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Adaptive Neuro-Fuzzy Inference System Based Modeling for Fibre Reinforced Polymer Jacketed HSC Columns

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Abstract:–The paper presents the results of a study on the performance of Glass Fibre Reinforced Polymer (GFRP) wrapped high strength concrete columns under uni-axial compression. The columns had slenderness ratios of 8, 16, 24 and 32. Three types of wrap materials (Chopped Strand Mat GFRP, Uni-Directional Cloth GFRP and Woven Roving GFRP) were used with 3 mm and 5 mm thicknesses. The columns were tested under monotonic axial compressive loading up to failure. The deflections and axial strain were noted for each load increment. The HSC columns with GFRP wrapping exhibited improved performance in terms of load and deformation capacity. Adaptive Neuro - Fuzzy Inference System (ANFIS) modeling has been proposed for predicting the performance parameters. A better correlation has been observed between the test results and those predicted through the proposed modeling.

Keywords:–ANFIS, Deformation, GFRP, High Strength Concrete, Strength, Stress

I. INTRODUCTION

Reinforced concrete columns confined with FRP composites exhibit higher compressive strength, axial strain and lateral strain at ultimate state. The ductility values are also higher for FRP confined columns. The effect of FRP wrap is not the same for columns with different slenderness ratios, although the available equations for predicting compressive strength do not consider slenderness ratio as a parameter. Most of the results for FRP confined concrete and theoretical models published in the literature are based on short stubs for which slenderness ratio is very minimal.

The effect of slenderness ratio on the performance of reinforced concrete columns with FRP wrap at yield level and ultimate level were studied. The combined effect of slenderness ratio and thickness of FRP wrap on stresses, axial strains and lateral strains for the columns were studied. Mirmiran et al. [1] investigated the slenderness limit for hybrid FRP confined concrete columns. Seven Concrete Filled FRP Tube (CFFT). Specimens having slenderness ratios of 4, 11, 18, 22, 30, 34 and 36 were prepared and tested uniaxial compression. Typical failure of specimens was characterized by rupture of FRP wrap at points of maximum stress concentration, which were away from the centre of the columns. It was shown that slenderness did not affect the stiffness of the hybrid system, but resulted in reduced compressive strength and axial strain characteristics. An analytical model was also proposed for estimating the strength of FRP confined concrete columns.

Girard and Bastien [2] studied the behaviour of reinforced concrete columns confined by lateral ties using a finite element bond slip model. The model was capable of accounting for the confinement provided by hoop reinforcement, softening of concrete and for the gradual loss of bond between concrete and steel. The results of finite element simulation agreed well with experimental results reported by other researchers.

Challal et al. [3] carried out extensive experimental investigations on short columns of square and rectangular shape, on a total of 90 specimens. Three ratios of shorter face to longer face of cross sections were adopted at 1.000, 0.654 and 0.500 with constant area and corner radius of 25.4 mm. Two grades of concrete at 20.7 MPa and 41.4 MPa were adopted with zero, one, two, three and four layers of CFRP wrapping. The investigation found that the rate of gain of strength fell down with increase in level of confinement, while the ductility levels showed remarkable increase with increasing confinement. The researchers categorized the behaviour of confined concrete as bilinear with three distinct regions: i) initial behaviour similar to plain concrete, ii) transition zone in which CFRP exerted confining pressure on the core, as the core deteriorated and iii) constant stiffness zone where the confinement effect of CFRP stabilized to a constant value. The poison's ratio for the columns was stable around 0.2 while the dilation ratio for plastic response was influenced by level of confinement.

Hadi and Li [4] investigated the behaviour of high strength concrete columns with FRP confinement. The specimens were confined using carbon, glass and kevlar fibre reinforced polymer of varying thicknesses and subjected to concentric as well as eccentric loading. All columns failed in a brittle manner. The failure of unconfined columns was highly explosive. Under concentric loading conditions, confinement using kevlar FRP resulted in some increase of deflection and ductility over the unconfined specimens. Carbon fibre wrapped specimens with single layer failed explosively, while those with three layers seemed to appear integral without any damage to the wrap even after failure of the column. Under eccentric loading, carbon FRP confined columns failed explosively, while kevlar and glass FRP confined specimens showed adequate warning in the form of white patches on FRP surface at the time of initiation of failure.

