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Adaptive Neuro-Fuzzy Inference System Model for Predicting the Tensile and Bending Properties of Carbon Fiber-Epoxy Composite

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Abstract

The aim of this work is to experimentally study the influence of fiber prestress and curing temperature on the tensile and flexural properties of carbon fiber-epoxy composite. Adaptive Neuro-Fuzzy Inference System model was used to predict the effect of fiber prestress and curing temperature on the tensile strength, tensile modulus, flexural strength and flexural modulus of carbon fiber-epoxy composite. It was found that, the best membership functions for predicting the tensile strength, tensile modulus and flexural modulus are Gaussian membership functions with 4 number of membership function, and for predicting the flexural strength are generalized bell membership functions with 4 number of membership functions. From the comparison between the experimental and predicted results of carbon fiber-epoxy composite properties, it is found that the prediction results of this model show a good agreement with experimental results.

1. Introduction

Basically, fiber prestressing and curing temperature is used as a technique to improve the mechanical properties of fiber composite laminates and to minimize the induced residual stress and fiber waviness in continuous carbon fiber reinforced epoxy composite materials. Induced residual stresses are generated during manufacturing of composite materials due to chemical shrinkage of the resin, various thermo-mechanical properties of the components, fiber pretension and humidity absorption. Prestressed composite is performed by applying a preload to an n-ply laminate prior to cure, the uncured matrix shows negligible resistance; therefore, all the applied preload would be carried by the fibers. The laminate would then be cured normally, causing the matrix to gel and solidify, after that the formation of bonding in the interfacial region will lead to develop the tensile residual stress in the matrix. Once the composite is cured and cooled down to room temperature, the fiber preload is released. After releasing the fibers preload, the fibers tend to recoil to their original state, while the surrounding solidified matrix impedes the fibers recovery. Therefore, some strain in the fiber is returned and leading to compress the cured matrix of the composite by some level depends on composite properties, the resulting elastic contraction of fibers will relieve the tensile residual stress in the fibers resulting from the curing cycle by generating compressive stresses in the matrix via the interfacial region which will reduce both the thermally-induced and cure-induced residual stresses resulting from the cure process [1].

The previous researchers have studied the parameters that influence on the mechanical properties of prestressed fiber reinforced composite materials. It was found that, as long as the fibers are subjected to a constant load throughout resin curing process, the tensile strength, tensile modulus, flexural strength and flexural modulus of carbon fiber-epoxy composite have been improved Various experimental investigations were carried out on the improvement of the mechanical properties of composite materials.

Krishnamurthy, 2006 [1] studied the influence of fiber prestress on induced residual stresses, fiber alignment, fatigue behavior, static tensile and compression properties of composites. From results found that, this prestress technique, on a 16-ply unidirectional E-glass/913 epoxy composite, improves the fiber alignment, minimizes the residual strain of the composite and improves the performance of composites by increasing the resistance to static and fatigue load. Kim and Lee, 2006 [2] proposed a suitable technique to remove all the thermal residual stresses in the bonding layer of the hybrid structure. The results showed that the proposed technique removed the thermal residual stresses completely and improved the strength at interfacial region of the steel/carbon fiber reinforced epoxy. Motahhari, 1998 [3] investigated the influences of fiber prestressing on flexural strength, flexural modulus, and impact strength. Two types of composite materials were used i.e glass-epoxy and carbon-epoxy. Abdullah, 2016 [4] investigated the effect of fiber prestress and curing temperature on strength and stiffness of carbon fiber-epoxy composite. The results showed that improvement in the tensile strength, tensile elastic modulus, flexural strength and flexural elastic modulus are 126.7%, 31.3%, 61.3% and 62.3% respectively. Al-Jeebory and Al-Mosawi, 2010 [5] studied the mechanical properties (e.g. impact strength, tensile strength, flexural strength and hardness) for araldite matrix composites incorporated with hybrid carbon-kevlar fibers. Zhao and Cameron, 1998 [6] applied different levels of prestress on glass fiber/polypropylene composites made by compression modeling method. The residual stresses in this composite introduced through manufacturing have been led to significantly degrade the strength of the composite which resulting in matrix cracking, debonding and reduced fracture toughness. Mechanical tests showed that fiber prestress can increase the interlaminar shear, flexural and tensile properties of the composites, and this exists at an optimum prestress level to get best properties for each external loading condition.

Theoretical methods were carried out to predict the mechanical properties and behavior of composite materials, mainly for comparison matters. Jarrah et al., 2002 [7] investigated the performance of different model structures in terms of the mean of squared error (MSE). An adaptive Neuro-Fuzzy modeling was implemented to predict the relationship between the input/output data of tension-tension and tension-compression loading of unidirectional glass fiber reinforced epoxy composites. The experimental input data were; the fiber orientation, maximum stress, and stress ratio, while the output data was the number of cycles to failure. The predicted results by an adaptive Neuro-Fuzzy model with bell shape membership functions were compared with experimental results. The results indicated good modeling performance. Vallalperumal and Vidivelli, 2016 [8] proposed Adaptive Neuro-Fuzzy Inference System (ANFIS) based model for predicting the performance characteristics of carbon fiber reinforced polymer (CFRP) sheets strengthened reinforced concrete circular columns and to compare it with the experimental results. The ANFIS predicted results showed good agreement with the experimental test results.

