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Structural Response of FRP Strengthened PSC Beams

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Abstract: The repair and rehabilitation of structural members is perhaps one of the most crucial problems in civil engineering applications. One of the advanced techniques is strengthening of unbonded prestressed concrete beam members by fibre reinforced polymer (FRP) composites. An experimental investigation was carried out on the flexural behaviour of unbonded post-tensioned prestressed concrete beams externally bonded with FRP laminates at the tension face of the beam. Three different configurations of FRP laminates of varying thickness were used for strengthening. The strengthened and non-strengthened prestressed concrete beams were tested under four-point loading system. From the results, it was found that FRP strengthened prestressed concrete beams increased the load carrying capacity and stiffness. The performance of FRP strengthened prestressed concrete beams were also predicted using Adaptive Neuro-Fuzzy Inference System (ANFIS). The results obtained from the experimental study were used as training and testing data for developing the model. ANFIS model predicts the ultimate load and ultimate deflection with reasonable accuracy.

Keywords: *ANFIS, Prestressed Concrete Beams, Post-tensioned, Unbonded, FRP*

1. Introduction

In recent years, post-tensioned prestressed concrete members are most widely used in many structures. The development of reliable prestressing techniques has certainly been an important innovation in the field of structural concrete. In particular, post-tensioning is a technology providing efficient, economic and elegant structural solutions for a wide range of applications.

In the present scenario, rehabilitation and strengthening of structures such as bridges, buildings, storm pipes, liquid holding tanks etc., are major challenges facing by structural engineers. The structures that have been built more than several years may require strengthening to meet the current service load demands. Several methods of strengthening structures using various materials have been studied and applied in the rehabilitation field. To meet this requirement, externally bonded fibre reinforced polymers have been proven to be an effective strengthening method. It is well recognized that composites offer many significant advantages for retrofit and repair of structures over the traditional materials. High strength to weight ratio makes them an ideal way to increase the performance of a structure without adding significant dead load. Many researches have been carried out in the field of FRP strengthening for various structural components such as beam, column, and slabs. [1, 2, 3, 4]

Meski et al [5] investigated on flexural behaviour of unbonded post-tensioned concrete members strengthened using external FRP composites. The study focused on evaluating the use of external fibre reinforced polymer (FRP) laminates for strengthening unbonded post-tensioned concrete members. It was found that the use of FRP laminates increased the load capacity and post-cracking stiffness of unbonded members. Failure of the specimens occurred either by concrete crushing or by FRP debonding or FRP fracture.

Hussien et al [6] conducted an experimental program on the behaviour of bonded and unbonded prestressed normal and high strength concrete beams. The author concluded that the partially prestressed concrete beams with bonded tendons provide better behaviour than those of unbonded tendons such as increase in ductility, initial stiffness and the ultimate deflection upto 265%,13% and 199% respectively.

Some investigations were also carried out to study the performance of concrete beams using ANFIS [7, 8]. Hassani et al [9] conducted a study on the application of ANFIS model in deflection prediction of concrete deep beams. It was concluded that ANFIS showed relatively higher accuracy and precision compared to the linear regression. The mean square error from ANFIS showed approximately 10 times lesser for training set and 20 times lesser for testing set.

Jiin-Po Yeh et al [10] conducted a study on the design of two-span continuous singly reinforced concrete beams using the application of Adaptive Neuro-Fuzzy Inference System (ANFIS). From the test results, ANFIS showed an excellent performance with correlation coefficients between outputs and targets of the steel ratios for positive and negative moments and the minimum cost of the testing data being 0.9983, 0.9984 and 0.9996 respectively.

This paper presents the results of an experimental investigation on the behaviour of FRP strengthened unbonded prestressed concrete beams. The study is also intended to predict the performance characteristics of FRP strengthened PSC beams using Adaptive Neuro-Fuzzy Inference System (ANFIS).

2. Experimental Program

2.1 Materials

Concrete

Two different types of concrete namely normal and high strength grades were used. The basic properties of the materials used in the concrete were investigated as per IS standards. The specific gravity [11] of cement was found to be 3.15. The fineness of cement [12] was found to be 8%. The tests were conducted as per IS standards [13] such as consistency, initial and final setting time and was found to be 28%, 32 and 540 minutes. Natural river sand confirming [14] to zone 1 was used as fine aggregate and the specific gravity was found to be 2.60. Crushed stone from quarry was used as coarse aggregate which has a specific gravity [14] of 2.68. Potable water [15] was used for concrete mix with a water-cement ratio of 0.45 and a trial mix of concrete was done. The average characteristic compressive strength for normal and high strength concrete was 43 N/mm^2 and 69 N/mm^2.

