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Fuzzy-Based Approach to Predict the Performance of Shear Connectors in Composite Structures

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ABSTRACT

Shear connectors in steel-concrete composite frames are essential elements to transfer the shear between steel and concrete. Several parameters must be considered in predicting the strength of these connectors. This research aims to estimate the performed rib shear strength of connectors in composite frames. To this end, four variables including the compressive strength of concrete, area of dowels, the transverse area in rib holes, and also connector height, are applied to a neuro-fuzzy model and the shear strength is selected as the target of the system. The model is trained using an experimental database and validated with an acceptable error. The estimated shear strength of connectors were satisfactorily similar to the measurements reported by the laboratories.

1. Introduction

Due to the simultaneous use of concrete and steel elements in composite structures and frames, the proper transfer of force between these elements is critical. Accordingly, various theoretical and experimental studies have been performed to investigate the performance and to identify the behavior of transducer members, such as shear connectors [1–3]. One of the topics of interest in

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this field is the shear strength of transducer members. The member must be selected in such a way that it has the capacity to transmit the forces fully. Given the behavioral complexity of both types of elements (steel and concrete), the use of newer computational methods that are more robust in estimating the shear strength could be conducive as the traditional approach of measurement may be time-consuming [4].

Fig. 1 shows a sample of shear connector [5]. In this figure, b, h, D, A_b, A_F, A_D, $A_{tr,r}$, b_f, L_c, h_{sc}, t_{sc} correspond to thickness and length of slab in front of the shear connector, area of connector, contact area, concrete area, area of the transverse reinforcement in holes, width of steel profile, contact length of steel and concrete, height and thickness of connectors, respectively.

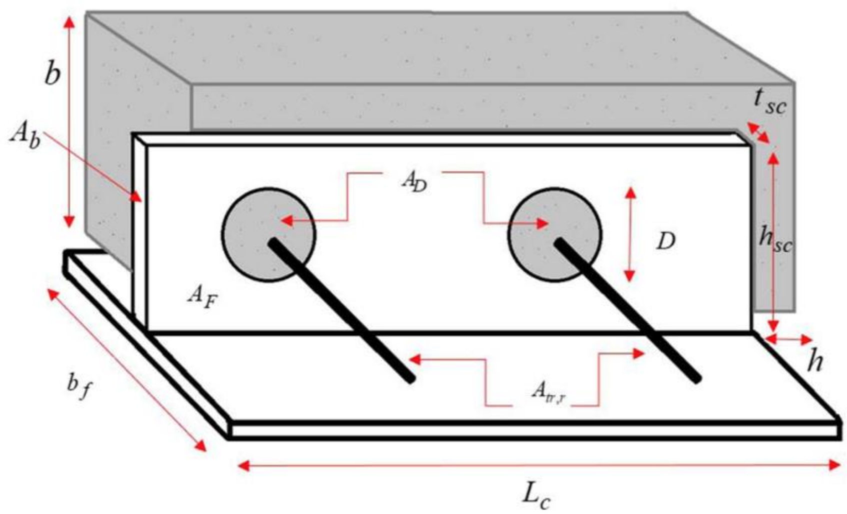

Fig. 1. Shear connector [5].

Soft computing involves a series of computational methods derived from nature whose various structures have been introduced by researchers, and its branches are still expanding. These methods are used in many studies because of their high flexibility and accuracy in engineering. Also, combining them can improve their performance. Many studies have been carried out on the ability of soft computing methods in the field of civil engineering [6–11]. In this paper, a hybrid approach is used to estimate the shear strength of connectors in composite frames. In the first section, the selected soft computing method to execute this research is introduced. Then, the laboratory database provided in this paper for training and testing the system is presented. The details of the proposed model are described below, and the results are discussed in the last section.