Aire et al. [5] investigated the stress-strain behaviour of axially loaded concrete cylinders with compressive strengths of 30 MPa and 70 MPa. Confinement was provided with GFRP and CFRP. The number of layers was 1, 3 and 6 for 30 MPa concrete core and 1, 3, 6, 9 and 12 layers for 70 MPa concrete. It was observed that CFRP was more effective in providing confinement and led to more compressive strength when compared to corresponding number of layers of GFRP. The failure of columns confined with CFRP was explosive while the failure of columns confined with GFRP was less explosive, although sudden in nature. The results indicated that hardening type failure was noticed in confined concrete with multiple layers of FRP. Both compressive strength and axial strain capacities improved due to confinement. It was observed that FRP confinement was more effective for normal strength concrete than for high strength concrete. An analytical model was also proposed as part of the work and the results from the model agreed well with experimental results.

Kaminski and Trapko [6] investigated the effect of varying configurations of FRP strengthening on the performance of reinforced concrete columns having square and circular cross sections. External CFRP strips in the longitudinal direction, CFRP longitudinal strips combined with transverse bands, CFRP longitudinal strips combined with full length transverse CFRP wraps, CFRP transverse wraps alone. Internal adhesive bonding of CFRP longitudinal strips,CFRP strips combined with bands and CFRP strips combined with wrap. The increase in load-carrying capacity was attributed to the lower strain in CFRP confined columns compared to unconfined columns at the same load levels. The specimens with longitudinal CFRP without bands or wraps showed that the failure was induced by damage at the contact surface. Some of band wraps failed in the case of longitudinal strips combined with band wraps.

Saenz and Pantelides [7] proposed a strain-based model for FRP confined concrete. The model estimated the stress corresponding to the given strain level. The secant modulus with a softening mechanism was used in the model. The fundamental behaviour of FRP under loading was described. Volumetric contraction was exhibited in the linear elastic axial response zone. As the concrete softened, the volumetric strain reached zero marking the transfer of load from concrete core to the FRP confinement. The radial strain at zero volumetric strain marked the activation of FRP confinement. The model consisted of linear elastic response regime, transition regime and ultimate axial stress-radial strain regime. The ultimate radial strain of the FRP confined column was expressed as a function of the confinement effectiveness.

The present study attempted to investigate the relationship between column parameters like slenderness ratio and thickness of FRP wrap and performance parameters like ultimate compressive stress and ultimate axial strain. The combined effect of slenderness and FRP wrap on the performance of concentrically loaded concrete columns was not so clearly established in the literature yet.

II. MATERIALS AND METHODS

2.1 Material Properties**:** The designed concrete mix was used for casting the specimens. The mix ratio for design strength of 60 MPa was 1:1.73:2.51 (1 part of cement: 1.73 part of fine aggregate: 2.51 part of coarse aggregate). The w/c ratio adopted in the mix 0.34 and corresponding percentage of hyper plasticizer used as 0.8. The characteristic compressive strength of the concrete obtained from the laboratory test was 63.64 MPa.. High yield strength deformed (HYSD) having an yield strength of 450 MPa were used for as longitudinal reinforcement and a yield strength of 300 MPa mild steel bars were used for as lateral ties. Properties of glass Fibre Reinforced Polymer (GFRP) is presented in Table 1.

Table1. Properties of glass Fibre Reinforced Polymer (GFRP)

Sl. No	Type of Fibre in GFRP	Thickness (mm)	Tensile Strength (Mpa)	Ultimate Elongation (%)	Elasticity Modulus (Mpa)
1.	Chopped Strand Mat	3	126.20	1.60	7467.46
2.	Chopped Strand Mat	5	156.00	1.37	11386.86
3.	Uni-Directional Cloth	3	446.90	3.02	13965.63

4.	Uni-Directional Cloth	5	451.50	2.60	17365.38
5.	Woven Rovings	3	147.40	2.15	6855.81
6.	Woven Rovings	5	178.09	1.98	8994.44

2.2 Preparation of Specimen: All the specimens were prepared by using asbestos cement pipe moulds. Asbestos cement pipes were cut to 300 mm, 600 mm, 900 mm, and 1200 mm size to suit the specimens. After cutting, the pipes were placed firmly in position using a lean mix mortar at the base. The bottom faces of the pipes were covered with polymer sheets to avoid any leaks. Cover blocks were placed at appropriate places to ensure adequate cover to the reinforcement. The inner surfaces of the pipes were lubricated oil using to prevent concrete from adhering to the asbestos cement pipe. Steel reinforcement cage was prepared for each specimen according to the requirements. The reinforcement cages were placed into the asbestos cement pipe formwork and positioned in such a way that pre determined cover was available on all sides. The designed concrete mix was filled into the moulds in layers. Adequate compaction was carried out using needle vibrator to avoid honeycombing. The specimens were removed from mould without any damage and cured in a standard manner for a period of 28 days.