Reinforcement

The longitudinal reinforcement used was high-yield strength deformed bars of 12 mm diameter at tension face and 10 mm diameter at compression face. The yield strength of steel [16] of 8 mm, 10 mm, 12 mm was found to be 436 N/mm^2. Transverse shear reinforcement provided over the span consisted of 2-legged of 8 mm diameter deformed steel stirrups spaced at 150 mm c/c.

High Tensile Steel (HTS)

High tensile steel of 7 mm diameter having ultimate tensile strength (UTS) value of 1532 N/mm^2 were used for prestressing.

FRP

The glass fibre reinforced polymer (GFRP) laminates were used for strengthening the beams. Three different orientations namely Uni-Directional Cloth (UDC), Chopped Strand Mat (CSM), Woven Rovings (WR) with 3 mm and 5 mm thicknesses were adopted. The mechanical properties of FRP are summarized in Table 1 and tested as per ASTM D638.

Table 1: *Properties of GFRP*

FRP orientation & Thickness (mm)	Tensile strength (MPa)	Ultimate elongation (%)	Modulus of Elasticity (MPa)
CSM3	126.20	1.60	7467.46
WR3	147.40	2.15	6855.81
UDC3	446.9	3.02	13965.63
CSM5	156.00	1.37	11386.86
WR5	178.09	1.98	8994.44
UDC5	451.5	2.60	17365.38

2.2 Test Specimens

The test beams had a rectangular cross-section of width 150 mm and 250 mm deep with a span of 2 m. Reinforcements provided were 2 numbers of 12 mm diameter bars at the tension face, 2 numbers of 10 mm diameter bars at the compression face of the beam. Two numbers of high tensile steel of 7 mm diameter were provided as a straight profile at an eccentricity of 50 mm below the centerline of beam. The longitudinal and cross-sectional details of the test specimens are shown in figure 1 and 1(a). In the beam ID, the first letter A and B respectively stands for normal concrete and high strength concrete, C - CSM, W - WR, U - UDC. Whereas 1 and 2 denotes the different thickness of FRP used in the study.

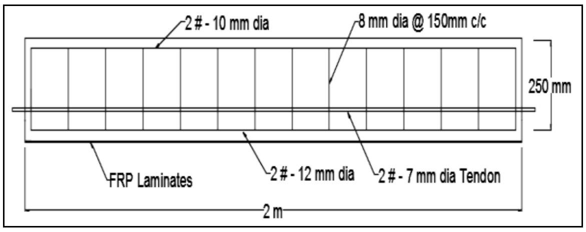

Figure 1 *Reinforcement details of beam*

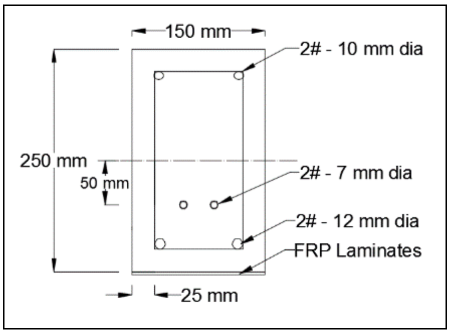

Figure (1a) *Cross-sectional details of beam*

2.3 Casting of Specimens

The reinforcement cage was fabricated according to the design requirements. Two numbers of HTS wire were placed inside the ducts and this assembly was placed at an eccentricity of 50 mm below the longitudinal axis of beam. Concrete was poured inside the mould in layers and good compaction was attained by using vibrators. The specimens were demoulded and curing was done for a period of 28 days. After completion of 28 days, beams were made ready for prestressing. Bearing plates were fixed at both ends of prestressing beams. After fixing of bearing plates, the wedges were inserted into the HTS wire at both ends. One end of the beam was locked and the other end was left free for prestressing. Hydraulic jack was inserted at the unlocked end of the beam and prestressing was carried out. Jack with a ram area of 14.65 cm^2 has a capacity of 10 tons was used to stress the HTS wire. The stressing was applied to an amount of 75% of the ultimate stress of HTS. During prestressing, slip was measured. After completion of prestressing GFRP laminates were attached to the bottom face of the beam specimens with two different thicknesses of 3mm and 5 mm.

2.4 Test Setup and Loading

All the beam specimens were tested in a loading frame of 100 ton capacity. The test setup is shown in figure 2. The applied load was measured using a 50 ton capacity load cell which was placed on top of the beam specimen. To measure the deflections in the beams, three linear variable differential transformers (LVDT) were placed at the tension face of the beam. One LVDT was placed at the centre of the beam and the other two were placed at one-third distance from the centre of the beam. Beam specimens were loaded with two concentrated point loads applied symmetrically relative to the middle of the span and separated by a distance equal to one-third the span length.