In this study, the experimental results of tensile strength, tensile modulus, flexural strength and flexural modulus are to be used to develop an Adaptive Neuro-Fuzzy Inference System model to predict the desired properties.

2. Experimental work

2.1. Composite material

In this work, the composite material consists of carbon fibers PAN-based T300 with trade name SikaWrap®-300 C. The continuous carbon fiber has a high strength of 3.9 GPa, and density of 1.79g/cm³ [9]. The epoxy resin with trade name Sikadur®-330. The tensile strength and density of epoxy are (30 MPa) and 1.31g/cm³ respectively [10].

2.2. Fabrication of carbon fiber-epoxy composite

The fabrication of prestressed composites was achieved by using the below machine as shown in Fig. 1. The EJPR machine is used in this work to fabricate the samples of carbon fiber-epoxy composite and to create changes in the mechanical properties of the fiber composite materials by absorbing residual stresses during prestressing and curing processes. The basic parts of this machine are prestress assembly, pulling-jack, and low temperature furnace. The prestress assembly of this machine has a surface of steel plate which can be used as an open molding technique to produce thin flat strip for the tensile test specimens.

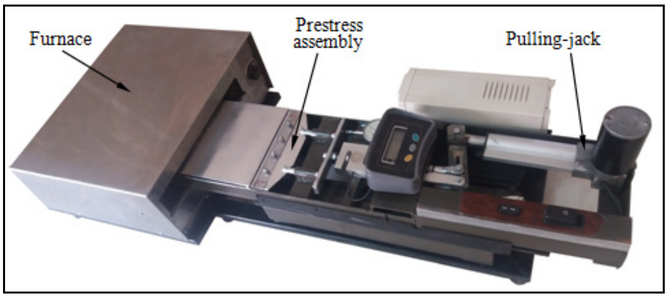


Fig. 1 Photograph of Electric-Jack Prestress Rig (EJPR) [4].

Two stages have been used to prepare the composite material as follows:

Hand lay-up: An Electric-Jack Prestress Rig (EJPR) methodology was used for preparing composites. The surface of steel plate must be cleaned and ready to be handling so that it does not bond with the laminate. Firstly, the surface of steel plate is coated with a very thin layer of wax using a smooth cloth. Then a film of release agent called polyvinyl alcohol (PVA) is applied over the dried wax using a brush. The epoxy is prepared by mixing the two parts (resin part A with hardener part B) as shown in Fig. 2(a) with a mixing ratio of 4:1 by weight [10]. Before spreading the matrix, one end of the carbon fiber plies must be fixed with one end in the prestress assembly by using four bolts, see Fig. 2(b). The first matrix coat is spread uniformly over the dried PVA using a brush. Then the first carbon fiber lamina is laid over the epoxy and gently rolled with the help of a teethed aluminum roller in the fiber direction before applying the next epoxy coat as shown in Fig. 2(c). This process is repeated until all the plies are placed. Then all other ends of the plies were clamped to the other end in the prestress assembly and fixed by using other four bolts as shown in Fig. 2(d).

Prestressing and Curing Process: After clamping all the fiber layers and the vacuum process had been completed, EJPR can apply mechanical loading to a predetermined level using load cell. Eight different prestress levels (0, 10, 12.5, 20, 25, 30, 40 and 45 MPa) were applied. After applied the required loading, the prestress assembly can be inserted easily with the help of sliding guides inside the furnace, which is already adjusted, to the required curing temperature (40, 55, 67, 80, 97, or 115 °C) as shown in Fig. 3. After eight hours of curing process, the furnace will be turned off and the laminate will be cooled down to ambient temperature. Usually cooling takes about two hours, then the prestress assembly with the cured laminate will be drawn out from the furnace to remove the preloading gradually.

2.3. Specimens preparation

The laminates are removed from the mold, then cut and grinded to the suitable specimen's dimension according to the suitable standard. The cutting processes were done by using a small power angle grinder, and the entire test specimens were finished by abrading the edges on a fine abrasive paper to avoid any edge defects that could initiate premature failure.