2. Fuzzy-based methodology

Fuzzy systems are approaches in which the inference of the human brain is inspired. Although these methods have been used successfully in many respects, creating a fuzzy model requires basic knowledge of the rules governing the problem. Since the shear strength discussed in this paper involves the consideration of the behavioral complexity of two types of materials (concrete and steel) simultaneously, adjusting the system rules is not easily possible. Accordingly, the use of the learning capability of neural networks, in combination with the fuzzy system, presents a powerful high-performance model introduced by Jang [12], namely ANFIS. This method has also been used in recent years in various civil engineering issues [13–18].

An ANFIS system uses a set of data and determines the unknown parameters of the fuzzy model using neural network learning algorithms. In these systems, the unknowns include the membership function coefficients as well as the coefficients of the linear output functions. In this paper, the ability of the above neuro-fuzzy system is evaluated to estimate the shear strength of the connectors in composite frames.

3. Database

The considered database in this article is a collection of 90 datasets extracted from experimental results [19–26]. Out of all these data points (Table 1), 72 were used to train the model, and the remaining 18 data points were used to test the model. Before applying the above data to the ANFIS structure, the range of each variable was mapped to values 0.1 to 0.9 to increase the accuracy of the model. Accordingly, the model output will also have a normalized value that needs to be converted to its actual range at the end. In the prediction model in this paper, four inputs and one output variable are used. The definitions of these variables are listed in Table 2. Fig. 2 illustrates the scattering of each input variable against the output. As shown in the figure, the variables considered for the system cover a wide range of values.

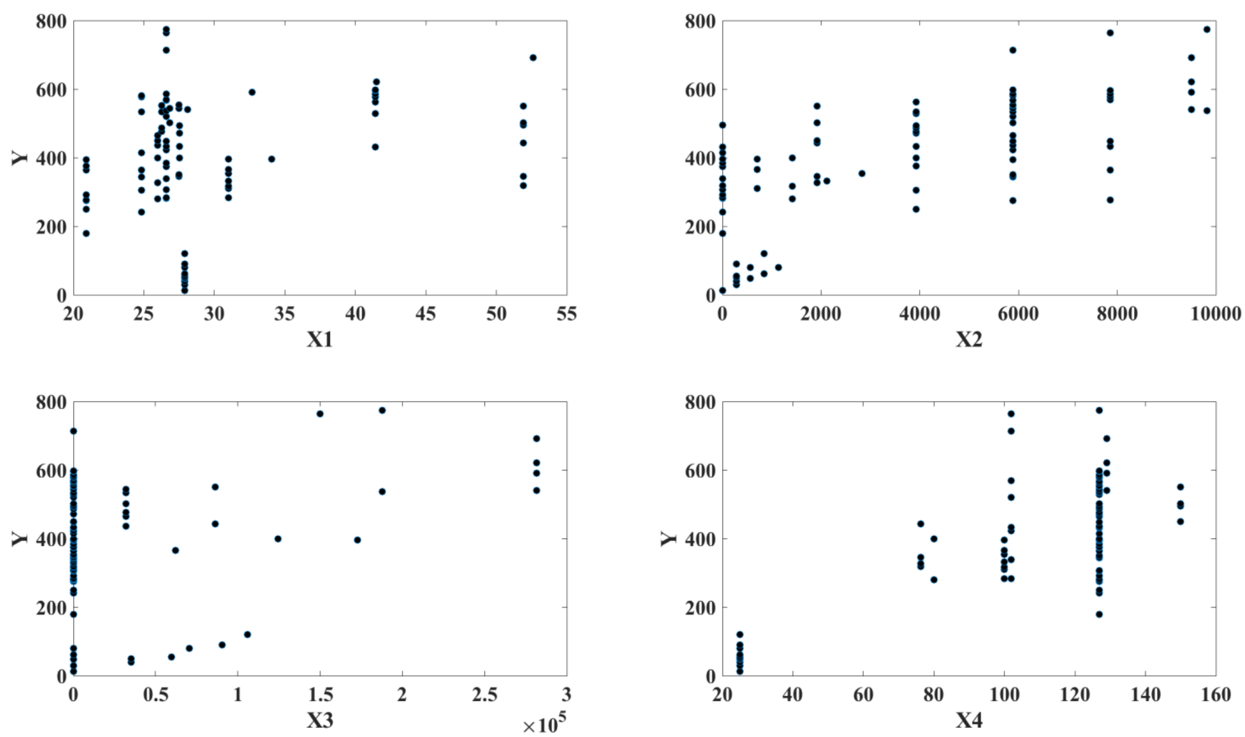

Fig. 2. Distribution of datasets.