The control and strengthened specimens were first subjected to cyclic loading consisting of six cycles ranging between minimum load P_{min} and maximum P_{max} respectively. The loads P_{min} and P_{max} corresponded to approximately 20% and 80% of the estimated nominal moment capacity of the unstrengthened specimens.

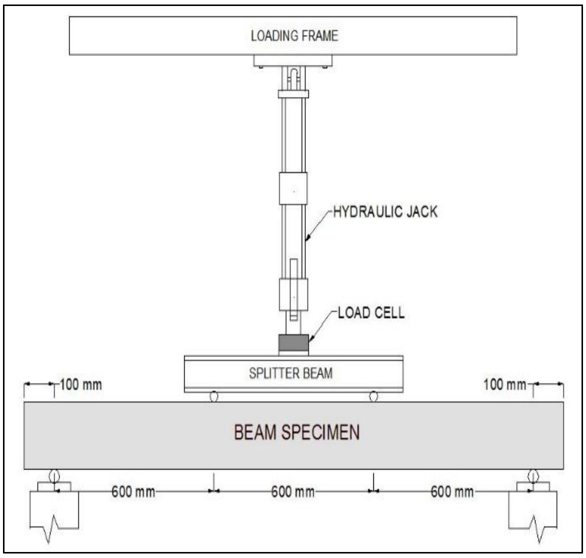

Figure 2 *Test setup*

3. Test Results and Discussion

Table 2 provides the summary of ultimate load (P_u), ultimate deflection (Δ_u) for various specimens. The ultimate load capacities of FRP strengthened unbonded PSC beams increased substantially relative to the control beam.

Table 2: *Test results*

Beam ID	P_u (kN)	Δ_u (mm)
A	51.5	64
AC1	59.5	42
AC2	69.4	50
AW1	70.2	55.2
AW2	79.5	64.5
AU1	85.2	68
AU2	97.5	75.5
B	70.5	72.4
BC1	79.5	56.9
BC2	82.3	60.7
BW1	81	64.3
BW2	85.2	71.34
BU1	88.6	78.5
BU2	108.7	86.54

It was observed that the AC1 and AC2 beam specimens exhibit an increase in load carrying capacity by 15.53% and 34.75%. AW1 and AW2 beam specimens showed an increase in load carrying capacity by 36.31% and 54.71%. AU1 and AU2 beam specimens showed an increase in load carrying capacity by 65.43% and 89.32% respectively when compared with the control beam specimen A. In case of high strength concrete beams, it was observed that BC1 and BC2 beam specimens exhibit an increase in load carrying capacity by 12.76% and 16.73%. BW1 and BW2 beam specimens showed an increase in load carrying capacity by 14.89% and 20.85%. BU1 and BU2 beam specimens exhibit an increase in load carrying capacity by 25.67% and 54.18% respectively when compared with the control beam specimens B. The FRP strengthened beams exhibit a maximum decrease by 15.79% in deflection at the ultimate load stage. Due to the strength of concrete of 69 MPa, the load carrying capacity and its deflection was also appreciably improved when compared to the concrete strength of 43 MPa. The beams strengthened with FRP showed a noteworthy improvement in ultimate load and deflection.

3.1 Load- Deflection Response

Figures 3 and 4 shows the load - deflection response of FRP strengthened unbonded specimens in comparison with the control specimen for normal and high strength concrete beams.

