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Comparison Study of Soft Computing Approaches for Estimation of the Non-Ductile RC Joint Shear Strength

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ABSTRACT

Today, retrofitting of the old structures is important. For this purpose, determination of capacities for these buildings, which mostly are non-ductile, is a very useful tool. In this context, non-ductile RC joint in concrete structures, as one of the most important elements in these buildings are considered, and the shear capacity, especially for retrofitting goals can be very beneficial. In this paper, three famous soft computing methods including artificial neural networks (ANN), adaptive neuro-fuzzy inference system (ANFIS) and also group method of data handling (GMDH) were used to estimating the shear capacity for this type of RC joints. A set of experimental data which were a failure in joint are collected, and first, the effective parameters were identified. Based on these parameters, predictive models are presented in detail and compare with each other. The results showed that the considered soft computing techniques are very good capabilities to determine the shear capacity.

1. Introduction

In the reinforcement concrete structures, shear failure of the element is very destructive, and it is highly regarded in the design of these type of elements. Shear failure of RC columns mainly due to weakness in transverse reinforcement is a common failure in the past and in the non-ductile

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RC joints which have a low percentage of the transverse reinforcement, there is a high risk of shear failure. There are many RC structures that because of lack of knowledge of the vulnerability were built non-ductile, especially in their joints. Many studies have been done to strengthen and improve the performance of these elements and several methods such as using FRP material were also proposed. The studies showed that shear failure of RC joint elements is very dangerous and very special attention is required. Some researchers investigated the shear strength of RC joint with different concrete types. For example, McLean and Pierce [1] investigated the shear of RCC (roller compacted concrete) joints based on an experimental study. They have presented the safety factors which can be used in analyses. Another case is a study which was done by Shiohara [2] to the analysis of the high strength reinforcement concrete joint in shear failure. The analysis of RC joint is a very useful tool to study the behavior of these elements. Ghobarah and Biddah [3] proposed a joint element for modeling of the joint in the nonlinear dynamic analysis with considering shear deformation. Their results show that the modeling of inelastic shear deformation in joints has a significant effect on the seismic response. Bakir and Boduroglu [4] presented a design equation for determining the shear strength of monotonically loaded exterior RC joints. They used several parametric studies to investigate the influence of variables on the behavior of RC joints based on the experimental database. Their results showed that their equation could be able to predict the joint shear strength exterior RC joints. An analytical model for shear strength of high strength RC joints is done by Sayed [5]. He was presented a general model for these type of joints.

One of the studies about the shear capacity of the RC joints is done by Jaehong and LaFave [6]. They used a collection of an extensive database of reinforced concrete (RC) beam-column connection test specimens which were subjected to cyclic lateral loading. They have determined the influence parameters for joint shear stress, and finally, the design checks recommended were examined. They also presented probabilistic joint shear strength models for design [7].

The joint shear strength of exterior concrete beam-column joints reinforced internally with Glass Fibre Reinforced Polymer (GFRP) reinforcements was investigated by Saravanan and Kumaran [8]. They tested eighteen specimens and used finite element analysis to simulate the behavior of the beam-column joints. A design equation for assessing the joint shear strength of the GFRP reinforced beam-column specimens was also proposed. Sharma et al. [9] presented a model for simulating the shear behavior of exterior reinforced concrete joints subjected to seismic loads. Their model does not need any special element or subroutine and uses limiting principal tensile stress in the joint. Shear behavior of ultra-high performance concrete was studied by Lee et al. [10]. The results of their tests have been compared with several design formulae for assessing the joint shear strength. The available models to predict the shear strength of beam-column joints were reviewed by Pradeesh et al. [11]. The concept, parameters considered, significant observations and their limitations of the models for predicting the joint shear behavior were summarized in their study. Elshafiey et al. [12] investigated the performance of exterior RC joints subjected to a combination of shear and torsion-based on the results of an experimental study. They also presented a three-dimensional truss model and showed that their model had an agreement with the experimental results. The shear strength and behavior of beam-column joints in unbonded precast prestressed concrete (PCaPC) frames based on the test results were investigated by Jin et al. [13]. The joint shear input was compared with the nominal shear strength of RC joint panels which was calculated based on common standards in their study.

This paper is an attempt to determine the shear capacity of RC non-ductile joints based on artificial neural networks (ANN), adaptive neuro-fuzzy inference system (ANFIS) and also group method of data handling (GMDH). A collection of experimental which were published in the literature were used, and predictive models were proposed to estimation the shear capacity.

2. Soft computing

Soft computing (SC) tried to build intelligent which provides the ability to derive the answer from the problems with high dimensions and complex. They used to develop systems in similar of the human mind and have been advantageous in many engineering applications. In general classification, SC techniques can be classified into three groups including artificial neural networks, fuzzy systems and neuro-fuzzy system (which is the combination of the first two groups).

In this section, three most famous soft computing methods including ANN, ANFIS and also GMDH were reviewed. These approaches are the considered methods which were used to the aim of this paper.

