Measurement 126 (2018) 299–308

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Shear resistance prediction of concrete beams reinforced by FRP bars using artificial neural networks

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ARTICLE INFO

Keywords:
ANN
FRP bar
Shear resistance
Concrete beam

ABSTRACT

In the past, remarkable behavior evaluations were carried out on concrete beams reinforced with FRP bars in the longitudinal direction without shear reinforcement. The aim of this study is to develop an artificial neural network (ANN) approach for predicting shear resistance of concrete beams. Proposed method considers geometric and mechanical properties of cross section and FRP bars, and shear span-depth ratio. Capability of the proposed method was compared with existing approaches in the literature using comprehensive database. The existing approaches include the American Concrete Institute design guide (ACI 440.1R-06), ISIS Canadian design manual (ISIS-M03-07), the British Institution of Structural Engineers guidelines (BISE), JSCE Design Recommendation, CNR-DT 203-06 Task Group, and Kara. The findings show that proposed method has excellent agreement with the experimental database.

1. Introduction

FRP Bars are intended for use as concrete reinforcing in areas where steel reinforcing has a limited life span due to the effects of corrosion. They are also used in situations where electrical or magnetic transparency is needed. In addition to reinforcing for new concrete construction, FRP bars are used to structurally strengthen existing masonry, concrete or wood members. Corrosion of steel reinforcement in concrete structures causes deterioration of concrete resulting in costly maintenance, repairs and shortening of the service life of structures. Government agencies throughout the world have recognized the potential benefits to society if our infrastructure can last longer and are thus funding significant amounts of research in the field of FRPs. The concept of FRP bars has been around since the 1960s, but advances in the field of polymers, advancements in production techniques and implementation of authoritative design guidelines have resulted in a rapid increase in usage of FRP bars in the last 15 years. Great number of studies has been focused on the use of FRP bars in structural members whom significant ones are summarized in the following.

In 1998, Theriault and Benmokrane investigated the influence of the FRP reinforcement ratio on flexural behavior of concrete beams. They proposed a theoretical model for predicting crack width and also model of failure [1]. In 2001, Yost et al. studied the strength of concrete beams reinforced with GFRP bars. Their investigation indicated that shear capacity is significantly overestimated when using ACI318-99 provision as a result of the large crack width, small compression block and reduced dowel action in GFRP-reinforced members [2]. Tureyen and Frosch (2002) conducted a series of shear tests on FRP-reinforced concrete beams with lack of steel stirrups. They compared their results with those calculated based on both ACI440.1R-01 and ACI318-99 provisions [3]. Concrete contribution to the shear strength of FRP-reinforced concrete members was investigated by Razaqpur et al. in 2004. They compared the results with some investigational codes and found CSA and JSCE recommendations are closer agreement with experimental data [4]. In 2006, Ashour proposed a simplified method for predicting the shear capacity of concrete beams with GFRP bars, which provided good correlation with experimental results [5]. In 2006, El-Sayed et al. reported experimental data on the shear strength of HSC beams reinforced with FRP bars. Their test results indicated that the HSC beams exhibited slightly lower relative shear strength compared to NSC beams. In addition, the ACI 440.1R-03 design method provided very conservative predictions whereas the proposed modified equation gave better results [6].

In 2006, Razaqpur and Isgor proposed an improved method for evaluating the shear strength of FRP-reinforced concrete members with without stirrups. Their method systematically accounts for the effect of parameters such as longitudinal reinforcement, moment-shear interaction, concrete strength and beam size [7]. The behavior and shear strength of concrete slender beams reinforced with fiber-reinforced polymer bars were also investigated by El-Sayed et al. (2006). Their test results indicated that the relatively low modulus of elasticity of FRP bars resulted in reduced shear strength compared to the shear strength

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https://doi.org/10.1016/j.measurement.2018.05.051
Received 13 January 2016; Received in revised form 16 April 2018; Accepted 12 May 2018
Available online 23 May 2018
0263-2241/

Table 1
Shear design formulas for FRP-reinforced concrete beam without shear reinforcement.

Author(s)/code	Year	Formula	Note
ACI440.1R [20]	2006	$V_{cf}=\frac{2}{5}\sqrt{f'_c}\,b_w c$	$c=kd,\ k=\sqrt{2\rho_f n+(\rho_f n)^2}-\rho_f n,\ n=\frac{E_f}{E_c}$
ISIS-M03 [21]	2007	$V_{cf}=0.2\lambda\phi_c\sqrt{f'_c}\,b_w d\sqrt{\frac{E_f}{E_s}}$ for $d\leqslant 300$	
		$V_{cf}=\left(\frac{260}{1000+d}\right)\lambda\phi_c\sqrt{f'_c}\,b_w d\sqrt{\frac{E_f}{E_c}}\leqslant 0.1\lambda\phi_c\sqrt{f'_c}\,b_w d\sqrt{\frac{E_f}{E_s}}$ for $d>300$	
BISE [22]	1999	$V_{cf}=0.79\left(100\rho_f\frac{E_f}{E_s}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f_{cu}}{25}\right)^{1/3}b_w d$	$f_{cu}=1.25f'_c$
JSCE [23]	1997	$V_{cf}=\beta_d\beta_p\beta_n f_{vcd}\,b_w d/\gamma_b$	$f_{vcd}=0.2(f'_c)^{1/3}\leqslant 0.72\ \mathrm{N/mm^2}$, $\beta_d=(1000/d)^{1/4}\leqslant 1.5$ $\beta_p=(100\rho_f E_f/E_s)^{1/3}\leqslant 1.5$ $\beta_n=1+M_0/M_d\leqslant 2$ for $N'_d\geqslant 0$ $\beta_n=1+2M_0/M_d\geqslant 0$ for $N'_d<0$ $\gamma_b=1.3$
CNR-DT203 [24]	2006	$V_{cf}=1.3\left(\frac{E_f}{E_s}\right)^{1/2}\tau_{rd}k_d(1.2+40\rho_f)b_w d$	$\tau_{rd}=0.25f_{ckt0.05},\ f_{ckt0.05}=0.7f_{ctm}$ $f_{ctm}=(0.3f'_c)^{2/3},\ k_d=1.6-d\geqslant 1$
CAN/CSA-S806 [25]	2002	$V_{cf1}=0.035\lambda\phi_c\left(f'_c\rho_f E_f\frac{V_f}{M_f}d\right)^{1/3}b_w d$ for $d\leqslant 300$	$0.1\lambda\phi_c\sqrt{f'_c}\,b_w d\leqslant V_{cf1}\leqslant 0.2\lambda\sqrt{f'_c}\,b_w d,\ \frac{V_f}{M_f}d\leqslant 1$
		$V_{cf2}=\left(\frac{130}{1000+d}\right)\lambda\phi_c\sqrt{f'_c}\,b_w d\geqslant 0.08\lambda\phi_c\sqrt{f'_c}\,b_w d$ for $d>300$	
Tottori and Wakui [26]	1993	$V_{cf}=0.2\left(100\rho f'_c\frac{E_f}{E_s}\right)^{1/3}\left(\frac{d}{1000}\right)^{-1/4}\left[0.75+\frac{1.4}{(a/d)}\right]b_w d$	
Michaluk et al. [27]	1998	$V_{cf}=\frac{E_f}{E_s}\left(\frac{1}{6}\sqrt{f'_c}\,bd\right)$	
Deitz et al. [28]	1999	$V_{cf}=3\frac{E_f}{E_s}\left(\frac{1}{6}\sqrt{f'_c}\,bd\right)$	
Tureyen and Frosch [29]	2003	$V_{cf}=\frac{5}{12}k\sqrt{f'_c}\,b_w d$	$k=\sqrt{2\rho_f n+(\rho_f n)^2}-\rho_f n,\ n=\frac{E_f}{E_c}$
El-Sayed et al. [6]	2006	$V_{cf}=\left(\frac{\rho_f E_f}{90\beta_1 f'_c}\right)^{1/3}\left(\frac{\sqrt{f'_c}}{6}b_w d\right)\leqslant\frac{\sqrt{f'_c}}{6}b_w d$	$\beta_1=0.85-0.05\left(\frac{f'_c-28}{7}\right)\geqslant 0.65$
Kara [11]	2011	$V_{cf}=b_w d\left(\sqrt[3]{\frac{d}{a}}f'_c\rho_f\frac{E_f}{E_s}(c_1^2/c_0)\right)^{1/3}(c_0/c_2)$	$c_0=7.696,\ c_1=7.245,\ c_2=7.718$

