

Evaluating the Generalization Capability of XGBoost Model in Predicting Shear Strength of Reinforced Concrete Deep Beams

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ABSTRACT: Extreme Gradient Boosting (XGBoost) is a powerful machine learning algorithm widely adopted for solving complex regression problems in structural engineering. This study investigates the capability of the XGBoost model in predicting the shear strength of reinforced concrete (RC) deep beams—a task characterized by highly nonlinear behavior and interaction between several geometric, material, and reinforcement parameters. The model was trained on a comprehensive database of 1177 experimental specimens using 25 input variables and achieved a high prediction accuracy with a coefficient of determination (R^2) of 0.96, indicating excellent fitting and learning capacity. To evaluate its generalization ability, the trained model was further validated using an unseen dataset consisting of 151 RC deep beam specimens described by 11 influential variables. The prediction accuracy on this external dataset reached an R^2 value of 0.83, demonstrating satisfactory robustness and reliable extrapolation performance. These results highlight the efficiency and precision of the XGBoost model in capturing the complex shear behavior of deep beams and confirm its strong potential as a practical predictive tool to assist in the analysis and preliminary design of RC deep beams.

KEYWORDS: Artificial Intelligence, Machine Learning, RC Deep Beams, XGBoost Model, Shear Strength.

I. INTRODUCTION

In recent years, civil engineering has witnessed significant advancements in integrating artificial intelligence and machine learning techniques in structural analysis and design[1]. One of the key applications is the estimation of shear strength in reinforced concrete deep beams Figure 1, which are critical structural elements due to their complex stress and strain distributions. Thus, accurate estimation of shear strength of reinforced concrete deep beams is necessary for design applications and can also be complex due to the various effective parameters used in the design and behavior of the deep beams[2]. In terms of their interaction and influence with one another, this results in time and cost being consumed, as well as a lack of testing facilities with the necessary tools and equipment[3]. The empirical equations in current design codes and published studies show a significant discrepancy and inefficiency in calculating the shear strength of deep beams. Accurate prediction of the ultimate shear strength of reinforced concrete deep beams is of prime importance for developing a reliable method for their design [4]. For this purpose, many experiments have been carried out to investigate the behavior of such beams.

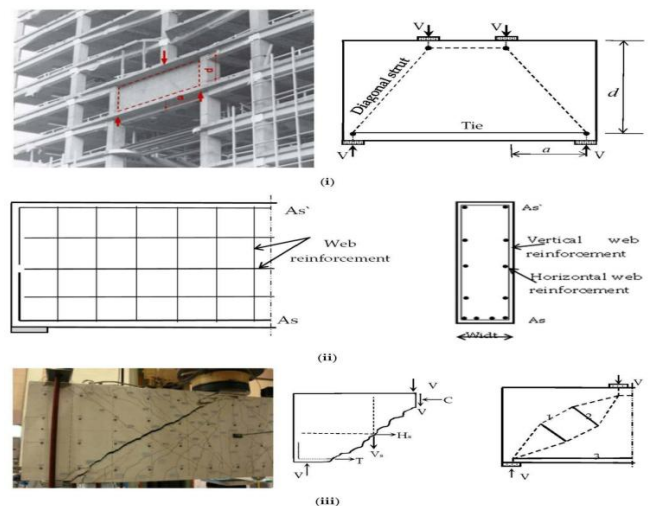


FIGURE 1. Shows an example of the use of deep concrete beams with their most important terms, basic reinforcement details, in addition to failure modes and force transmission path within them.[4]