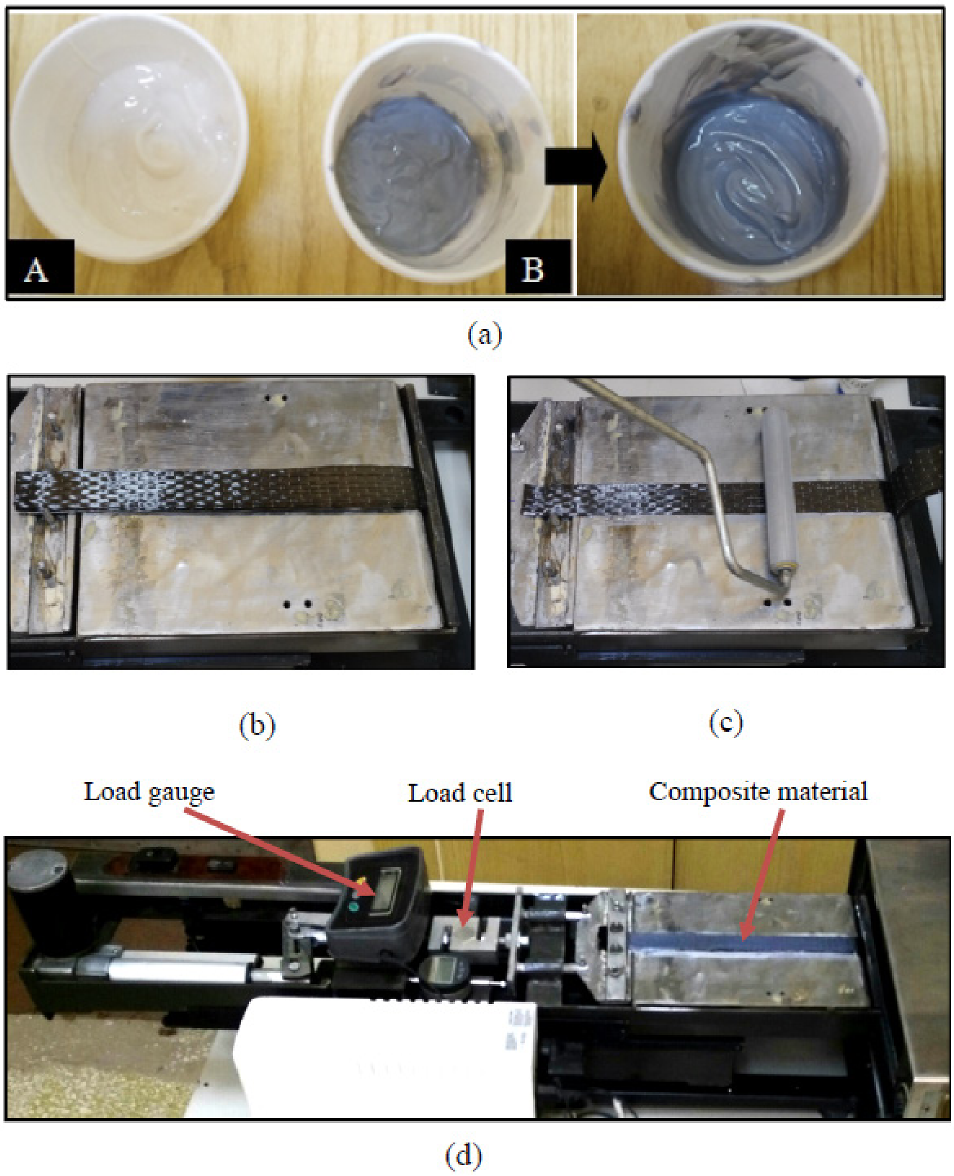


Fig. 2 (a) Mixing of epoxy parts, (b) Fixed carbon fiber plies with one end in the prestress assembly, (c) Vacuum process using teethed aluminum roller, and (d) Fixed carbon fiber plies with another end in the prestress assembly.

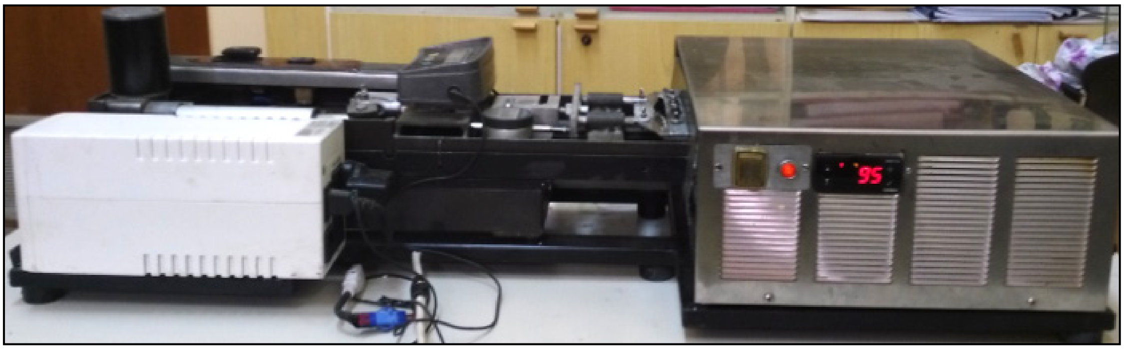


Fig. 3 Prestressing and curing.

2.4. Mechanical testing

Hydraulic Instron testing machine model 5900 was implemented for calculating the longitudinal tensile properties. This test was conducted according to the ASTM D 3039 [11]. The dimensions of the longitudinal tensile test specimens were 250 × 15 × 1 mm with a gauge length of 138 mm as shown in Fig. 4. Five specimens were tested to measure the tensile properties of each prestressed level and each curing temperature level (see Fig. 5).

The ultimate tensile strength of composite material (σ_c^u is measured by the maximum stress that a material can withstand while being stretched or pulled before breaking. The longitudinal tensile moduli of composite materials (*Ec*) are calculated from the slope of the stress-strain curve in elastic region.

