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ANFIS BASED MODELLING OF CFRP CONFINED CONCRETE COLUMNS UNDER AXIAL COMPRESSION

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ABSTRACT

This paper presents the results of Adaptive Neuro-Fuzzy Inference System (ANFIS) based model for Reinforced circular columns strengthened with Carbon fibre reinforced polymer (CFRP) sheets. The main objective of this paper is to propose ANFIS based model for predicting the performance characteristics of CFRP strengthened RC columns and to compare it with the experimental results. ANFIS uses neural network for computing the numerical results of functions and fuzzy logic for making decisions based on the resulting values. The ANFIS predicted results show good agreement with the experimental test results.

Keywords: ANFIS; CFRP; confinement; neural network and reinforced concrete.

1. INTRODUCTION

Concrete is the most widely used construction material. Because of its specialty of being cast in any desirable shape, it has some serious deficiencies which, but for its remarkable qualities of resilience, flexibility, and ability to redistribute stress, would have prevented its use as a building material. In the past two decays, the use of carbon fibre reinforced polymer (CFRP) as an externally wrapping have achieved considerable popularity for the strengthening and repair of concrete structures. The CFRP wrapping have been used successfully for retrofitting and strengthening of existing structures and deficient reinforced concrete elements.

One popular technique of CFRP strengthening is the externally wrapping of reinforced concrete columns to increase the axial strength, shear strength, and increase the stiffness and deflection. In this application, the CFRP sheet mainly wrapped around the columns with fibre oriented mainly in the circumferential (hoop) direction. The fibre confines the cover

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concrete and increase the strength and stiffness.

Reinforced concrete columns need to be laterally confined in order to ensure large deformation under applied loads before failure and to provide an adequate bearing capacity. When the CFRP wrapped concrete column is subjected to an axial compressive loading, the concrete core expands laterally. This expansion is resisted by the CFRP and therefore the concrete core is changed to a three dimensional compressive stress state. In this state the performance of concrete core is significantly influenced by the confinement pressure. Many investigations have been conducted into the behaviour of CFRP- wrapped concrete column subjected to a uni-axial compressive load, it will established that fibres should be aligned along the concrete core. In practice, however, almost all the columns are subjected to an eccentric axial load which can be resolved into a uni-axial compressive and bending moment.

2. RESEARCH SIGNIFICANCE

This study is intended to evaluate the effect of carbon fibre reinforced polymer wrapping on the performance characteristics of reinforced concrete circular columns. Different thickness of 0.35 mm and 0.70 mm with different types of wrapping (full wrap and band wrap) were considered as study parameters for assessing the strength and ductility of reinforced concrete circular columns and also to develop a ANFIS based model to predict the performance characteristics of CFRP confined RC circular columns. This investigation will provide an understanding on the relationship between internal steel confinement in the form of hoops and external CFRP confinement in the form of band and full wraps. This investigation is significant on account of the development of Adaptive Neuro-Fuzzy Inference System (ANFIS) based model for estimating the strength and deformation characteristics of CFRP confined reinforced concrete columns.

3. LITERATURE REVIEW

Ahmed Shaban Abdel-Hay [1] studied the effect of partial strengthening of R.C square columns using CFRP. For their study a total of ten square columns of size 200 x 200 x 2000 mm were used. One of them was a control specimen and the other nine specimens were strengthened with CFRP. The main principal parameters considered were the compressive strength of the upper part, the height of the upper poor concrete part, and the height of CFRP wrapped part of column. The authors concluded that partial strengthening of square columns with poor concrete at upper part can be used and significant to wrap the poor part only using one layer of CFRP.

Benzaid et al. [2] conducted tests on square prismatic concrete column, strengthened with external glass fibre composite. It was found that the stiffness of the applied FRP jacket was the key parameter in the design of external jacket retrofits.

