A REVIEW ON EXISTING SHEAR DESIGN PROVISIONS FOR STEEL FIBER REINFORCED CONCRETE BEAMS

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ABSTRACT

Concrete that is reinforced with steel fibers to enhance its structural integrity and performance is known as Steel Fibre Reinforced Concrete (SFRC).Due tothe integration of steel fibers into concrete, the shear behaviour of SFRC beams diverges significantly from conventional Reinforced Concrete (RC) beams. The intricate interaction of the steel fibers with the concrete matrix makes it challenging to estimate the shear strength of SFRC beams and due to this, mechanics-based models have not been developed yet. For a robust and cost-effective design, an accurate shear design provision for SFRC beam is vital. A lack of comprehensive codified equations challenges the precise design of SFRC beam. Numerous empirical formulas have been suggested by many researchers. This paper overviews the available shear design provisions and optimized equations for SFRC slender beams ($a/d \geq 2.5$) and SFRC deep beams ($a/d< 2.5$). However, majority of these conventional empirical equations are based on limited dataset making it questionable if they can reliably determine the shear strength of SFRC beams. Furthermore, available data-driven machine learning (ML) models are discussed. Recently, data-driven machine learning (ML) models have become popular for creating complex underlying relationships. It is found that the ML models are developed based on the improved dataset which outperformed the empirical equations.

Keywords: *Steel fiber reinforced concrete, slender beam, deep beam, shear strength, machine learning*

1. INTRODUCTION

The incorporation of fibers to strengthen brittle construction materials like concrete is not a recent innovation. In the last century, there has been a progressive rise in the utilization of fibers as a means of reinforcing concrete. Presently, concrete incorporates four major types of fibers: natural, glass, synthetic, and steel. The extensive use of natural fibers in developing countries is attributed to their affordability and local availability, particularly in the African construction industry, where they utilized in the construction of concrete pipes, tanks, and houses. While these fibers enhance the flexural, shear, and tensile strength of concrete, they exhibit lower durability compared to other fibers due to susceptibility to degradation in the high alkaline concrete pore water (James I. Daniel, 1996). In response to this durability concern, remedies like the development of coatings made from natural fibers have been introduced. Concrete can become more robust and long-lasting by using a small amount of synthetic fibres (Majdzadeh F, 2006)Greenough and Nehdi (Greenough T, 2008)suggested that, despite having benefits, this fiber may not match the performance of steel fibers in augmenting the shear strength. To better comprehend the spreading of synthetic fibres within the concrete structure and expand their mechanical properties, more research is required (Wang Y B. S., 1987). Moreover, the absence of fully developed standardized testing procedures is currently hindering the widespread commercial utilization of synthetic fibers in concrete beams (Narayanan R, 1987). Glass fiber emerged as a prospective reinforcing material for concrete in 1960. Concerns arose due to the durability issues regarding glass fibers and attributed to the impact of concrete alkalinity on the fibers. Despite this, the lightweight nature and vertical formability of glass fiber reinforced concrete have predominantly found their application in architectural contexts, particularly for features like façade and cladding panels (James I. Daniel, 1996). Then the steel fiber reinforced concrete was introduced. At present, SFRC is predominantly utilized in situations where the installation of traditional steel bars is tough. This includes applications in hydraulic structures, large slabs, bridge decks etc.(Narayanan R, 1987). Ongoing research explores additional applications of SFRC that have yet to be fully integrated into the construction sector. One potential application is the use of SFRC for reinforcing beam-column joints in seismic regions. Wang and Lee (Wang Y L. M., 2007)conducted experiments which showcased the substantial improvement in ductility, flexural strength, and shear strength of inside beam-column connections through SFRC jacketing, as opposed to conventional concrete jacketing. Adding steel fibers makes the material better at resisting cracks, more flexible, and improves its ability to absorb energy and withstand impacts. The inclusion of such fibers in concrete mixture enhances both the shear strength and toughness, as indicated by research findings (DR., 1991). It contributes to the formation of bridges as cracks develop in the concrete, enhancing resistance to crack propagation. This mitigates the risk of abrupt concrete failure, enabling a more gradual and controlled failure process (Lim DH, 1999).