of the control beams reinforced with steel. Based on the obtained experimental results, they proposed modification to the ACI 440.1R design equation [8]. In 2008, Fico et al. focused on the assessment of Eurocode-based design equations for the evaluation of the shear strength of FRP RC members, as proposed by the guidelines of the Italian Research Council CNR-DT 203 and verified them through comparison with the equations given by ACI, CSA and JSCE guidelines [9]. In 2010, Bentz et al. summarized the results of 11 large shear tests of GFRP bar-reinforced beams. It was resulted that members with multiple layers of longitudinal bars appear to perform better than those with a single layer of longitudinal reinforcing bars [10].

Prediction of shear strength of FRP-reinforced concrete beams without stirrups using GEP (Gene Expression Programming) by Kara in 2011. Furthermore, a parametric study was also carried out to evaluate the ability of the proposed GEP model and current available shear design guidelines to quantitatively account for the effects of basic shear design parameters on the shear strength of FRP-reinforced concrete beams [11]. In 2013, Alam and Hussein the results of an experimental study which had been performed in order to evaluate the size effect on shear strength of FRP bar-reinforced concrete beams. The results were compared with Bažant's size effect law including different parameters, and a reasonably good trend was observed [12]. In 2014, Kim and Jang suggested a new equation for predicting the contribution of concrete to the shear strength of FRP-reinforced concrete beams without shear reinforcement. Their proposed equation more accurately predicted the results of various available experiments available in the literature than the equations of an American Concrete Institute standard, and yielded similar degrees to the equations of a Canadian Standards Association standard, despite making somewhat higher predictions [13].

In this article, available equations for determining shear strength of concrete beam with FRP bars has been evaluated by comparing the results derived from them. Then an efficient ANN-based computational technique for forecasting the shear strength of concrete beams reinforced with FRP bars is presented. Proposed method considers all important parameters affecting the shear strength.

2. Artificial neural networks

ANN is a powerful tool in solving complex problems of civil engineering. Recently, researchers have applied ANN for many structural engineering studies such as predicting compressive strength of confined concrete [14], axial strength of composite column [15], strength of recycled aggregate concrete [16], and displacement determination of RC building [17]. In many of proposed ANN-approaches, multilayer feed forward-back propagation network (MFBPN) has been applied. A typical MFBPN often has one or more hidden layers with sigmoid transfer function which followed by an output layer of linear neurons. Multiple layers of neurons with nonlinear transfer functions allow the network to learn complex nonlinear relationships between input and output vectors [18]. Neurons in hidden layer were connected to previous and next layer by network weights and biases. Application of training function, would adjust network weights matrix for each epoch. The most common backpropagation training algorithm is Levenberg–Marquardt which was used in this investigation. There are many numerical optimization techniques which have been successfully used to speed up the convergence of the backpropagation learning algorithm. However, Levenberg-Marquardt is a standard nonlinear least squares optimization algorithm, and was showed how to incorporate it into the backpropagation algorithm. This algorithm was tested on several function approximation problems, and it was compared with the conjugate gradient algorithm and with variable learning rate backpropagation. The results indicate that the Levenberg-Marquardt

DIFFERENT LEARNING ALGORITHMS

algorithm is very efficient when training networks. This is especially true when high precision is required. Moreover, in many cases the Levenberg-Marquardt algorithm converged when the conjugate gradient and variable learning rate algorithms failed to converge. In other words, the convergence rate, generalisation performance, and precision of Levenberg-Marquardt is more than other algorithms and less iterations (epochs) would be required to achieve a low error levels [19]. In general, on function approximation problems, for networks that contain up to a few hundred weights, the Levenberg-Marquardt algorithm will have the fastest convergence. This advantage is especially noticeable if very accurate training is required.

3. Shear strength equations

Several researchers and design guidelines have proposed different equations for determining shear strength of concrete beams with FRP bars. Most important equations are presented in Table 1. The first six equations are from codes and guidelines including American Concrete Institute design guide (ACI 440.1R-06), ISIS Canadian design manual (ISIS-M03-07), the British Institution of Structural Engineers guideline (BISE), JSCE Design Recommendation, CNR-DT 203-06 Task Group and CAN/CSA-S806-02. The rest of equations are reported from recent works by researchers all over the world.

NO. OF HIDDEN LAYERS

4. Proposed model based on ANN

4.1. Description of experimental database

In this study, an experimental database including 177 concrete beams reinforced with FRP bars have been collected. Descriptive statistics of the experimental tests database is presented in Table 2. The selected parameters for obtaining appropriate network which is derived from previous studies are: width of web (b), effective depth of tensile reinforcement (d), shear span-depth ratio (a/d), compressive strength of concrete (f_c'), FRP reinforcement ratio (ρ_f), modulus of elasticity of FRP (E_f), and shear resistance of beam (V).

4.2. Utilization of LM-ANN

Choosing input vectors of network to develop ANN model was derived from significant parameters on the shear resistance of RC beams based on previous researches and published literatures. The Levenberg–Marquardt (LM) method was applied for training the algorithm. Input and output vectors are divided randomly into three sets including training, validation and testing for constructing networks with LM algorithm.

DISTRIBUTION OF DATA

In this paper, 60 percent of the data were selected for training, 20 percent are used for validation, and 20 percent used for testing the network. The training set was utilized to adjusted connection weights and biases. The validation data monitored network overtraining. When overtraining occurs, the error in validation data commences to rise. An over-trained ANN-model has poor predictive performance [30]. Finally the testing data was used to measure the network performance after training process. Another crucial factor in ANN training is number of

Table 2
Descriptive statistics of the experimental tests database.

	b (mm)	d (mm)	a/d	f_c' (MPa)	ρ_f	E_f (GPa)	V (kN)
Min	114	147	2	22.7	0.18	29	12.5
Max	457	594	4.5	88.3	3.02	147.9	155.2
Mean	207.15	263.34	3.27	41.09	0.97	76.42	47.18
Standard deviation	74.47	86.81	0.7	15.45	0.63	47.44	30.93
Coefficient of variation	0.36	0.33	0.21	0.38	0.65	0.62	0.66

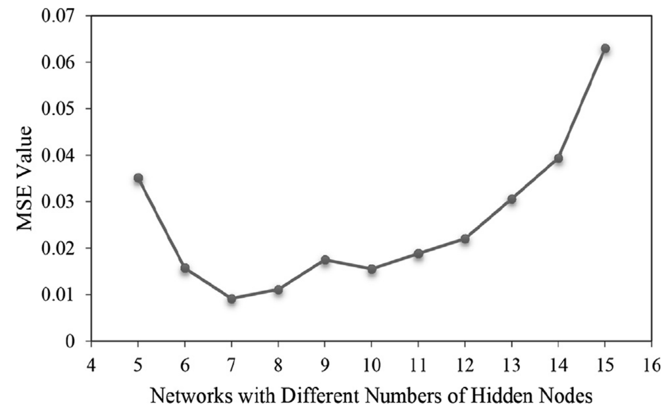

Fig. 1. MSE-values versus number of hidden layer nodes.

