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Fiber reinforced concrete corbels: Modeling shear strength via symbolic regression

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Abstract. In this study, a novel application of symbolic regression (SR) is employed for the prediction of ultimate shear strength of steel fiber reinforced (SFRC) and glass fiber reinforced (GFRC) corbels without stirrups, for the first time in the literature. A database is created using the test results (42 tests) conducted by the authors of current paper as well as the previous studies available in the literature. A symbolic regression based empirical formulation is proposed using this database. The formulation is unique in a way that it has the capability to predict the shear strength of both SFRC and GFRC corbels. The performance of proposed model is tested against randomly selected testing set. Additionally, a parametric study with a wide range of variables is carried out to test the effect of each parameter on the shear strength. The results confirm the high prediction capacity of proposed model.

Keywords: symbolic regression; reinforced concrete corbel; fiber reinforced concrete; shear strength; glass fiber; steel fiber

1. Introduction

Recently, the precast reinforced concrete elements are commonly preferred by designers for the construction of buildings and bridges. As an example of such elements, corbels are used to transfer loads from beams or slabs to columns or walls. Brackets or corbels either project out from a column or a structural wall or is the overhanging portion of a beam (Fig. 1). In most cases, the shear span-to-depth ratio of a corbel is equal to or less than 1 ($a/d \leq 1$). Corbels can be provided to support rails which transfer heavy loads from moving cranes in heavy-duty factory workshops. Corbels are also provided at the cantilevered end of the girders in double cantilever balanced reinforced concrete bridges to support the end spans of the bridge.

Steel fiber reinforced concrete (SFRC) is manufactured using hydraulic cement with aggregate (fine or course) and discrete steel fibers shown in Fig. 2(a). Steel fibers for SFRC are produced as short, discrete lengths of steel with an aspect ratio (length-to-diameter ratio) varying between 20 and 100. Steel fibers are small enough to be dispersed randomly in unhardened concrete mix using concrete mixture process (ACI 2002).

1.1 Steel fibers

Provision of steel fibers leads to a number of significant behavioral enhancements to concrete. In compression, steel fibers do not significantly affect the ascending curve of the compressive stress-strain response. However, they cause the descending post-peak response curve to decline in a shallower fashion than the curve of plain concrete, resulting in an increased ductility and toughness (Fanella and Naaman 1985). The peak compressive strength is not significantly affected, i.e., the researchers have observed a maximum strength gain of only 15% (ACI 2002, Fanella and Naaman 1985, Thomas and Ramaswamy 2007). However, the peak strain increases perceptibly with the provision of steel fibers.

The addition of steel fibers has a much more noticeable effect on the tensile behavior of the composite. In typical fiber volume contents, the material exhibits strain-softening behavior; yet, the degradation in load-carrying capacity is slower than that of plain concrete. This results in the composite having greater ductility and energy absorption capabilities than the plain concrete. In addition, because the fibers bridge the cracks in the composite and aid in the transfer of forces across the cracks, crack widths are less than those in plain concrete. If the reinforcing bars are present, multiple cracks can form even for a strain-softening material. As compared to the plain concrete, there will be more cracks at shorter spacing and with smaller widths (Deluce 2011).

1.2 Glass fibers

Being an alkali resistant material, glass fibers are used for manufacturing of various universal products. The addition of glass fibers in reinforced concrete yield many advantages such as alkali resistance in structural member. High flexural strength, ability to reproduce, low maintenance requirements, and environmental friendliness are some other advantages of glass fibers. As shown in Fig.

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Fig. 1 Precast elements of Structural Mechanics Laboratory, University of Gaziantep

(a) (b)

Fig. 2(a) Hooked end steel fibers; (b) Unorganized alkali resistant glass fibers

2(b), glass fibers are unorganized and are easily dispersed in unhardened concrete due to their thin and soft nature. The diameter of thin glass fiber or filament ranges from approximately 3 to 24 μm. The 17μm fiber diameter is most commonly used for FRC products for structural engineering (ACI 2002).

Glass fibers do not extremely affect the ascending portion of compressive stress and strain curve. Yet, glass fibers show significant contribution to improve tensile strength as compared to compressive strength (ACI 2002).

2. Fiber reinforced concrete corbels

Fibers in concrete can be considered as reinforcements spread out all over the depth of a member. The addition of steel fibers to the concrete provides substantial increase in the shear strength. The effectiveness of fiber reinforcement to increase shear resistance is dependent on several factors, including matrix properties, fiber properties (material properties, aspect ratio, and shape), fiber content, and bond stress versus slip response of fibers.

2.1 Steel fiber reinforced concrete (SFRC) corbels

A series of experimental studies have been carried out on normal strength steel fiber reinforced concrete corbels by Fattuhi and Hughes (Fattuhi 1987, Fattuhi 1990, Fattuhi 1994, Fattuhi and Hughes 1989, Fattuhi and Hughes 1989). Fattuhi and Hughes investigated effects of steel fiber on load carrying capacity of corbels. The authors used various parameters (tensile and compressive strength of concrete, steel fiber volume fraction, shear span, fiber aspect ratio, effective depth, reinforcement ratio) and observed the mechanical response of SFRC corbels. Fattuhi (1994) also investigated the mechanical behavior of trapezoidal normal strength SFRC corbels (Fattuhi 1994).

Campione *et al.* (2007) studied the flexural behavior of fibrous reinforced concrete corbels experimentally and suggested simple analytical expressions for bearing capacity by considering the shear contribution due to steel reinforcements and fibers (Campione *et al.* 2007). Campione (2009) carried out two experimental studies about SFRC corbels (Campione 2009). The performance of SFRC corbels under the combined effect of vertical and horizontal loads was investigated. In another study, flexural response of SFRC corbels were implemented.

Fattuhi (1994) proposed a practical empirical formulation based on experimental results, which predicts the ultimate load capacity of both RC and SFRC corbels by considering some parameters which influence the mechanical behavior (Fattuhi 1994). The expression of the formula is

$$V_u = k_1 bh(f_t)^{k_2}\left(\frac{a}{h}\right)^{k_3}\left(\frac{f_y}{f_{cu}}\right)^{k_4}\left(\frac{d}{h}\right)^{k_5}(\rho)^{k_6} \quad (1)$$

where k_1=57.292, k_2=0.315 k_3=-0.812, k_4=-0.049, k_5=0.678, k_6=0.626.