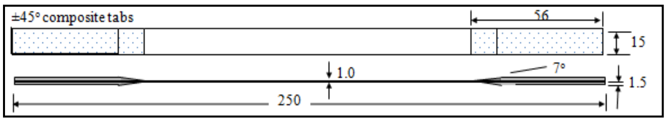
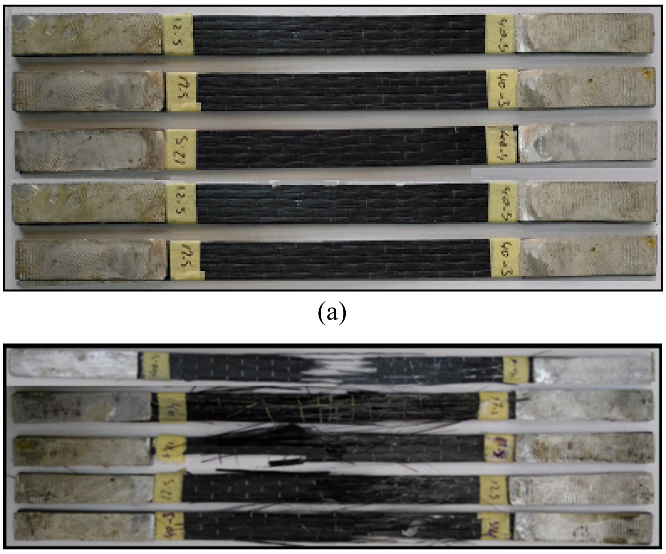


Fig. 4 Tensile test specimen according to the ASTM D 3039 for 0° [11].



(a)

(b)

Fig. 5 Tensile test specimens: (a) Before test, and (b) After test.

3. Adaptive Neuro-Fuzzy Inference System (ANFIS)

A Neuro-Fuzzy approach was used for prediction of the mechanical properties of CFRE composite materials namely tensile strength-modulus and flexural strength-modulus. All are under combined situations such as; prestress level and curing temperature. Fuzzy logic (FL) is based on the concept of fuzzy sets. A fuzzy set is a class of objects with a continuum of grades of membership function. Such a set is described by a membership function which assigns to each object a grade of membership ranging between zero and one.

A fuzzy inference system (FIS) consists of three steps: (1) fuzzification of the input variables, (2) evaluation of the output for each rule, (3) defuzzification. Fuzzy inference systems (FIS) can be appropriately constructed in prediction mode using initial structure with linear or nonlinear parameters which are to be tuned or adapted during a learning operation using a suitable input and output data. One of the most commonly used learning systems for adapting the linear and nonlinear parameters of an FIS, is the ANFIS [12].

The ANFIS after implementing Takagi-Sugeno fuzzy rules, is systematically creating unknown fuzzy rules from a given input-output data set. Though ANFIS has a structured knowledge representation in the form of fuzzy “if-then” rules. Therefore, neural network learning concepts have been integrated in FIS, resulting in ANFIS. The ANFIS is a network which consists of a number of interconnected nodes. Every node is described by a node function with adjustable parameters. ANFIS can be constructed as five layers with the following layer operations [13]; Layer 1: generate fuzzy membership values for input variable, Layer 2: multiply the incoming signals from the previous layer and estimation the firing strength of each rule, Layer 3: compute the normalized firing strength, Layer 4: the node in this layer calculate the contribution of the (ith) rule in the model output based on first-order Takagi-Sugeno rules, and Layer 5: calculates the overal output as the summation of all incoming signals. In this model, mean square error (MSE) and correlation coefficient (R) are used to evaluate the prediction capability of ANFIS trained by each data set. The MSE and R can be defined as:

$$MSE = \frac{1}{N}\sum_{t=1}^{N}(A_t - F_t)^2 \qquad (1)$$

Where A_t and F_t are actual and fitted values, respectively and N is the number of training or testing data set.

$$R = \frac{\sum_{t=1}^{N}(A_t - \overline{A})(F_t - \overline{F})}{\sqrt{\sum_{t=1}^{N}(A_t - \overline{A})^2 \sum_{t=1}^{N}(F_t - \overline{F})^2}} \qquad (2)$$

Where $\overline{A} = \frac{1}{N}\sum_{t=1}^{N} A_t$ and $\overline{F} = \frac{1}{N}\sum_{t=1}^{N} F_t$ are the average values of A_t and F_t of the training or testing data.

ANFIS is used to predict certain mechanical properties of carbon fiber reinforced epoxy composites. The effect of prestress level and curing temperature on the output results is studied. These parameters can be defined as input variables of the model. The parameters used to produce training, checking and testing data. The MATLAB package codes of ANFIS model were used to predict the tensile strength, tensile modulus, flexural strength and flexural modulus of CFRE composite material. The numbers of testing and checking data are taken randomly approximately (20% for testing and 20% for checking) from the total experimental data and the rest for training. The performance of ANFIS in these programming codes was investigated by changing several combinations such as; type of membership functions, number of membership functions (MFs) and number of epochs. Where these factors are important in building the ANFIS architecture.

Type and number of membership functions to input variables are appropriately fixed when testing data set has the highest correlation coefficient (R) and less mean square error (MSE). After the necessary attempts, it was found that the best structure of the ANFIS for predicting tensile and flexural properties is two inputs in the first layer, eight input membership functions in the second layer, sixteen rules in third layer, sixteen output membership functions in fourth layer and single output in the fifth layer, as shown in Fig. 6.

Figure 7 shows three-dimensional view of ANFIS surface, where the values of prestress level, curing temperature, tensile strength, tensile modulus, flexural strength and flexural modulus are normalized. Also, it was observed that, generalized bell membership functions with 4 number of membership function were used for predicting the flexural strength, and gaussian membership functions with 4 number of membership functions were used for predicting the tensile strength, tensile modulus and flexural modulus, as illustrated in Table 1. Whereas, the correlation coefficient (R) and mean square error (MSE) of the best performance for predicting tensile and flexural properties are summarized in Table 1. The best fit lines for prediction of properties for training and testing specimens of this model are shown in Fig. 8.