NO. OF NEURONS

neurons. The network with too few neurons would not sufficiently predict the data. Similarly, network with too many neurons have poor performance and may occur overtraining phenomenon. In order to develop improved performance of network, inputs and target parameters were normalized (mean = 0 and standard deviation = 1).

In this study, one hidden layer was used. Number of neurons in hidden layer varies from 5 to 15. The implemented configuration utilized in this study was called ANN6-n-1, where the first digit is the number of input nodes, n is the number of hidden neurons and third digit is the number of output nodes. The two main criteria for stopping the training of the networks were Mean Square Error (MSE-values) and Regression values (R-values). MSE-value is the average squared difference between outputs and targets. Lower values mean better performance of the network. R-value measures the correlation between outputs and targets in the networks; An R-value of 1 means a close relationship and in contrast, 0 means a random correlation. The maximum absolute MSE (Eq. (1)) and R-values (Eq. (2)) of the networks with different numbers of hidden nodes are shown in Figs. 1 and 2 respectively.

MSE
Reg.

$$MSE = \frac{1}{n}\sum_{n}^{i=1} (V_{(calc)} - V_{(test)})^2 \tag{1}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (V_{(calc)} - V_{(test)})^2}{\sum_{i=1}^{n} (V_{(calc)})^2} \tag{2}$$

After the network evaluation process, network with seven neurons (ANN6-7-1) was selected as the desirable network. The network configuration of ANN6-7-1 is illustrated in Fig. 3. The outcomes of the ANN6-7-1 are shown in Figs. 4 and 5. Weights and biases related to training set of ANN6-7-1 are given in Section 5.2.

5. Results and discussion

The experimental database was utilized to evaluate the precision of shear resistance proposed method. The comparison and discussed statistical analysis are presented in the following.

5.1. Comparison between ANN prediction and existing equations

To compare the ANN prediction and existing equations based on experimental database, the ratio V_{Test}/V_{Calc} was used (the whole results could be found in Appendix A). V_{test} and V_{calc} are the shear resistance of beam based on experimental works and prediction models, respectively. The mean error for the ANN-model for predicting the experimental results is equal to 9.72% while the mean error for the other models including ACI 440.1R-06, ISIS-M03-07, BISE, JSCE, CNR DT 203, and Kara et al. are 45.68%, 29.37%, 17.94%, 25.89%, 28.56%, 16.92% respectively. The results of ANN-model versus experimental database

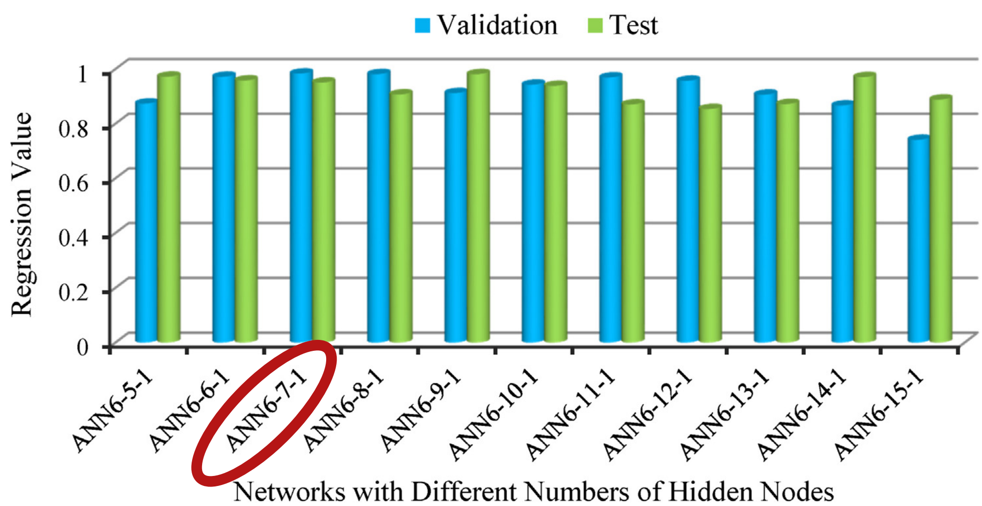

Fig. 2. R-values versus number of hidden layer nodes.

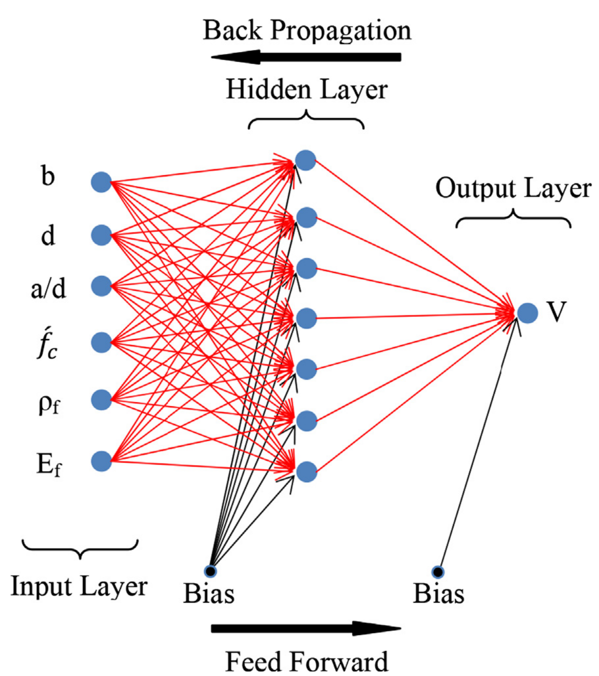

Fig. 3. Final network configuration to calculate shear resistance of FRP-reinforced beam.

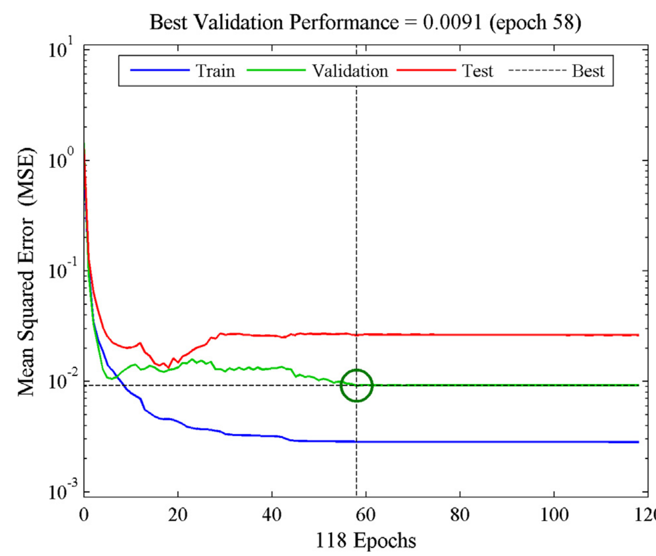

Fig. 4. Performances function of ANN6-7-1 network.

are shown in Fig. 6. Also, differential between experimental and predicted shear resistance are shown in Fig. 7.