2.1. ANN

Artificial neural networks (ANN) are systems which were widely used for function approximation based on a collection of existing samples. They can be able to train the solutions from these data. They are applied in areas where the presentation of an answer is difficult by traditional methods. They have been used to solve engineering problems by three general layers namely input layer, hidden layer or layers and also output layer. There are several neurons as computational units. These neurons are connected in layers, and signals travel from the first (input) to the last (output) layer. ANN used a set of data to estimate the weights and bias for the input and output signals of each neuron. It is clear that a big and reliable dataset has more ability to estimate the parameters.

2.2. ANFIS

Adaptive neuro-fuzzy inference system (ANFIS) is a fuzzy inference system implemented in the framework of adaptive networks which was introduced by Jang [14]. It was applied both of the fuzzy rules and input-output data pairs. ANFIS is one of the powerful soft computing approaches which was presented a Sugeno-type fuzzy system in a five-layer network (the input layer not counted by Jang). They are the ability of ANN and fuzzy systems together. To create an ANFIS model, three methods are commonly used: grid partition (GP), subtractive clustering (SC) and also fuzzy c-means (FCM) clustering. GP algorithm divides the data space into rectangular sub-spaces. SC algorithm divides the considered data into groups called clusters to discover the solution patterns. FCM which was used in this paper is an unsupervised algorithm. FCM consider the dataset into fuzzy clusters and also allows one data to belong to two or more clusters. This can be very useful to have a flexible and strongest ANFIS.

2.3. GMDH

Group Method of Data Handling (GMDH) network which introduced by Ivakhnenko [15] is a multi-layered perceptron-type network structure for mathematical modeling of systems. It is able to get the solution algorithm using data samples. Each node in GNDH has two input signals and use a second-order polynomial based on these two inputs. A collection of the dataset is applied to determine the coefficient values of polynomials based on least squares approach. They also can self-neglect ineffective inputs. Because of the mathematical manner of GMDH, these type of networks is widely used in engineering problems.

3. Experimental data

For calculation of the considered soft computing methods, a collection of 149 data which were published in literature was used [16–50]. These data are related to non-ductile RC joints which were a failure in shear, and their shear capacity has been reported to them. Table 1 and Fig.1 provides the details of the considered dataset. In this table, h_B, BI, ρ_b, f_{yB}, f'_c, JP and also $v_{j,exp}$ are beam height, beam index, beam longitudinal reinforcement, the yield stress of beam longitudinal reinforcement, a ratio of the number of sub-assemblages, The effective width of the joint panel and also the shear strength of the joint respectively.

Table 1
Information of dataset.

	$h_B\ (mm)$	$BI = (\rho_b \times f_{yB})/f'_c$	ρ_b	f_{yB}	$f'_c\ (MPa)$	JP	b_j	$v_{j,exp}(MPa)$
Average	343.38	0.26	0.015	493.81	30.95	0.81	226.52	5.62
Maximum	762.00	0.78	0.041	746.00	100.80	1.00	600.00	10.45
Minimum	150.00	0.06	0.003	315.00	8.30	0.75	100.00	1.19
Median	300.00	0.24	0.013	500.00	31.60	0.75	200.00	5.45
Mode	300.00	0.15	0.009	500.00	31.60	0.75	200.00	5.08
St.Dev	139.69	0.14	0.007	91.37	10.83	0.11	100.16	1.94
Range	612.00	0.73	0.038	431.00	92.50	0.25	500.00	9.26

JP (In plane geometry) =1 for interior, 0.75 for exterior.