Jason Fitzwilliam and Luke Bisby [3] studied the slenderness effects on circular CFRP confined reinforced concrete columns. The authors reported that CFRP wraps increase the strength and deformation capacity of slender columns, although the beneficial confining effects are proportionally greater for short columns, and that theoretical axial-flexural interaction diagrams developed using conventional sectional analysis (but incorporating a simple FRP confined concrete stress-strain model) provide conservative predictions for nonslender CFRP wrapped columns under eccentric loads. The authors demonstrated that the use of longitudinal CFRP wraps was to reduce lateral deflections and also to allow slender columns to achieve higher strengths, similar to otherwise identical nonslender columns.

Fujikake [4] proposed an analytical model for predicting the behaviour of FRP confined concrete subjected to axial compressive forces. The model adopts an incremental constitutive relationship. The model proposed a basic relationship between stresses and strains in three dimensional coordinates. The model proposed criteria for the determination of ultimate strength, ultimate strain and residual strength of FRP confined concrete. Poisson's ratio was also considered as an important parameter and was modeled as a function of its initial value, current strain and ultimate strain values rather than being treated as a constant. The predictions from the model were validated against experimental results published by several researchers. The experimental results and predictions were in close agreement.

Houssam et al. [5] studied the behaviour of large-scale rectangular columns. It was found that the higher aspect ratio resulted in a reduction in the confinement pressure and the compressive strength of a confined column increased as the corner radius increased.

Manuel and Carios [6] have conducted tests on models of circular cylindrical columns of concrete with GFRP jackets subjected to axial loading for different heights of cylinders and it was found that the increase in number of layers led to an increase in the maximum load.

Richard et al. [7] investigated the retrofit of square concrete columns with Carbon Fibre Reinforced Polymer (CFRP) for seismic resistance. The author investigated the prospect of strengthening deficient and repairing damaged square columns with CFRP jackets. It was found that added confinement with CFRP at critical locations enhanced ductility, energy dissipation capacity and strength of all substandard members.

Jagannathan et al. [8] evaluate the performances of GFRP confined high strength concrete columns under uni-axial compression in terms of load and deformation capacity. For their study high strength concrete columns strengthened with different configuration and stiffness of GFRP wraps were tested under axial compression until failure. The findings of the study reported that GFRP wrapped high strength concrete columns exhibit enhances performance. The authors concluded that out of three GFRP materials attempted UDC GFRP provided the maximum benefit with respect to load and deformation. The maximum ultimate stress was increased by 36.13% for 5 mm thick UDC wrapping when compared to reference column and the maximum ultimate axial strain was increased by 54.23% for 5 mm thick UDC wrapping when compared to reference column.

Sheik and Yau [9] have investigated the seismic behaviour of concrete columns confined with steel and Fibre Reinforced Polymer. The main variables investigated were axial load level, spacing of spiral, thickness and type of FRP. It was concluded that the use of FRP significantly enhances strength, ductility, and energy absorption capacity.

Zhang [10] studied the effectiveness of confining concrete columns using FRP having different fibres and resins. E-glass and carbon fibres were used with vinyl-ester and epoxy resins. The experiments revealed that glass fibres combined with vinyl-ester resin had very low cost of raw materials. The ratio between radius of column to thickness (R/T) of wrap proved to be a measure of effectiveness of the wrap. Fibre reinforcement in the hoop direction provided high confining efficiency. It was however suggested that some fibres in the axial direction may also be needed for composite wraps for slender columns.

4. EXPERIMENTAL COLUMNS

The concrete used for all RC column specimens had a compressive strength of 40MPa with a mix ratio of 1:1.54:3:0.5. The longitudinal reinforcement consisted of high yield strength deformed bars of characteristic strength 415MPa. The lateral ties consisted of mild steel bars of yield strength 250MPa. All the column specimens were provided with 12mm diameter bars as longitudinal reinforcement and 6mm diameter mild steel as ties at 120 mm spacing. Two types of CFRP wrapping were used for the study, namely, full wrap and band wrap of 0.35mm and 0.70mm thickness. The CFRP sheets were of Uni-Directional Cloth (UDC) having fibre orientation at 0° to the direction of CFRP fabric or perpendicular to the axis of column.