2.3 Wrapping with FRP: The cured specimens were prepared for wrapping with FRP. The surfaces of the specimens were grounded with a high grade grinding wheel to remove all loose and deleterious material from the surface. A jet of compressed air was applied on the surface to blow off any dust and dirt. Then, all surface cavities were filled up with mortar putty to ensure a uniform surface and to achieve proper adhesion of FRP wraps to the outer surface of concrete columns. The specimens were wrapped with GFRP fabrics of appropriate fibre type by applying the resin on the surface of the specimens, wrapping them with FRP fabric and measured quantities of resin to the application of successive layers of FRP fabric and resin. The wrapped surfaces were gently pressed with a rubber roller to ensure proper adhesion between the layers and proper distribution of resin. Figs.1-3 shows the application of FRP wrap on the surface of the column specimen.

Fig 1 Air-Cleaning under Progress

Fig.2 Wrapping under Progress

Fig 3 Wrapped Specimens

III. TEST SPECIMENS

The test specimen comprised of 28 column specimens having 150 mm diameter with slenderness ratios of 8, 16, 24 and 32. The longitudinal reinforcement consisted of 6 bars of 8 mm diameter and internal ties consisted of 6 mm diameter bars at 115 mm spacing. Out of the twenty eight columns, one reference column was tested without any wrapping and the remaining columns were wrapped with GFRP of varying configuration with different thickness for each slenderness ratio. The specimen designations, slenderness ratios, geometrical details and wrap details are provided in Table 2.

Table 2 Specimen Details

Sl No	Details of specimens	Diameter (mm)	Height (mm)	Type of GFRP	Thickness of GFRP (mm)	Nominal slenderness
	S8R0	150	300	-	0	8
	S8CSM3	150	300	CSM	3	8
	S8CSM5	150	300	CSM	5	8
	S8UDC3	150	300	UDC	3	8
	S8UDC5	150	300	UDC	5	8
	S8WR3	150	300	WR	3	8
	S8WR5	150	300	WR	5	8
	S16R0	150	600	-	0	16
	S16CSM3	150	600	CSM	3	16
	S16CSM5	150	600	CSM	5	16
	S16UDC3	150	600	UDC	3	16
	S16UDC5	150	600	UDC	5	16
	S16WR3	150	600	WR	3	16
	S16WR5	150	600	WR	5	16
	S24R0	150	900	-	0	24
	S24CSM3	150	900	CSM	3	24
	S24CSM5	150	900	CSM	5	24
	S24UDC3	150	900	UDC	3	24
	S24UDC5	150	900	UDC	5	24
	S24WR3	150	900	WR	3	24
	S24WR5	150	900	WR	5	24
	S32R0	150	1200	-	0	32
	S32CSM3	150	1200	CSM	3	32
	S32CSM5	150	1200	CSM	5	32
	S32UDC3	150	1200	UDC	3	32
	S32UDC5	150	1200	UDC	5	32
	S32WR3	150	1200	WR	3	32
	S32WR5	150	1200	WR	5	32

IV. TEST SET-UP

Testing of specimens having heights of 300 mm, 600 mm, 900 mm and 1200 mm was carried out on a loading frame of 2000 kN capacity. Two deflectometers, one at each end were fixed the column to measure the axial deformation. One extensometer was fixed along circumference of the column at mid height to observe the lateral deformation of the column. The least count of all the defletometers was found to be 0.01 mm and for the extensometer is 0.001 mm. Fig 4 shows the instrumentation for columns having 900 mm height on a loading frame

Fig. 4 Test set-up with instruments

After the completion of the proper curing of GFRP wrapped columns, the specimens were placed and positioned in the column testing frame. The verticality of all columns was perfectly maintained after providing necessary end caps for the column at both ends. The columns were placed co axially with the line of action of the application of axial load. Initially, all the dial gauges of deflecto meters, extensometer and proving ring were adjusted to zero. A monotonic static load was applied in steps to the column with an increment of 25 kN up to its failure.

