16	1.19	1.27	1.35	2.24	1.34	1.50	1.36	1.04	1.11	1.20
101	167.0	1.14	0.99	0.91	0.98	1.00	1.11	1.13	1.52	1.13	1.26	1.14	0.96	0.89	0.96
102	252.0	1.38	1.19	1.10	1.18	1.14	1.37	1.36	1.97	1.44	1.51	1.38	1.08	1.07	1.22
103	180.0	0.89	0.77	0.71	0.78	0.76	0.80	0.89	1.29	0.87	0.91	0.89	0.93	0.93	0.79
104	212.0	0.94	0.80	0.75	0.82	0.80	0.82	0.94	1.52	0.91	0.96	0.94	1.02	1.02	0.86
105	248.0	0.99	0.85	0.79	0.86	0.84	0.86	0.99	1.77	0.97	1.01	0.99	1.02	1.03	0.93
106	329.0	1.26	1.08	1.01	1.10	1.09	0.97	1.29	1.90	1.16	1.16	1.28	1.00	1.00	1.14
107	431.0	1.22	1.05	0.98	1.07	1.04	0.92	1.25	1.85	1.14	1.12	1.24	1.05	1.04	1.20
108	400.0	1.10	0.93	0.88	0.96	0.90	0.80	1.16	1.43	1.03	0.91	1.16	0.96	0.92	1.01
109	504.0	1.25	1.07	0.99	1.09	1.09	0.82	1.34	1.68	1.11	1.03	1.31	1.02	1.06	1.20
110	825.0	1.34	0.94	1.07	1.17	0.96	1.09	1.09	1.66	1.20	1.24	1.44	0.97	0.86	0.94
111	1071.0	1.32	0.94	1.06	1.16	0.93	1.06	1.08	2.05	1.20	1.23	1.42	1.00	0.98	1.01
112	911.0	1.17	0.82	0.93	1.02	0.79	0.91	0.96	1.22	1.10	0.97	1.25	0.98	0.97	0.84
113	1248.0	1.50	1.06	1.20	1.31	1.10	1.03	1.24	2.19	1.32	1.25	1.60	1.00	1.08	1.11
114	547.0	1.16	0.96	0.92	1.07	0.88	0.98	1.18	2.11	1.35	1.06	1.17	1.48	1.30	1.20
115	438.0	1.22	1.00	0.98	1.18	1.04	0.93	1.25	1.84	1.13	1.12	1.24	1.00	1.04	1.17
116	1492.0	1.39	0.96	1.11	1.28	0.98	1.06	1.14	2.13	1.25	1.29	1.49	1.02	1.13	1.13
117	1600.0	1.19	0.82	0.95	1.10	0.75	1.01	0.98	2.23	1.34	1.10	1.27	1.11	1.29	1.02
118	386.0	1.36	1.16	1.09	1.19	1.15	1.08	1.38	2.01	1.27	1.25	1.38	1.03	1.00	1.24
119	451.0	1.35	1.15	1.08	1.18	1.18	0.99	1.38	2.02	1.25	1.24	1.37	1.29	1.25	1.30

No.	V_{test} [kN]	$\frac{V_{test}}{V_{Eq.1}}$	$\frac{V_{test}}{V_{Eq.2}}$	$\frac{V_{test}}{V_{Eq.3}}$	$\frac{V_{test}}{V_{Eq.4}}$	$\frac{V_{test}}{V_{Eq.5}}$	$\frac{V_{test}}{V_{Eq.8}}$	$\frac{V_{test}}{V_{Eq.9}}$	$\frac{V_{test}}{V_{Eq.10}}$	$\frac{V_{test}}{V_{Eq.11}}$	$\frac{V_{test}}{V_{Eq.12}}$	$\frac{V_{test}}{V_{Eq.13}}$	$\frac{V_{test}}{V_{XGB}}$	$\frac{V_{test}}{V_{RF}}$	$\frac{V_{test}}{V_{Eq.18}}$