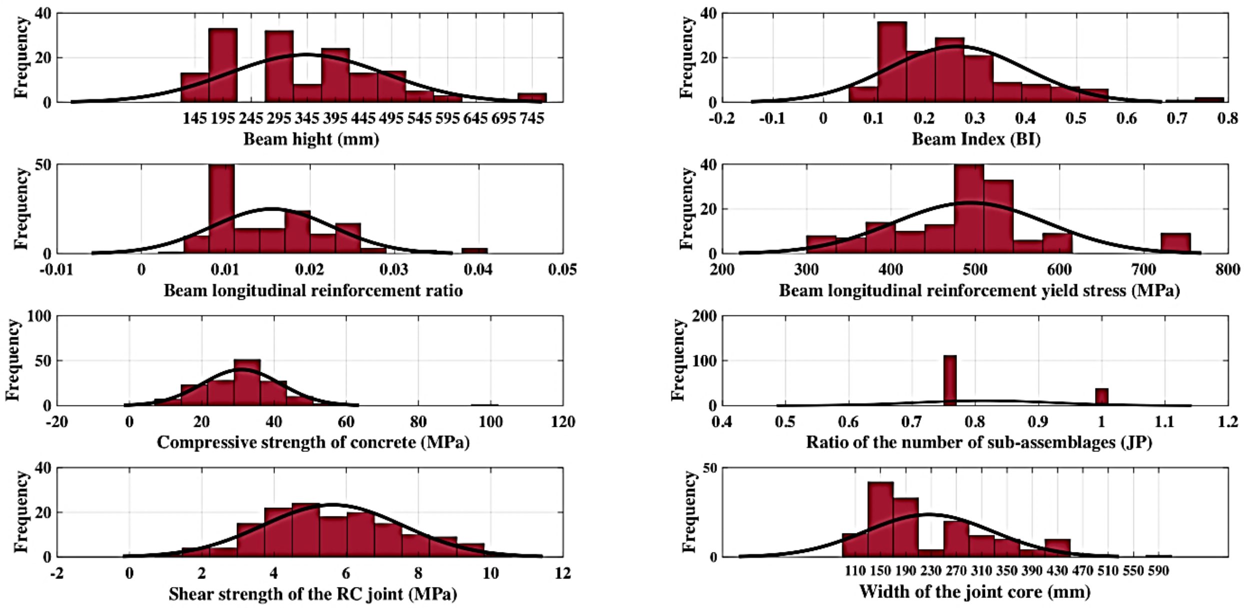

Fig. 1. Distribution of the considered dataset.

To normalization, a relationship which created the data within the value of 0.1 to 0.9 is used by Eq.1:

$$x_{normal} = 0.8\left(\frac{x_{real} - x_{min}}{x_{max} - x_{min}}\right) + 0.1 \qquad (1)$$

For training the models, 126 data, which has randomly chosen from the dataset, was used. The remained 22 data means used for the testing phase of the proposed models.

4. Selected models for shear capacity prediction

The initial modeling of the considered SC methods showed that the most powerful inputs were f'_c, *BI* and *JP*. Therefore, these parameters were selected and used as Inputs. This section, the structures and the parameters of the proposed models for considering estimation were presented in details. The results were discussed in section 5.

4.1. ANN-model

The proposed ANN structure was shown in Fig. 2. The shear strength was considered by v^n in the figure. BI^n , JP^n and $f_c'^n$ are also the normal values of input 1, 2 and 3 respectively. They considered as *X1*, *X*2 and *X3* in this paper. It was clear from the figure that the hidden layer has eight neurons. These nodes transfer its values to the final layer by Tangent-Sigmoid function. For the output layer, the Purelin function was used. The details of the layers were presented in Tables 2 and 3. In these tables, $b_1$and b_2 are the bias of the hidden and output layer respectively.

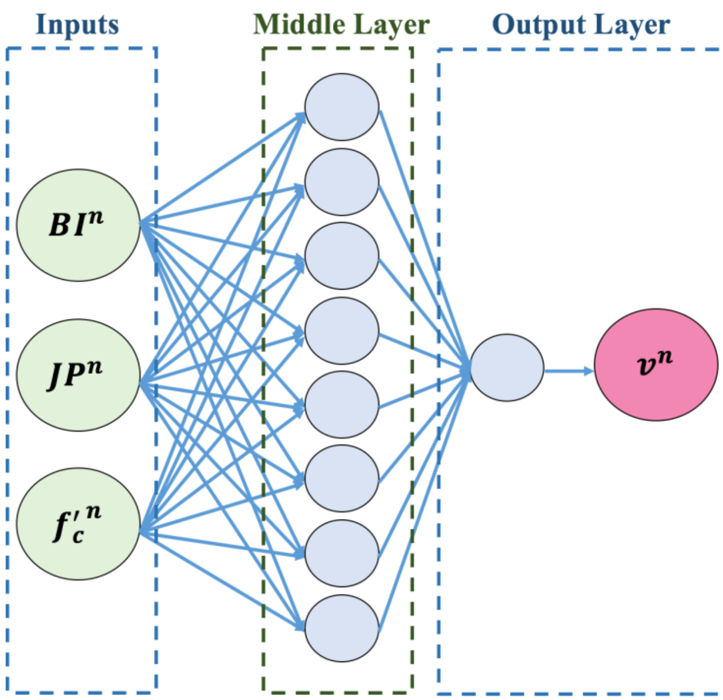

Fig. 2. The proposed ANN structure.

Table 2
Layer weights and bias for the final layer.

Layer weights								b_2
Neuron 1	Neuron 2	Neuron 3	Neuron 4	Neuron 5	Neuron 6	Neuron 7	Neuron 8	
-0.3565	-0.3483	0.9888	-0.3566	0.3564	-0.3584	-1.4283	1.0587	-0.6522

Table 3
Input weights and bias for the hidden layer.

Neuron	Input weights			b_1
	Input 1	Input 4	Input 5	
Neuron 1	-0.1299	0.0532	-0.2158	0.1388
Neuron 2	-0.1282	0.0577	-0.2109	0.1358
Neuron 3	-1.3420	0.2517	0.5692	0.2158
Neuron 4	-0.1299	0.0532	-0.2158	0.1388
Neuron 5	0.1299	-0.0533	0.2157	-0.1388
Neuron 6	-0.1302	0.0515	-0.2172	0.1395
Neuron 7	-0.9260	0.0178	-1.0580	-1.1287
Neuron 8	0.6463	0.3571	-1.0240	0.6312

4.2. ANFIS-model

The selected ANFIS model, used FCM algorithm and had Gaussian membership function (eq.2) for input parameters as follows:

$$\mu\,(x;\,\sigma, c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \quad (2)$$

Where c is the mean and σ is the variance of x. The proposed ANFIS structure presented in Fig.3.