Table 1
Database of the shear connectors.

X1	X2	X3	X4	Y	X1	X2	X3	X4	Y
27.9	850.59	0	25	61.2	26.28	5890.49	31918.58	127	533.1
26.6	5890.49	0	102	713.4	27.9	567.06	0	25	47.38
24.82	3926.99	0	127	304.9	27.9	283.53	59729.53	25	55.29
28.1	9503.32	281486.7	129	539.53	20.91	3926.99	0	127	249.1
26.28	3926.99	31918.58	127	477.3	51.9	0	0	76.2	319.28
20.91	3926.99	0	127	375.2	26.6	5890.49	0	102	520.6
32.7	9503.32	281486.7	129	590.65	26.6	7853.98	0	102	433.4
27.49	5890.49	0	127	554.2	26.6	0	0	102	338.8
27.52	3926.99	0	127	432.5	27.9	283.53	35342.92	25	49.25
41.43	7853.98	0	127	577	26.6	5890.49	0	127	448.4
27.49	5890.49	0	127	345.9	26	1924.23	0	76.2	326.83
25.97	5890.49	31918.58	127	464.4	31	706.86	0	100	309.44
26	1924.23	0	150	450.2	31	706.86	172787.6	100	395.68
27.9	283.53	0	25	29.48	24.82	5890.49	0	127	580.9
41.5	9503.32	281486.7	129	620.55	41.43	5890.49	0	127	584.9
51.9	1924.23	0	76.2	344.85	24.82	5890.49	0	127	343.8
41.43	3926.99	0	127	563	31	706.86	62203.53	100	365.93
51.9	1924.23	86393.8	76.2	443.03	26.85	5890.49	31918.58	127	544.1
20.91	0	0	127	292	27.9	283.53	90477.87	25	89.16
27.9	0	0	25	13.14	27.49	5890.49	0	127	543.2
24.82	7853.98	0	127	577.9	31	1413.72	0	100	317.52
26.28	5890.49	0	127	552	24.82	0	0	127	413.5
26.6	0	0	127	373.7	27.9	850.59	106028.75	25	119.85
27.9	567.06	70685.83	25	79.39	26.6	0	0	102	282.5
26.6	5890.49	0	127	568	31	2120.58	0	100	331.35
26.6	0	0	127	305.9	26.6	7853.98	150168.13	102	764.2
51.9	1924.23	86393.8	150	549.7	24.82	7853.98	0	127	364.7
27.9	283.53	35342.92	25	39.98	26.28	3926.99	0	127	485.8
51.9	0	0	150	495	41.43	0	0	127	431
31	2827.43	0	100	354.03	34.05	0	0	127	396.1
27.49	5890.49	0	127	349.8	26.6	0	0	127	384.6
20.91	0	0	127	179.4	25.97	5890.49	31918.58	127	435.5
26.6	7853.98	0	102	569.4	26.6	0	0	127	282
26.85	5890.49	31918.58	127	502.2	51.9	1924.23	0	150	501.48
27.9	1134.11	0	25	79.24	24.82	0	0	127	240.7
26.6	9817.48	187710.16	127	774.2	26	1413.72	0	80	280.05
26.6	9817.48	187710.16	127	536.6	52.6	9503.32	281486.7	129	692.2
26.6	5890.49	0	102	422	41.43	7853.98	0	127	595.9
27.52	3926.99	0	127	493.2	26.6	7853.98	0	127	585.4
24.82	3926.99	0	127	533.1	27.52	3926.99	0	127	398.6
41.43	5890.49	0	127	597.8	20.91	5890.49	0	127	393.6
27.52	3926.99	0	127	471.8	20.91	5890.49	0	127	274
31	0	0	100	283.51	26	1413.72	124407.07	80	398.86
26.6	7853.98	0	127	447.4	41.43	3926.99	0	127	528.1
20.91	7853.98	0	127	363.7	20.91	7853.98	0	127	276.5

Table 2
Definition of the parameters.