II. EXTREME GRADIENT Boosting (XGBoost)

It is one of the most powerful machine learning models based on gradient boosted trees[5]. It has gained widespread popularity in forecasting due to its fast training speed, excellent ability to handle nonlinear data, and its ability to handle small and medium-sized datasets without the need for complex statistical assumptions[6]. In civil engineering, especially critical structural elements such as deep reinforced concrete beams (RC deep beams), accurately estimating shear strength is a significant challenge due to the complex nonlinear behavior and the influence of numerous interconnected variables, such as shear space ratio, longitudinal and shear reinforcement ratio, section dimensions, and concrete strength[7]. Using XGBoost in this context helps model the nonlinear and interconnected relationships between various structural factors and provides accurate shear strength predictions based on experimental test data and databases extracted from previous studies[8]. The model is characterized by its ability to automatically select the most influential variables and reduce the problem of overfitting by using advanced regularization mechanisms. This positively impacts the prediction accuracy and generalization of results when tested on data on which it has not been previously trained Figure 2. Practical application results demonstrated that the XGBoost model is capable of achieving a high level of accuracy and efficiency in predicting shear strength compared to traditional methods and some other machine learning models[9]. It recorded high coefficients of determination (R^2) and low root mean square error (RMSE) when the model was tested on independent experimental data[10]. Therefore, XGBoost can be considered an effective and promising tool for improving the estimation of the behavior of deep beams under shear and supporting engineers in making more reliable design decisions based on artificial intelligence[11].

- Providing a proposed model that can be relied upon as a design aid for engineers in practical and future applications. The most important contributions of this work are:
- Using an extensive experimental database that includes laboratory results from previous and recent studies to ensure strong generalization.
- Testing the model using independent data not used in training to verify its effectiveness.
- Providing an intelligent framework that can be built upon to develop future design systems based on artificial intelligence techniques in structural engineering.

III. LITERATURE REVIEW

Several studies have shown that XGBoost exhibits high predictive performance compared to other models such as Artificial Neural Networks (ANN), linear regression, and Random Forest. For example:

- Chou et al. (2022) indicated that the accuracy of XGBoost increases with a greater number of input variables[13].
- Mia et al. (2023) found that XGBoost outperforms ANN and RF in predicting shear and flexural strength[14].
- Memon et al. (2019) recommended using XGBoost for modeling complex experimental data due to its accuracy and fast performance[10].

IV. DATA AND METHODOLOGY

A. OTHER RECOMMENDATIONS

A total of 1177 samples of reinforced concrete deep beams were used for training, collected from previous experimental research. The dataset was split as follows:

- Training: 80%
- Testing: 20%

B. OTHER RECOMMENDATIONS

In this study, five machine learning models were developed using experimental data to predict the shear strength of deep reinforced concrete beams through training and testing phases. Among these models, the most accurate and lowest prediction error was selected. This section presents new experimental data, which was not previously used in any of the machine learning phases. This dataset consists of 151 deep concrete beam samples containing 11 variables [15]. After pre-processing, this data was directly fed into the optimized model to evaluate its efficiency, accuracy, and generalization ability. The updated database includes 10 input variables and one output, the measured ultimate shear strength (V_{exp}). The variables include: concrete compressive strength ($f'c$), beam height (h), beam width (bw), effective depth (d), shear path length (a), shear path to depth ratio (a/d), yield strength of longitudinal reinforcement in the boundary element (f_yl), longitudinal reinforcement ratio (ρ_l), horizontal reinforcement ratio in beams (ρ_h), and

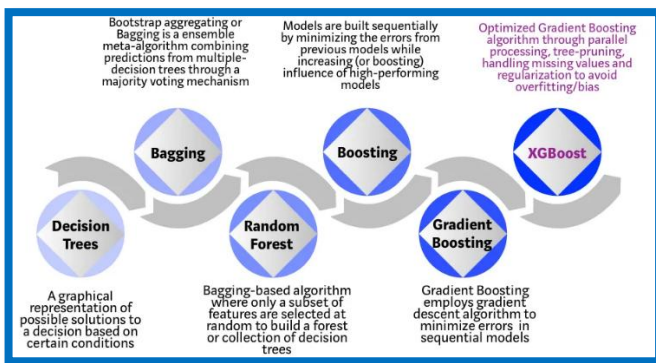


FIGURE 2. The Evolution of Tree-Based Algorithms [12]

This study aims to:

- Evaluate the accuracy and generalizability of the XGBoost model in predicting shear strength in deep reinforced concrete beams.
- Compare the model's performance with other independent data not used in machine learning models.