The Gaussian parameters of the membership functions presented in Table 4 for all input parameters. Fig.4-6 showed membership functions of the selected ANFIS.

Table 4
Gaussian membership function's parameters.

Membership function	Parameter	Inputs		
		X1	*X2*	*X3*
C1	c	0.2883	0.1013	0.3440
	σ	0.0461	0.0672	0.0311
C2	c	0.5382	0.8988	0.1734
	σ	0.0878	0.1779	0.0359
C3	c	0.4737		0.3059
	σ	0.0619		0.0236
C4	c	0.1954		0.2234
	σ	0.0514		0.0407
C5	c	0.3641		0.2394
	σ	0.0566		0.0315
C6	c	0.3116		0.4174
	σ	0.0327		0.0485
C7	c	0.2048		0.3273
	σ	0.0567		0.0286
C8	c	0.4959		0.2384
	σ	0.0745		0.0216
C9	c	0.2528		0.2905
	σ	0.0479		0.0242

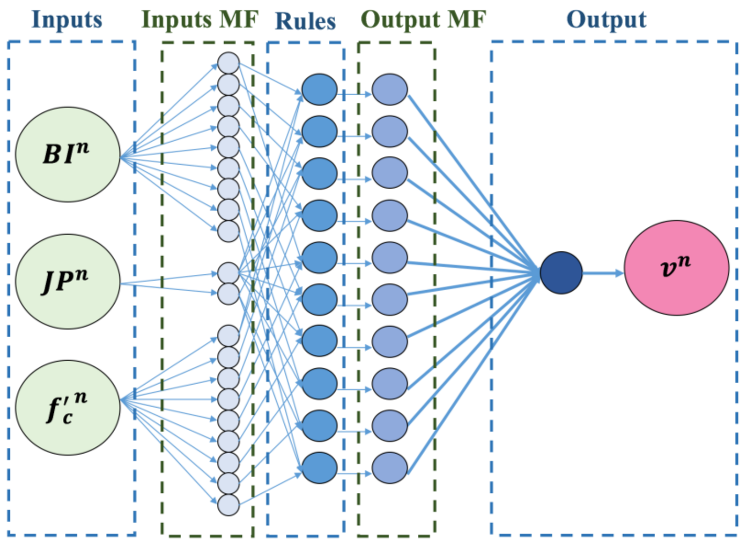

Fig. 3. The proposed ANFIS structure.

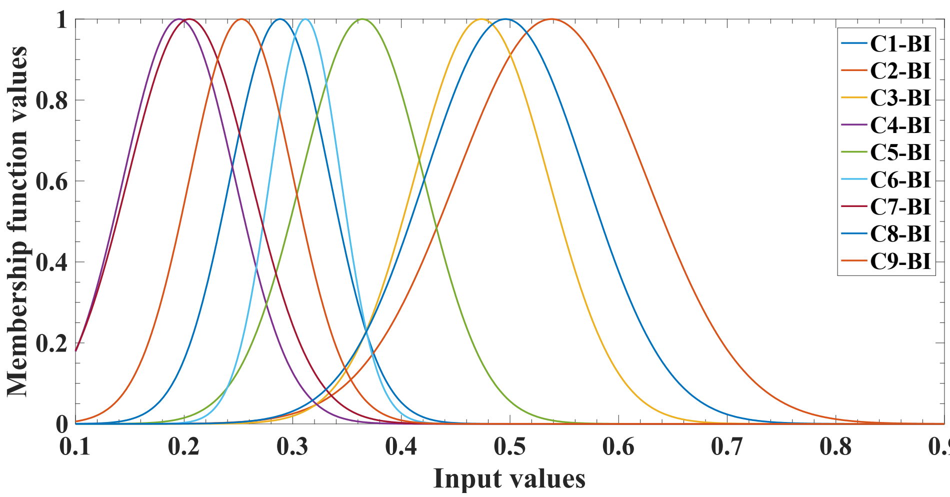

Fig. 4. Membership functions for input 1.

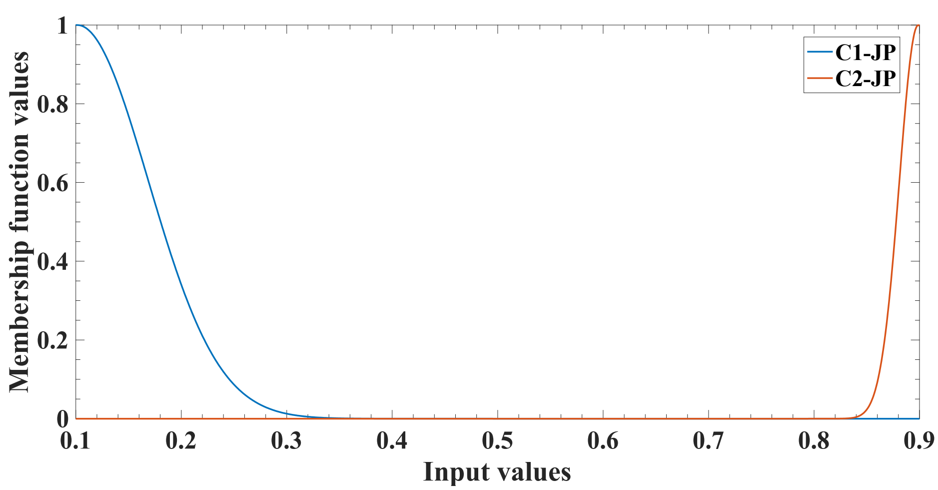

Fig. 5. Membership functions for input 2.