Variable	Description	Unit	Minimum	Maximum
X1	Compressive Strength of Concrete	MPa	20.91	52.6
X2	Total area of concrete dowels	mm^2	0	9817.48
X3	Area of transverse reinforcement bars in rib holes (mm^2) multiply by yield stress of reinforcement bars in rib holes (MPa)	N	0	281486.7
X4	Connector height	mm^2	25	150
Y	Shear strength	kN	13.14	774.2

4. The proposed model

The general structure of the predictive model in this article is shown in Fig. 3. The determined model for estimating the shear strength has four Gaussian membership functions (M1, …, M4) for each of the four input variables (Fig. 4). Each Gaussian membership function has two unknown parameters, including the variance (σ) and the mean (m), as presented in Table 3. The membership functions also have algorithms used to train the ANFIS is c-means, which is a fuzzy clustering approach. Such systems need fewer clusters to present the best answers in comparison with the sub-clustering approach. Also, fuzzy c-means is more accurate and faster than the grid partitioning algorithm.

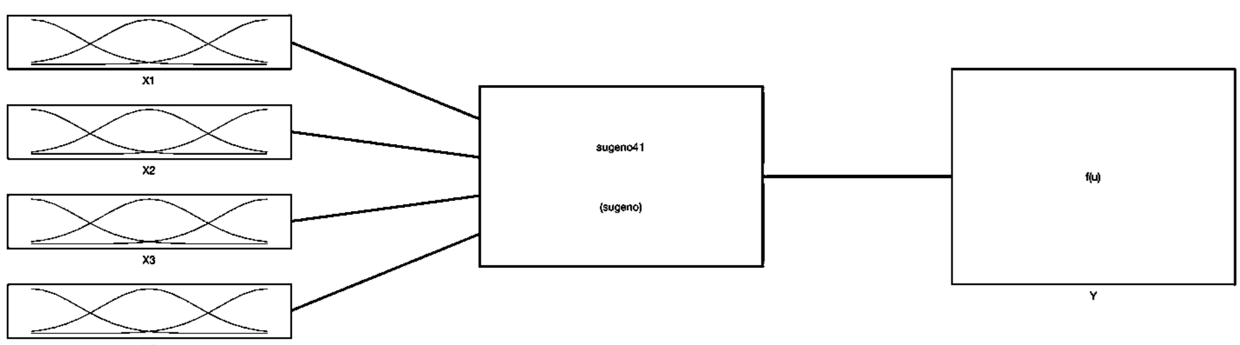

Fig. 3. The general structure of the proposed ANFIS.

The proposed ANFIS model in this article has four linear output functions (f1, …, f4) and in each function, there are five unknown parameters (unknown coefficient of input variable 1 to 4 including C_{X1} to C_{X4} as well as constant of the equation, C_0) whose values can be seen in Table 4.