The potential of shear failure is a notable worry in designing of concrete beams. To prevent such potentially catastrophic occurrences, designers incorporate transverse reinforcement, commonly known as stirrups (Shahnewaz M, 2020). However, adherence to code practices often results in tightly spaced stirrups, creating challenges during concrete pouring due to the congested arrangement of reinforcement. This, in turn, poses a risk to the effective bonding between the concrete and reinforcement, while also escalating labor costs associated with arranging transverse reinforcement. Some designers suggest utilizing ultra-high-strength concrete and high-strength steel in response to these challenges(Shahnewaz M, 2020). Although this method enables a decrease in member size and necessary reinforcement, it tends to render the resulting concrete more brittle (Bichitra Singh Negi, 2022). To tackle this problem, the adoption of discontinuous fibers as an unconventional form of mass reinforcement has emerged as a promising solution.

The fibrous composition of the concrete necessitates the extraction and separation of fibers through pull-out and debonding processes, providing effective crack-bridging and enhancing the material's resistance to crack development. As a result, it has better energy dissipation capabilities and a pseudo-ductile tensile characteristic as compared to regular concrete (Chalioris CE). A significant alternative involves replacing traditional steel stirrups with fibers, particularly in design situations that recommend a higher transverse steel ratio. Substituting could result in a reduction of stirrup spacing and holds significant potential in addressing the issues associated with shear failure and reinforcement congestion (Perceka W, 2016).

2. PARAMETERS AFFECTING SHEAR STRENGTH OF SFRC BEAMS:

The shear strength of SFRC beams is dependent upon various parameters like shear span to depth ratio (*a/d*), concrete compressive strength (f'_c), longitudinal reinforcement ratio (ρ), fiber volume fraction (V_f), the cross-section of the beam, fiber aspect ratio (l_f/d_f), fiber factor (F) etc.(Narayanan R, 1987). According to Khuntia et al.,(Khuntia M, 1999) the shear strength of SFRC beams grows exponentially when the concrete's compressive strength rises. A significant drop in the shear strength of an SFRC beam occurs when the *a/d* ratio increases, primarily attributed to the exponential decline resulting from the arching action of the beam. In general, a large volume of steel fibers yields greater shear strength, though the precise extent of this increase remains challenging to predict. It was observed that higher tensile reinforcement ratios result in an increased rate of shear strength (Emma Slater, 2011).

3. EXISTING SHEAR DESIGN EQUATIONS FOR SFRC SLENDER BEAMS:

Numerous empirical shear models have been formulated in the past by many researchers using limited number of datasets for SFRC slender beams. These models are outlined as follows:
1. Ashour et al proposed the following two equations using the experimental data of 18 high-strength SFRC beam specimens based on simple linear regression analysis. They included the fiber factor (F) in their first equation which was derived from the shear equation of the ACI Building Code to take the impact of steel fiber size and shape into consideration. To acknowledge the contributions of concrete and reinforcement to shear capacity, this equation additionally accounts for the *a/d* ratio. By modifying Zsutty's equation and adding the fiber component, Ashour et al. got their second equation (Ashour SA, 1992).

1st Equation of Ashour et al.:

$$V_u = \left[\frac{(0.7\sqrt{f'_c}+7F)d}{a} + 17.2\frac{\rho d}{a}\right] \quad (1)$$

2nd Equation of Ashour et al.:

$$V_u = \left[(2.11\sqrt[3]{f'_c} + 7F)\left(\frac{\rho\, d}{a}\right)^{0.333}\right] \quad (2)$$

These equations rely on simplified assumptions about the behaviour of SFRC beams, assuming that the fibers are distributed uniformly throughout the concrete matrix. In reality, the distribution and alignment of fibers may vary affecting the actual performance of the beam (Ashour SA, 1992).