120	511.0	1.18	1.01	0.94	1.03	1.00	0.80	1.26	1.60	1.06	0.97	1.24	1.04	1.08	1.15
121	782.0	1.23	0.86	0.98	1.07	0.86	1.02	1.00	1.48	1.11	1.13	1.31	0.98	0.88	0.87
122	1027.0	1.38	0.98	1.10	1.21	1.01	1.05	1.13	2.24	1.26	1.28	1.48	1.00	0.95	1.03
123	1195.0	1.39	0.98	1.11	1.21	0.94	1.14	1.13	2.08	1.34	1.28	1.48	1.00	1.07	1.07
124	1020.0	1.51	1.06	1.20	1.32	1.09	1.09	1.24	1.69	1.31	1.26	1.61	1.03	1.02	1.05
125	251.0	0.59	0.46	0.47	0.55	0.47	0.46	0.56	0.93	0.54	0.54	0.60	1.21	1.20	0.52
126	268.0	0.55	0.43	0.44	0.52	0.44	0.42	0.53	0.83	0.51	0.50	0.56	1.02	0.99	0.51
127	277.0	0.53	0.41	0.42	0.50	0.42	0.40	0.50	0.77	0.48	0.48	0.54	1.01	0.99	0.49
128	239.0	0.57	0.45	0.46	0.54	0.46	0.45	0.55	0.91	0.53	0.53	0.58	0.93	1.05	0.51
129	159.0	0.37	0.29	0.30	0.35	0.30	0.29	0.36	0.59	0.34	0.34	0.38	0.77	0.76	0.33
130	191.0	0.45	0.35	0.36	0.42	0.36	0.35	0.43	0.71	0.41	0.41	0.46	0.93	0.95	0.40
131	344.0	1.18	0.98	0.94	1.15	0.93	1.07	1.23	1.74	1.37	2.04	1.19	1.00	1.04	0.54
132	365.0	1.30	1.08	1.04	1.27	1.04	1.17	1.36	1.92	1.49	2.24	1.30	1.09	1.15	0.60
133	300.0	1.10	0.95	0.88	1.00	0.87	1.00	1.15	1.50	1.28	1.90	1.11	0.98	0.97	0.51
134	295.0	1.13	0.97	0.90	1.02	0.90	1.01	1.18	1.55	1.29	1.94	1.13	1.07	0.97	0.52
135	251.0	0.47	0.37	0.38	0.45	0.34	0.42	0.45	0.72	0.55	0.44	0.48	1.00	0.81	0.45
136	272.0	0.45	0.35	0.36	0.42	0.32	0.39	0.43	0.76	0.52	0.41	0.45	0.95	0.76	0.43
137	288.0	0.44	0.34	0.35	0.41	0.31	0.37	0.42	0.80	0.50	0.40	0.45	0.98	0.83	0.43
138	548.0	1.04	0.79	0.83	1.02	0.81	0.77	1.02	1.51	0.98	0.95	1.08	0.98	0.94	0.75
139	665.0	1.33	1.02	1.06	1.31	1.06	0.97	1.31	1.91	1.19	1.22	1.38	1.05	1.07	0.94
140	566.0	1.13	0.86	0.90	1.11	0.90	0.82	1.11	1.62	1.01	1.03	1.17	0.96	0.97	0.80
141	716.0	1.19	0.91	0.95	1.18	0.93	0.87	1.17	1.65	1.12	1.09	1.24	1.01	1.05	0.89
142	576.0	1.38	1.06	1.10	1.36	1.08	1.07	1.36	1.68	1.30	1.27	1.44	1.13	1.09	0.94
143	436.0	1.05	0.80	0.84	1.03	0.82	0.81	1.03	1.28	0.98	0.96	1.09	0.85	0.83	0.71
144	363.0	0.90	0.69	0.72	0.89	0.72	0.72	0.86	1.44	0.84	0.83	0.92	1.03	1.13	0.78