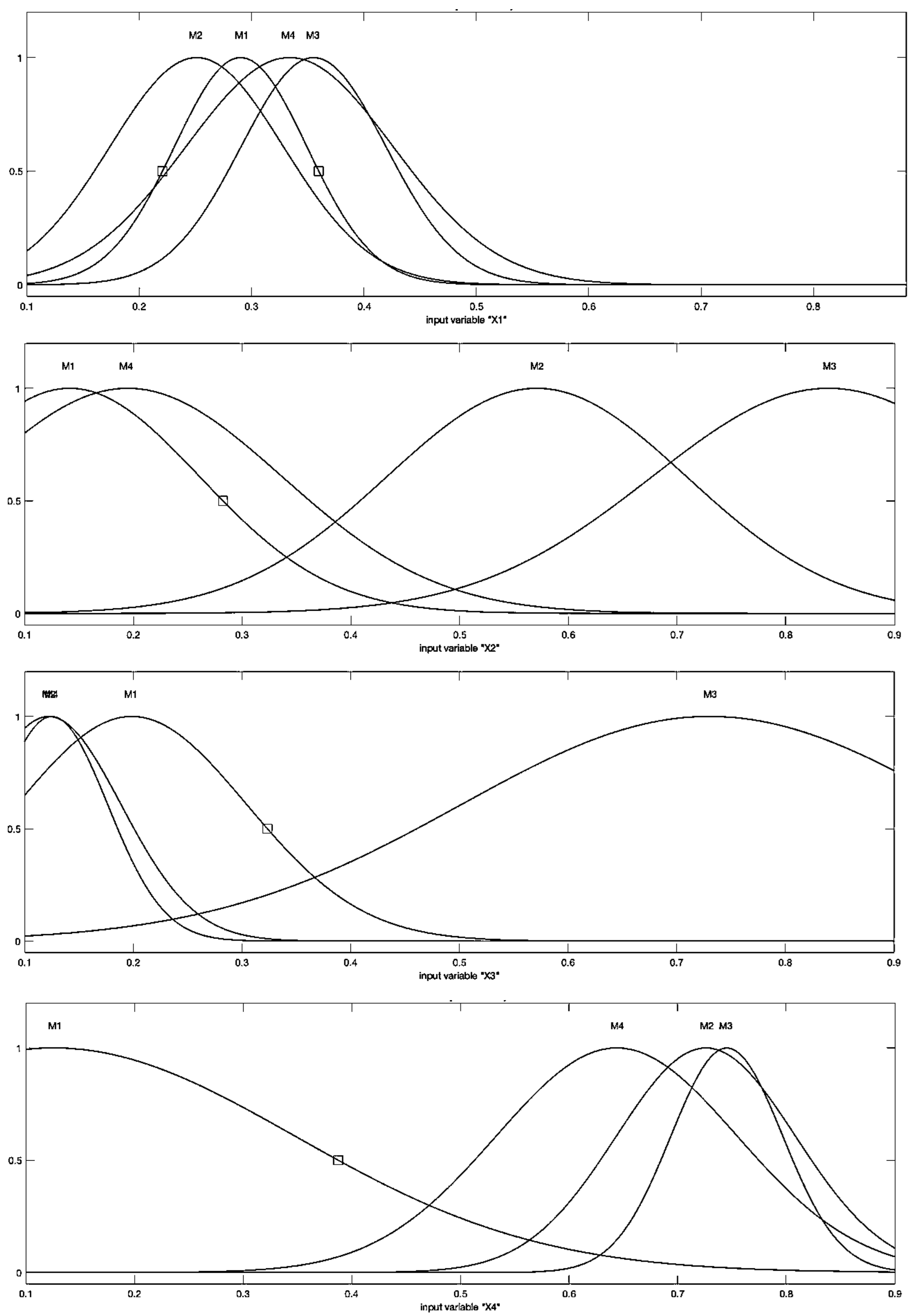

Fig. 4. Membership function of the inputs.

Table 3
Variances and means of the membership functions.

Membership Function	X1		X2		X3		X4	
	σ	m	σ	m	σ	m	σ	m
M1	0.05907	0.2902	0.1198	0.1413	0.106	0.1986	0.2224	0.1256
M2	0.07738	0.2511	0.138	0.5709	0.06686	0.1219	0.08253	0.726
M3	0.06462	0.3551	0.1625	0.8393	0.2288	0.7302	0.05158	0.7453
M4	0.0924	0.3337	0.1422	0.1948	0.05152	0.1249	0.1111	0.6439

Table 4
Coefficients of the linear output functions.