The applied loads were observed using the dial gauge of the hydraulic pump and verified using that of the proving ring. The lateral deflectometers and the axial strains were observed for each and every load increment. The loads were applied till the failure of the columns. At failure stage, ultimate load, corresponding deformation and axial strain were noted. After the completion of all observations the load was released using the hydraulic pump and the specimens were replaced. Photographs were taken and presented to show the crack pattern of the wrapped at corresponding load stages.

V. RESULT AND DISCUSSION

The ultimate loads, stresses and strains reached by the experimental specimens are presented in Table 3.The stress-strain curves for all the twenty eight reinforced concrete columns (with and without GFRP wrapping) tested for the experimental investigations1. The stress-strain curves for the columns grouped by slenderness ratio are presented in Figs. 5 to 8, grouped by thickness of GFRP wrapping are presented in Figs.9 to11.

Table 3 Ultimate Loads, Stresses and Strains for Tested GFRP Wrapped Columns

Specimen Designation	**Ultimate Load (kN)**	**Ultimate Deflection (mm)**	**Ultimate Stress (MPa)**	**Ultimate Axial micro-Strain ($\mu\varepsilon$)**
S8R0	1150	2.93	65.08	9766.67
S16R0	1080	3.01	61.12	5016.67
S24R0	1000	3.29	56.59	3655.56
S32R0	900	3.45	50.93	2875.00
S8CSM3	1220	3.02	69.04	10066.67
S16CSM3	1140	3.16	64.51	5266.67
S24CSM3	1050	3.56	59.42	3955.54
S32CSM3	990	3.62	56.02	3016.67
S8CSM5	1300	3.32	73.56	11066.67
S16CSM5	1200	3.46	67.91	5766.67
S24CSM5	1175	3.89	66.49	4322.22
S32CSM5	1025	4.02	58.00	3350.00
S8UDC3	1370	4.70	77.53	15666.67
S16UDC3	1300	4.82	73.56	8033.33
S24UDC3	1275	4.90	72.15	5444.44
S32UDC3	1190	5.04	67.34	4200.00
S8UDC5	1450	4.83	82.05	16100.00
S16UDC5	1375	4.94	77.81	8233.33
S24UDC5	1330	5.04	75.26	5600.00
S32UDC5	1225	5.35	69.32	4458.33
S8WR3	1270	3.92	71.87	13066.67

Specimen Designation	Ultimate Load (kN)	Ultimate Deflection (mm)	Ultimate Stress (MPa)	Ultimate Axial micro-Strain ($\mu\varepsilon$)
S16WR3	1170	4.23	66.21	7050.00
S24WR3	1120	4.17	63.38	4633.33
S32WR3	1050	4.35	59.42	3625.00
S8WR5	1320	4.28	74.70	14266.67
S16WR5	1225	4.33	69.32	7216.67
S24WR5	1185	4.33	67.06	4811.11
S32WR5	1090	4.90	61.68	4083.33

5.1 Stress-Strain Behaviour of Tested HSC Columns

The stress-strain curves for all the twenty eight reinforced concrete columns (with and without GFRP wrapping) tested for the experimental investigations1. The stress-strain curves for the columns grouped by slenderness ratio are presented in Figs. 5 to 8, grouped by thickness of GFRP wrapping are presented in Figs.9 to11.