145	378.0	0.85	0.65	0.68	0.83	0.69	0.66	0.81	1.30	0.76	0.78	0.87	0.99	0.99	0.76
146	425.0	0.86	0.66	0.69	0.84	0.69	0.66	0.82	1.28	0.78	0.79	0.88	1.03	1.08	0.79
147	380.0	0.80	0.61	0.64	0.78	0.58	0.70	0.76	1.17	0.88	0.73	0.82	1.00	0.95	0.73
148	421.0	1.09	0.83	0.87	1.06	0.88	0.86	1.04	1.75	0.98	1.00	1.11	1.03	1.06	0.94
149	296.0	0.74	0.57	0.59	0.72	0.59	0.59	0.71	1.18	0.69	0.68	0.75	0.88	0.93	0.64
150	320.0	0.83	0.65	0.66	0.79	0.67	0.66	0.80	1.30	0.76	0.76	0.85	1.01	1.03	0.72
151	719.0	1.70	1.37	1.35	1.43	1.25	1.52	1.57	2.37	1.77	1.64	1.74	1.02	1.02	1.49
152	410.0	0.73	0.59	0.59	0.63	0.59	0.51	0.70	1.03	0.63	0.63	0.76	0.99	0.86	0.76
153	360.0	0.71	0.57	0.56	0.61	0.56	0.50	0.67	1.02	0.60	0.60	0.73	0.88	0.79	0.71
154	370.0	0.83	0.67	0.66	0.72	0.67	0.60	0.80	1.19	0.71	0.71	0.86	0.99	0.81	0.81
155	199.0	1.10	1.01	0.88	0.99	0.98	0.98	1.21	1.95	1.20	1.12	1.08	1.06	0.99	1.14
156	617.2	1.23	0.94	0.98	1.10	0.90	1.12	1.10	2.17	1.23	1.26	1.27	1.01	0.94	1.07
157	479.3	0.92	0.70	0.73	0.83	0.67	0.84	0.83	1.65	0.93	0.94	0.95	0.79	0.73	0.81
158	167.8	1.03	0.94	0.82	0.92	0.96	0.87	1.13	1.79	1.03	1.04	1.01	0.97	0.92	1.04
159	520.0	1.16	0.89	0.92	1.04	0.90	1.00	1.04	2.05	1.04	1.19	1.20	0.99	0.99	0.98
160	461.0	0.82	0.63	0.65	0.79	0.59	0.72	0.79	1.33	0.95	0.75	0.84	1.04	1.16	0.78
161	541.0	0.83	0.64	0.66	0.80	0.59	0.72	0.79	1.41	0.97	0.76	0.85	1.05	1.15	0.82
162	604.0	0.83	0.65	0.67	0.81	0.59	0.71	0.80	1.40	0.99	0.77	0.85	0.99	1.16	0.84
163	103.0	0.94	0.75	0.75	1.18	0.86	1.08	1.05	1.90	1.15	1.14	0.90	1.21	1.05	0.92
164	127.0	1.00	0.81	0.80	1.26	0.91	1.13	1.12	2.08	1.24	1.22	0.96	1.11	1.07	1.02
165	112.0	0.84	0.67	0.67	1.05	0.78	0.91	0.94	1.67	0.99	1.02	0.80	0.97	1.00	0.87
166	79.0	0.71	0.57	0.57	0.90	0.65	0.82	0.80	1.44	0.88	0.87	0.69	0.93	0.81	0.70
167	107.0	0.87	0.70	0.69	1.09	0.80	0.97	0.97	1.79	1.04	1.06	0.83	0.98	0.97	0.88
168	262.0	0.94	0.69	0.75	1.12	0.86	0.75	0.95	1.84	0.95	0.96	0.93	0.99	1.23	0.85
169	191.0	1.04	0.97	0.83	0.93	1.04	0.75	1.23	1.95	1.05	0.95	1.06	0.87	0.92	1.08