Fattuhi also proposed two more models namely as “Flexural Model” and “Truss Model” for the load carrying capacities of steel fiber reinforced concrete corbels. Basic formulas for these models are:

Flexural Model

$$V_{MODEL} = \frac{f_y A_s}{a}\left(d - \frac{a_1}{2}\right) + \frac{k_0 f_t b}{2a}\left(h - \frac{a_1}{\beta_1}\right)\left(h + \frac{a_1}{\beta_1} - a_1\right) \quad (2)$$

where

$$k_0 = \frac{9.519}{(f_c)^{0.957}} \text{ and } a_1 = \frac{f_y A_s + k_0 f_t hb}{0.85 f_c b + k_0 f_t \left(\frac{b}{\beta_1}\right)} \quad (3)$$

Truss Model

$$V_{MODEL} = \frac{f_y A_s\left(d - \left(\frac{l\sin\beta}{2}\right)\right) + 0.5k_0 f_t bh(h - (l\sin\beta))}{a + 0.5(l\sin\beta)\cot\beta} \quad (4)$$

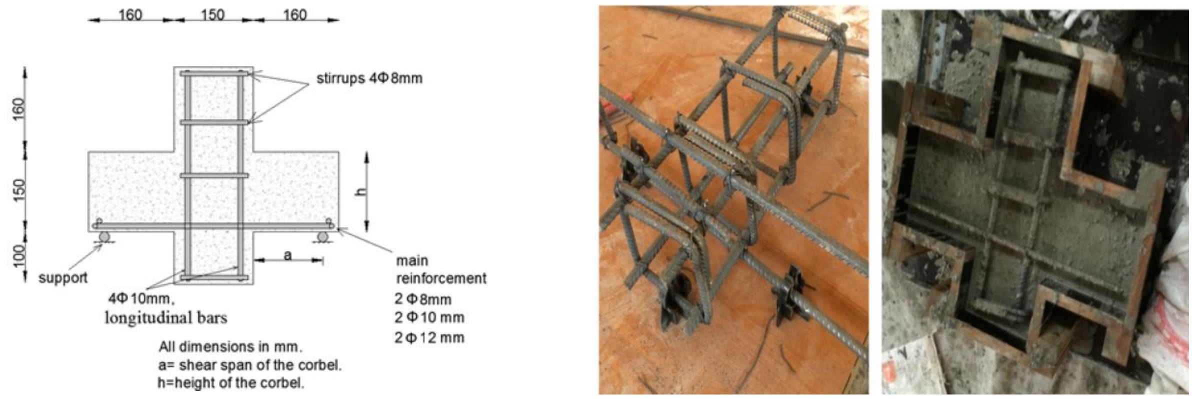
where

$$l\sin\beta = \frac{f_y A_s + k_0 f_t bh}{0.85 f_c b + k_0 f_t b} \quad (5)$$

and $\cot\beta$ is determined from following quadratic equation

$$0.425 f_c b(l\sin\beta)^2\cot^2\beta + 0.85 f_c ab(l\sin\beta)\cot\beta - f_y A_s\left(d - \frac{(l\sin\beta)}{2}\right) - 0.5k_0 f_t bh(h - (l\sin\beta)) = 0 \quad (6)$$

k_0 is determined from Eq. (3). In the equations, b and h are width and height of the corbel in mm, respectively, f_t is



(a) Geometric and reinforcement configuration of SFRC and GFRC corbels experimented by the authors (Gulsan 2015, Kamil 2016, Abdi 2016)

(b) Reinforcement preparation and concreting of GFRC and SFRC corbels

Fig. 3 Geometric and reinforcement details and preparation of SFRC and GFRC corbels before loading tests

the splitting tensile strength of fibrous concrete in MPa, d/a is the reciprocal of the shear span-to-depth ratio and A_s is cross sectional area of main reinforcement. Ultimate load carrying capacity of SFRC corbel is in Newtons.

On the other hand, mechanical behavior and performance of high strength SFRC corbels were investigated by various studies. High strength SFRC corbels in trapezoidal form were experimented by Muhammad (1998) under monotonic and cyclic loading (Muhammad 1998). Yang *et al.* (2011) investigated the influence of steel fibers on the serviceability of reinforced concrete corbels (Yang *et al.* 2011).

Second author of the present paper (Gulsan 2015) investigated the shear strength of SFRC corbels without stirrups (Gulsan 2015) whose test configuration is shown in Fig. 3(a). Thus, Gulsan (2015) tested twenty-four normal strength concrete corbels, sixteen of which were prepared with SFRC. The author concluded that the use of steel fibers in reinforced concrete corbels possesses considerable advantages such as ductile behavior and higher load carrying capacity. These outputs prove that steel fibers can be used as secondary reinforcement instead of horizontal stirrups. However, the use of steel fibers does not guarantee the ductile behavior, since this behavior depends also on other parameters such as shear span, reinforcement ratio and compressive concrete strength. Therefore, in design of SFRC, the proper selection of concrete class, main reinforcement diameter, shear span values, and fiber percentage is crucial.

2.2 Glass fiber reinforced (GFRC) corbels

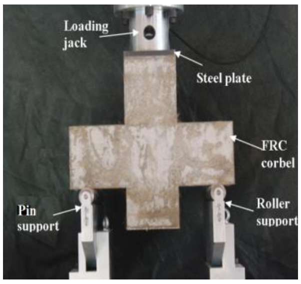
As opposed to SFRC corbels mentioned above, the literature does not contain any research covering the shear strength of GFRC corbels except for the studies conducted by the third (Abdi 2016) and the fourth author (Kamil 2016) of the present paper. Some details of the experiments carried out by the authors are shown in Fig. 3(a) and 3(b).

The third author of this article (Abdi 2016) conducted tests on nine normal strength GFRC corbels without stirrups (Abdi 2016). Six corbels were manufactured with GFRC while remaining three corbels prepared without fibers for comparison purposes. Different percentage of glass fibers 0%, 0.2% and 0.4% were used with three shear spans (8, 10, and 12) cm. The ratio of shear span to effective depth (*a/d*) were 0.63, 0.79 and 0.95. All corbels were reinforced with $2\times\phi8$ mm steel reinforcement bars. The author reported that the increase in average load carrying capacity for GFRC are 6.9% and 13.5% for fiber volumes 0.2%, and 0.4%, respectively. Reduction in crack widths leads to longer service life of corbels.

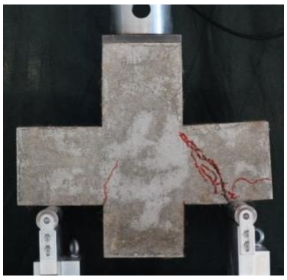
On the other hand, the fourth author of the current paper (Kamil 2016) studied the shear strength of glass fiber reinforced concrete (GFRC) corbels with high strength concrete (Kamil 2016). Kamil (2016) conducted tests on a total of nine corbels, six of which were prepared with GFRC, without stirrups. The corbels were divided into three groups with various parameters. Different percentage of glass fibers 0%, 0.2% and 0.4% were used with three levels of shear spans (8, 10, and 12) cm. The ratio of shear span to effective depth (*a/d*) were 0.67, 0.83 and 1. All corbels were reinforced with $2\times\phi8$ mm steel reinforcement bars. The author concluded that the provision of glass fibers can increase the post-cracking load and the bearing capacity, and change the failure mode from brittle to ductile manner.

Fig. 4(a) shows the test setup of FRC corbel experiments conducted by Gulsan (2015), Kamil (2016), and Abdi (2016) at Structural Mechanics Laboratory of University of Gaziantep. All three authors used the same universal testing machine with 500 kN capacity and all specimens were loaded concentrically. Experiments were carried out in displacement controlled mode. Loads were transferred to two corbels which are supported by roller and pin supports. Loading rate was 0.2 mm/min. for the experiments. Details of cross-sectional and material properties and experimental ultimate shear strength (V_{exp}) are given in Table A.1. Fig. 4(b)-(d) give examples of crack patterns obtained from SFRC and GFRC corbel tests conducted by Gulsan (2015), Kamil (2016) and Abdi (2016).