4.1 Details of column specimens

A total of 10 column specimens were tested. The principal variables considered in the study were type of CFRP wrap and thickness of CFRP sheet. The column specimens were of 150mm diameter and 1200mm in height. All the column specimens were provided with 12mm diameter bars as longitudinal reinforcement and 6mm diameter mild steel as ties at 120 mm spacing. Out of 10 specimens two served as control specimens without any wrapping, four specimens were confined with CFRP full wrap having 0.35mm and 0.70mm thickness and the remaining four specimens were confined with CFRP band wrap having 0.35mm and 0.70mm thickness. The details of all column specimens were presented in Table 1.

Table 1: Details of column specimens

Sl.No	Specimen Designation	Diameter (mm)	Tie Spacing (mm)	Type of CFRP	Type of Wrap	Thickness of CFRP (mm)
1	CCC1	150	120	-	-	0
2	CCC2	150	120	-	-	0
3	BWC1(0.35)	150	120	UDC	Band	0.35
4	BWC2(0.35)	150	120	UDC	Band	0.35
5	FWC1(0.35)	150	120	UDC	Full	0.70
6	FWC2(0.35)	150	120	UDC	Full	0.70
7	BWC1(0.70)	150	120	UDC	Band	0.35
8	BWC2(0.70)	150	120	UDC	Band	0.35
9	FWC1(0.70)	150	120	UDC	Full	0.70
10	FWC2(0.70)	150	120	UDC	Full	0.70

4.2 Bonding of CFRP Sheets

Figs. 1 to 6 shows the various steps involved in bonding the CFRP sheets to the test specimens.

Figure 1. Surface preparation

Figure 2. Putty application

Figure 3. Epoxy resin

Figure 4. Primer application

Figure 5. CFRP sheet application (full wrap)

Figure 6. CFRP sheet application (band wrap)

5. EXPERIMENTAL TEST SET-UP

Testing of specimens was carried out on a loading frame of 2000 kN capacity, by applying monotonically increasing compressive load at increments of 2 kN. The instrumentation details for the column specimens as line sketch was shown in Fig. 7 and the actual experimental test set-up was shown in Fig. 8. The specimen was placed on the loading frame, with dial gauges touching the top and bottom plates of the cap for recording axial deformation. Two dial gauges was placed at mid height of the column to measure lateral expansion.

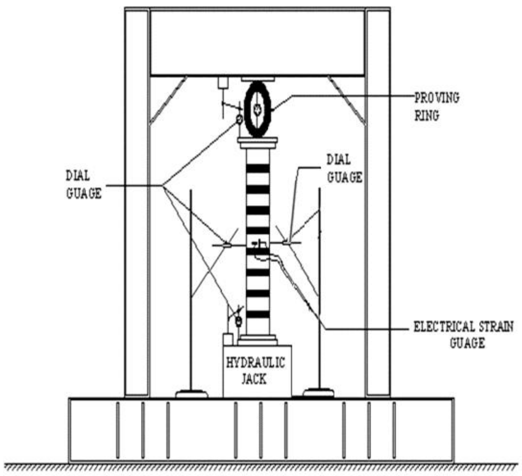


Figure 7. Test setup on concrete column under axial compression

Figure 8. Experimental test set-up

6. RESULTS AND DISCUSSION

Experimental Test Results Table 2 summarizes the test results at ultimate stage of control and CFRP strengthened RC circular columns. The stress – strain behaviour of all tested specimens are shown in Figs. 9 and 10.