170	289.0	1.31	1.16	1.04	1.17	1.23	0.95	1.43	2.38	1.28	1.20	1.32	1.06	1.09	1.26
171	413.0	1.50	1.25	1.19	1.33	1.34	1.10	1.50	2.53	1.42	1.37	1.52	1.44	1.32	1.32
172	209.0	1.08	1.01	0.86	0.96	1.08	0.74	1.31	1.94	1.08	0.95	1.12	0.92	0.94	1.12
173	232.0	1.15	1.08	0.92	1.03	1.14	0.80	1.39	2.08	1.14	1.02	1.20	0.93	0.91	1.19

No.	V_{test} [kN]	$\frac{V_{test}}{V_{Eq.1}}$	$\frac{V_{test}}{V_{Eq.2}}$	$\frac{V_{test}}{V_{Eq.3}}$	$\frac{V_{test}}{V_{Eq.4}}$	$\frac{V_{test}}{V_{Eq.5}}$	$\frac{V_{test}}{V_{Eq.8}}$	$\frac{V_{test}}{V_{Eq.9}}$	$\frac{V_{test}}{V_{Eq.10}}$	$\frac{V_{test}}{V_{Eq.11}}$	$\frac{V_{test}}{V_{Eq.12}}$	$\frac{V_{test}}{V_{Eq.13}}$	$\frac{V_{test}}{V_{XGB}}$	$\frac{V_{test}}{V_{RF}}$	$\frac{V_{test}}{V_{Eq.18}}$
174	221.0	1.27	1.18	1.01	1.13	1.27	0.89	1.53	1.91	1.27	1.12	1.32	1.02	0.96	1.26
175	236.0	1.27	1.19	1.01	1.13	1.25	0.92	1.50	1.91	1.27	1.16	1.29	1.01	1.02	1.31
176	253.0	1.35	1.26	1.08	1.20	1.33	0.98	1.59	2.04	1.35	1.24	1.38	1.04	1.04	1.40
177	237.0	1.33	1.23	1.06	1.21	1.28	1.00	1.56	2.10	1.31	1.22	1.35	1.06	1.01	1.34
178	280.0	1.42	1.32	1.13	1.26	1.41	0.98	1.71	2.05	1.42	1.25	1.47	1.10	1.08	1.46
179	134.0	0.24	0.19	0.19	0.23	0.17	0.22	0.24	0.39	0.30	0.22	0.25	0.78	0.53	0.24
180	295.5	1.14	0.97	0.91	1.00	1.01	0.89	1.14	1.91	1.09	1.10	1.15	1.06	1.03	1.04
181	405.2	1.24	1.05	0.99	1.09	1.09	0.93	1.24	1.91	1.18	1.20	1.25	1.29	1.41	1.19
182	290.1	1.08	0.91	0.86	0.94	0.94	0.85	1.07	1.80	1.02	1.04	1.09	1.01	0.98	0.97
183	295.8	1.05	0.88	0.84	0.91	0.89	0.84	1.04	1.77	0.97	1.01	1.06	0.90	0.92	0.95
184	238.1	1.00	0.84	0.79	0.87	0.92	0.74	0.99	1.63	1.00	0.96	1.00	0.98	0.90	0.87
185	329.0	1.11	0.92	0.88	0.97	0.94	0.86	1.10	1.66	1.00	1.02	1.13	0.99	0.92	0.98
186	431.0	1.06	0.88	0.85	0.92	0.88	0.80	1.05	1.60	0.97	0.97	1.08	1.11	1.04	1.01
187	825.0	1.76	1.29	1.40	1.54	1.30	1.44	1.49	2.01	1.55	1.63	1.86	0.85	0.78	1.27
188	1071.0	1.65	1.20	1.31	1.44	1.19	1.31	1.39	2.44	1.48	1.52	1.73	1.00	0.99	1.29