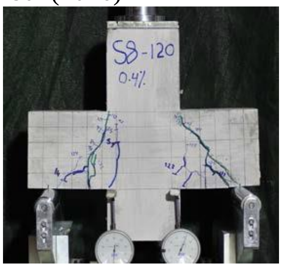
Current studies (Fattuhi 1987, Fattuhi 1990, Fattuhi 1994, Fattuhi and Hughes 1989, Fattuhi and Hughes 1989, Fattuhi 1994, Kumar and Barai 2010) present models on the prediction of SFRC corbels, only. In the study presented herein, however, the results of new tests with SFRC and



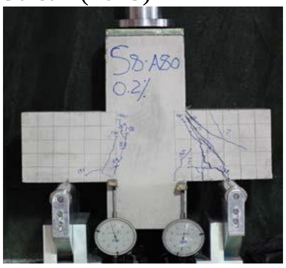
(a) Test setup by Gulsan (2015), Kamil (2016), and Abdi (2016)



(b) Crack pattern of a SFRC corbel sample by Gulsan (2015)

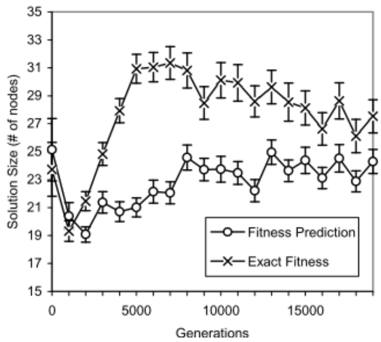


(c) Crack pattern of GFRC corbels experimented by Kamil (2016)

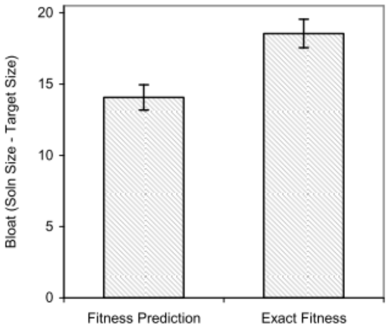


(d) Crack pattern of a GFRC corbel sample experimented by Abdi (2016)

Fig. 4 Test setup and crack pattern for FRC corbel tests



(a)



(b)

Fig. 5(a) The size of best solution during regression averaged over 100 test runs, (b) Total average bloat averaged over 500 randomly generated expressions

GFRC corbels are also included in the database and a unified model covering the prediction of both SFRC and GFRC corbels was prepared.

3. Symbolic regression

Symbolic regression (*SR*) is a well-known technique based on evolutionary computing for exploring the space of mathematical formulations while minimizing several error metrics (Koza 1994).

The algorithm of symbolic regression differs from established regression techniques that are based on fitting the parameters to an equation of a predetermined structure. Unlike those established regression techniques, symbolic regression searches for the parameters as well as the structure of equations. Random combination of mathematical expressions such as algebraic operators (+, -, ÷, ×), constants, analytical functions (e.g., *sine* and *cosine*) and state variables is utilized to generate initial expressions. In the next step, new equations are produced by recombination of former equations and probabilistically changing sub-expressions of produced equations. The equations that fit the experimental data with minimum error are kept and the other solutions are eliminated. The algorithm returns the set of equations that reached to a desired level of accuracy. Although it is possible to use symbolic regression for the purpose of finding explicit (Duffy and Engle-Warnick 2002) and differential equations (Bongard and Lipson 2007), finding conservation laws and invariant equations using symbolic regression approach may not be as effective (Schmidt and Lipson 2009).

The unary operations (e.g., *exp*, *abs*, *log*) or binary operations (e.g., *add*, *div*, *mult.)* can be used. The operation types can be narrowed down in case some information about the problem is known (Augusto and Barbosa 2002, Schmidt and Lipson 2005).

The change of operation type (e.g., *mult.* to *div.*) is possible by mutation in symbolic regression method such as changing an operation argument (e.g., change x+1 to x+x), adding an operation (e.g., change $x+x$ to $x+(x*x)$) or deleting an operation (e.g., change $x+x$ to x).

The exchange of sub-trees (or sub-graphs) from two parents can be implemented by crossover function. In order to illustrate it better, this example can be considered: Crossing $f_1(x)=x^3+3$ and $f_2(x)=x^4+cos(x)+x^2$could produce a child $f_3(x)=x^3+cos(x)$. In this example, the leaf node +3 was exchanged with the $cos(x)$ term (Schmidt and Lipson 2007).

3.1 Fitness prediction

Minimization of error on the training set is the main objective of the fitness in symbolic regression (Dolin *et al.* 2002, Eggermont and Van Hemert 2000, Hoai *et al.* 2002, Keijzer 2003).

For the calculation of error, numerous ways such as squared error, absolute error, log error are available. Despite the fact that the choice of fitness measurement method is not critical, it is known that different metrics work better on different problems. In this paper, we utilize the mean absolute error (MAE) for fitness measurement

$$fitness(s)=\frac{1}{N}\sum_{i=1}^{N}\left|s(x_i)-y_i\right| \tag{7}$$

Table 2 Ranges and statistics of experimental data

	a/d	ρ (%)	f_f (Mpa)	f_y (Mpa)	f_c(Mpa)	f_t(Mpa)	v_f(%)	V_{exp} (kN)
Max	1.47	1.53	3400.00	560.00	92.79	9.28	2.50	228.00
Min	0.43	0.44	1100.00	448.70	22.30	1.90	0.00	37.57
Mean	0.88	0.84	1447.62	491.47	38.08	4.74	1.21	114.64
Std. dev.	0.20	0.32	800.56	45.84	16.47	1.17	0.74	38.26

where s is a possible solution (algebraic expression), x_i and y_i are training data input and outputs, and N is the total number of training examples in training data set.

Fitness prediction is considered to be a new method that is applied to determine the performance of different mathematical expressions on explanation of the experimental data more efficiently and optimization of the pressure to fit multiple aspects of data (Schmidt and Lipson 2008a, Schmidt and Lipson 2008b). Fig. 5 illustrates solution sizes and bloat for fitness prediction and exact fitness.

4. Numerical application

The main object of this study is to provide a unified model for the shear capacity of fiber reinforced concrete corbels via symbolic regression (*SR*) employing the data obtained from the current experimental studies and the previous studies (Gulsan 2015, Abdi 2016, Kamil 2016). The data consist of 126 experimental results, 42 of which are obtained from the current studies (Gulsan 2015, Abdi 2016, Kamil 2016) conducted by second, third and fourth author of this article at Structural Mechanics Laboratory of University of Gaziantep. The structure of the developed model consisted of seven input parameters, i.e., strength of main reinforcement (f_y), concrete compressive strength (f_c), concrete tensile strength (f_t), (a/d) span-to-depth ratio reinforcement ratio (ρ), tensile strength of fiber (f_f), tensile volume fraction (v_f) and an output parameter, that is, experimental shear strength ($V_{proposed}$).

Ranges of input and output parameters are summarized in Table 2. The input variables contained cylinder compressive strength data, both for normal strength concrete (NSC) and high strength concrete (HSC).