2. Sharma et al. formulated an empirical relationship that solely relies on the *d/a* ratio and the tensile strength of concrete (f_{ct}) which is based on results of tension tests conducted indirectly. Despite being dependent on only these two parameters, the relation demonstrates effective predictive accuracy (AK., 1986).

$$V_u = \left[\frac{2}{3} \times 0.8\sqrt{f'_c}\ \left(\frac{d}{a}\right)^{0.25}\right] \quad (3)$$

Sharma ignored crucial factors fiber aspect ratio (l_f/d_f) and fiber factor (F) that significantly contribute to SFRC beam's shear capacity. Still, this equation has been validated through the examination of 41 experimental tests conducted by the author.

3. Shahnewaz and Alam et al. employed the following genetic algorithm model that integrated a 2k factorial design term to analyze the shear capacity using 358 experimental test results. The primary factors considered in this factorial design include concrete compressive strength (f'_c), *a/d* ratio, longitudinal reinforcement ratio (ρ), fibre aspect ratio(l_f/d_f), and volume fraction of fiber(V_f)(Shahnewaz M, 2020).

$$V_u=0.2+0.072(f'_c)^{0.85}+12.5\rho^{0.084}-24\left(\frac{a}{d}\right)^{0.07}+13.5\,V_f{}^{0.07}-450(\frac{l_f}{d_f})^{-2}-0.0002(\left(\frac{a}{d}\right)V_f)^{3.9}-27.699(\left(\frac{a}{d}\right)\left(\frac{l_f}{d_f}\right))^{-0.84}+1181(V_f\left(\frac{l_f}{d_f}\right))^{-2.69}-21.89(\left(\frac{a}{d}\right)V_f\left(\frac{l_f}{d_f}\right))^{-0.9} \quad (4)$$

4. Shahnewaz et al. later introduced a genetic algorithm programming method that incorporates the Metamodel of Optimal Prognosis (MOP). *a/d* ratio, longitudinal reinforcement ratio (ρ), fiber volume fraction (V_f), and compressive strength of concrete (f'_c) are the four main input parameters of the model (Shahnewaz M, 2020).

$$V_u=3.2+0.072f'_c+\rho V_f\left[1.26-\frac{0.25a}{d}\right]-\frac{a}{d}\left[1.92+0.017f'_c-0.38\frac{a}{d}\right] \quad (5)$$

This method is employed to forecast optimal outcomes using algorithms grounded in existing experimental data. The predictions do not involve mechanics, leading to notable limitations when anticipating new experimental test results.

5. Sarveghadi et al. developed a model suitable for both normal and high-strength SFRC beams using multi expression programming (MEP). *a/d* ratio, ρ, $V_b$andf_t are the only four parameters accounted for this model (Sarveghadi Masoud, 2019).

$$V_u=\left[\rho+\frac{\rho}{\upsilon b}+\frac{d}{a}\left(\rho f'_t(\rho+2)\left(\frac{f'_t a}{d}-\frac{3}{\upsilon b}\right)\left(\frac{d}{a}\right)+f'_t\right)+\upsilon_b\right] \quad (6)$$

$$\upsilon_b=1.75015*F \quad (7)$$

$$f'_t=0.79*\sqrt{f'_c} \quad (8)$$

6. Greenough and Nehdi et al. inspected the shear behavior of slender self-consolidating concrete beams. They derived a comprehensive formula for determining the shear capacity of various concrete taking into account eight input parameters such as f'_c, *d, F,* ρ, *a/d,* τ, ηo, and b_w. The ACI 318 building code was modified by the researchers to create this model (Greenough T, 2008).

$$V_u=\left((0.35\left(1+\sqrt{\frac{400}{d}}\right)f'_c{}^{0.18}(1+F)\rho\frac{d}{a}\right)^{0.4}+(0.9\eta_o\tau F)b_w d \quad (9)$$

7. Kang et al. adjusted the Ashour et al.'s model for the stirrup less steel fiber-reinforced lightweight concrete beams. They incorporated a modification for lightweight concrete by adding a factor (λ) dependent on M/V_d(Kang TH-K, 2011).