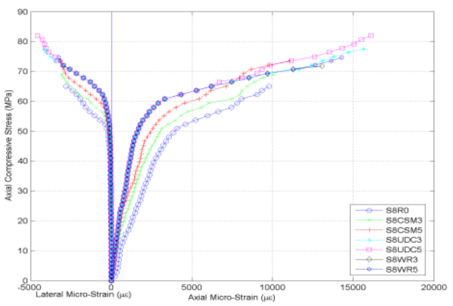

Fig. 5 Stress- Strain Curves for Columns R8

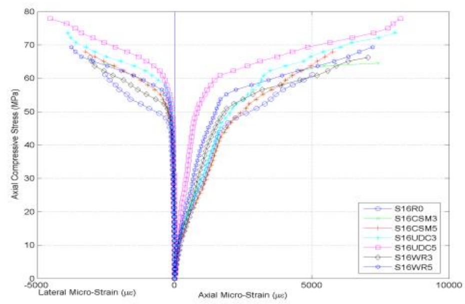

Fig. 6 Stress- Strain Curves for Columns R16

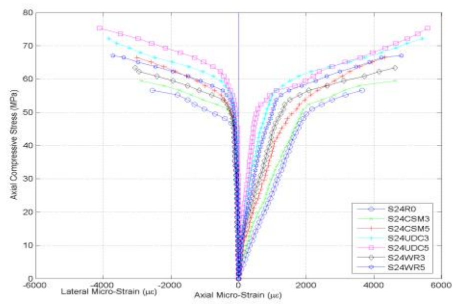

Fig. 7 Stress -Strain Curves for Columns R24

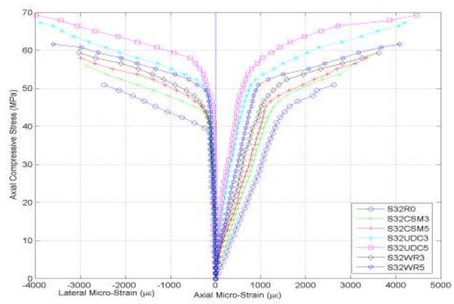

Fig. 8 Stress -Strain Curves for Columns R32

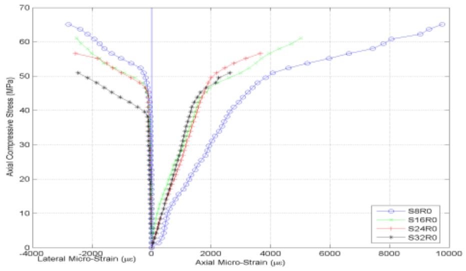

Fig. 9 Stress- Strain Curves for Columns (without wrap)

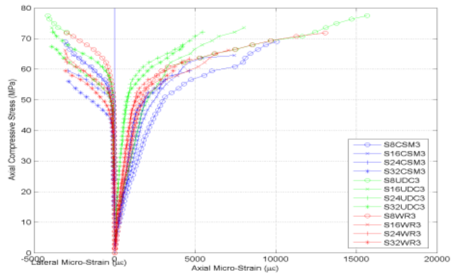

Fig. 10 Stress- Strain Curves for Columns - 3 mm Thick GFRP Wrap

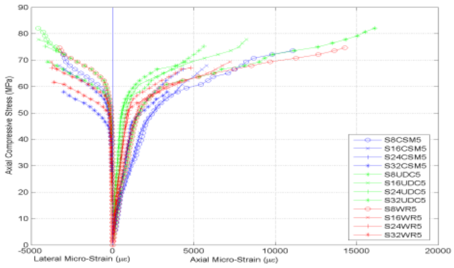

Fig. 11 Stress- Strain Curves for Columns with 5 mm Thick GFRP Wrap

The stress-strain curves indicate the general trend that all the columns exhibit similar behaviour in the initial phase. The differences arising due to the variations in wrapping thickness and material are first exhibited in the form of different levels of yield stresses, although the differences are not as high as those for ultimate stresses. The yield point on the stress-strain curve signifies the point at which the concrete core begins to crush. Until reaching the yield point, the concrete core is sound and resists much of the load applied on it.

The columns with UDCGFRP wrapping normally showed better stress-strain behaviour. The stress levels and strain levels reached by UDCGFRP wrapped columns were higher than those reached by corresponding columns with CSMGFRP or WRGFRP of the same thickness. The columns wrapped with 3 mm thick CSMGFRP and WRGFRP showed similar stress-strain trends up to failure. But the behaviour of 5 mm thick WRGFRP wrapped column was better than that of 5 mm thick CSMGFRP wrapped column. In the group of columns with slenderness ratio of 16, the 5 mm thick UDCGFRP wrapped column reached the highest stress and strain values. The stress and strain levels reached by 3 mm thick UDCGFRP wrapped column and 5 mm thick WRGFRP wrapped column were very close, but the stress-strain paths followed by the two were different. In the case of columns with slenderness ratio of 24, the stress-strain curve for 3 mm thick UDCGFRP was very closely followed that of column with 5 mm thick UDCGFRP, but failed at lower stress value. The columns with 3 mm thick CSMGFRP and WRGFRP reached same stress levels, but the strain for CSMGFRP was lower. The stress and strain levels reached by 3 mm thick UDCGFRP wrapped column were higher than those reached by even 5 mm thick CSMGFRP and WRGFRP wrapped columns.