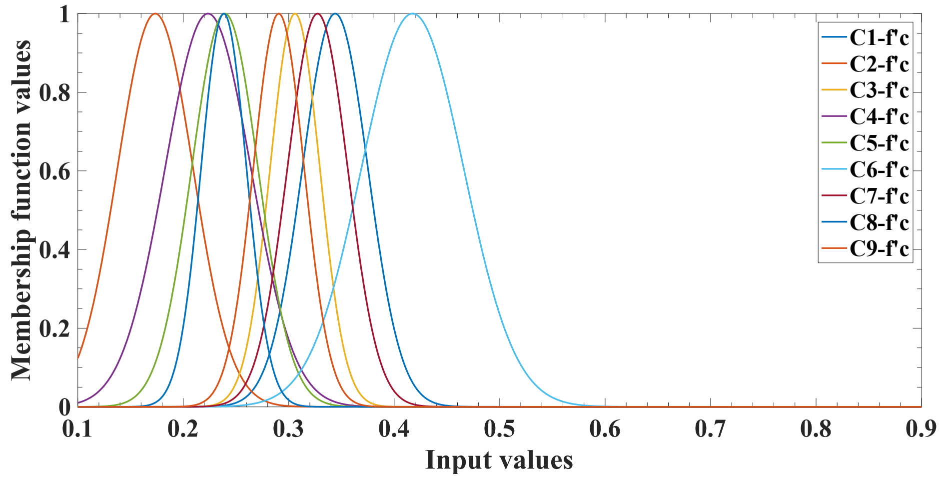

Fig. 6. Membership functions for input 3.

In ANFIS-FCM structure, there are several clusters (CL) for the target. Each of clusters includes a linear function which is showed in eq.3.

$$CL_j = a_1x_1 + a_2x_2 + a_3x_3 + C \qquad j=1, \ldots, 10 \tag{3}$$

The parameters $a_1, \ldots, a_6$ are coefficients of the input $x_1, \ldots, x_3$. The parameter C is deal with a constant value. The amounts of these parameters presented in Table 5.

For the selected ANFIS, the rule base and also rule's weights showed in Table 6 and 7 respectively.

Table 5
Parameters of the output's clusters.

Cluster	Inputs coefficients (a_i)			Constant (C)
	a_1	a_2	a_3	
CL1	-3.8580	0.2218	-1.7900	2.2180
CL2	-0.5828	0.0854	0.2812	0.8538
CL3	0.5490	-5.8310	5.3360	4.6020
CL4	0.9090	-0.0661	3.8080	-0.6607
CL5	-0.4401	0.0207	0.5480	0.2067
CL6	-1.4010	0.0793	0.8190	0.7933
CL7	4.3990	-0.1364	1.6800	-1.3640
CL8	1.4100	-0.2046	5.5820	-2.0460
CL9	0.4603	-4.6700	1.6390	4.1180
CL10	1.5740	0.0695	2.4130	-0.5313

Table 6
ANFIS rules.

Number	Rules
Rule 1	If XI is $C1_{X1}$ and X2 is $C1_{X2}$ and X3 is $C1_{X3}$ then $v_{j,n}$ is CL1.
Rule 2	If XI is $C2_{X1}$ and X2 is $C1_{X2}$ and X3 is $C1_{X3}$ then $v_{j,n}$ is CL2.
Rule 3	If XI is $C3_{X1}$ and X2 is $C2_{X2}$ and X3 is $C2_{X3}$ then $v_{j,n}$ is CL3.
Rule 4	If XI is $C4_{X1}$ and X2 is $C1_{X2}$ and X3 is $C3_{X3}$ then $v_{j,n}$ is CL4.
Rule 5	If XI is $C1_{X1}$ and X2 is $C1_{X2}$ and X3 is $C4_{X3}$ then $v_{j,n}$ is CL5.
Rule 6	If XI is $C5_{X1}$ and X2 is $C1_{X2}$ and X3 is $C5_{X3}$ then $v_{j,n}$ is CL6.
Rule 7	If XI is $C6_{X1}$ and X2 is $C1_{X2}$ and X3 is $C6_{X3}$ then $v_{j,n}$ is CL7.
Rule 8	If XI is $C7_{X1}$ and X2 is $C1_{X2}$ and X3 is $C7_{X3}$ then $v_{j,n}$ is CL8.
Rule 9	If XI is $C8_{X1}$ and X2 is $C2_{X2}$ and X3 is $C8_{X3}$ then $v_{j,n}$ is CL9.
Rule 10	If XI is $C9_{X1}$ and X2 is $C2_{2}$ and X3 is $C9_{X3}$ then $v_{j,n}$ is CL10.