On the other hand, fiber tensile strength data for steel fiber (f_f=1000-1100 MPa) and glass fiber (f_f=3400 MPa) are also included. Fig. 6 visualizes the sample distributions for input parameters. The dataset was divided into training (75%) and testing (25%) sets to avoid over fitting based on random selection. The model was developed using a commercially available software package named *Eureqa*. Selected mathematical building blocks were multiplication (*), division (/), negation (-), natural logarithm (*ln*), square root (√) and exponential (*e*). The program has created several models via the minimization of error metric which was selected as absolute error. Among the several models, the model with lowest absolute error and highest goodness of fit (Eq. (8)) was chosen for parametric study.

$$V_{proposed} = c * \left(k_1 + \frac{k_2 \rho^{k_3} f_f^{k_4} f_c^{k_5} (e^{v_f})^{k_6} \ln(f_t)}{f_y^{k_7} (a/d)^{k_8}} \right) \tag{8}$$

where c is the coefficient for fiber type (1 for steel fiber, 0.5 for glass fiber), k_1=10.07, k_2=20.6, k_3=0.541, k_4=0.406, k_5=0.22, k_6=3.27, k_7=0.0338, k_8=0.807

Fig. 7 shows the predictions of Eq. (8) for both training and testing data. In Fig. 7, predicted data as compared to experimental data are clustered around a 45° line and the fitness coefficient (R^2) is found as 0.9259. On the other hand, by random selection, 25% of the data is employed as testing set to further investigate the performance of the model as shown in Table 3. This further evidences the high performance of proposed formulation.

5. Parametric study

A parametric study is conducted to test the generalization capability of the proposed model (Eq. (8)). For this purpose, a database is generated in which each input has three values kept in the range listed in Table A.1. Afterwards, this database is employed in the proposed model and the main trends of each input on the output are plotted. Main effect graphs are significant tools to figure out whether the proposed model is capable of predicting any data within the experimental data range. Fig. 8 shows the effect of each input on the output and evidences that the proposed model has the generalization capability.

Main effect trends confirm that the most important parameter is the shear-span-to-depth ratio (*a/d*) which exert a significant inverse effect on the shear strength of FRC corbels. Additionally, reinforcement ratio (ρ), concrete compressive strength (f_c), fiber tensile strength (f_f) and concrete tensile strength (f_t) seem to have a dominant effect as compared to the effects of main reinforcement yield strength (f_y) and fiber volume fraction (v_f). As presented in Fig. 8, the yield strength of main reinforcement (f_y) appears to have almost no effect on the shear strength. This can be attributable to the failure of corbels before the steel reinforcement reaches the yield strength limit.

On the other hand, interaction plots are derived using the same parametric database. These plots illustrate the interaction effect of any two variables on the output and are obtained by using the mean values of all variables.

The influence of reinforcement ratio on shear strength of FRC corbels is given in Fig. 9(a) for three values of span to depth ratio, i.e., a/d=0.7, 0.95 and 1.20. Increasing the shear-span-to-depth ratio values lead to a higher effect of reinforcement ratio on the shear strength. Additionally, the rate of increase appears to be higher for lower shear-span-to-depth ratio values.

Fig. 9(b) illustrate that the rise in fiber tensile strength yields higher shear strength and the rate of increase in the shear strength of FRC corbels remains almost unchanged for all values of shear-span-to-depth ratio.

As shown in Fig. 9(c), the tensile strength of steel reinforcement has significantly small effect on the shear strength, which can be attributed to the failure of corbels before steel reinforcements reach to yield strength limit. Yet, the interactive effect of shear-span-to-depth ratio on the influence of f_y is quite marginal.

The effect of concrete compressive strength on shear strength of FRC corbels at varying shear-span-to-depth

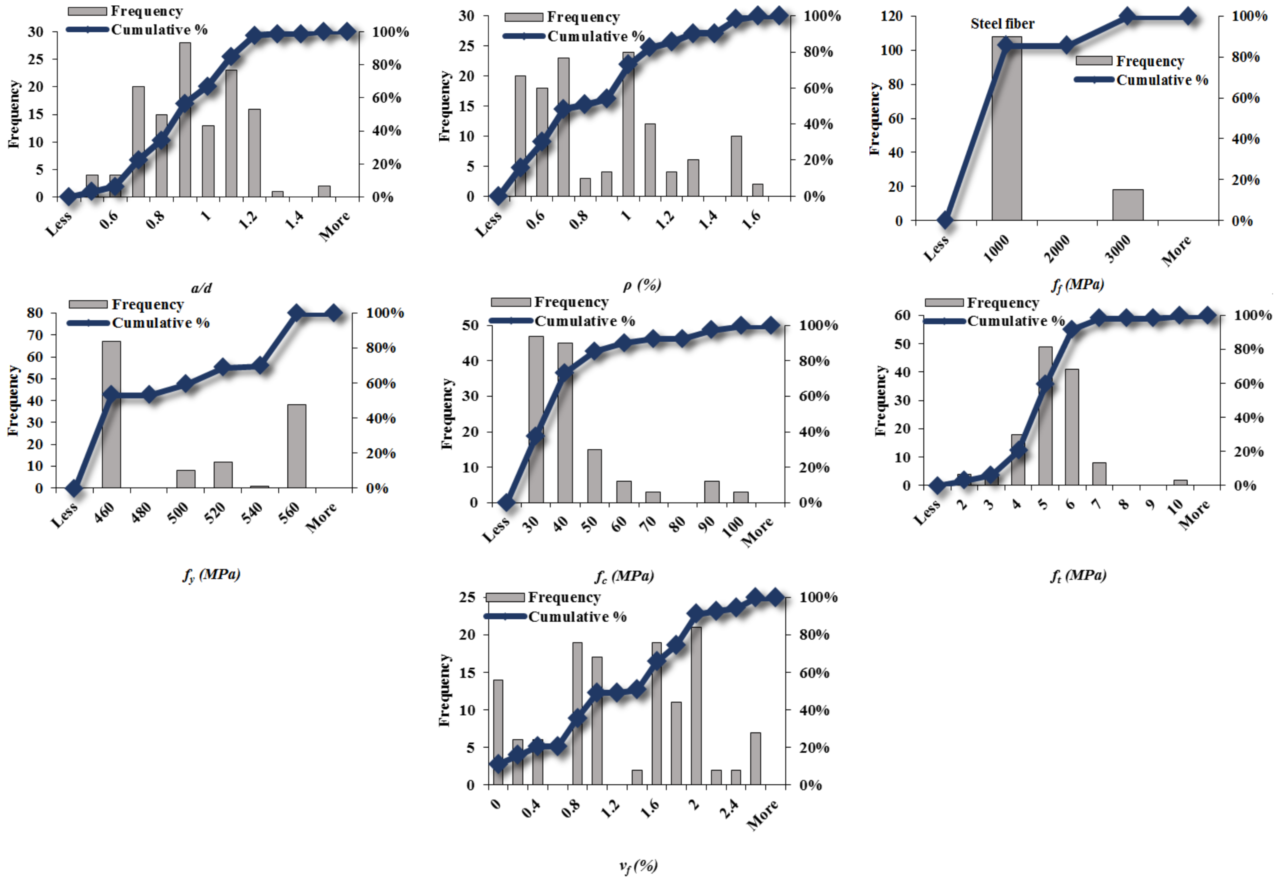


Fig. 6 Histograms of the input variables

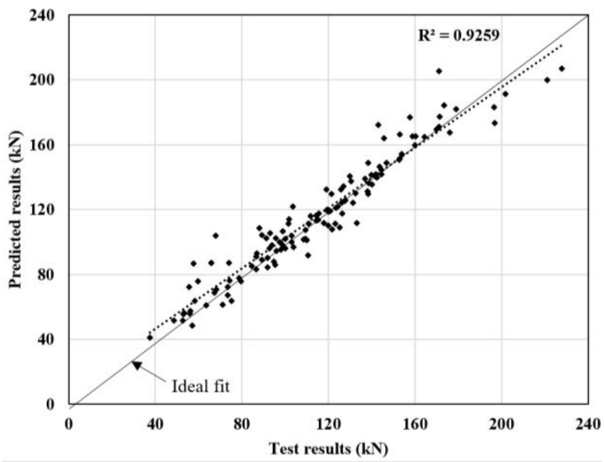


Fig. 7 Prediction performance of Eq. (8)