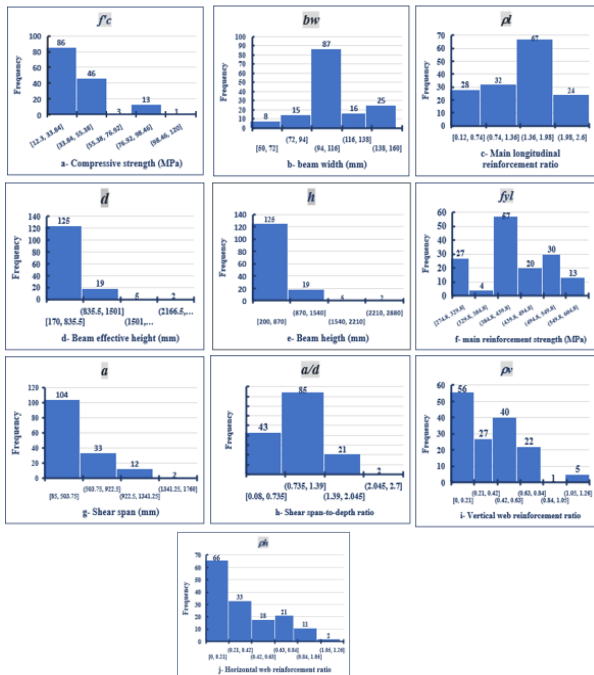
vertical reinforcement ratio in beams (ρ_v). Table (1) shows the statistical characteristics of these variables, including minimum and maximum values, mean, standard deviation, and coefficient of variation.

FIGURE 3. Statistical Distributions of Input Variables: (a) f_c (MPa); (b) bw (mm); (c) ρ_l (%); (d) d (mm); (e) h (mm); (f) f_{yl} (MPa); (g) a (mm); (h) a/d (%); (i) ρ_v (%); (j) ρ_h (%).

TABLE I
STATISTICS CHARACTERISTICS OF THE PARAMETERS IN RC DEEP BEAM

Variable	Unit	Minimum	Maximum	Mean	Standard Deviation	COV* %	Type
f_c	MPa	12.3	120	35.73	22.38	0.63	(Input 1)
h	mm	200	2880	617.47	423.12	0.69	(Input 2)
d	mm	170	2832	560.98	408.94	0.73	(Input 3)
bw	mm	50	160	108.48	22.42	0.21	(Input 4)
a	mm	85	1760	485.43	335.37	0.69	(Input 5)
a/d	%	0.08	2.7	0.97	0.48	0.5	(Input 6)
ρ_l	%	0.12	2.6	1.53	0.72	0.47	(Input 7)
f_{yl}	MPa	274.8	600	440.89	82.79	0.19	(Input 8)
ρ_h	%	0	1.16	0.31	0.32	1.05	(Input 9)
ρ_v	%	0	1.25	0.38	0.31	0.81	(Input 10)
$V_{exp.}$	MPa	47.8	1636	328.73	298.95	0.91	(Output)

*COV = Coefficient of Variation.



V. MODEL PERFORMANCE ASSESSMENT CRITERIA

A set of statistical measures was adopted to measure the performance of the models and determine the most accurate in predicting the shear strength of the shear wall. These are: the coefficient of determination (R^2), the root mean square error (RMSE), the mean absolute error (MAE), the mean absolute percentage error (MAPE), the dispersion coefficient (SI), and the objective value (OBJ). They were defined by the following formulas:

$$R^2 = \left(1 - \frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{\sum_{i=1}^n (\hat{y}_i - \bar{y})^2} \right) \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{y}_i - y_i)^2} \quad (2)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |\hat{y}_i - y_i| \quad (3)$$

$$MAPE = \frac{100\%}{n} \sum_{i=1}^n \left| \frac{\hat{y}_i}{y_i} - 1 \right| \quad (4)$$

$$SI = \frac{RMSE}{\frac{1}{n} \sum_{i=1}^n y_i} \quad (5)$$

$$OBJ = \frac{n_{test}}{n} * \frac{RMSE+MAE}{R^2+1} \quad (6)$$

The symbol n represents the number of data sets, y_i represents the true value of the i -th set, \hat{y}_i is the predicted value, and n_{test} refers to the test data. The optimal values for most evaluation indicators are zero, with the exception of the coefficient of determination R^2 , which has an optimal value of 1. Regarding the coefficient of dispersion (SI), model performance is considered poor if $SI > 0.3$, acceptable if $0.2 < SI < 0.3$, good if $0.1 < SI < 0.2$, and excellent if $SI < 0.1$ [16].