The normal value of the joint shear strength based on the considered ANFIS-FCM model can be determined by eq.4.

$$v^n = \frac{\sum_{j=1}^{10} w_{Rule,j} CL_j}{\sum_{j=1}^{10} w_{Rule,j}} \tag{4}$$

Table 7
Rule's weight.

Number	Weight's relationship
W_{Rule1}	$(C1_{X1}) \times (C1_{X2}) \times (C3_{X3})$
W_{Rule2}	$(C2_{X1}) \times (C1_{X2}) \times (C3_{X3})$
W_{Rule3}	$(C3_{X1}) \times (C2_{X2}) \times (C2_{X3})$
W_{Rule4}	$(C4_{X1}) \times (C1_{X2}) \times (C3_{X3})$
W_{Rule5}	$(C1_{X1}) \times (C1_{X2}) \times (C4_{X3})$
W_{Rule6}	$(C5_{X1}) \times (C1_{X2}) \times (C5_{X3})$
W_{Rule7}	$(C6_{X1}) \times (C1_{X2}) \times (C6_{X3})$
W_{Rule8}	$(C7_{X1}) \times (C1_{X2}) \times (C7_{X3})$
W_{Rule9}	$(C8_{X1}) \times (C2_{X2}) \times (C8_{X3})$
W_{Rule10}	$(C9_{X1}) \times (C2_{X2}) \times (C9_{X3})$

4.3. GMDH-model

The GMDH structure which was used in this paper presented in Fig. 7. The predictive model has two polynomials in the middle layer with equations 5 and 6.

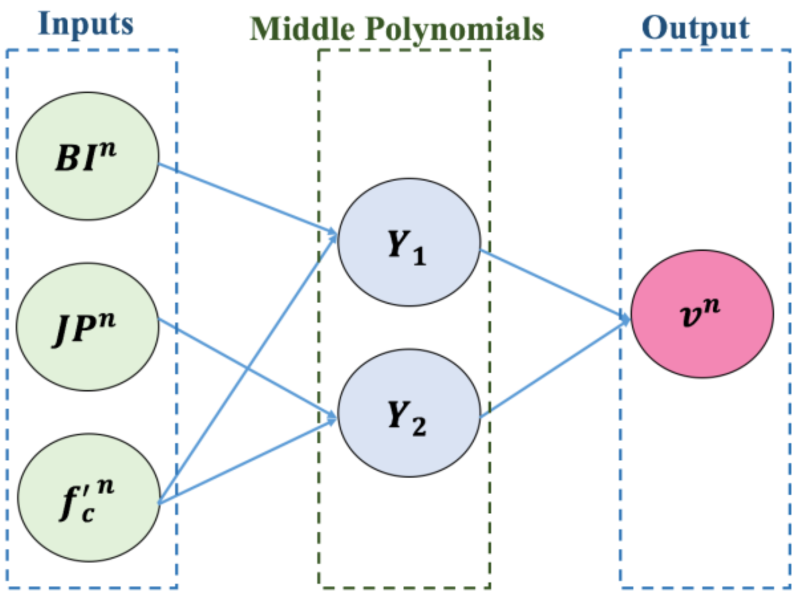

Fig. 7. Membership functions for input 3.

$$Y_1 = -0.3981 + 1.9293\,X_1 + 1.9412\,X_3 - 1.1377\,X_1^2 - 0.8803\,X_3^2 - 0.9544\,X_1X_3 \quad (5)$$

$$Y_2 = 0.0021 + 0.1768\,X_2 + 1.6035\,X_3 + 1.1766\,X_2^2 - 0.7743\,X_3^2 - 0.1645\,X_2X_3 \quad (6)$$

Based on the previous polynomials (eq.5 and 6), the final output of the model was calculated by eq.7.

$$v^n = -0.2115 + 1.4396\,Y_1 - 0.0419\,Y_2 - 0.3626\,Y_1^2 + 1.0406\,Y_2^2 - 0.6305\,Y_1Y_2 \quad (7)$$

5. Results and comparison

The output values of the proposed models are normal value and need to be converted to its real value and for this purpose, eq.8 was used:

$$\mathrm{v_j} = \left(\frac{|\mathrm{v^n} - 0.1|(10.45 - 1.19)}{0.8}\right) + 1.19 \quad (8)$$

In the equation, $\mathrm{v_j}$ is the joint shear strength of the non-ductile RC joints which determine by the proposed models. Based on the real values, the distribution of the results of these models presented in Figs 8-10. It was clear from the figures that the considered soft computing approaches had suitable predictions.