5.2 Results at Ultimate Stage

The performance of GFRP wrapped columns at ultimate stage showed the influence of GFRP wrap material on stress and strain values. The influence of GFRP wrapping was more on the stress and strain values at ultimate stage than those at yield stage. The yield point marked the start of participation of GFRP in resisting applied stresses, while the ultimate point marked the failure of the wrapping mechanism after exhausting its capacity. The axial deflections for columns with higher slenderness ratios were more than those for the columns with lower slenderness ratios. But the ultimate axial strains reached by the columns with more slenderness turned out to be lower than those reached by columns with lower slenderness. The reinforced concrete columns with UDCGFRP wrapping showed the highest in ultimate stress and ultimate axial strain. The columns wrapped with CSMGFRP and WRGFRP exhibited similar performance in terms of stresses and strains but the values were generally lower than those for UDCGFRP. The ultimate stresses and ultimate axial strain were shown in Figs 12 and 13.

VI. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM (ANFIS)

Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid system consisting of a Fuzzy Inference System whose membership functions are tuned to perform well using a back propagation neural network. The use of neural network makes the fuzzy inference system adaptive and permits the outputs to be so adjusted as to produce the least error. ANFIS is highly suitable for function approximation works, where the input parameters and output values are known, but the mathematical relationship between them is not available, as in the case of experimental results.

ANFIS as modelling systems consists of three distinct segments: i) the input parameters and membership functions, ii) the adaptive neuro-fuzzy inferencing system, iii) the output parameter and the defuzzifier, if necessary. A schematic view of an ANFIS object is shown in Fig.14.

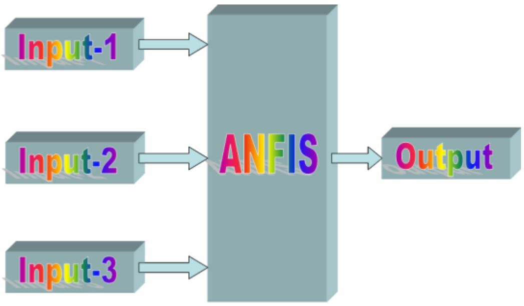

Fig. 14 Schematic View of ANFIS

The present implementation of ANFIS model was carried out using the fuzzy logic toolbox available in MATLAB software. The implementation permits choosing the number and type of membership function associated with each input and the number of epochs required for training the ANFIS. The generation of the network and tuning of the network parameters to match the expected target values are fully automated, with provision for supplying a test data set along with the training set to avoid over-fitting the inference system.

The ANFIS model is capable of predicting only one output parameter, although the input parameters may be many in number. Hence, each prediction parameter requires a separate ANFIS object to be generated. The input parameters supplied to ANFIS objects are the tie spacing, the type of wrap material and the thickness of wrap material and they remain the same for all objects. ANFIS objects were produced at the rate of one object per parameter for ultimate load, ultimate deflection, ultimate lateral deflection, ultimate stress and ultimate axial micro-strain. The training and test data used for developing the Fuzzy Inference Systems (FIS).

Triangular membership function was selected for the input data and constant membership function was selected for the output. The number of membership functions was two per parameter for most of the cases. The choice of membership functions was made by conducting a trial run of the ANFIS objects generated using several alternative functions like triangular membership function, trapezoidal membership function, pi membership function, sigmoid membership function, generalized bell membership function, Gaussian membership function, S-Shaped membership function *etc.*. The performance of certain membership functions is good for certain data patterns. The present data showed minimum error levels for triangular input membership function.

The output membership function can either be a constant membership function or a linear membership function. For the present data, constant output membership function produced the minimum error. The representation of triangular membership functions is shown in Fig.15.

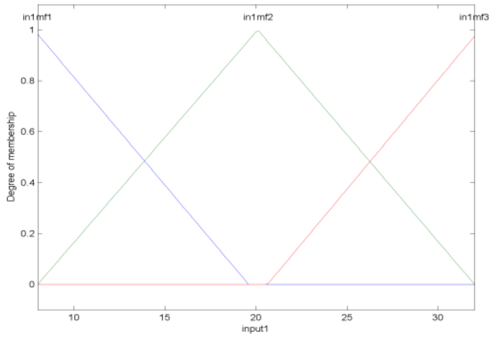

Fig.15 Typical Triangular Membership Function

The ANFIS command takes the following inputs: the genfis1 object, maximum number of epochs of training, target value for training, training parameters like initial step size, step down factor, step up factor, display parameters to decide whether to display general ANFIS information, error, step size at each parameter update, final results and the checking data. The checking data, if provided, helps the ANFIS object to avoid over-fitting to the training data and return the ANFIS object which produced the least amount of error for the testing data. Hence, the ANFIS object having desired properties should be ready on running the ANFIS command. Schematic view of typical ANFIS object is shown in Fig.16.