From the experimental results (Table 2, Figs. 9 and 10), it can be observed that, at ultimate load level a significant increase in axial strength was achieved by CFRP confined RC columns. This increase may be attributed to the increase in tensile cracking strength of Concrete due to confinement by the UDC CFRP sheets. CFRP increased the axial strength in the range of 11.96% to 19.72% for columns confined by CFRP band wrap with varying thickness 0.35mm and 0.70mm when compared to unwrapped control specimen. At the same time for columns confined by CFRP full wrap with varying thickness 0.35mm and 0.70mm the axial strength increased in the range of 36.64% to 45.33% with respect to unwrapped control specimen. At ultimate stage the load carrying capacity of CFRP confined RC column increased by 45.33% when compared to control specimen. The effect of CFRP on axial deformation got increased in the range of 18.23% to 25.65% for CFRP band wrapped specimens with 0.30mm and 0.70mm thick and 23.10% to 32.91% for CFRP fully wrapped specimens with 0.30mm and 0.70mm thick. The FWC (0.7) specimen exhibit 32.91% increase in axial deformation when compared to control specimen.

Table 2: Test results at ultimate load level

Specimen Designation	Ultimate Load (kN)	Ultimate Axial Deflection (mm)	Axial Strain	Lateral Strain	Ultimate Stress (MPa)	Deflection Ductility	Energy Ductility	Deflection Ductility Ratio	Energy Ductility Ratio	Energy Absorption (kJ)
CCC1	540	4.05	0.01281	0.0039	30.55	4.98	19.59	1	1	785.04
BWC1(0.35)	640	4.97	0.01431	0.0041	36.21	6.02	21.47	1.21	1.09	1260.64
FWC1(0.35)	874	5.02	0.01817	0.0081	49.48	13.18	23.93	2.64	1.22	1868.56
BWC1(0.70)	705	5.65	0.01679	0.0060	39.89	13.25	25.13	2.66	1.28	2016.17
FWC1(0.70)	985	6.22	0.02047	0.0097	55.75	13.88	45.41	2.78	2.31	1827.55
CCC2	574	4.26	0.01391	0.0039	32.46	5.08	15.91	1	1	965.52
BWC2(0.35)	652	5.21	0.01522	0.0042	36.87	5.99	16.21	1.17	1.01	1386.8
FWC2(0.35)	906	5.54	0.01863	0.0082	51.25	12.22	29.08	2.40	1.82	1405.33
BWC2(0.70)	715	5.73	0.01679	0.0062	40.46	12.64	30.45	2.48	1.91	1674.55
FWC2(0.70)	1050	6.35	0.02104	0.0106	59.41	13.60	35.7	2.67	2.24	2046.52

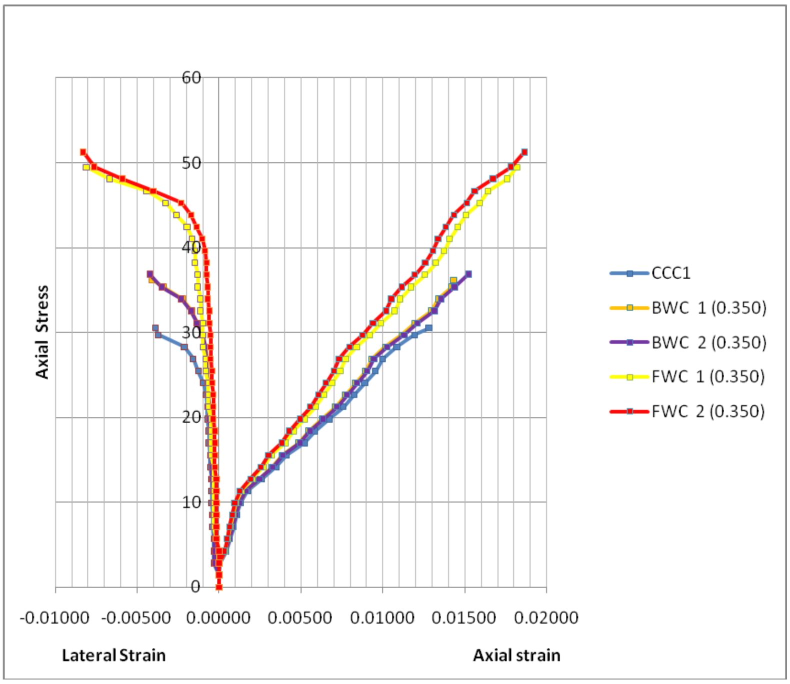


Figure 9. Typical stress-strain behaviour of control and (0.35 mm) CFRP confined RC columns