189	365.6	1.13	0.95	0.90	1.08	0.99	0.80	1.25	1.62	1.03	1.03	1.19	0.92	0.94	1.34
190	391.6	1.00	0.84	0.80	0.96	0.85	0.71	1.11	1.38	0.96	0.91	1.05	0.98	0.96	1.24
191	431.6	1.03	0.86	0.82	0.98	0.88	0.71	1.14	1.37	0.96	0.94	1.08	1.00	1.03	1.30
192	477.1	1.41	1.18	1.13	1.35	1.21	1.03	1.56	2.05	1.34	1.29	1.48	1.11	1.06	1.69
193	137.2	0.77	0.67	0.61	0.69	0.69	0.63	0.80	1.08	0.74	0.74	0.77	0.91	0.88	0.68
194	158.8	0.75	0.65	0.60	0.67	0.68	0.60	0.78	1.25	0.72	0.72	0.75	0.98	0.93	0.69
195	172.3	0.76	0.67	0.61	0.68	0.69	0.59	0.80	1.24	0.74	0.73	0.76	0.91	0.87	0.73
196	443.2	1.24	1.00	0.99	1.10	1.08	0.90	1.19	1.93	1.16	1.14	1.27	1.02	1.04	1.07
197	429.0	1.27	1.02	1.01	1.12	1.05	0.98	1.21	1.90	1.14	1.17	1.30	1.04	1.05	1.08
198	328.4	1.05	0.84	0.83	0.92	0.87	0.82	1.00	1.46	0.94	0.96	1.07	0.91	0.86	0.87
199	415.2	1.19	0.96	0.95	1.05	1.04	0.85	1.14	1.83	1.12	1.09	1.21	1.04	1.02	1.03
200	393.9	1.24	1.00	0.99	1.10	1.08	0.91	1.19	2.00	1.17	1.14	1.27	1.00	0.98	1.04
201	334.7	1.24	0.99	0.98	1.09	1.07	1.02	1.16	2.15	1.20	1.26	1.26	0.92	0.90	1.03
202	504.3	1.38	1.11	1.10	1.22	1.20	0.91	1.36	1.96	1.25	1.14	1.45	1.01	1.01	1.15
203	350.0	1.25	1.00	0.99	1.10	1.08	1.00	1.17	2.11	1.20	1.24	1.27	0.76	0.92	0.87
204	438.8	1.31	1.05	1.04	1.16	1.14	0.91	1.27	1.95	1.21	1.13	1.35	1.00	0.94	0.98
AVG	443.8	1.19	0.97	0.94	1.13	0.99	0.95	1.19	1.84	1.16	1.17	1.21	1.00	1.00	1.02
STD	302.7	0.36	0.29	0.28	0.39	0.29	0.30	0.35	0.55	0.34	0.38	0.37	0.11	0.12	0.28
Min	79.0	0.24	0.19	0.19	0.23	0.17	0.22	0.24	0.39	0.30	0.22	0.25	0.62	0.53	0.24
Max	1600.0	2.41	1.97	1.92	2.57	1.91	2.27	2.27	3.48	2.32	2.47	2.48	1.48	1.41	1.71

Equation	Source	Equation	Source
Eq.1	(Matthys & Taerwe, 2000)	Eq.10	ACI 440.11-22
Eq.2	(Ospina et al., 2003)	Eq.11	JSCE-97
Eq.3	(El-Ghandour et al. (2003)	Eq.12	CAN/CSA S806-12
Eq.4	(Jacobson et al., 2005)	Eq.13	EN 1992-1-1 (2023)
Eq.5	El-Gamal et al., 2005a)	XGB	eXtreme Gradient Boosting model
Eq.8	(Hemzah et al., 2019)	RF	Random Forest model
Eq.9	Ju et.al (2021)	Eq.18	Symbolic Regression Technique