$$V_u=(2.11\sqrt[3]{\lambda^2 f'_c}+7F)(\rho\frac{d}{a})^{\frac{1}{3}}bd \quad (10)$$

8. Xu et al. suggested SFRC can either show signs of tensile strain-softening or tensile strain-hardening. They formulated an equation that incorporates effects of *a/d* ratio, splitting tensile strength (f_{sp}), reinforcement ratio (ρ) etc(Xu Shilang, 2012).

$$V_u = \alpha + \beta \left[\left(f_f \; f_t \right)^{\frac{3}{4}} \left(\left(\rho \frac{d}{a} \right)^{\frac{1}{3}} \right) d^{\frac{1}{3}} \right] \tag{11}$$

9.Khuntia et al. created a proposed version of the ACI 318 Building Code shear capacity equation that takes fiber effect into account. When developing the equation, they took into account the fiber-reinforced concrete's (FRC) post-cracking tensile properties, subsequently validating it through test results of SFRC beam from 68 specimens (Khuntia M, 1999).

$$Vu = \left[(0.167 + 0.25F)\sqrt{f'_c} \right] \tag{12}$$

Khuntia discarded a number of significant elements that affect shear strength, including the *a/d* ratio, the reinforcement ratio (ρ), and the fiber volume (V_f).

4. EXISTING SHEAR DESIGN EQUATIONS FOR SFRC DEEP BEAMS:

The shear behavior of deep beams is different than that of slender beams. In deep beams, shear transfer is primarily controlled by arch action. A few empirical shear models have been formulated in the by many researchers using limited number of datasets for SFRC deep beams. These models are outlined as follows:

1. Ashour et al.proposed the following equation considering the shear span to depth ratio (*a/d*), the reinforcement ratio (ρ), compressive strength of concrete (f'_c), fiber factor (F) etc. for stirrup less SFRC beams having *a/d* ratio less than 2.5 (AK., 1986).

$$V_u = \left[\left((2.11 \sqrt[3]{f'_c} + 7F)\left(\frac{\rho d}{a}\right)^{0.333} \right) 2.5 \frac{d}{a} + \upsilon b \left(2.5 - \frac{a}{d}\right) \right] \tag{13}$$

2. Khuntia et al.included the effect of fibers for shear capacity calculation. 68 SFRC beam specimens were used in tests to validate the equation which demonstrates a higher accuracy in forecasting the shear strength of low-strength SFRC beams characterized by $a/d < 2.5$ and crimped/plain fibers, as indicated by its impressive R^2 value of 0.96 (Khuntia M, 1999).

$$V_u = \left[\left(0.167 \left(2.5 \frac{d}{a} \right) + 0.25F \right) \sqrt{f'_c} \right] \tag{14}$$

3. Xu et al.proposed the following equation considering the effect of the reinforcement ratio (ρ), splitting tensile strength (f_{sp}), and *a/d* ratio, as well as the interactions between these variables (Xu Shilang, 2012).

$$Vu = 9.16 \left[\left(f_f \right)^{\frac{2}{3}} (\rho)^{\frac{1}{3}} \frac{d}{a} \right] \tag{15}$$

5. EXISTING ML MODELS FOR PREDICTING THE SHEAR STRENGTH OF SFRC BEAMS

Computational algorithms or systems called Machine Learning (ML) models are made to learn from data and generate predictions, choices, or suggestions without being explicitly programmed to carry out particular functions. Machine learning (ML) models are becoming increasingly valuable across a range of fields because they provide a number of advantages over empirical and semi-empirical regression models (Grayson, 2022).