A statistical analysis was used to compare ANN-model with experimental specimens (Table 3). The MSE value was used to determine the average squared difference between predicted and experimental values.

Also, the mean absolute percent error (MAE) was determined to give an index factor of total error in the predicted value with regard to the experimental database which has been defined by the following equation:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |(V_{(calc)} - V_{(test)})| \tag{3}$$

In addition to the standard deviation (SD), mean, and coefficient of variation (COV) of the shear resistance ratio ($\frac{V_{Test}}{v_{ANN}}$) were evaluated to determine proximity of the ANN results to the experimental data found in the database. If the mean value is close to one and the standard deviation is small, it is an indication that the ANN network has good ability to generalize the information. The coefficient of variation was applied to indicate the precision of the results obtained using the ANN model. It shows the extent of variability in relation to mean value. A smaller coefficient of variation indicates a minimized amount of scatter in the results.

5.2. Sensitivity analysis

To determine the importance factor of input parameters on shear resistance of FRP-reinforced concrete beams, the Garson's factor [44] was used. In ANN-model with one hidden layer, Garson proposed following equation:

$$Q_{ik} = \frac{\sum_{j=1}^{L}\left(\frac{w_{ij}}{\sum_{r=1}^{N} w_{rj}} v_{jk}\right)}{\sum_{i=1}^{N}\left(\sum_{j=1}^{L}\left(\frac{w_{ij}}{\sum_{r=1}^{N} w_{rj}} v_{jk}\right)\right)} \tag{4}$$

where $\sum_{r=1}^{N} w_{rj}$ is the sum of the connection weights between the N input neurons and the hidden neuron j, and v_{jk} is connection weight between the hidden neuron j and the output neuron k. Fig. 8 shows the relative influence of each input parameters.

Note that the ANN models were obtained based on a series of inputs and output data which scaled as mean and standard deviation equal zero and one, respectively.

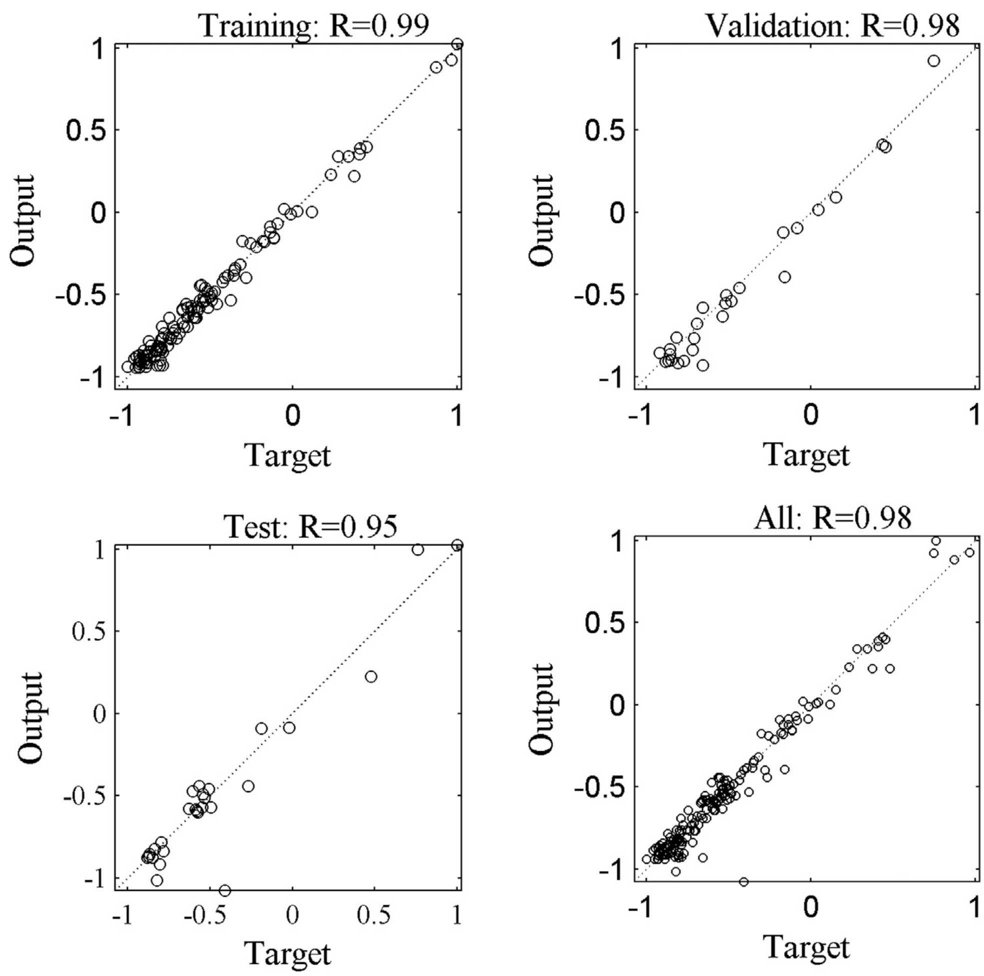

Fig. 5. Regression values of ANN6-7-1 network.

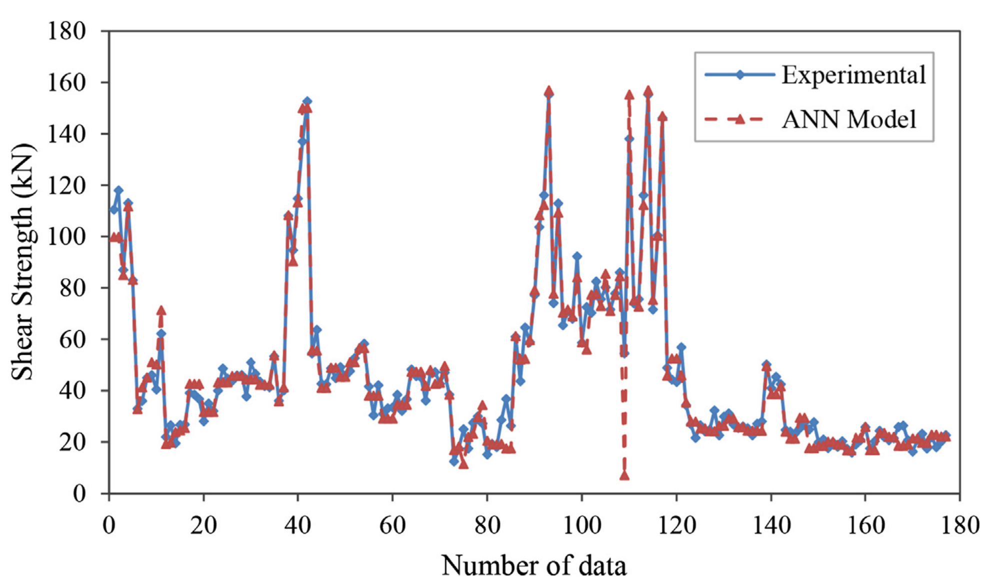

Fig. 6. Comparison of predicted shear resistance with experimental shear resistance.