Table 1. The best performance for predicting the mechanical properties of carbon fiber-epoxy composite material.

Output parameter	Type of MFs	No. of MFs	No. of epoch	Training		Testing	
				R	MSE × 10^{-4}	R	MSE
Tensile strength	Gaussian	4	665	1.0000	0.008190	0.9997	15.243
Tensile modulus	Gaussian	4	500	0.9999	22.00000	0.9988	0.1388
Flexural strength	Generalized bell	4	600	1.0000	0.063700	0.9999	7.3969
Flexural modulus	Gaussian	4	500	1.0000	0.001580	0.9974	0.2656

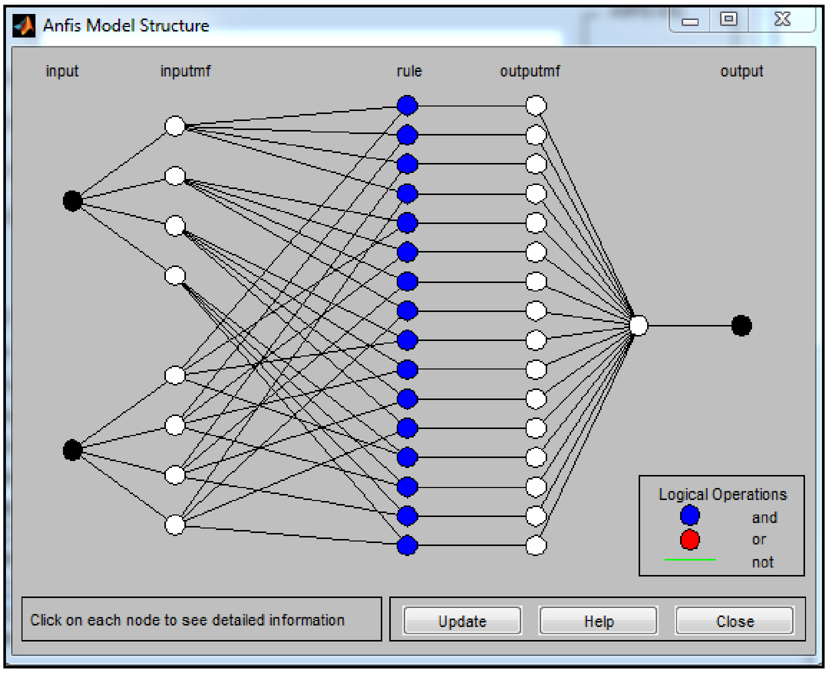


Fig. 6 ANFIS structure of carbon fiber-epoxy composite properties with 4-membership functions for tensile and flexural properties.