ML models are capable of handling extremely intricate and non-linear variable relationships. The linear relationships that are frequently assumed by empirical and semi-empirical regression models may not be enough to capture the underlying patterns in the data. From the data, ML models can automatically extract pertinent features (Grayson, 2022). However, in order to build suitable models, empirical and semi-empirical models frequently rely on predetermined features, necessitating domain knowledge. With less manual feature engineering required, machine learning models may be more flexible when applied to a variety of datasets. ML models are non-parametric, particularly those in the deep learning domain. Because of this, they are not limited by predefined equations and can therefore be adjusted to a greater variety of data patterns. They also do not assume a fixed functional form large datasets are effectively handled by ML models. Due to computational constraints or distributional assumptions, empirical models may not perform well with large amounts of data. Scalable to handle large datasets, machine learning models can be trained on distributed computing clusters (Majdi Maabreh, 2023).

1. Jesika et al. developed a data-driven machine learning method using the most extensive database aggregation of 507 experimental data for SFRC beam for shear strength calculation. This database's beam types are categorized as 66 percent slender beams (a/d> 2.5) as well as 34 percent deep beams (a/d< 2.5), splitting the 80% data for testing and 20% for testing (Jesika Rahman, 2021)**.**This study takes into account the following input features: longitudinal reinforcement ratio, concrete compressive strength, aspect ratio, volume fraction, the ratio of shear span to effective depth and type of fiber and the dataset was validated using 10-foldcross validation. Eleven machine learning (ML) were developed and assessed to look how well they find out the SFRC beams' strength at shear.
Table 1 shows that out of the 11 ML models the XGBoost model outperformed the other models. The smallest root mean square error (RMSE) & mean absolute error (MAE) and a maximum R^2values are being produced by the proposed XGBoost model (Jesika Rahman, 2021)**.**

Table 1: Performance metric for the developed models by Jesika et al. (Jesika Rahman, 2021)

	Training data				Testing data			
Model	**RMSE**	**R^2**	**Adjusted R^2**	**MAE**	**RMSE**	**R^2**	**Adjusted R^2**	**MAE**
XB	0.099	0.998	0.998	0.058	1.346	0.739	0.722	0.704
RF	0.301	0.978	0.977	0.207	1.370	0.729	0.712	0.769
SVR	0.603	0.910	0.909	0.383	1.454	0.695	0.676	0.843
ANN	0.965	0.770	0.766	0.698	1.352	0.736	0.720	0.872
DT	0.089	0.998	0.998	0.029	1.410	0.713	0.695	0.880
AB	0.824	0.832	0.830	0.679	1.536	0.660	0.638	0.994
KNN	0.560	0.922	0.921	0.363	1.485	0.682	0.662	0.859
LR$_1$	1.021	0.742	0.737	0.755	1.384	0.724	0.703	0.930
RR	1.021	0.742	0.738	0.755	1.384	0.723	0.706	0.931
LR$_2$	1.021	0.742	0.738	0.755	1.384	0.724	0.706	0.930
CB	0.193	0.991	0.991	0.150	1.428	0.706	0.684	0.811

Jesika et al. also conducted the feature importance analysis in order to understand the effect of input parameters. Figure1 describes the feature importance analysis of the developed XGBoost model where the a/d ratio is found to be the most the influential parameter in predicting the shear strength of SFRC.

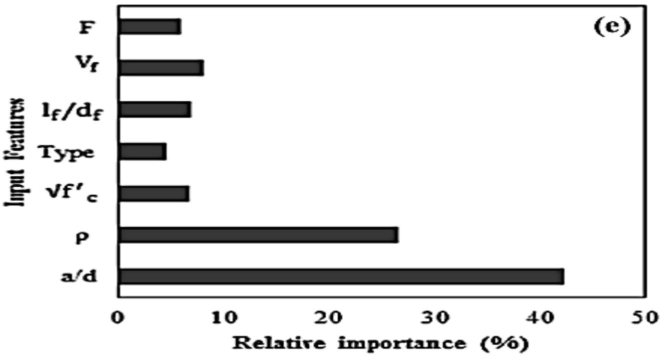

Figure 1:Feature Importance Analysis for the proposed XGBoost model (Jesika Rahman, 2021)