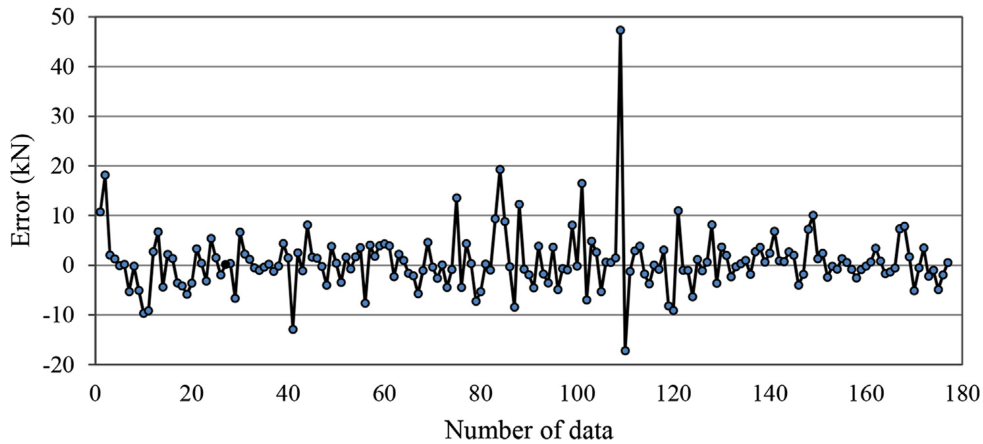

Fig. 7. The differential shear resistance values distribution for whole data.

Table 3
Statistical analysis of shear strength prediction using ANN modeling.

Authors	Number of data	V_{Test}/V_{ANN}			MAE (%)
		Mean	Std. deviation	COV (%)	
Tottori and Wakui [26]	3	1.10	0.08	7.16	9.16
Nagasaka et al. [31]	2	1.01	0.01	0.87	0.62
Nakamura and Higai [32]	2	0.94	0.09	10.11	7.66
Zhao et al. [33]	3	0.90	0.09	10.51	11.78
Mizukawa et al. [34]	1	0.87	0	0	14.74
Duranovic et al. [35]	2	1.24	0.14	11.35	18.82
Swamy and Aburawi [36]	2	0.95	0.19	20.27	15.36
Deitz et al. [28]	1	1.05	0	0	5.1
Yost et al. [2]	18	0.99	0.09	8.84	7.18
Alkhrdaji et al. [37]	3	0.99	0.02	1.83	1.46
Tureyen and Frosch [3]	5	1.00	0.05	5.06	3.43
Tariq and Newhook [38]	12	1.02	0.06	6.08	4.54
Gross et al. [39]	12	1.03	0.10	9.95	8.96
Razaqpur et al. [4]	6	0.98	0.08	8.13	5.75
Ashour [5]	6	1.15	0.53	46.62	22.85
Guadagnini et al. [40]	1	0.79	0	0	26.69
Matta et al. [41]	6	1.30	0.50	38.29	26.65
Alam [42]	22	1.01	0.10	9.73	5.85
Bentz et al. [10]	4	2.63	3.33	126.71	25.69
Alam and Hussein [43]	6	1.00	0.03	3.28	2.35
Jang and Kim [13]	60	1.03	0.16	15.46	10.6

$$[IW1] = \begin{bmatrix} 3.6885 & -3.9516 & 1.3669 & -1.0293 & -0.16445 & 3.6913 \\ 1.5915 & 1.2398 & -0.2656 & 0.90046 & 1.2499 & -0.35917 \\ -17.1911 & -16.9466 & 5.0169 & 1.912 & 1.1331 & -3.0019 \\ -40.4366 & -75.4956 & -205.316 & -26.44 & -176.057 & -98.7953 \\ 10.7821 & -18.5675 & 22.3121 & -2.2846 & 1.2723 & -8.6823 \\ -1.1187 & 1.2398 & -2.2025 & 0.75078 & 1.1621 & 3.6708 \\ 50.7267 & -11.251 & -27.8303 & -7.4025 & -22.6942 & -9.4776 \end{bmatrix}$$

$$[IW2] = [-0.34855 \quad 0.62126 \quad -0.22107 \quad -0.17827 \quad 0.16401 \quad 0.36296 \quad 014547]$$

$$[b1]^T = [-3.8161 \quad -0.86742 \quad -14.9472 \quad -110.79 \quad -0.56398 \quad 2.7432 \quad 27.5371]$$

$$[b2] = [-0.21301]$$

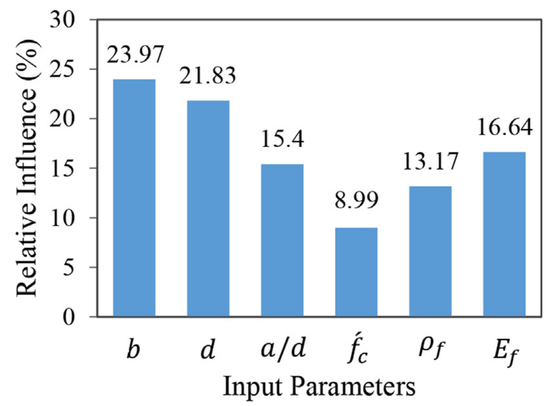

Fig. 8. The relative importance of input parameters.

$$\text{Tan-Sigmoid Transfer Function (a)} = \frac{e^a - e^{-a}}{e^a + e^{-a}}$$

$$\text{Linear Transfer Function (a)} = a$$

The results indicate that all considered input parameter have a remarkable relative importance on target values. b and d are most important parameters affecting the target and compressive strength of the concrete has the least importance in this regard. It is clear that beam with large depth results in the formation of longer diagonal shear cracks at ultimate stage of loading. As consequence of the longer crack, beam exhibit higher shear strength value. Based on the existing formulas, which presented in Table 1, average shear stress value is equal to the shear force divided by the cross-sectional area. So the increase in the width of the beam has direct effect on the shear strength of the beam.

6. Conclusions

Experimental data are sporadic and the models obtained by linear regression analysis are not able to predict the behavior with proper accuracy. This study proposed an efficient computational method for predicting the shear resistance of FRP-reinforced concrete beams based on the experimental data from literature using artificial neural networks. The Levenberg–Marquardt (LM) technique was applied for training the networks. After the network evaluation process, network with seven neurons (ANN6-7-1) was selected as the desirable one. Efficiency of the ANN model was compared with existing approaches in the literature using comprehensive database. The mean error for the ANN-model for predicting the experimental results was equal to 9.72% while the mean error for the other models including ACI 440.1R-06, ISIS-M03-07, BISE, JSCE, CNR DT 203, and Kara et al. were (approximately) equal to 46%, 29%, 18%, 26%, 29%, 17% respectively. Finally, in order to determine the importance factor of input parameters on shear resistance of FRP-reinforced concrete beams, a sensitivity analysis was performed which indicated that dimensions of beams are most important parameters affecting the shear resistance. Based on the findings of the study, proposed approach can be used for the pre-design of concrete beams reinforced with FRP bars.

Appendix A

See Table A1.

Table A1
Experimental tests on FRP-reinforced concrete beams: specimen details and results.