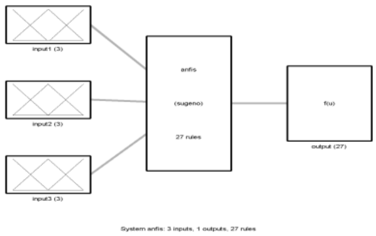

Fig. 16 Schematic View of typical ANFIS General Object

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

The data presented in column of Table 4 correspond to the errors associated with testing data, which was not used for training the parameters, but only for checking the performance of the ANFIS objects generated using the training data. These error values provide a means for validation of the performance of the ANFIS objects. The Root Mean Square Percentage Error (RMSPE) for training data ranged from 0.7038% to 3.3604% and that for testing data ranged from 5.0385% to 14.7418%. The errors both training and testing data lie within reasonable limit and hence the model performance is agreeable for prediction purposes.

Table 4 Errors in Training and Testing Parameters

Sl. No.	Parameter	RMS Percentage Error in Training	RMS Percentage Error in Testing
1	Ultimate Stress (MPa)	0.7038	5.0385
2	Ultimate Micro-Strain	3.3604	14.7418

6.1 Using the ANFIS objects for Simulation:

After validation of the ANFIS objects, they may be used for making predictions for input data at points other than the training and testing points. Points at very close intervals might be used for getting the predictions of ANFIS objects and the results plotted in the form of surfaces. These might help in two ways: i) getting a rough idea of the values one can obtain from the ANFIS object for given input data, without actually invoking the ANFIS object, ideally suited for preliminary studies and ii) a form of finer validation of the performance of the ANFIS objects at points other than the training and testing points, which might reveal absurd or unreasonable values if the ANFIS object was improperly trained. The three dimensional surfaces generated for each prediction parameter for each one of the three types of GFRP wrapping (CSM, UDC and WR) are presented in Figs. 17 to 24.