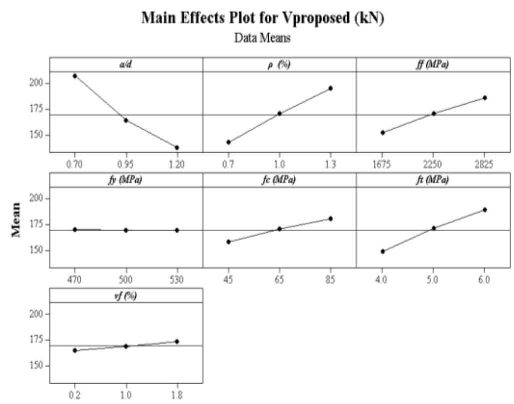


Fig. 8 Main effect trends of input variables for proposed model (Eq. (8))

Table 3 Statistical parameters of training, testing and total set

	COV ($V_{exp}/V_{proposed}$)	*RMSE*	R^2
Training set	0.087	9.42	0.9331
Testing set	0.122	13.53	0.9192
Total set	0.095	10.47	0.9259

ratios is given in Fig. 9(d). Increasing effect of f_c is apparent for all shear-span-to-depth ratio values and yet, the higher values of shear-span-to-depth ratio lead to small change in the rate of increase

Fig. 9(e) shows the influence of concrete tensile strength on the shear strength for the positive change in shear-span-to-depth ratio. It is evident from the Fig. 9(e) that concrete tensile strength has an increasing trend for up to f_y=5 MPa. Yet, this trend is pronounced slightly less for higher values of *a/d*. Additionally, the trend of f_t effect gets smaller for the higher values of shear-span-to-depth ratio for values greater than 5 MPa.

Fig. 9(f) illustrates the shear strength effect of fiber volume fraction for varying shear-span-to-depth ratio values. It is clear from the figure that the positive influence of fiber volume fraction pronounced much more at lower values of shear-span-to-depth ratio.

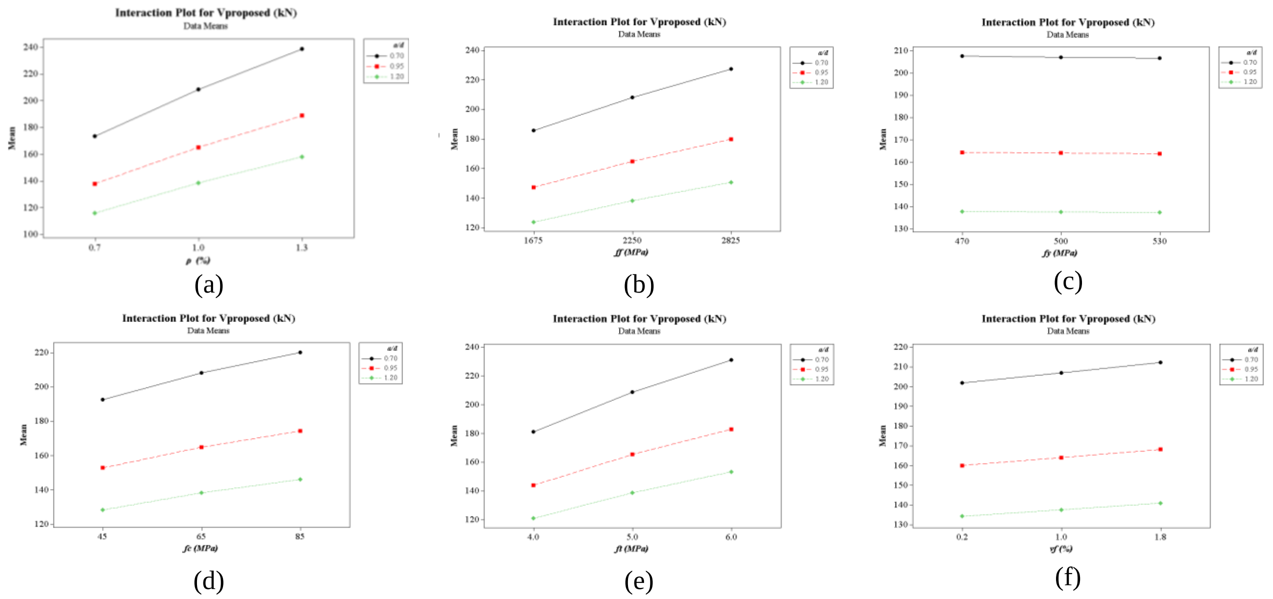


Fig. 9 Influence of input parameters (a) reinforcement ratio; (b) fiber tensile strength; (c) tensile strength of main reinforcement; (d) cylinder compressive strength; (e) concrete tensile strength; (f) fiber volume fraction

6. Conlusions

This study presents an investigation on the shear strength of fiber reinforced concrete (FRC) corbels without stirrups. A robust variant of genetic programming (GP) namely as symbolic regression (SR) is employed to develop an empirical model to predict the shear capacity of both SFRC and GFRC corbels, for the first time in literature. Successful applications of GP for solving various engineering problems are also available in the literature (Saridemir 2016, Ozturk *et al.* 2016, Alemdag *et al.* 2016, Tapkin *et al.* 2015). A database was created using the experimental findings on steel fiber reinforced (SFRC) corbel by Fattuhi and Hughes (Fattuhi 1987, Fattuhi 1990a, Fattuhi 1994, Fattuhi and Hughes 1989, FattuhiI and Hughes 1989, Fattuhi 1994). Additionally, the results of the corbel experiments conducted at our laboratory are also added to the database. These tests included the SFRC corbel shear strength tests by the second author (Gulsan 2015) and glass fiber reinforced polymer (GFRC) corbel shear strength tests by the third (Abdi 2016) and fourth (Kamil 2016) authors of the present paper. The shear strength was modeled in terms of several input factors (a/d, ρ, f_f, f_y, f_c, f_t, v_f) affecting the corbel behavior.

Several equations were developed and the model with minimum absolute error and maximum fitness was selected for parametric study. A comparison with the available models was not possible since those models were developed only for SFRC corbels. Also, the generalization capability of the proposed model was tested using a parametric data. Experimental evidence supported the parametric study results. Based on the findings summarized above, following conclusions can be drawn:

• The proposed model (Eq. (8)) shows high performance on predicting the shear strength of simply supported FRC (steel and glass fiber) corbels subjected to vertical loading with varying geometry and material properties, i.e., shear-span-to-depth ratio, main reinforcement ratio, fiber tensile strength, reinforcement tensile strength, concrete compressive strength (normal and high strength), concrete tensile strength and fiber volume fraction.

• Parametric study results confirmed that the generalization capability of proposed model was excellent. Thus, the model is valid not only for the data used, but also for the unseen input values within the range presented herein.

• Shear span-to-depth (a/d) ratio exert a dominant influence on the shear strength and plays a significant role on the influence of other parameters on the shear strength.