Authors	b (mm)	d (mm)	a/d	f'c (MPa)	ρ_f	E_f (GPa)	V_{Test}/V_{Calc}						
							ACI440 [20]	ISISM03 [21]	BISE [22]	JSCE [23]	CNR-DT203 [24]	Kara [11]	ANN
Tottori and Wakui [26]	200	325	3.2	44.6	0.7	137	2.91	1.57	2.00	2.31	1.36	1.71	1.11
	200	325	3.2	45	0.7	137	3.10	1.67	2.13	2.46	1.45	1.82	1.18
	200	325	3.2	46.9	0.9	58	2.97	1.85	1.89	2.20	1.41	1.62	1.02
Nagasaka et al. [31]	250	265	3.1	34.1	1.9	56	3.01	2.76	2.01	2.33	1.72	1.81	1.01
	250	265	3.1	22.9	1.9	56	2.48	2.47	1.69	1.95	1.64	1.51	1.00
Nakamura and Higai [32]	300	150	4	22.7	1.3	29	2.30	2.02	1.21	1.51	1.41	1.29	1.01
	300	150	4	27.8	1.8	29	2.05	1.99	1.11	1.38	1.20	1.18	0.87
Zhao et al. [33]	150	250	3	34.3	1.51	105	1.79	1.41	1.22	1.41	0.94	1.11	1.00
	150	250	3	34.3	3.02	105	1.38	1.45	0.99	1.14	0.72	0.90	0.90
	150	250	3	34.3	2.27	105	1.36	1.27	0.96	1.11	0.73	0.87	0.81
Mizukawa et al. [34]	200	260	2.7	34.7	1.3	130	1.73	1.26	1.20	1.38	0.93	1.06	0.87
Duranovic et al. [35]	150	210	3.65	27.965	1.31	45	1.69	1.39	1.01	1.17	0.98	0.98	1.14
	150	210	3.65	32.385	1.31	45	1.95	1.56	1.16	1.34	1.07	1.12	1.34
Swamy and Aburawi [36]	254	222	3.2	39	1.55	34	0.80	0.67	0.47	0.55	0.43	0.44	0.82
	305	192	4.1	38	0.36	41.4	1.92	0.81	0.92	1.07	0.69	0.92	1.09
Deitz et al. [28]	305	157.5	4.5	28.6	0.73	40	1.85	1.17	0.94	1.15	0.91	1.00	1.05
Yost et al. [2]	229	225	4.06	36.3	1.11	40.3	1.94	1.40	1.12	1.30	1.00	1.08	0.92
	229	225	4.06	36.3	1.11	40.3	1.91	1.38	1.11	1.28	0.98	1.07	0.90
	229	225	4.06	36.3	1.11	40.3	1.82	1.32	1.06	1.22	0.94	1.02	0.86
	178	225	4.06	36.3	1.42	40.3	1.60	1.30	0.96	1.11	0.86	0.92	0.89
	178	225	4.06	36.3	1.42	40.3	1.99	1.62	1.19	1.38	1.07	1.15	1.10
	178	225	4.06	36.3	1.42	40.3	1.83	1.48	1.09	1.27	0.98	1.05	1.01
	229	225	4.06	36.3	1.66	40.3	1.65	1.44	1.01	1.16	0.90	0.97	0.93
	229	225	4.06	36.3	1.66	40.3	2.01	1.74	1.22	1.41	1.10	1.18	1.13
	229	225	4.06	36.3	1.66	40.3	1.85	1.60	1.12	1.30	1.01	1.08	1.03
	279	225	4.06	36.3	1.81	40.3	1.43	1.29	0.88	1.02	0.79	0.85	0.96
	279	225	4.06	36.3	1.81	40.3	1.50	1.35	0.92	1.06	0.82	0.89	1.00
	279	225	4.06	36.3	1.81	40.3	1.50	1.36	0.92	1.07	0.83	0.89	1.01
	254	224	4.08	36.3	2.05	40.3	1.28	1.23	0.80	0.92	0.71	0.77	0.85
	254	224	4.08	36.3	2.05	40.3	1.74	1.66	1.08	1.25	0.96	1.04	1.15
	254	224	4.08	36.3	2.05	40.3	1.59	1.51	0.99	1.14	0.88	0.95	1.05
	229	224	4.08	36.3	2.27	40.3	1.57	1.57	0.99	1.14	0.87	0.95	1.03
	229	224	4.08	36.3	2.27	40.3	1.51	1.51	0.95	1.10	0.84	0.92	0.99
	229	224	4.08	36.3	2.27	40.3	1.49	1.49	0.94	1.09	0.83	0.90	0.98
Alkhrdaji et al. [37]	178	279	2.7	24.1	2.3	40	2.23	2.45	1.51	1.75	1.51	1.32	0.99
	178	287	2.6	24.1	0.77	40	2.39	1.61	1.44	1.67	1.40	1.24	1.01
	178	287	2.6	24.1	1.34	40	2.06	1.79	1.33	1.54	1.35	1.15	0.97
Tureyen and Frosch [3]	457	360	3.4	39.7	0.96	40.5	1.74	1.21	1.11	1.29	0.94	0.93	1.00
	457	360	3.4	39.9	0.96	37.6	1.58	1.10	1.00	1.15	0.85	0.84	1.05
	457	360	3.4	40.3	0.96	47.1	1.72	1.18	1.12	1.29	0.91	0.94	1.01
	457	360	3.4	42.3	1.92	40.5	1.59	1.49	1.10	1.27	0.92	0.92	0.91
	457	360	3.4	42.5	1.92	37.6	1.83	1.72	1.25	1.45	1.05	1.05	1.02
Tariq and Newhook [38]	160	346	2.8	37.3	0.72	42	2.99	1.82	1.83	2.12	1.51	1.52	0.98
	160	346	2.8	37.3	0.72	42	3.49	2.13	2.14	2.48	1.77	1.78	1.15
	160	346	3.3	43.2	1.1	42	1.85	1.33	1.19	1.37	0.97	1.00	1.04
	160	346	3.3	43.2	1.1	42	1.84	1.32	1.18	1.37	0.97	1.00	1.03
	160	325	3.5	34.1	1.54	42	2.06	1.78	1.37	1.59	1.23	1.19	1.00
	160	325	3.5	34.1	1.54	42	1.90	1.64	1.27	1.46	1.13	1.09	0.92
	130	310	3.1	37.3	0.72	120	2.30	1.30	1.56	1.80	1.09	1.34	1.08
	130	310	3.1	37.3	0.72	120	2.14	1.21	1.45	1.68	1.01	1.25	1.01
	130	310	3.7	43.2	1.1	120	1.78	1.17	1.25	1.44	0.86	1.10	0.93
	130	310	3.7	43.2	1.1	120	1.97	1.29	1.38	1.60	0.96	1.21	1.03
	130	310	3.7	34.1	1.54	120	1.94	1.55	1.42	1.64	1.07	1.25	0.99
	130	310	3.7	34.1	1.54	120	2.03	1.61	1.48	1.71	1.12	1.30	1.03
Gross et al. [39]	203	225	4.06	79.6	1.25	40.3	1.78	1.14	1.00	1.38	0.69	0.96	1.09
	203	225	4.06	79.6	1.25	40.3	1.30	0.83	0.73	1.01	0.50	0.70	0.80
	203	225	4.06	79.6	1.25	40.3	1.80	1.15	1.01	1.40	0.70	0.97	1.11
	152	225	4.06	79.6	1.66	40.3	1.55	1.13	0.90	1.25	0.62	0.87	1.06
	152	225	4.06	79.6	1.66	40.3	1.66	1.21	0.96	1.33	0.67	0.93	1.13
	152	225	4.06	79.6	1.66	40.3	1.68	1.22	0.98	1.35	0.67	0.94	1.15
	165	224	4.08	79.6	2.1	40.3	1.60	1.30	0.96	1.32	0.65	0.92	1.11