2.Moiz Tariq et al.constructed a Gene Expression Programming (GEP) model which was capable in predicting the shear strength of steel fiber reinforced concrete beams. For this, 488 test results from different literatures were compiled. Various statistical precision evaluators including the performance factor (PF), AAE, and CoV are utilized to obtain a quantitative insight of the model's performance. It is found that the suggested model significantly enhances the ability to forecast the steel fiber's shear strength beams made of reinforced concrete demonstrating the significance of fiber tensile strength. Table 2 shows the efficacy of the proposed model with a $R^2$of 0.97, a performance factor of 1, an average absolute error (AAE) of 16% indicating that the proposed model predicts more accurately than the other models (Moiz Tariq, 2022).

Table 2:Shear strength models of SFRC beams and their predictive abilities (Moiz Tariq, 2022)

Author	**Mean**	**AAE (%)**	**R^2**
Greenough and Nehdi	1.14	24.00	0.91
Kunita et al.	1.32	37.00	0.83
Shin et al.	1.67	38.00	0.81
Sharma et al.	1.25	27.00	0.81
Imam et al.	1.18	40.00	0.25
Ashour et al.	1.30	28.00	0.70
Kwak et al.	1.03	23.00	0.82
Narayanan and Darwish	1.14	26.00	0.72
Shahnewaz and Alam	1.42	28.00	0.86
Shahnewaz and Alam	1.57	35.00	0.84
RILEM	2.50	55.00	0.78
Gandomi et al.	0.90	28.00	0.90
Sarveghadi et al.	2.53	56.00	0.75
Chaabene and Nehdi	1.10	22.00	0.65
Sabetifar et al.	1.30	30.00	0.82
Proposed Model	**1.00**	**16.00**	**0.97**

3. Odey Alshboul et al. aimed to develop the Gene Expression (GEP), Light Gradient Boosting Machine (LightGBM), and Extreme Gradient Boosting (XGBoost) algorithms to predict the shear strength of stirrup-free SFRC deep beams using 172 test data. Table 3 indicates that out of these 3 models the LightGBM performs the best with aR^2 value of 97.8%, MAPE of 4.90%, RMSE of 0.369 and MAE of 0.248. The GEP model performs worst in predicting the shear capacity (Odey Alshboul, 2023).

Table 3: Performance of the models by Alshboul et al. (Odey Alshboul, 2023)

Performance Metrics	Prediction models			
	LightGBM	**XGBoost**	**GeneExpressionEq.**	**Eq.**
MAE	0.248	0.319	0.963	1.85
RMSE	0.369	0.576	1.241	2.56

MAPE	4.9%	5.8%	22.4%	32.04%
R^2	97.8%	94.5%	78.9%	53.7%

Figure 2 describes the feature importance analysis of the all three developed models where the effect depth (*d*) is found to be the most the influential parameter in predicting the shear strength of SFRC.

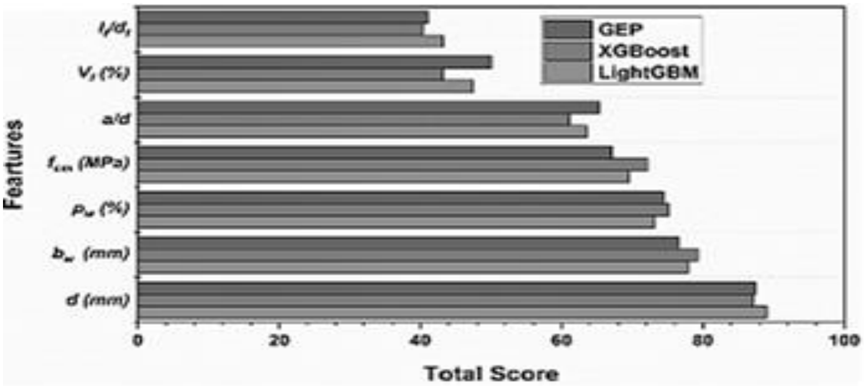

Figure 2:Total score of feature importance for all three models developed by Alshboul et al. (Odey Alshboul, 2023)