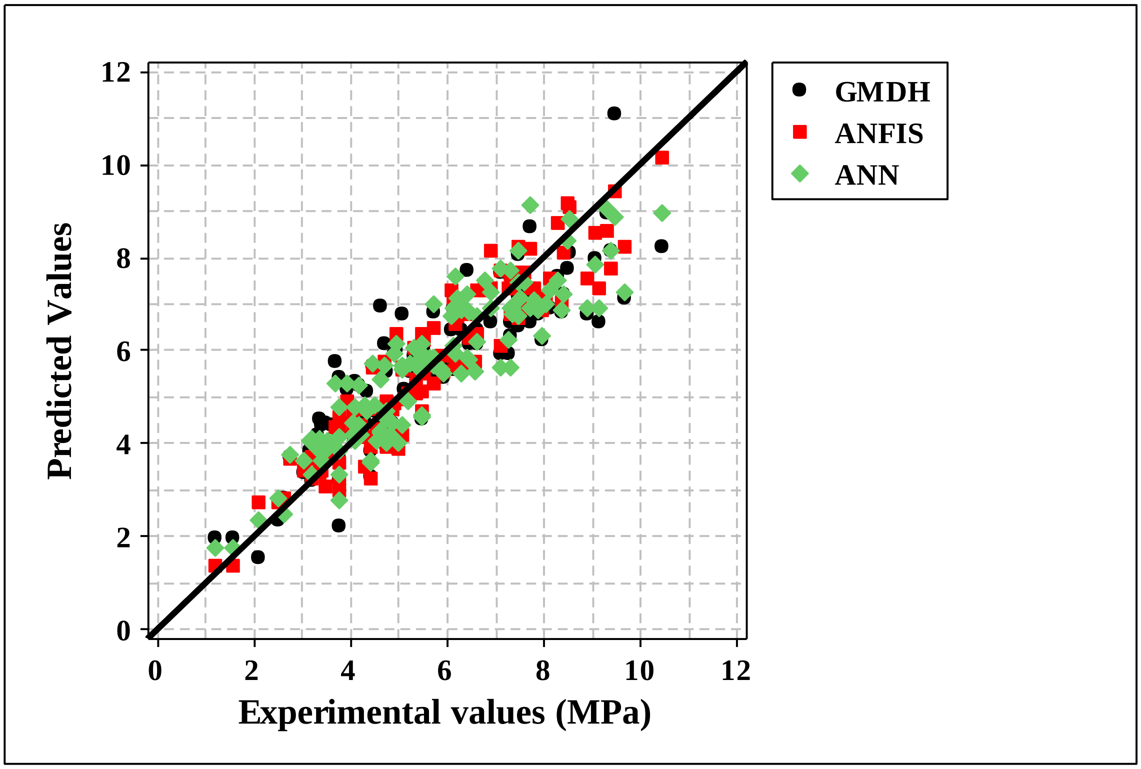

Fig. 8. Distributed results for all 126 train data.

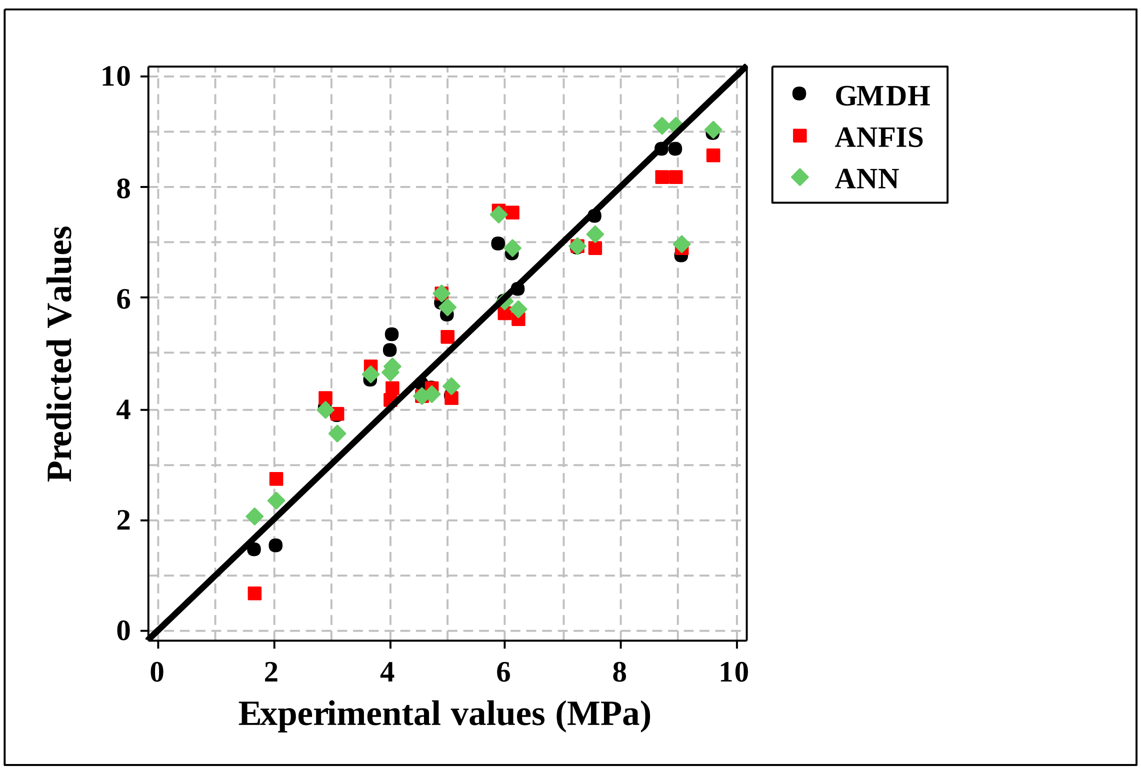

Fig. 9. Distributed results for all 22 test data.