(continued on next page)

Table A1 (*continued*)

Authors	b (mm)	d (mm)	a/d	f'c (MPa)	ρ_f	E_f (GPa)	V_{Test}/V_{Calc}						
							ACI440 [20]	ISISM03 [21]	BISE [22]	JSCE [23]	CNR-DT203 [24]	Kara [11]	ANN
	165	224	4.08	79.6	2.1	40.3	1.34	1.09	0.80	1.11	0.55	0.77	0.93
	165	224	4.08	79.6	2.1	40.3	1.53	1.24	0.91	1.26	0.62	0.88	1.06
	203	224	4.08	79.6	2.56	40.3	1.50	1.33	0.92	1.27	0.61	0.88	1.02
	203	224	4.08	79.6	2.56	40.3	1.42	1.25	0.87	1.20	0.58	0.84	0.97
	203	224	4.08	79.6	2.56	40.3	1.40	1.24	0.86	1.18	0.57	0.83	0.96
Razaqpur et al. [4]	200	225	2.67	40.5	0.25	145	2.19	0.74	1.23	1.42	0.73	1.13	0.86
	200	225	2.67	49	0.5	145	1.97	0.88	1.19	1.40	0.77	1.09	0.98
	200	225	2.67	40.5	0.63	145	1.89	0.97	1.18	1.37	0.85	1.09	1.11
	200	225	2.67	40.5	0.88	145	1.48	0.88	0.96	1.11	0.72	0.88	0.99
	200	225	3.56	40.5	0.5	145	2.08	0.96	1.27	1.47	0.88	1.20	0.95
	200	225	4.2	40.5	0.5	145	1.70	0.79	1.04	1.20	0.72	1.00	1.00
Ashour [5]	150	171	3.9	28.9	0.45	38	2.06	1.04	1.00	1.20	0.88	1.03	0.74
	150	218	3.1	28.9	0.71	32	1.98	1.24	1.06	1.23	1.01	1.00	0.95
	150	268	2.5	28.9	0.86	32	2.11	1.45	1.22	1.41	1.18	1.07	2.19
	150	168	4	50.15	1.39	32	1.63	1.23	0.86	1.06	0.74	0.89	0.80
	150	218	3.1	50.15	1.06	32	2.23	1.48	1.22	1.44	1.01	1.15	1.19
	150	268	2.5	50.15	1.15	32	1.91	1.32	1.11	1.31	0.91	0.97	1.01
Guadagnini et al.[40]	150	223	3.3	50.4	1.28	45	1.69	1.21	0.99	1.18	0.78	0.93	0.79
Matta et al. [41]	114	294	3.11	59.7	0.59	40.8	1.35	0.65	0.75	0.94	0.51	0.65	0.74
	114	294	3.11	32.1	0.59	40.8	2.02	1.13	1.17	1.35	0.99	1.02	1.01
	114	294	3.11	32.1	0.59	40.8	1.90	1.06	1.09	1.27	0.92	0.96	0.95
	229	147	3.11	59.7	0.59	40.8	2.53	1.22	1.18	1.59	0.86	1.22	1.48
	229	147	3.11	32.1	0.59	40.8	3.84	2.14	1.86	2.32	1.68	1.94	2.10
	229	147	3.11	32.1	0.59	40.8	2.74	1.53	1.33	1.66	1.20	1.39	1.50
Alam [42]	250	305	2.5	39.8	0.86	46.5	2.10	1.32	1.29	1.49	1.04	1.09	1.00
	250	305	3.5	39.8	0.86	46.5	1.50	0.95	0.92	1.07	0.75	0.81	0.84
	250	310	2.5	34.5	0.42	145.2	1.87	0.84	1.23	1.42	0.85	1.03	1.23
	250	310	3.5	34.5	0.42	145.2	1.71	0.77	1.12	1.29	0.77	0.98	0.99
	250	440	2.5	44.7	0.9	46.7	1.74	1.20	1.17	1.35	0.93	0.90	0.98
	300	584	2.5	37.1	0.91	46.2	1.54	1.23	1.13	1.30	1.02	0.81	0.96
	250	442	2.5	74.2	1.25	48.2	1.93	1.38	1.31	1.77	0.90	1.01	1.03
	300	578	2.5	74.2	1.37	48.2	1.57	1.28	1.16	1.57	0.85	0.84	0.99
	250	460	2.5	42.4	0.45	144.4	1.33	0.65	0.96	1.11	0.64	0.73	0.95
	300	594	2.5	37	0.43	146.5	1.38	0.75	1.06	1.23	0.79	0.76	1.03
	250	296	2.5	39.8	1.43	46.3	1.84	1.46	1.19	1.38	1.00	1.02	0.93
	250	296	2.5	42.4	1.43	46.3	1.96	1.53	1.27	1.46	1.04	1.08	0.99
	250	455	2.5	37.1	0.35	46.5	2.43	1.14	1.47	1.70	1.06	1.12	0.99
	250	434	2.5	37.1	1.47	46.3	1.78	1.60	1.28	1.48	1.12	0.99	1.10
	250	310	2.5	42.4	0.18	144.4	2.38	0.69	1.38	1.60	0.72	1.16	1.00
	250	310	2.5	34.5	0.67	143.3	1.72	0.95	1.18	1.37	0.89	1.00	1.29
	250	460	2.5	42.4	0.22	145.5	1.74	0.62	1.15	1.33	0.65	0.88	0.91
	250	439	2.5	42.4	0.65	144.6	1.32	0.75	0.98	1.13	0.69	0.75	1.06
	250	291	2.5	65.3	0.89	46.2	2.35	1.34	1.39	1.80	0.96	1.19	1.04
	250	291	2.5	88.3	0.89	46.2	2.30	1.22	1.33	1.91	0.83	1.14	0.94
	250	310	2.5	65.3	0.42	145.6	1.74	0.68	1.10	1.42	0.61	0.92	1.01
	250	310	2.5	88.3	0.42	145.6	1.74	0.63	1.08	1.54	0.55	0.91	1.01
Bentz et al. [10]	450	438	3.48	35	0.55	37	1.62	0.95	1.00	1.16	0.84	0.80	1.02
	450	194	3.93	35	0.66	37	2.13	1.23	1.10	1.28	0.97	1.10	7.62
	450	405	3.77	35	2.36	37	1.45	1.61	1.05	1.22	0.94	0.87	0.89
	450	188	4.05	35	2.54	37	1.62	1.72	0.98	1.15	0.89	0.99	0.98
Alam and Hussein [43]	250	291	2.5	65.3	0.87	46.3	2.37	1.34	1.40	1.81	0.96	1.20	1.04
	250	442	2.5	74.2	1.25	48.2	1.93	1.38	1.31	1.77	0.90	1.01	1.03
	300	578	2.5	74.2	1.37	48.2	1.57	1.28	1.16	1.57	0.85	0.84	0.99
	250	310	2.5	65.3	0.42	136	1.80	0.70	1.12	1.45	0.61	0.95	0.95
	250	449	2.5	74.2	0.69	144	1.31	0.68	0.95	1.28	0.57	0.73	1.00
	300	594	2.5	74.2	0.65	144	1.23	0.69	0.95	1.29	0.60	0.68	0.99
Kim and Jang [13]	200	215.5	2	30	0.33	146.2	2.94	1.21	1.72	2.00	1.21	1.55	1.07
	150	215.5	2	30	0.44	146.2	3.13	1.46	1.89	2.19	1.42	1.70	0.84
	150	215.5	2	30	0.44	146.2	3.06	1.43	1.86	2.15	1.39	1.67	0.83
	150	213.5	2	30	0.79	147.9	3.13	1.89	2.01	2.32	1.67	1.81	1.24
	200	215.5	2.5	30	0.33	146.2	2.07	0.85	1.21	1.40	0.85	1.12	0.97
	150	215.5	2.5	30	0.44	146.2	1.90	0.89	1.15	1.33	0.86	1.06	0.96
	150	215.5	2.5	30	0.44	146.2	1.52	0.71	0.92	1.07	0.69	0.85	0.77
	150	213.5	2.5	30	0.79	147.9	1.46	0.88	0.94	1.08	0.78	0.86	1.05
	150	213.5	2.5	30	0.79	147.9	1.33	0.80	0.85	0.99	0.71	0.79	0.96
	200	215.5	3.5	30	0.33	146.2	1.49	0.61	0.87	1.01	0.62	0.84	1.03
	200	215.5	3.5	30	0.33	146.2	1.94	0.80	1.14	1.32	0.80	1.09	1.34
	150	215.5	3.5	30	0.44	146.2	1.59	0.75	0.97	1.12	0.72	0.92	0.86
	150	215.5	3.5	30	0.44	146.2	2.11	0.99	1.28	1.48	0.96	1.22	1.14
	150	213.5	3.5	30	0.79	147.9	1.71	1.03	1.10	1.27	0.91	1.05	1.07
	150	213.5	3.5	30	0.79	147.9	1.47	0.89	0.95	1.09	0.79	0.91	0.92
	200	215.5	4.5	30	0.33	146.2	1.53	0.63	0.90	1.04	0.63	0.89	0.99
	200	215.5	4.5	30	0.33	146.2	1.57	0.65	0.92	1.07	0.65	0.91	1.01