4. Majdi Maabreh et al.(Majdi Maabreh, 2023)evaluated the shear strength of stirrup less Deep SFRC Beams (SFRC-DBs) & use ML techniques to predict shear strengths using a database of 170 SFRC-DBs. Five standard performance metrics are used to evaluate machine learning algorithms. A variety of techniques were used in the evaluation process, including linear regression, decision tree, the multilayer perceptron (MLP), lasso, ridge, elastic net, random forest (RF), extreme gradient boosting (XGBoost), AdaBoost, Gradient Boosting (GB) furthermore the k-nearest neighbour. Figure 3 shows that among all, the Gradient Boosting (GB) algorithm performs the best as it's R^2=87.2, MAE=23.3%, RMSE=41.0%, MAPE=16.9 % (Majdi Maabreh, 2023).

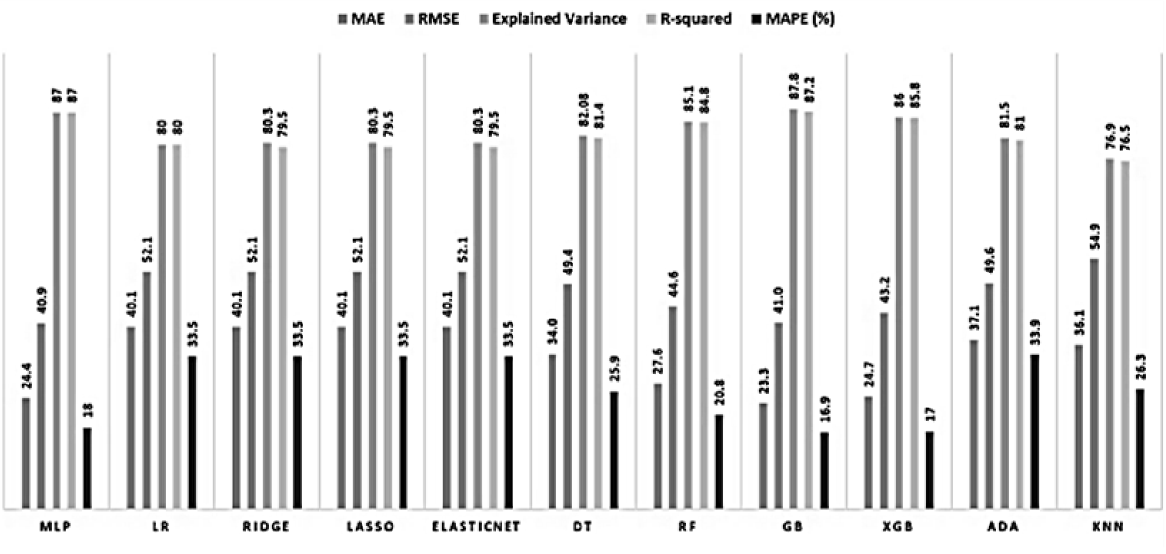

Figure 3**:** The evaluation metrics of regressors by Majdi Maabreh (Majdi Maabreh, 2023)

6. CONCLUSION

This paper overviews the existing shear design equations for SFRC slender and deep beams. It also describes the parameters that are mostly affecting in forecasting the shear strength, the flaws & deficiency of these equations. It has been found from this study that the existing shear design equations were empirical and developed based on a limited test data. Most of equations did not consider all the factors that affect the shear capacity of SFRC beams. Hence, it is debatable if these traditional empirical equations can accurately calculate the shear strength of SFRC beams. It is found from this study that the machine learning models specially the boosting algorithms such as Extreme Gradient Boosting (XGBoost), Gradient Boosting (GB), Light Gradient Boosting Machine (LightGBM) algorithms, which were created using the updated dataset, performed better in forecasting the shear strength of SFRC beams than the empirical equations.The performance of the machine learning (ML) algorithms is adaptively increased by the availability of new data for training. Thus, it is recommended that in order to increase prediction accuracy of the models, new experimental data should be added on a regular basis.

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