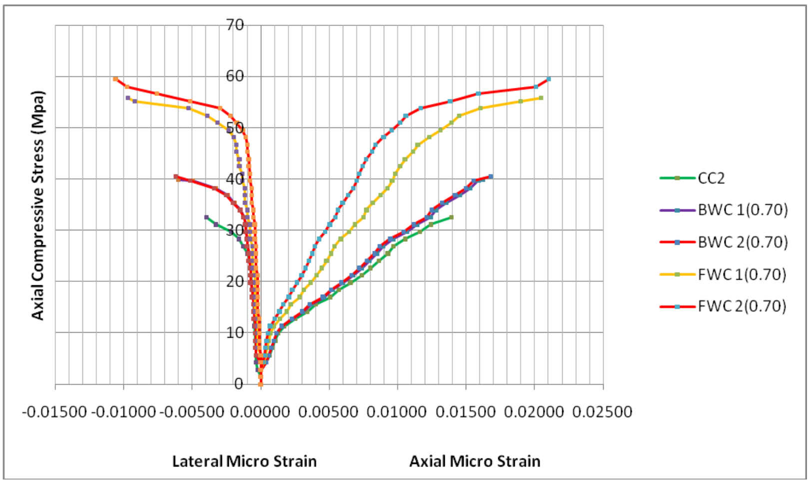


Figure 10. Typical stress-strain behaviour of control and (0.70 mm) CFRP confined RC columns

ANFIS Modeling

The ANFIS model for predicting the performance characteristics of CFRP confined RC columns was developed by preparing the data sets for training and testing of the ANFIS. The ANFIS model was generated on MATLAB software.

ANFIS as modelling systems consists of three distinct segments:

i) input parameters and membership functions,
ii) adaptive neuro-fuzzy inferencing system,
iii) output parameter and the defuzzifier, if necessary.

A schematic view of an ANFIS object is shown in Fig. 11.

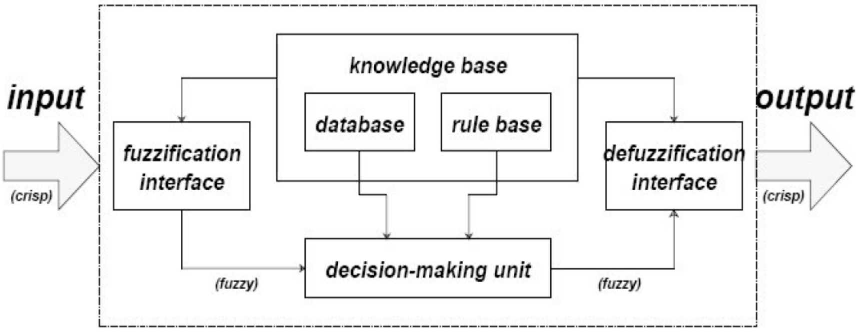


Figure 11. ANFIS schematic view

The ANFIS model is capable of predicting only one output parameter for various input parameters. Hence, each prediction parameter requires a separate ANFIS object to be generated. The input parameters supplied to ANFIS objects are the type of wrap (0-Unwrapped, 1-Bandwrap and 2-Fullwrap) and the thickness of wrap material (0.35mm and 0.70 mm) which remain same for all objects. ANFIS objects were produced at the rate of one object per parameter for ultimate load, ultimate axial deflection, ultimate stress, ultimate axial micro-strain, ultimate lateral micro-strain, energy absorption (EA), deflection ductility (DD), energy ductility (ED), deflection ductility ratio (DDR) and energy ductility ratio (EDR).