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Table A1 (*continued*)

Authors	b (mm)	d (mm)	a/d	f'c (MPa)	ρ_f	E_f (GPa)	V_{Test}/V_{Calc}						
							ACI440 [20]	ISISM03 [21]	BISE [22]	JSCE [23]	CNR-DT203 [24]	Kara [11]	ANN
	150	215.5	4.5	30	0.44	146.2	1.79	0.84	1.09	1.26	0.81	1.07	1.04
	150	215.5	4.5	30	0.44	146.2	1.59	0.75	0.97	1.12	0.72	0.95	0.92
	150	213.5	4.5	30	0.79	147.9	1.49	0.90	0.96	1.11	0.79	0.94	1.11
	150	213.5	4.5	30	0.79	147.9	1.54	0.93	0.99	1.14	0.82	0.98	1.15
	200	215.5	2	30	0.33	48.2	5.05	2.17	2.56	2.97	1.95	2.31	1.01
	150	215.5	2	30	0.44	48.2	4.80	2.36	2.54	2.94	2.06	2.28	1.06
	150	215.5	2	30	0.44	48.2	5.32	2.61	2.81	3.25	2.28	2.53	1.18
	150	213.5	2	30	0.79	49.1	3.80	2.45	2.17	2.51	1.93	1.95	1.02
	200	215.5	2.5	30	0.33	48.2	2.48	1.07	1.26	1.46	0.96	1.16	1.03
	150	215.5	2.5	30	0.44	48.2	2.81	1.38	1.48	1.72	1.20	1.37	1.13
	150	215.5	2.5	30	0.44	48.2	2.73	1.34	1.44	1.67	1.17	1.33	1.09
	150	213.5	2.5	30	0.79	49.1	2.27	1.46	1.29	1.50	1.16	1.20	0.86
	150	213.5	2.5	30	0.79	49.1	2.47	1.59	1.41	1.63	1.26	1.30	0.94
	200	215.5	3.5	30	0.33	48.2	2.50	1.07	1.27	1.47	0.97	1.22	1.41
	200	215.5	3.5	30	0.33	48.2	2.79	1.20	1.41	1.64	1.08	1.35	1.57
	150	215.5	3.5	30	0.44	48.2	2.33	1.14	1.23	1.42	1.00	1.18	1.07
	150	215.5	3.5	30	0.44	48.2	2.46	1.21	1.30	1.50	1.05	1.24	1.13
	150	213.5	3.5	30	0.79	49.1	1.58	1.02	0.90	1.04	0.81	0.87	0.88
	150	213.5	3.5	30	0.79	49.1	1.78	1.14	1.01	1.17	0.91	0.97	0.99
	200	215.5	4.5	30	0.33	48.2	1.83	0.79	0.93	1.08	0.71	0.92	0.96
	200	215.5	4.5	30	0.33	48.2	2.04	0.88	1.04	1.20	0.79	1.02	1.07
	150	215.5	4.5	30	0.44	48.2	2.03	1.00	1.07	1.24	0.87	1.05	1.03
	150	215.5	4.5	30	0.44	48.2	1.86	0.91	0.98	1.14	0.80	0.97	0.95
	150	213.5	4.5	30	0.79	49.1	1.71	1.10	0.97	1.13	0.87	0.96	0.88
	150	213.5	4.5	30	0.79	49.1	1.86	1.20	1.06	1.23	0.95	1.05	0.96
	200	215.5	3	33.6	0.33	146.2	1.50	0.60	0.88	1.01	0.59	0.82	0.99
	150	215.5	3	33.6	0.44	146.2	1.20	0.55	0.72	0.83	0.52	0.68	1.04
	150	215.5	3	33.6	0.44	146.2	1.39	0.63	0.84	0.97	0.60	0.79	1.20
	200	215.5	3	40.3	0.33	146.2	1.35	0.52	0.78	0.90	0.50	0.73	1.03
	200	215.5	3	40.3	0.33	146.2	1.22	0.47	0.70	0.81	0.45	0.66	0.93
	150	215.5	3	40.3	0.44	146.2	1.35	0.59	0.80	0.93	0.54	0.75	0.94
	150	215.5	3	40.3	0.44	146.2	1.40	0.61	0.83	0.96	0.57	0.78	0.97
	150	213.5	3	40.3	0.44	147.9	1.69	0.74	1.01	1.16	0.69	0.95	1.40
	150	213.5	3	40.3	0.44	147.9	1.72	0.76	1.03	1.19	0.70	0.97	1.42
	200	215.5	3	33.6	0.33	41	2.18	0.91	1.07	1.24	0.81	1.01	1.09
	150	215.5	3	33.6	0.44	41	2.00	0.96	1.02	1.19	0.82	0.96	0.76
	150	215.5	3	33.6	0.44	41	2.56	1.23	1.31	1.52	1.05	1.24	0.97
	200	215.5	3	40.3	0.33	41	2.33	0.94	1.13	1.31	0.80	1.07	1.18
	200	215.5	3	40.3	0.33	41	1.76	0.71	0.85	0.99	0.61	0.80	0.89
	150	215.5	3	40.3	0.44	41	2.56	1.18	1.30	1.50	0.98	1.22	0.96
	150	215.5	3	40.3	0.44	41	2.10	0.97	1.07	1.23	0.80	1.00	0.79
	150	213.5	3	40.3	0.44	40	2.41	1.11	1.21	1.40	0.92	1.15	0.91
	150	213.5	3	40.3	0.44	40	2.71	1.25	1.36	1.58	1.04	1.29	1.02

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