• The results of parametric analyses guarantee the robustness and effectiveness of the model for the assessment of shear strength of FRC corbels beyond the training domain

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CC

Symbol list

a	Shear span for corbels
b	Width of the corbel
d	Effective depth of the corbel
h	Height of the corbel
f_c	Compressive strength of the concrete for cylinder specimens
f_{cu}	Compressive strength of the concrete for cube specimens
f_f	Tensile strength of fiber
f_t	Splitting tensile strength of fiber reinforced concrete
ρ	Steel reinforcement ratio
f_y	Yield strength of steel reinforcement
v_f	Volumetric fiber ratio
A_s	Cross-sectional area of main reinforcement
V_{exp}	Experimental load carrying capacity of fiber reinforced corbels
$V_{proposed}$	Load carrying capacity of corbels resulted from the proposed equation

Table A.1 Experimental database

References	Corbel designation	Fiber type	a/d (mm)	b (mm)	h (mm)	ρ (%)	f_f (MPa)	f_y (MPa)	f_{cu} (Mpa)	f_c (MPa)	f_t (MPa)	v_f (%)	V_{exp} (kN)	$V_{proposed}$ (kN)	$V_{exp}/V_{proposed}$
	C2	**Steel Fiber**	**1.04**	**152**	**147.5**	**0.70**	**1100**	**558**	**53.51**	**43.34**	**4.37**	**0.7**	**84.50**	**85.04**	**0.99**
	C3	Steel Fiber	1.05	152	146	0.71	1100	558	52.60	42.61	5.45	0.7	92.90	95.94	0.97
(Fattuhi 1987)	**C4**	**Steel Fiber**	**1.02**	**151**	**149.5**	**0.70**	**1100**	**558**	**51.40**	**41.63**	**4.79**	**0.7**	**91.80**	**90.24**	**1.02**
	C5	Steel Fiber	1.05	152	146	0.71	1100	558	51.10	41.39	5.36	0.7	96.00	94.55	1.02
	C6	Steel Fiber	1.07	156	146.5	0.69	1100	558	40.10	32.48	3.19	0.7	75.20	63.73	1.18
	C27	Steel Fiber	0.43	153	148.5	0.45	1100	495	47.30	38.31	4.64	0.7	125.80	132.44	0.95
	C28	Steel Fiber	0.72	151	148	0.45	1100	495	55.70	45.12	6.09	0.7	88.20	108.61	0.81
(FattuhiI and Hughes 1989)	C29	Steel Fiber	0.96	153	149	0.44	1100	495	55.70	45.12	6.09	0.7	65.90	87.25	0.76
	C30	Steel Fiber	0.43	154	146.5	0.70	1100	558	51.40	41.63	4.79	0.7	171.00	171.00	1.00
	C31	**Steel Fiber**	**0.55**	**153**	**146**	**1.02**	**1100**	**491**	**57.00**	**46.17**	**5.05**	**0.7**	**179.00**	**181.90**	**0.98**
	C32	Steel Fiber	1.06	153	148	1.00	1100	491	47.30	38.31	4.64	0.7	110.10	101.15	1.09
	T3	Steel Fiber	0.73	152	148	0.70	1100	558	47.90	38.80	4.66	0.7	133.00	111.64	1.19
	T4	Steel Fiber	0.72	151	147	0.71	1100	558	55.90	45.28	6.19	1.4	142.50	139.85	1.02
(Fattuhi and Hughes 1989)	T6	Steel Fiber	0.72	152	147	0.70	1100	537	57.40	46.49	9.28	2.1	143.00	172.26	0.83
	T10	Steel Fiber	0.76	151	147	1.02	1100	491	47.90	38.80	4.66	0.7	138.00	131.14	1.05
	T11	Steel Fiber	0.74	152	146	1.02	1100	491	55.90	45.28	6.19	1.4	160.20	165.18	0.97
	T12	Steel Fiber	0.74	152	147	1.02	1100	491	57.40	46.49	9.28	2.1	171.20	205.16	0.83
	1	Steel Fiber	0.65	152.5	149	1.00	1100	452	41.40	33.53	5.84	1.7	153.00	166.20	0.92
	2	Steel Fiber	0.65	155	150	0.98	1100	449	43.40	35.15	5.44	1.7	160.00	159.87	1.00
	3	Steel Fiber	0.63	152.5	150	0.44	1100	451	42.00	34.02	4.86	1.7	91.20	102.36	0.89
	4	Steel Fiber	0.64	155	149	0.44	1100	451	40.60	32.89	5.30	1.7	93.00	105.47	0.88
	5	Steel Fiber	1.14	155	149	0.98	1100	452	40.51	32.81	5.46	1.7	103.00	104.03	0.99
	6	Steel Fiber	1.13	154.5	150	0.98	1100	452	38.00	30.78	5.35	1.7	95.70	102.26	0.94
	7	Steel Fiber	1.11	153	150	0.44	1100	451	33.80	27.38	3.89	0.7	53.30	56.51	0.94
	8	**Steel Fiber**	**1.12**	**153**	**149.5**	**0.44**	**1100**	**451**	**36.90**	**29.89**	**3.72**	**0.7**	**53.10**	**55.53**	**0.96**
(Fattuhi 1990)	**9**	**Steel Fiber**	**0.65**	**152.5**	**149**	**1.00**	**1100**	**452**	**34.51**	**27.95**	**5.29**	**1.7**	**152.90**	**151.65**	**1.01**
	10	Steel Fiber	1.14	155.5	149	0.98	1100	452	37.10	30.05	5.24	1.7	102.90	100.00	1.03
	11	Steel Fiber	1.11	153	150	0.44	1100	451	35.80	29.00	3.76	0.7	56.00	55.93	1.00
	12	Steel Fiber	0.64	154	149	0.44	1100	451	38.00	30.78	3.89	0.7	92.00	84.38	1.09
	13	Steel Fiber	0.89	154.7	149	0.99	1100	452	34.00	27.54	5.04	1.7	111.70	115.83	0.96
	14	Steel Fiber	0.88	153.5	149	0.44	1100	451	36.51	29.57	4.24	0.7	68.30	70.65	0.97
	15	Steel Fiber	0.87	152.5	150	0.44	1100	451	39.00	31.59	3.92	0.7	67.20	68.74	0.98
	16	**Steel Fiber**	**0.89**	**154.5**	**149.5**	**0.98**	**1100**	**452**	**37.70**	**30.54**	**4.94**	**1.7**	**114.30**	**116.34**	**0.98**
	18	Steel Fiber	0.71	154	150.5	0.99	1100	452	32.60	26.41	4.98	1.0	119.00	132.21	0.90
	20	Steel Fiber	0.89	153	149.5	0.99	1100	452	38.60	31.27	5.43	1.8	126.00	124.18	1.01
	21	Steel Fiber	0.90	156	148	0.98	1100	452	37.00	29.97	4.73	1.5	118.00	111.57	1.06
	22	Steel Fiber	0.81	153	149	0.69	1100	454	37.00	29.97	4.73	1.5	108.50	101.45	1.07
	23	Steel Fiber	0.90	153	148.5	1.00	1100	452	33.80	27.38	5.12	2.0	126.50	117.53	1.08
(Fattuhi 1990)	24	Steel Fiber	0.65	153	150	0.69	1100	454	33.80	27.38	5.12	2.0	131.50	124.35	1.06
	27	Steel Fiber	0.65	153.5	149.5	0.99	1100	452	42.30	34.26	6.29	2.5	171.50	177.18	0.97
	28	Steel Fiber	0.48	154	150	0.68	1100	454	42.30	34.26	6.29	2.5	173.50	184.20	0.94
	29	**Steel Fiber**	**0.61**	**151.5**	**148.5**	**0.45**	**1100**	**451**	**37.30**	**30.21**	**4.42**	**1.0**	**100.00**	**95.99**	**1.04**
	30	Steel Fiber	1.00	153.9	146.2	0.70	1100	454	37.30	30.21	4.42	1.0	86.50	83.30	1.04
	31	Steel Fiber	1.09	154.5	150	1.19	1100	452	40.60	32.89	5.50	2.0	119.50	120.03	1.00