The training and test data used for developing the Fuzzy Inference Systems (FIS) are shown in Table 3.

Table 3: Training and testing data

Specimen Designation	Type of Wrap	Wrap Thickness (mm)	Ultimate Load (kN)	Ultimate Axial Deflection (mm)	Axial Strain	Lateral Strain	Ultimate Stress (MPa)	Deflection Ductility	Energy Ductility	Deflection Ductility Ratio	Energy Ductility Ratio	Energy Absorption (kJ)
Training Data												
CCC2	0	0	574	4.26	0.01391	0.0039	32.46	5.08	15.91	1	1	965.52
BWC2(0.35)	1	0.35	652	5.21	0.01522	0.0042	36.87	5.99	16.21	1.17	1.01	1386.8
FWC2(0.35)	2	0.35	906	5.54	0.01863	0.0082	51.25	12.22	29.08	2.40	1.82	1405.33
BWC2(0.70)	1	0.70	715	5.73	0.01679	0.0062	40.46	12.64	30.45	2.48	1.91	1674.55
FWC2(0.70)	2	0.70	1050	6.35	0.02104	0.0106	59.41	13.60	35.7	2.67	2.24	2046.52
CCC1	0	0	540	4.05	0.01281	0.0039	30.55	4.98	19.59	1	1	785.04
BWC1(0.35)	1	0.35	640	4.97	0.01431	0.0041	36.21	6.02	21.47	1.21	1.09	1260.64
FWC1(0.35)	2	0.35	874	5.02	0.01817	0.0081	49.48	13.18	23.93	2.64	1.22	1868.56
Testing Data												
BWC1(0.70)	1	0.70	705	5.65	0.01679	0.0060	39.89	13.25	25.13	2.66	1.28	2016.17
FWC1(0.70)	2	0.70	985	6.22	0.02047	0.0097	55.75	13.88	45.41	2.78	2.31	1827.55

Triangular membership function was selected for the input data and for output data the output membership function was constant membership function as shown in Fig. 11

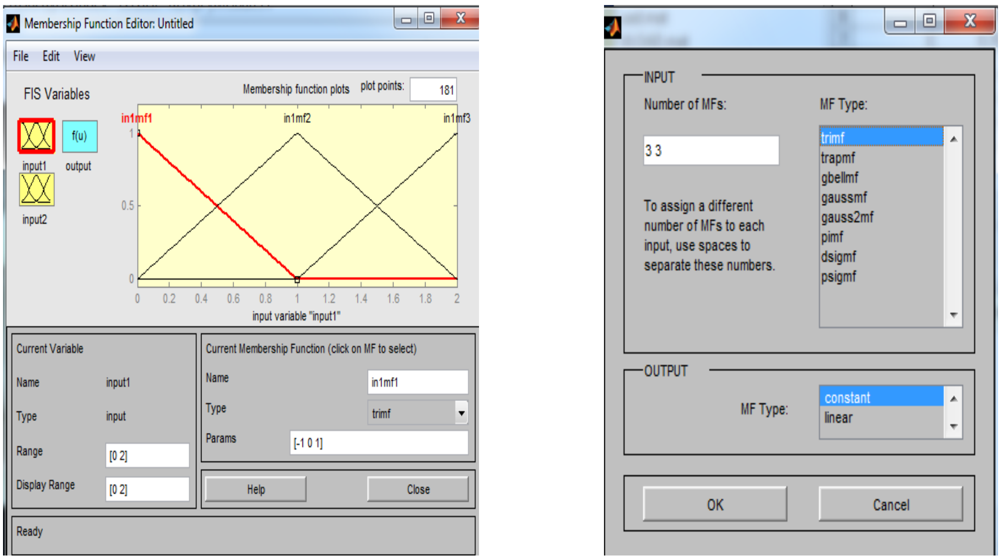


Figure 11. Input and output membership function

The ANFIS objects developed for predicting various performance parameters related to the CFRP confined reinforced concrete columns predicted data with varying degrees of errors.