Output Function	C_{X1}	C_{X2}	C_{X3}	C_{X4}	C_0
f1	-1.151	0.5005	0.1841	0.8047	0.2797
f2	0.8922	0.1049	0.5142	-0.3529	0.5183
f3	0.2418	3.105	0.02523	-3.833	0.7915
f4	0.1954	0.414	0.1134	0.3904	0.03124

5. Results and discussion

The best ANFIS structure was determined using the laboratory data sets. The error values based on the results for these data are shown in Fig. 5 and 6. In these figures, the ratio of the experimental value to the value predicted by ANFIS for each data is presented. Accordingly, the close values to 1 (Y=1) represent a lower error in the corresponding data. As shown in the figure, the model performed well in estimating the shear strength of the considered connectors. In Fig. 7 and 8, the distribution of the predicted data against the target values is illustrated. The close distance between the dots in the figure from the line Y=X represents that the model performed well in both training and testing stages.

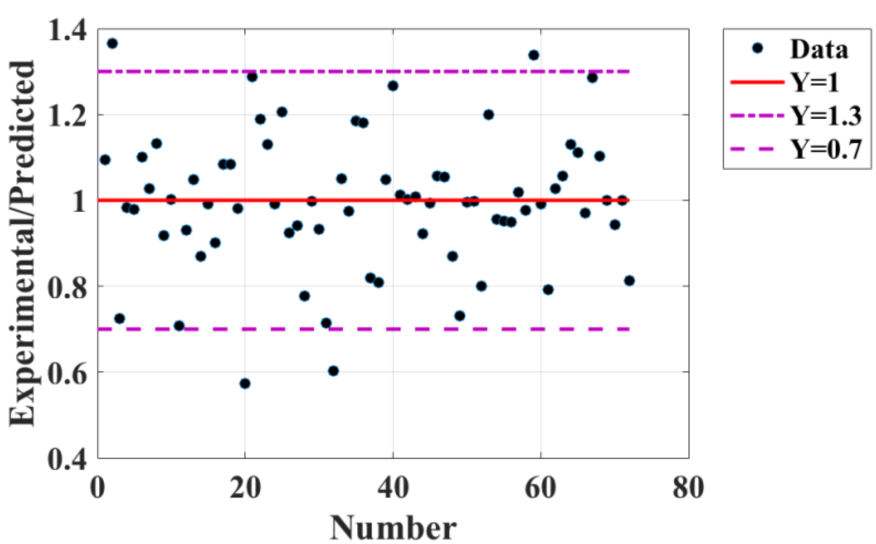

Fig. 5. Errors of the proposed model for the train data.

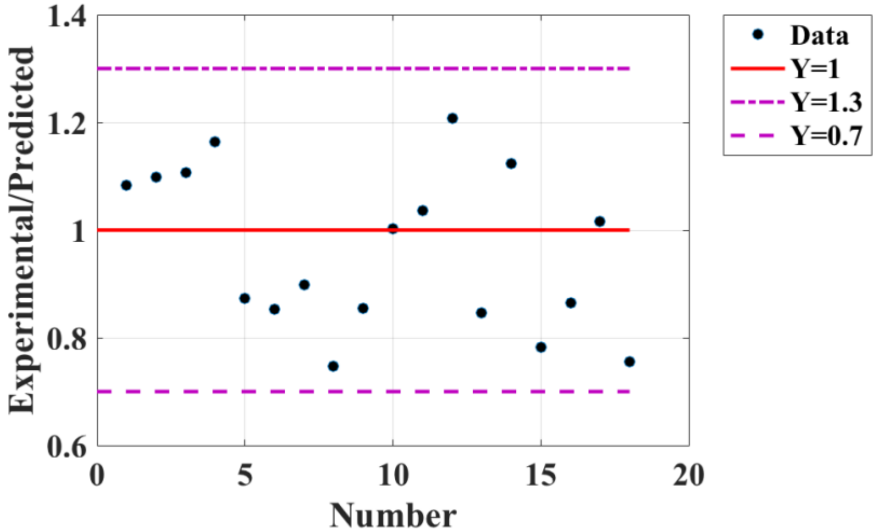

Fig. 6. Errors of the proposed model for the test data.