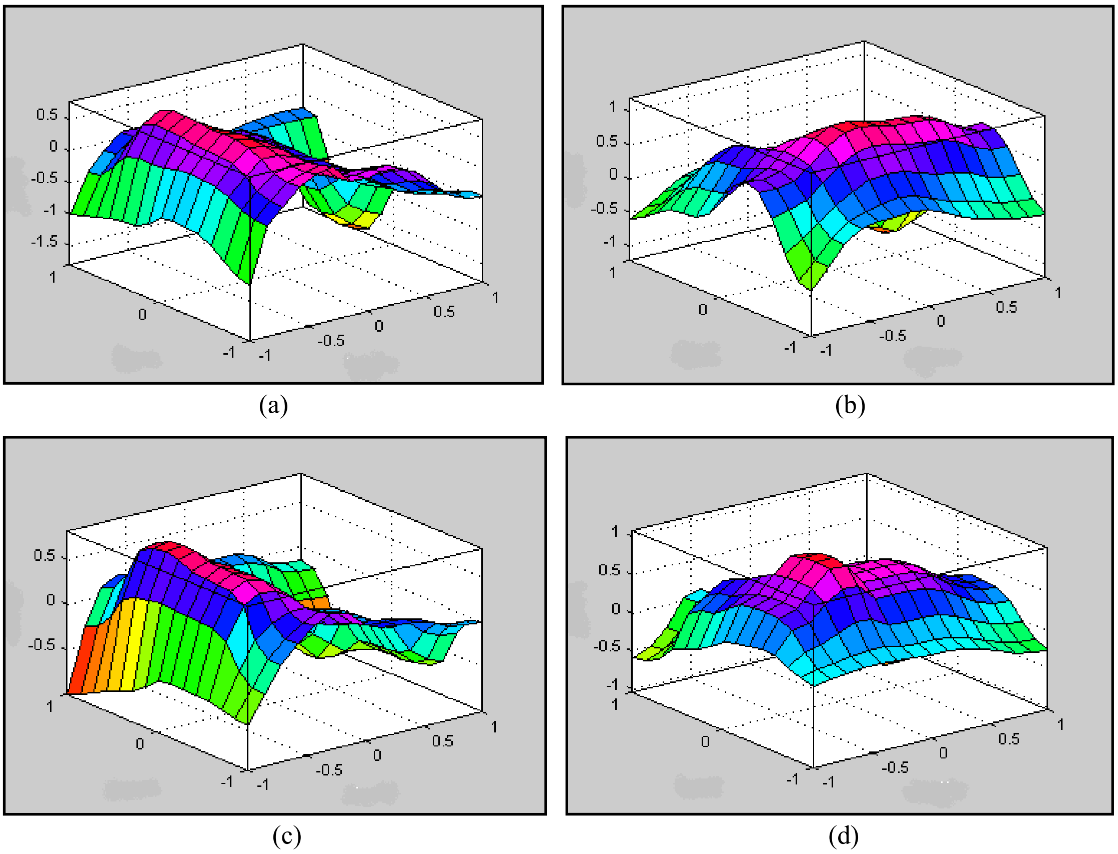
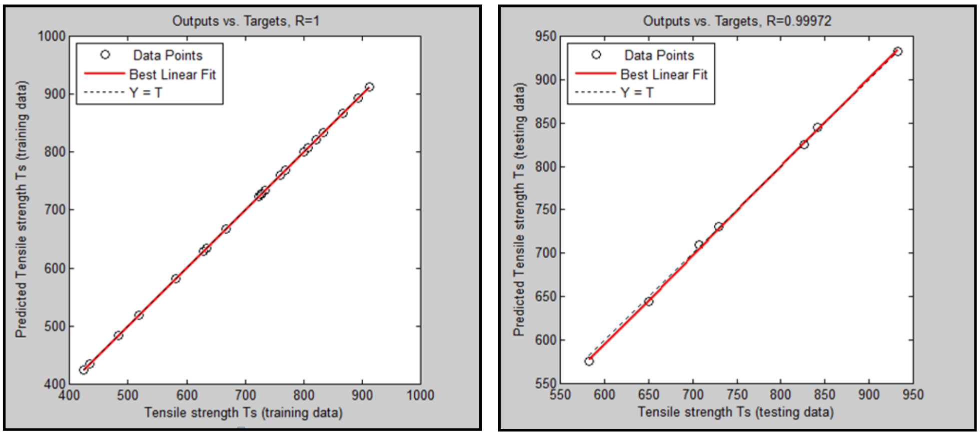
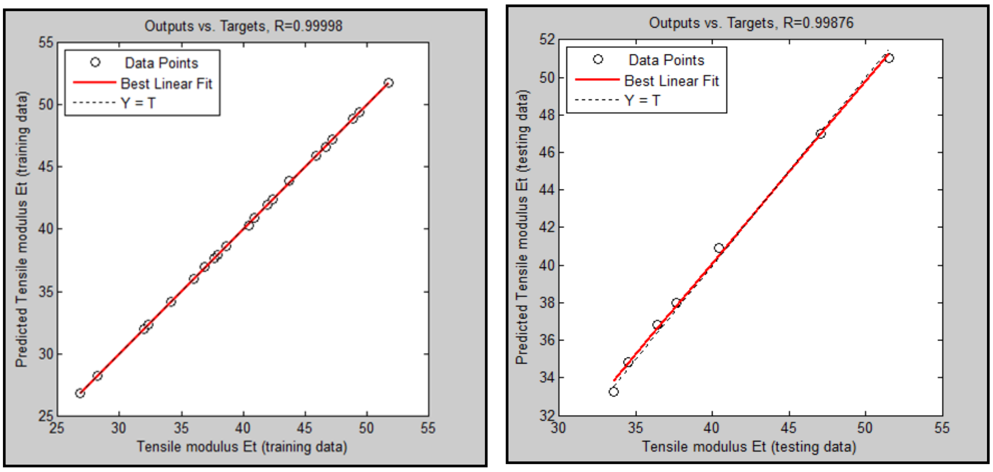


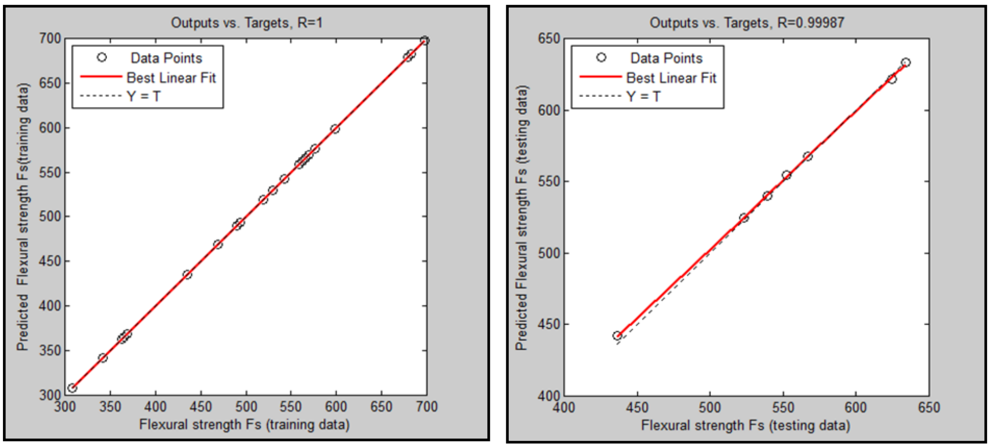
Fig. 7 Three dimensional view of ANFIS surface for, (a) Tensile strength, (b) Tensile modulus, (c) Flexural strength and (d) Flexural modulus.