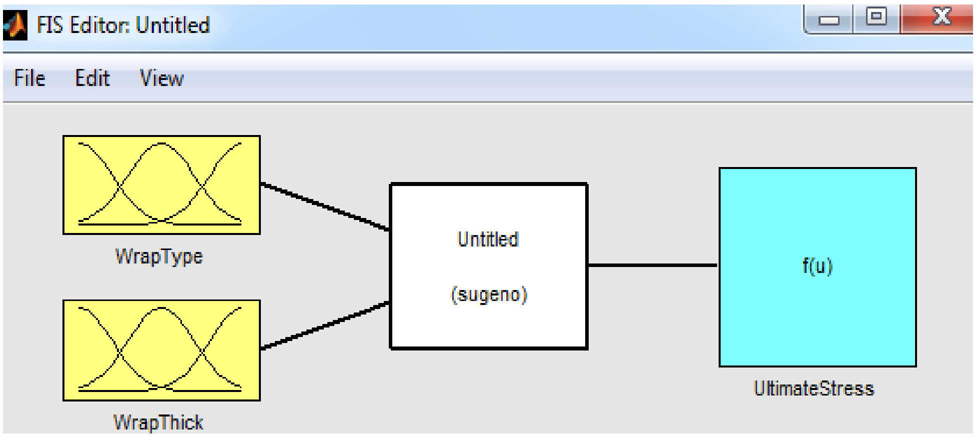
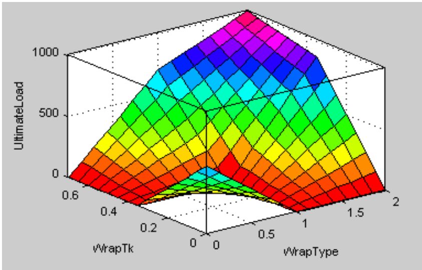


Figure 13. Schematic view of typical ANFIS object

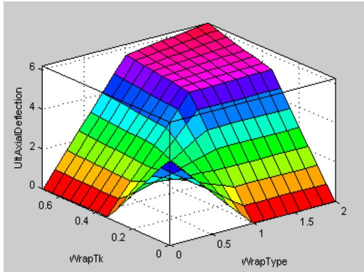
The schematic view of typical ANFIS object is shown in Fig. 13. The errors associated with the final ANFIS objects are shown in Table 4. The errors displayed in the tables, called Root Mean Squared Percentage Errors, were calculated as the root mean squared error for the parameter divided by the mean of the parametric values and converted to percentage.

Table 4: Errors in training and testing parameters

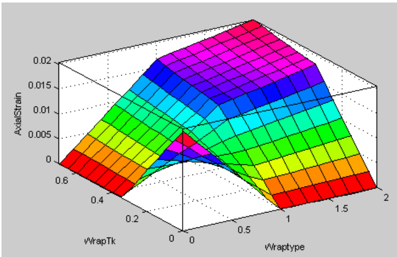
Sl. No.	Parameter	RMSE Percentage Error in Training	RMSE Percentage Error in Testing
1	Ultimate Load (MPa)	6.991	7.631
2	Ultimate Axial Deflection (mm)	3.492	5.107
3	Ultimate Stress (MPa)	0.703	5.0385
4	Ultimate Axial Micro-Strain	3.360	4.791
5	Ultimate Lateral Micro - Strain	5.687	8.393
6	Deflection Ductility	0.627	0.863
7	Deflection Ductility Ratio	0.080	0.2773
8	Energy Ductility	4.799	5.1385
9	Energy Ductility Ratio	0.232	0.6347
10	Energy Absorption (kJ)	13.814	16.315