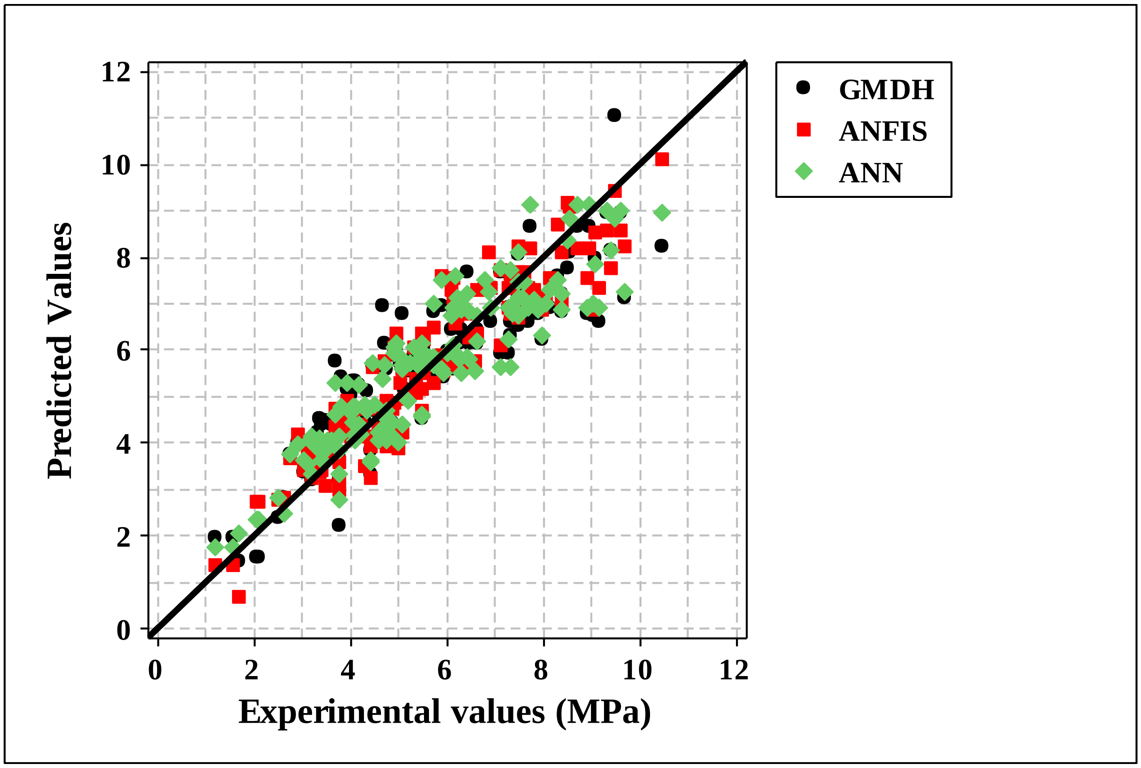

Fig. 10. Distributed results for all 149 data.

A summary of the final results was also presented in Table 8. It was concluded that although all of the considered methods had suitable results, for all 149 data, ANFIS had less error and higher correlation factor than other models.

Table 8
Summary results.

Model	Train data (126 data)			Test data (22 data)			All data (149 data)		
	R^2	*MAE*	*RMSE*	R^2	*MAE*	*RMSE*	R^2	*MAE*	*RMSE*
ANN	0.905	0.565	0.807	0.928	0.765	0.924	0.910	0.658	0.807
ANFIS	0.939	0.526	0.646	0.904	0.793	0.938	0.932	0.567	0.699
GMDH	0.875	0.727	0.911	0.929	0.633	0.821	0.886	0.713	0.897

In this table: *R2* is correlation coefficient, *MAE* is mean absolute error and *RMSE* is the root mean squared error.

6. Conclusions

Determination of the shear strength of non-ductile of RC joint using three soft computing methods including ANN, ANFIS, and GMDH was considered in this paper. For train and test the models, a collection of experimental was used and the structures of the predictive models presented in details. it was mention that based on try and error approach for all of the considered methods, three inputs including BI, f_c' and *JP* had more effect on the shear strength and therefore was used for modeling. The results showed that the proposed models have high performance for determining the shear strength. Additionally, the predicted values by ANFIS was more accurate than other two models. The importance results and the predictive models which were presented in this paper can be very useful for purposes such as retrofitting.

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