Models were compared according to these criteria, with a low RMSE value and a high R^2 value indicating superior prediction. The (OBJ) index in Equation (6) was also used as one of the evaluation metrics to measure the efficiency of the proposed models.

VI. EVALUATION AND GENERALIZATION RESULTS

A. PERFORMANCE ON TEST DATASET

The results of the evaluation of the XGBoost model in predicting the shear strength of deep reinforced concrete beams demonstrated its superiority over all other machine learning models used in the study. The model achieved a high coefficient of determination (R^2) = 0.962, demonstrating the model's ability to explain 96.2% of the variance in the actual data. The mean absolute error (MAE) = 21.62 kN, and the mean absolute percentage error (MAPE) = 7%, a low value indicating high prediction accuracy. The dispersion coefficient (SI) = 0.092 rated the performance as "excellent" according to the approved statistical criteria, while the objective value (OBJ) = 5.84, confirming the model's superiority. Together, these indicators reflect the strength, accuracy, and efficiency of the XGBoost model in estimating shear strength, making it an effective and reliable tool for the analysis and preliminary design of deep reinforced concrete beams.

- $R^2 = 0.962$
- MAE = 21.62 kN
- MAPE = 7%
- SI = 0.092
- OBJ = 5.84

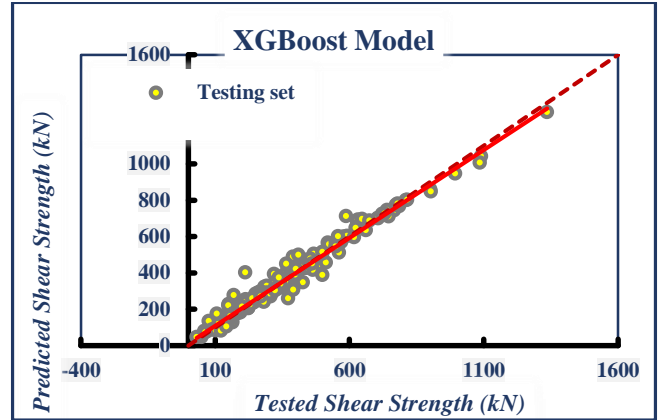


FIGURE 4. Tested Values Versus Values Predicted by The XGBoost Model

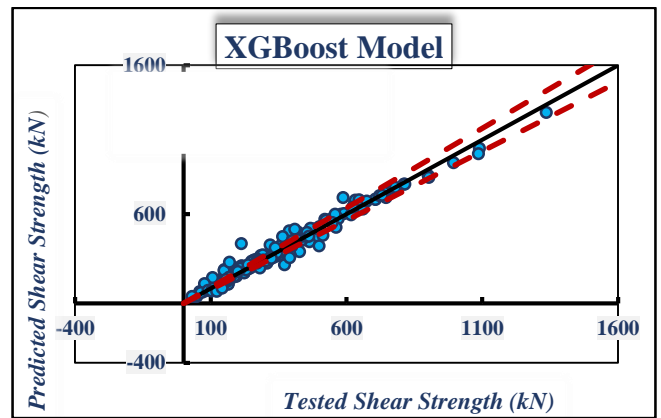


FIGURE 5. Comparison Between Actual and Predicted Shear Strength Using the XGBoost Model. B. PERFORMANCE ON NEW DATASET (151 Samples)

The results obtained from testing the XGBoost model on new data comprising 151 samples and 10 variables demonstrated the model's good ability to predict the shear strength of deep reinforced concrete beams. The coefficient of determination, R^2 , was 0.834, meaning the model explained approximately 83.4% of the variance in the actual data. However, the margin of error was $\pm 26.37\%$, indicating a significant discrepancy between the predicted and actual values in some cases. This discrepancy reflects the need to improve model performance by expanding the training database, fine-tuning the model parameters, and reviewing the quality of the new data to ensure it adequately represents the true range of beam characteristics. Nevertheless, the model's accuracy remains largely acceptable, supporting its potential use as an aid in predicting shear strength, provided that the margin of error is considered in practical applications.