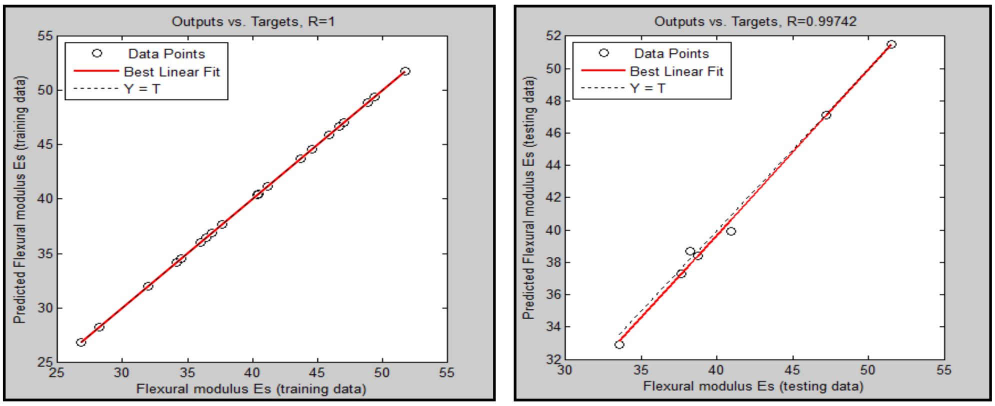
(a)



(b)



(c)



(d)

Fig. 8 The best fit lines of the predicted values of carbon fiber-epoxy composite properties achieved by ANFIS model for, (a) Tensile strength, (b) Tensile modulus, (c) Flexural strength, (d) Flexural modulus.

4. A Graphical User Interface (GUI)

A graphical user interface program was constructed and designed to present the results of ANFIS on a graphical screen. The window of (GUI) is provided with input data: Prestress level and curing temperature and the output data: tensile strength, tensile modulus, flexural strength and flexural modulus.

5. Experimental results

In this study, the tensile properties such as modulus of elasticity and longitudinal tensile strength of carbon fiber-epoxy composite were measured by longitudinal 0° static tension testing. Five specimens were prepared for each test condition under different prestress levels by using EJPR. These specimens are tested to examine their strength and stiffness properties as basis to determine the effect of fiber prestress on the mechanical properties of CFRE composites.

The tensile properties of the carbon fiber-epoxy composite were determined under prestress levels (12.5, 25 and 40 MPa) and curing temperatures (40, 67 and 97 °C), while the tensile properties at other values of prestress level and curing temperature were taken from Abdullah [4]. After the tensile test, the ultimate stress position for each specimen was specified in the stress-strain curve, and then the average ultimate value of five specimens for each prestress level was determined. For stiffness investigation, longitudinal tensile moduli of the carbon fiber-epoxy composites were calculated using the slope of the linear part of the stress-strain curve in each test, and then the average tensile modulus value of five specimens for each prestress level was determined.

6. Results of ANFIS model

The daptive Neuro-Fuzzy Inference System model develoed with two input parameters: Prestress level and curing temperature and one output may be: tensile strength, tensile modulus, flexural strength or flexural modulus. It was found that generalized bell membership functions with 4 number of membership function were used for predicting the flexural strength, and gaussian membership functions with 4 number of membership functions were used for predicting the tensile strength, tensile modulus and flexural modulus as shown in Table 1. From Table 1, it can be noted that a high correlation coefficients and less mean square errors were achieved in predicting the tensile strength, tensile modulus, flexural strength and flexural modulus. Table 2 shows the experimental and predicted ANFIS results with its percentage error. It is clear that the mean error between the experimental and predicted ANFIS results is 0.444%, 0.891%, 0.412%, 1.071% for tensile strength, tensile modulus, flexural strength and flexural modulus respectively. It can be seen that the predictions of this model show a good agreement with experimental values.

Table 2. Comparison between the experimental and predicted ANFIS results of carbon fiber-epoxy composite properties.

Tensile strength (MPa)			Tensile modulus (GPa)		
Exp.	ANFIS	Error%	Exp.	ANFIS	Error%
582.67	574.94	1.327	33.56	33.27	0.864
730.03	730.17	0.019	47.10	47.00	0.212
827.05	825.08	0.238	34.49	34.86	1.073
932.61	932.84	0.025	40.40	40.90	1.238
841.79	845.33	0.421	51.50	51.02	0.932
707.39	709.46	0.293	37.65	37.98	0.876
649.43	644.31	0.788	36.43	36.81	1.043
Mean error %		0.444	Mean error %		0.891
Flexural strength (MPa)			Flexural modulus (GPa)		
Exp.	ANFIS	Error %	Exp.	ANFIS	Error %
552.19	554.42	0.404	33.56	32.88	2.026
436.13	441.90	1.323	38.20	38.69	1.283
522.82	524.37	0.296	51.50	51.52	0.039
634.43	633.59	0.132	37.64	37.30	0.903
624.84	621.77	0.491	40.90	39.92	2.396
566.93	567.80	0.153	38.70	38.42	0.724
539.20	539.64	0.082	47.20	47.14	0.127
Mean error %		0.412	Mean error %		1.071

7. Results of Graphical User Interface (GUI)

A graphical user interface program was constructed and designed to present the results of ANFIS on a graphical screen. All ANFIS models of tensile strength, tensile modulus, flexural strength and flexural modulus were recalled by using (GUI). In addition to prior data, other inputs data are only tested theoretically by using (GUI), three of these input data at: Prestress levels (12.5, 25 and 40 MPa) and curing temperatures (40, 67 and 97 °C) respectively, are calculated experimentally to be ensure from reality performance of ANFIS model. Table 3 shows the comparison between these three experimental and predicted GUI results with its percentage error for tensile strength and tensile modulus.