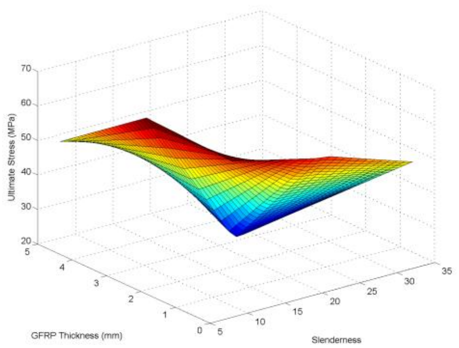

Fig.17 Ultimate Stress: Unwrapped

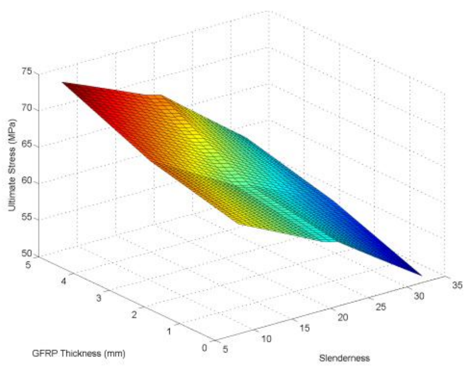

Fig.18 Ultimate Stress: CSM

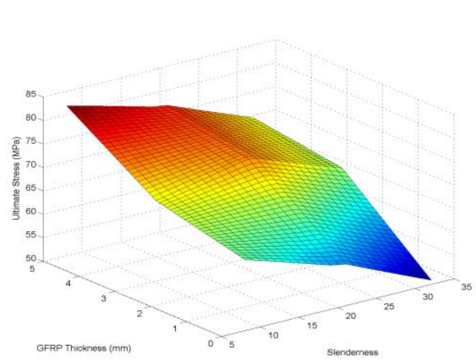

Fig. 19 Ultimate Stress: UDC

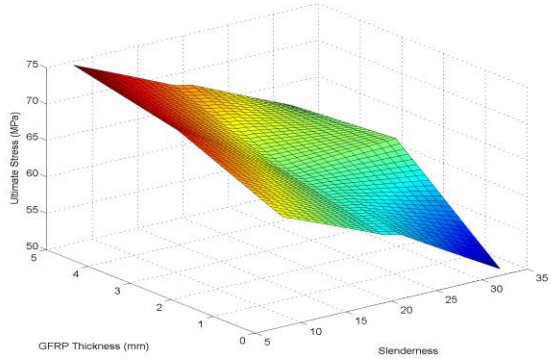

Fig. 20 Ultimate Stress: WR

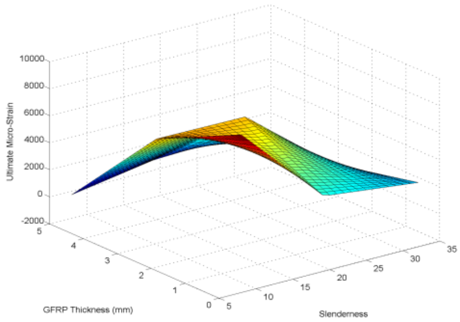

Fig. 21 Ultimate Micro-strain: Unwrapped

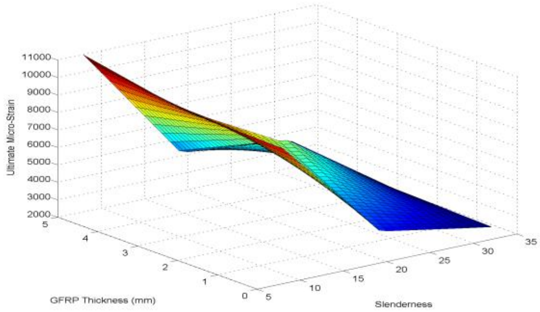

Fig. 22 Ultimate Micro-strain: CSM

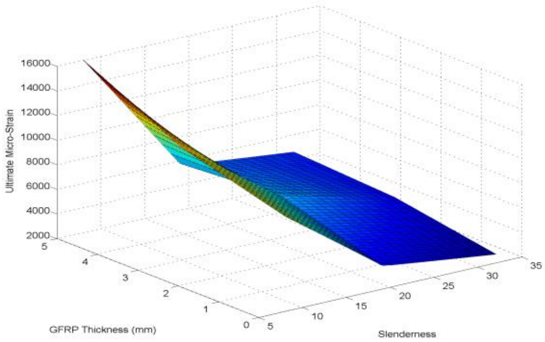

Fig. 23 Ultimate Micro-strain: UDC

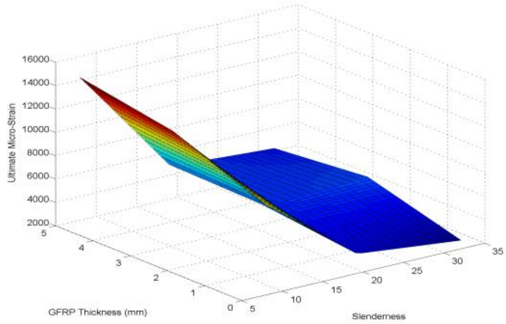

Fig. 24 Ultimate Micro-strain: WR

The simulation surfaces signify the three dimensional visualization of the generalization functions brought about by the ANFIS objects. The simulation surfaces exhibit acceptable values throughout the domain of interest for input data. 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 GFRP wrapped reinforced concrete columns perform well to predict the required properties within the domain of research input data. The stability of the predictions outside the domain of interest are not guaranteed. Hence, the ANFIS objects should not be used for simulation when input parameters fall outside the experimental input range.

VII. CONCLUSIONS

Based on the results obtained through the experimental investigation and the ANFIS modeling, the following conclusion are made

- UDCGFRP resulted in better performance of the wrapped columns considering ultimate stress, axial strain and lateral strain, when compared to the other wrap materials of CSMGFRP and WRGFRP.
- The slenderness ratio of the reinforced concrete columns affected the ultimate stress levels attained by them, resulting in a maximum of 27.78% increase for unwrapped columns and 5.00% to 36.11% increase for GFRP wrapped columns.

- The columns with 5mm thick UDCGFRP wrapping increase in ultimate stresses in the range of 26.09% to 36.11%.
- The unwrapped reinforced concrete columns, decreasing the slenderness ratio resulted in higher ultimate axial strain which increased up to 239.71% for reduction of slenderness ratio from 32 to 8.
- The ultimate strain was increased in the range 3.07% to 64.17% in axial direction.
- Columns with 5mm thick GFRP wrapping increase in ultimate axial strain in the range of 53.19% to 64.17% for UDCGFRP.
- The ANFIS modeling proposed as part of this study can be used for predicting the performance of GFRP wrapped columns. The ANFIS modeling consider slenderness ratio as a parameter, which makes predictions more accurate for given column geometry.

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