- $R^2 = 0.834$
- Error Margin = $\pm 26.37\%$

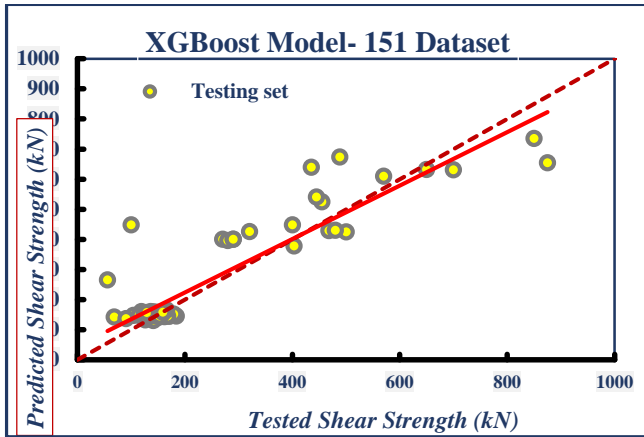


FIGURE 6. New Tested Values Versus Values Predicted by the XGBoost Model

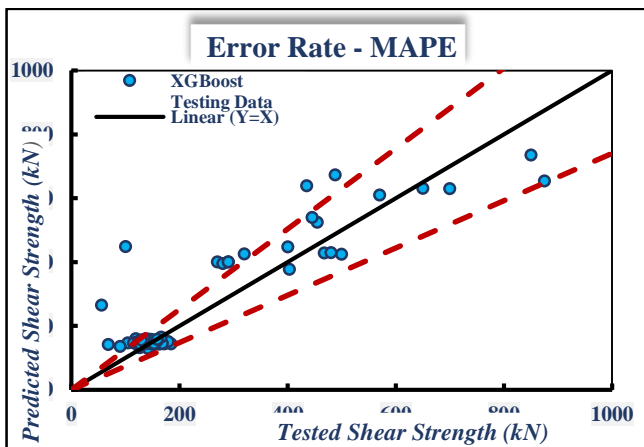


FIGURE 7. Comparison Between Actual and Predicted Shear Strength Using the XGBoost Model

VII. DISCUSSION

The results indicate that the XGBoost model can predict shear strength accurately, even when exposed to previously unseen data. The level of data scatter was within acceptable bounds, enhancing the model’s reliability in practical applications. Therefore, the model is recommended as an effective design aid for RC deep beams.

VIII. DISCUSSION

The XGBoost model has proven its high efficiency in estimating the shear strength of deep reinforced concrete beams, demonstrating excellent predictive accuracy and significantly outperforming traditional models such as design equations (ACI and EC2) as well as many other AI models, such as artificial neural networks (ANNs) and random forest models. XGBoost is capable of handling nonlinear and complex data, providing accurate predictions even when there is a complex interaction between variables. The tunability of its hyperparameters significantly enhances its accuracy when using techniques such as Bayesian

optimization. Furthermore, the use of interpretation tools such as SHAP enables this model to not only predict but also understand the impact of each variable on the final outcome, enhancing engineers' confidence in the design decisions based on it. Accordingly, the XGBoost model is recommended as an effective and reliable tool for estimating the shear strength of deep beams, especially during the preliminary design and structural safety verification phases.

- The XGBoost model proved to be effective and superior in predicting shear strength.

- It showed excellent generalization capability when validated on new data.

- It can be adopted as a practical tool for designing reinforced concrete structures.

ACKNOWLEDGMENT

The preferred word for "acknowledgment" in American English is without the "e" after the "g". As well as, avoid expressions such as "One of us (Q.M.Y.) would like to thank" Instead, write "M. A. Author thanks" often, sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page, not here.

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