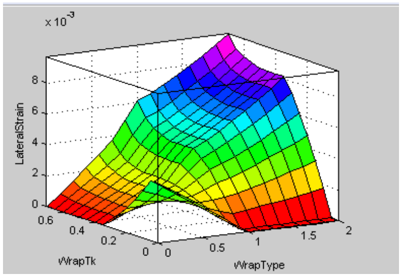
Ultimate Load



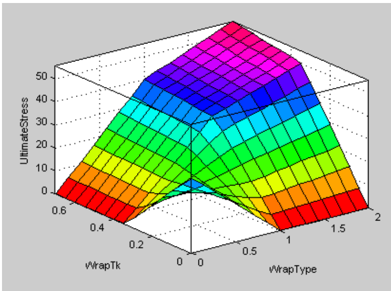
Ultimate Axial Deflection



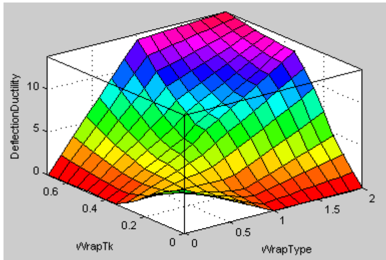
Axial Strain



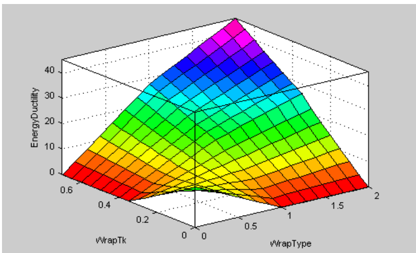
Lateral Strain



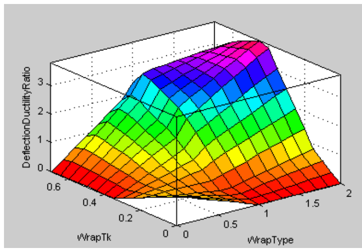
Ultimate Stress



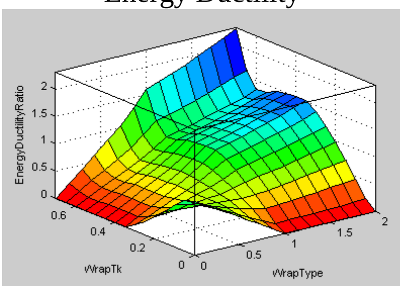
Deflection Ductility



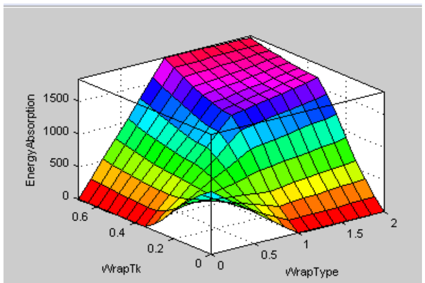
Energy Ductility



Deflection Ductility Ratio



Energy Ductility Ratio



Energy Absorption

Figure 14. Three dimensional surface plot for all performance characteristics

The simulation surfaces exhibit acceptable values throughout the domain of interest for experimental data as input. The absence of any abnormal changes in the slope of the simulation surfaces indicates the ability of the ANFIS objects to smoothly predict the values at points other than the training points. Hence, the models generated for predicting the properties of CFRP confined reinforced concrete columns perform well to predict the required properties within the domain of experimental input data.

7. CONCLUSIONS

Based on the test results the following conclusions are drawn:

- Strengthening of RC columns using UDC-CFRP sheets exhibit higher load carrying capacity. The percentage increase in ultimate load varied from 11.96% to 45.33% for CFRP strengthened RC columns.
- The percentage increase in axial deflection at ultimate stage was 22.26% for 0.35mm CFRP band wrapped RC columns and 26.89% for 0.35mm CFRP full wrapped RC columns.
- The percentage increase in axial deflection at ultimate stage was 29.31% for 0.70mm CFRP band wrapped RC columns and 36.22% for 0.70mm CFRP full wrapped RC columns.
- CFRP strengthened RC columns failed in buckling mode only.
- The ANFIS based model show good agreement with the experimental test results. The simulation surfaces exhibit acceptable values throughout the domain of interest for experimental data

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