Table A.1 Continued

	32	**Steel Fiber**	**1.00**	**154**	**146.2**	**1.23**	**1100**	**452**	**40.60**	**32.89**	**5.50**	**2.0**	**132.50**	**130.07**	**1.02**
	35	Steel Fiber	1.10	155.1	148.5	1.48	1100	452	38.70	31.35	4.91	1.5	124.50	121.68	1.02
	36	Steel Fiber	0.49	154.8	148	0.44	1100	451	38.70	31.35	4.91	1.5	123.50	121.21	1.02
	37	Steel Fiber	1.10	153.8	149.1	1.49	1100	452	39.60	32.08	5.72	2.0	140.00	135.49	1.03
	38	Steel Fiber	0.89	152.2	150	0.44	1100	451	39.60	32.08	5.72	2.0	74.00	86.97	0.85
(Fattuhi 1990)	**39**	**Steel Fiber**	**0.89**	**153.5**	**150**	**1.20**	**1100**	**452**	**38.70**	**31.35**	**5.64**	**2.3**	**144.50**	**141.76**	**1.02**
	40	**Steel Fiber**	**1.02**	**155.5**	**148.8**	**1.47**	**1100**	**452**	**38.70**	**31.35**	**5.64**	**2.3**	**142.00**	**141.74**	**1.00**
	44	Steel Fiber	1.10	153.8	148.6	1.21	1100	452	35.40	28.67	4.85	1.5	109.50	107.44	1.02
	45	Steel Fiber	1.10	153	148.3	1.50	1100	452	34.80	28.19	4.37	1.0	120.00	110.19	1.09
	46	Steel Fiber	0.82	154.5	146	0.45	1100	451	34.80	28.19	4.37	1.0	74.50	76.21	0.98
	48	**Steel Fiber**	**0.86**	**155.5**	**148.2**	**0.68**	**1100**	**454**	**35.70**	**28.92**	**5.16**	**2.0**	**100.00**	**102.07**	**0.98**
	49	Steel Fiber	0.66	154.1	148.2	1.00	1100	452	37.60	30.46	5.81	2.5	164.50	164.81	1.00
	51	Steel Fiber	0.83	153.4	148.3	1.00	1100	451	38.60	31.27	5.83	2.0	130.50	137.60	0.95
	52	Steel Fiber	1.17	152.2	150	1.00	1100	451	38.60	31.27	5.83	2.0	99.00	106.75	0.93
	53	Steel Fiber	1.01	153.6	149.6	1.48	1100	451	41.10	33.29	5.68	2.0	144.50	144.51	1.00
	54	Steel Fiber	1.44	151.7	149.8	1.49	1100	451	41.10	33.29	5.68	2.0	101.50	111.43	0.91
	55	Steel Fiber	0.55	153.7	149.3	0.44	1100	451	36.90	29.89	4.06	1.0	104.00	96.86	1.07
	56	Steel Fiber	0.65	152.9	149.8	0.44	1100	451	36.90	29.89	4.06	1.0	95.50	85.92	1.11
	57	**Steel Fiber**	**0.59**	**152.2**	**150.1**	**0.69**	**1100**	**451**	**38.80**	**31.43**	**5.92**	**2.0**	**138.50**	**148.81**	**0.93**
	58	**Steel Fiber**	**0.71**	**152.8**	**148.3**	**0.69**	**1100**	**451**	**38.80**	**31.43**	**5.92**	**2.0**	**121.50**	**129.56**	**0.94**
	59	Steel Fiber	1.18	153	150	0.99	1100	451	36.20	29.32	5.37	2.0	97.50	99.83	0.98
	60	Steel Fiber	0.98	152.8	148.6	1.49	1100	451	36.20	29.32	5.37	2.0	142.00	140.16	1.01
	61	Steel Fiber	0.63	152.6	149	0.44	1100	451	36.30	29.40	4.82	1.5	98.50	98.50	1.00
	62	Steel Fiber	1.18	153	150.1	1.20	1100	451	36.30	29.40	4.82	1.5	109.50	101.82	1.08
	63	Steel Fiber	0.85	153	150	0.68	1100	451	38.20	30.94	5.94	2.5	101.80	114.13	0.89
(Fattuhi 1994)	**64**	**Steel Fiber**	**0.65**	**152.6**	**147.5**	**1.00**	**1100**	**451**	**38.20**	**30.94**	**5.94**	**2.5**	**170.00**	**169.26**	**1.00**
	75	Steel Fiber	0.60	154.3	149.9	0.44	1100	451	31.00	25.11	4.05	1.0	94.80	87.79	1.08
	76	Steel Fiber	0.79	154.5	148.8	0.44	1100	451	31.00	25.11	4.05	1.0	73.50	72.33	1.02
	77	Steel Fiber	0.90	153.1	148.3	1.00	1100	451	33.20	26.89	4.96	1.5	114.50	113.33	1.01
	78	Steel Fiber	1.11	153.1	147.7	1.50	1100	451	33.20	26.89	4.96	1.5	120.00	118.65	1.01
	79	**Steel Fiber**	**1.09**	**153.2**	**149.4**	**1.48**	**1100**	**451**	**33.80**	**27.38**	**5.26**	**2.0**	**128.00**	**125.80**	**1.02**
	80	Steel Fiber	0.90	154	148.1	1.00	1100	451	33.80	27.38	5.26	2.0	120.80	119.32	1.01
	81	Steel Fiber	1.11	153.6	147.6	1.22	1100	451	35.40	28.67	5.04	2.0	110.80	111.17	1.00
	82	**Steel Fiber**	**1.20**	**154**	**148**	**1.00**	**1100**	**451**	**35.40**	**28.67**	**5.04**	**2.0**	**98.00**	**95.32**	**1.03**
	83	Steel Fiber	1.21	150.4	147.9	1.53	1100	451	34.90	28.27	4.96	1.5	115.30	113.58	1.02
	84	Steel Fiber	1.47	152.4	147.7	1.51	1100	451	34.90	28.27	4.96	1.5	94.00	97.91	0.96
	85	Steel Fiber	0.98	154.2	148.5	0.99	1100	451	35.10	28.43	5.17	2.0	123.30	111.29	1.11
	86	Steel Fiber	1.19	153.2	149.9	1.48	1100	451	35.10	28.43	5.17	2.0	115.50	117.66	0.98
	87	**Steel Fiber**	**0.64**	**152.9**	**148.5**	**0.69**	**1100**	**451**	**36.20**	**29.32**	**6.01**	**2.5**	**139.80**	**141.24**	**0.99**
	88	**Steel Fiber**	**0.86**	**153.1**	**149.1**	**1.00**	**1100**	**451**	**36.20**	**29.32**	**6.01**	**2.5**	**138.80**	**136.41**	**1.02**
	50-0-10-100	**Steel Fiber**	**0.82**	**150**	**150**	**0.86**	**1200**	**560**	**48.15**	**39.00**	**3.10**	**0.0**	**65.91**	**87.00**	**0.76**
	50-0-10-130	Steel Fiber	1.06	150	150	0.85	1200	560	48.15	39.00	3.10	0.0	55.52	72.34	0.77
	50-0-12-100	**Steel Fiber**	**0.81**	**150**	**150**	**1.22**	**1200**	**510**	**47.53**	**38.50**	**3.10**	**0.0**	**68.06**	**103.94**	**0.65**
(Gulsan 2015)	**50-0-12-130**	**Steel Fiber**	**1.02**	**150**	**150**	**1.18**	**1200**	**510**	**47.53**	**38.50**	**3.10**	**0.0**	**57.65**	**86.68**	**0.67**
	50-1-10-100	Steel Fiber	0.83	150	150	0.70	1200	560	50.00	40.00	3.70	1.0	110.58	91.93	1.20
	50-1-10-130	Steel Fiber	1.05	150	150	0.70	1200	560	50.00	40.00	3.70	1.0	78.80	77.79	1.01
	50-1-12-100	**Steel Fiber**	**0.82**	**150**	**150**	**1.01**	**1200**	**510**	**50.00**	**38.00**	**3.60**	**1.0**	**121.78**	**107.86**	**1.13**
	50-1-12-130	Steel Fiber	1.07	150	150	1.01	1200	510	50.00	38.00	3.60	1.0	89.18	88.97	1.00