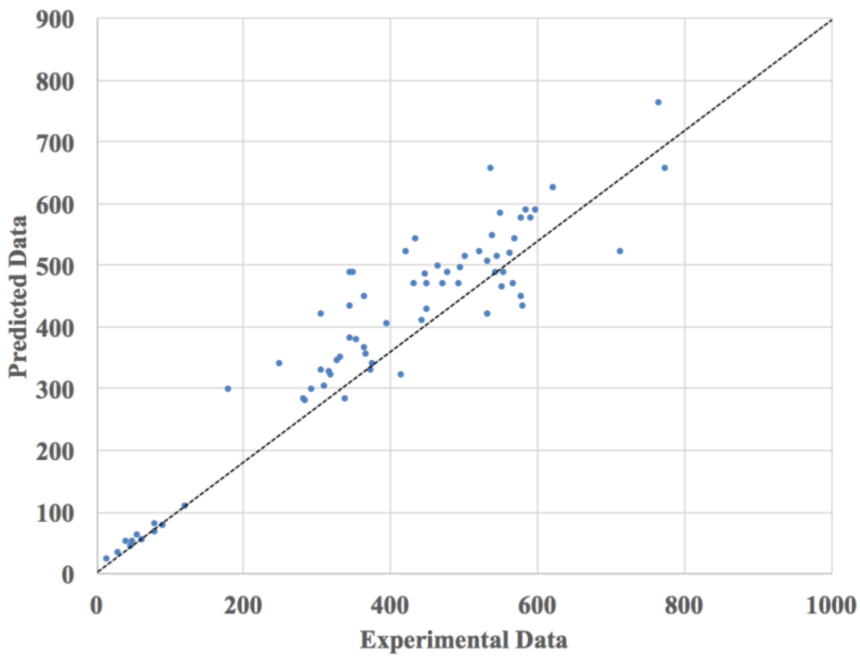

Fig. 7. Scatters for the train data.

In order to more effectively investigate the ANFIS model, the values of *MAE* (mean absolute error), *RMSE* (root mean square error), as well as the correlation coefficient (R^2) were calculated for the datasets. Accordingly, the correlation values are higher than 88%, which means a significant overlap between the laboratory and the predicted values. Also, the RMSE values in the training and testing phases are 62.87 and 58.303, which are acceptable for the range of output parameters (see Table 2). *MAE* with a value of 44.148 for the whole dataset is also desirable. In Fig. 9 and 10, the error histograms are depicted. In this figure, *StDev* and *N* mean the standard deviation and the number of data, respectively. The Mean parameter also shows the mean of the errors.

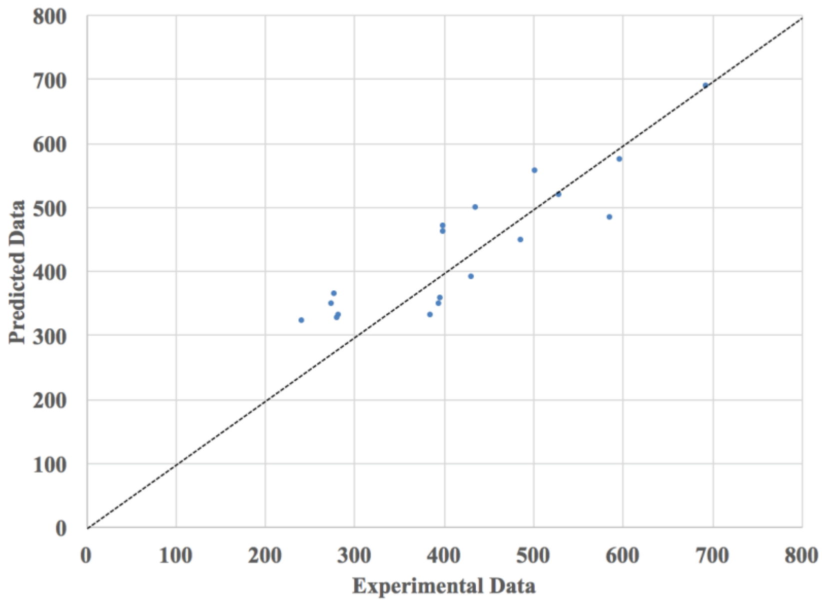

Fig. 8. Scatters of for the test data.