Table 3. Comparison between the experimental and predicted GUI results of carbon fiber-epoxy composite properties.

Tensile strength (MPa)			Tensile modulus (GPa)		
Exp.	GUI	Error %	Exp.	GUI	Error %
750.845	780.778	3.9865	42.069	41.171	2.1345
823.736	887.267	7.7125	52.333	53.470	2.1726
761.291	733.837	3.6062	41.567	37.856	8.9278

8. Conclusions

The most important conclusions that can be noted from this work are summarized as follows:

1. It was noted that carbon fiber prestress and curing processes of the epoxy were much helpful in improving the tensile strength, tensile modulus, flexural strength and flexural modulus of the carbon fiber-epoxy composite. Also, it can be noted that a high correlation coefficients and less mean square errors were achieved in predicting the tensile strength and tensile modulus.
2. Adaptive Neuro-Fuzzy Inference System (ANFIS) to model the mechanical properties of CFRE composite under tensile and flexural testing was used successfully in this work. The results show that the mean error between the experimental and predicted ANFIS results is 0.444%, 0.891%, 0.412%, 1.071% for tensile strength, tensile modulus, flexural strength and flexural modulus respectively. Also, it was observed that, the best membership functions for predicting the flexural strength are generalized bell membership functions with 4 number of membership function, and for predicting the tensile strength, tensile modulus and flexural modulus are gaussian membership functions with 4 number of membership functions. The performance of various model structures was investigated in terms of the R and MSE. The results showed good modeling performance.

9. Recommendations

Study the damage resistance behavior of the CFRE composite by using the low velocity impact test with the aid of C-scan techniques to measures the damaged area or the impact energy of this composite.

References

[1] S. Krishnamurthy, “Prestressed Advanced Fiber Reinforced Composites”, Ph.D. thesis, Cranfield University, 2006. http://hdl.handle.net/1826/1039

[2] H. S. Kim, D. G. Lee, “Avoidance of Fabricational Thermal Residual Stresses in Co-Cure Bonded Metal-Composite Hybrid Structures”, Journal of Adhesion Science and Technology, Vol. 20, Issue 9, pp. 959-979, 2006. https://doi.org/10.1163/156856106777657805

[3] S. Motahhari, “A Study of the Influences of Fiber Prestressing on the Mechanical Properties of Polymer Matrix Composites”, Ph.D. thesis, Queen's University, Kingston, Ontario, Canada, 1998.

[4] O. A. Abdullah, “Effect of Fiber Prestress and Curing Temperature on the Tensile and Flexural Properties of Carbon Fiber-Epoxy Composite”, Ph.D. thesis, University of Basrah, 2016.

[5] A. A. Al-Jeebory, A. I. Al-Mosawi, “Mechanical Properties of Araldite Matrix Composites Reinforced with Hybrid Carbon-Kevlar Fibers”, Al-Qadisiya Journal for Engineering Sciences, Vol. 3, Issue 1, pp. 44-50, 2010.

[6] J. Zhao, J. Cameron, “Polypropylene Matrix Composites Reinforced with Pre-Stressed Glass Fibers”, Polymer Composites, Vol. 19, Issue 3, pp. 218-224, 1998. https://doi.org/10.1002/pc.10093

[7] M. A. Jarrah, Y. Al-Assaf, H. E. Kadi, “Neuro-Fuzzy Modeling of Fatigue Life Prediction of Unidirectional Glass Fiber/Epoxy Composite Laminates”, Journal of Composite Materials, Vol. 36, Issue 6, pp. 685-700, 2002. https://doi.org/10.1177/0021998302036006176

[8] N. Vallalperumal, B. Vidivelli, “Anfis Based Modelling of CFRP Confined Concrete Columns Under Axial Compression”, Asian Journal of Civil Engineering (BHRC), Vol. 17, Issue 6, pp. 803-815, 2016.

[9] A. D. Habeeb, “Adaptive Neuro-Fuzzy Inference System Model for Predicting the Mechanical Properties of Carbon Fiber-Epoxy Composite”, M.Sc. thesis, University of Basrah, 2017.

[10] Sika Kimia Sdn Bhd, SikaWrap®-300 C Product Data Sheet, Edited by Lot 689 Nilai Industrial Estate, Malaysia, 2010.

[11] Sika Gulf B.S.C., Sikadur®-330 Product Data Sheet, Edited by Bldg. 925, Kingdom of Bahrain, 2006.

[12] ASTM D 3039. Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. Annual Book of ASTM Standards. Current edition published July 2000.

[13] I. O. Bachi, N. Abdulr azzaq, Z. He, “Neuro Fuzzy Model for Predicting the Dynamic Characteristics of Beams”, Acta Mechanica Solida Sinica, Vol. 27, Issue 1, pp. 85-96, 2014. https://doi.org/10.1016/S0894-9166(14)60019-7

[14] J. S. R. Jang, C. Tsai, E. Mizutani, Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence, Simon & Schuster/A Viacom Company, 3rd Edition, United States of America, 1997.