Table A.1 Continued

	50-1.5-10-100	**Steel Fiber**	**0.81**	**150**	**150**	**0.70**	**1200**	**560**	**50.00**	**42.50**	**4.50**	**1.5**	**125.13**	**108.95**	**1.15**
	50-1.5-10-130	Steel Fiber	1.04	150	150	0.70	1200	560	50.00	42.50	4.50	1.5	86.58	90.89	0.95
	50-1.5-12-100	Steel Fiber	0.81	150	150	1.01	1200	510	50.00	42.50	4.20	1.5	127.54	125.35	1.02
	50-1.5-12-130	Steel Fiber	1.04	150	150	1.01	1200	510	50.00	42.50	4.20	1.5	89.13	104.30	0.85
	30-0-10-100	Steel Fiber	0.81	150	150	0.85	1200	560	30.00	22.30	1.90	0.0	57.22	48.72	1.17
	30-0-10-130	Steel Fiber	1.06	150	150	0.85	1200	560	30.00	22.30	1.90	0.0	37.57	41.30	0.91
	30-0-12-100	Steel Fiber	0.81	150	150	1.22	1200	510	30.00	22.30	2.00	0.0	63.53	61.05	1.04
	30-0-12-130	Steel Fiber	1.04	150	150	1.21	1200	510	30.00	22.30	2.00	0.0	48.65	51.56	0.94
(Gulsan 2015)	**30-1-10-100**	**Steel Fiber**	**0.81**	**150**	**150**	**0.70**	**1200**	**560**	**30.00**	**22.30**	**2.50**	**1.0**	**71.00**	**61.47**	**1.15**
	30-1-10-130	Steel Fiber	1.05	150	150	0.70	1200	560	30.00	22.30	2.50	1.0	52.60	51.77	1.02
	30-1-12-100	Steel Fiber	0.81	150	150	1.01	1200	510	30.00	22.30	2.30	1.0	73.39	67.17	1.09
	30-1-12-130	Steel Fiber	1.02	150	150	1.01	1200	510	30.00	22.30	2.30	1.0	56.15	57.48	0.98
	30-1.5-10-100	**Steel Fiber**	**0.82**	**150**	**150**	**0.70**	**1200**	**560**	**30.00**	**25.50**	**3.10**	**1.5**	**79.66**	**75.87**	**1.05**
	30-1.5-10-130	Steel Fiber	1.06	150	150	0.70	1200	560	30.00	25.50	3.10	1.5	58.35	63.56	0.92
	30-1.5-12-100	Steel Fiber	0.79	150	150	1.01	1200	510	30.00	25.50	3.10	1.5	87.01	92.93	0.94
	30-1.5-12-130	Steel Fiber	1.05	150	150	1.01	1200	510	30.00	25.50	3.10	1.5	59.79	75.94	0.79
	S8-80	Glass Fiber	0.66	150	150	0.53	3400	550	102.66	92.79	4.79	0.0	100.95	95.61	1.06
	S8-100	**Glass Fiber**	**0.84**	**150**	**150**	**0.56**	**3400**	**550**	**102.66**	**92.79**	**4.79**	**0.0**	**72.80**	**81.92**	**0.89**
	S8-120	Glass Fiber	0.99	150	150	0.53	3400	550	102.66	92.79	4.79	0.0	64.90	70.28	0.92
	S8-80-0.2	**Glass Fiber**	**0.63**	**150**	**150**	**0.53**	**3400**	**550**	**96.15**	**83.76**	**4.99**	**0.2**	**110.50**	**99.90**	**1.11**
(Kamil 2016)	S8-100-0.2	Glass Fiber	0.80	150	150	0.54	3400	550	96.15	83.76	4.99	0.2	88.00	83.67	1.05
	S8-120-0.2	Glass Fiber	0.95	150	150	0.53	3400	550	96.15	83.76	4.99	0.2	71.80	73.15	0.98
	S8-80-0.4	**Glass Fiber**	**0.63**	**150**	**150**	**0.53**	**3400**	**550**	**98.69**	**88.26**	**5.14**	**0.4**	**114.00**	**103.41**	**1.10**
	S8-100-0.4	**Glass Fiber**	**0.80**	**150**	**150**	**0.54**	**3400**	**550**	**98.69**	**88.26**	**5.14**	**0.4**	**98.50**	**86.58**	**1.14**
	S8-120-0.4	Glass Fiber	0.96	150	150	0.54	3400	550	98.69	88.26	5.14	0.4	76.30	75.43	1.01
	S8-A80	Glass Fiber	0.66	150	150	0.55	3400	550	70.50	61.33	4.21	0.0	79.50	82.51	0.96
	S8-A100	Glass Fiber	0.83	150	150	0.55	3400	550	70.50	61.33	4.21	0.0	68.50	69.43	0.99
	S8-A120	**Glass Fiber**	**0.99**	**150**	**150**	**0.55**	**3400**	**550**	**70.50**	**61.33**	**4.21**	**0.0**	**51.85**	**60.89**	**0.85**
	S8-A80 – 0.2%	Glass Fiber	0.63	150	150	0.53	3400	550	63.71	52.60	4.78	0.2	78.90	88.36	0.89
(Abdi 2016)	S8-A100 -0.2%	Glass Fiber	0.79	150	150	0.53	3400	550	63.71	52.60	4.78	0.2	73.50	74.46	0.99
	S8-A120-0.2%	Glass Fiber	0.95	150	150	0.53	3400	550	63.71	52.60	4.78	0.2	69.20	64.86	1.07
	S8-A80-0.4%	Glass Fiber	0.63	150	150	0.53	3400	550	68.84	56.30	4.91	0.4	98.30	91.64	1.07
	S8-A100-0.4%	Glass Fiber	0.79	150	150	0.53	3400	550	68.84	56.30	4.91	0.4	77.00	77.19	1.00
	S8-A120 -0.4%	Glass Fiber	0.95	150	150	0.53	3400	550	68.84	56.30	4.91	0.4	63.50	67.21	0.94
														Mean	0.99
														St. Dev.	0.094
														CoV	0.095
														RMSE	10.475
														MAPE	7.20
														R^2	0.9259

* bold rows indicate randomly selected data used as testing set