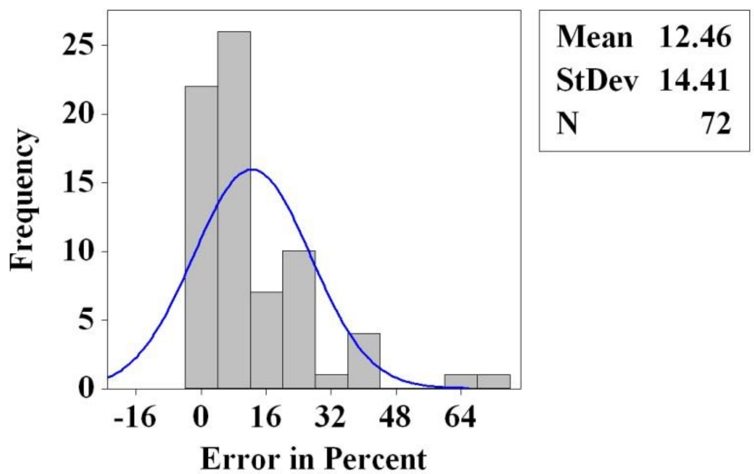

Fig. 9. Error histogram for the train data.

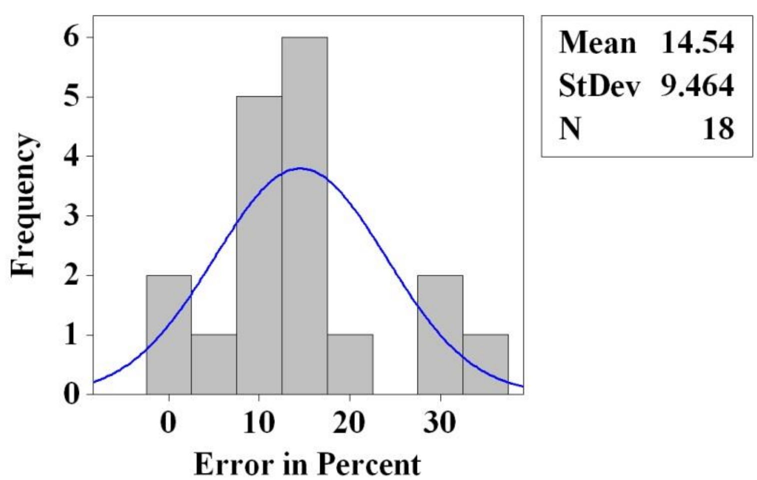

Fig. 10. Error histogram for the test data.

Table 5
Results.

	RMSE	**MAE**	**R^2**
Train Data	62.870	42.123	0.939
Test Data	58.303	52.246	0.889
All Data	61.983	44.148	0.934

6. Conclusion

This article presented a neuro-fuzzy model based on a fuzzy c-means algorithm to predict the shear strength of the shear connectors in composite frames. For this purpose, four input variables that are related to the properties of the elements of concrete, steel, and connectors are considered and used to train the model using a collection of 90 datasets. This database is divided into two sections including 72 and 18 datasets for the train and tests the presented system. After the learning phase of the neuro-fuzzy model, the best architecture for the ANFIS in this article, which has four Gaussian membership functions and also, four linear output functions, is determined. This model presents its output with suitable errors in both training and testing phases. Also, the results indicated that the proposed model of this research could use as an appropriate framework to predict the considered target.

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