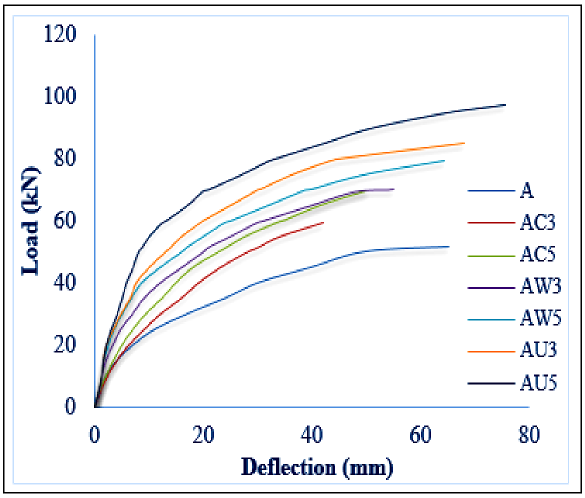

Figure 3: *Load - deflection curve for normal concrete beams*

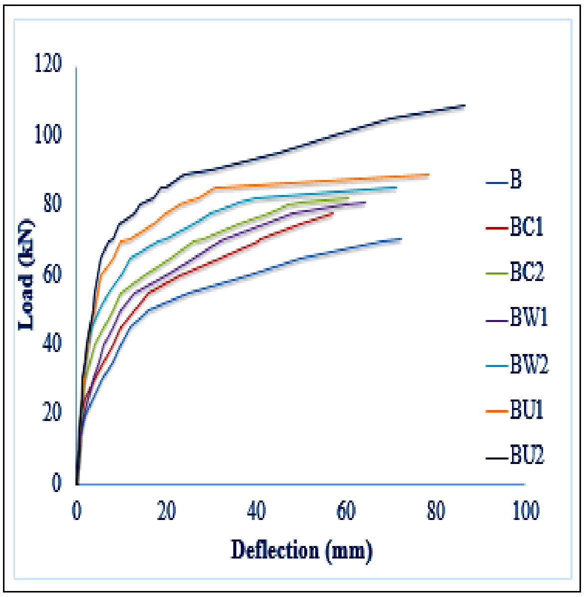

Figure 4: *Load - deflection curve for HSC*

The behaviour of load-deflection curve for the tested beams was similar to that of reinforced concrete beams. A tri-linear behaviour was observed in the all the beams that representing uncracked, cracked pre-yielding and cracked post-yielding stages. It was noticed in the FRP strengthened unbonded post-tensioned beams increased its post-yielding stiffness in the cracking state.

From the load - deflection curve, it is clear that the uni-directional cloth type of FRP has greater load carrying capacity and stiffness when compared to other type of specimens. This was due to the orientation of fibres. In this case, 90% of fibres were aligned parallel to the longitudinal axis of beam specimens. Hence, the load carrying capacity was significantly higher than that of the other strengthened specimens. In the UDC type of FRP, the stiffness has greatly improved at all stages when compared to control and other strengthened beams.

3.2 Failure Modes & Crack Pattern

In all the beam specimens, the first cracks were observed within the constant moment region. As the load increased, the new cracks were formed in the flexure zone along with the propagation of existing cracks in the beam specimens. It was noticed that on increasing the load; cracks were also started in the shear span region. The unbonded post-tensioned concrete beam specimen was failed by yielding of tension steel reinforcement followed by the crushing of concrete at the compression face as presented in figure 5. It was observed that the crack widths were smaller for externally bonded post-tensioned concrete beam specimens. The failure of strengthened PSC beam specimens occurred by rupture and delamination of GFRP and is presented in figure 6. The delamination has observed after the load reached the ultimate state.

Figure 5 *Concrete crushing in AU2*

Figure 6 *Delamination of FRP in AU2*

4. Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS is a fuzzy logic based computational system which utilizes the power of Neural Networks to optimize the performance of the traditional fuzzy system. Hence, the generation of ANFIS does not require much human intervention towards fine tuning the system, other than making a choice on the basic construction parameters. ANFIS is a 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. Fuzzy Inference System is an entity which takes input values, translates numerical values into fuzzy values suitable for logical processing, processes them using fuzzy rules, and translates fuzzy values into crisp values again to display the results.

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. Figure 7 shows ANFIS Architecture.

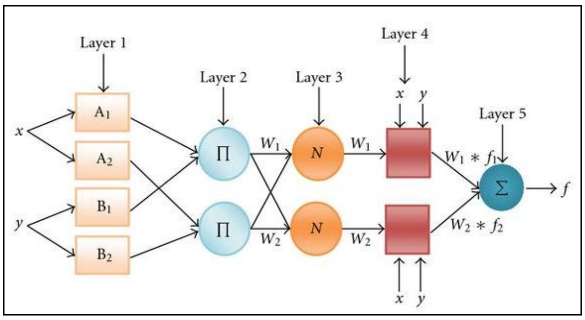

Figure 7: *ANFIS architecture*

ANFIS system uses two neural network and fuzzy logic approaches. When these two systems are combined, they may qualitatively and quantitatively achieve an appropriate result that will include either fuzzy intellect or calculative abilities of neural network.

4.1 Fuzzy Membership Function

Fuzzy Membership Function is a mathematical function which takes numerical input and produces fuzzy membership values as the result. All results obtained from fuzzy membership function vary between zero and one. Several types of fuzzy membership functions are available, Triangular membership function (trimf), Trapezoidal membership function (trapmf), Gaussian curve membership function (gaussmf), PI membership function (pimf), Sigmoid membership function (sigmf), Generalized bell membership function (gbellmf).

Proper choice of the type of membership function and the number of membership functions per input parameter are essential to make the ANFIS objects perform well against the input-output pairs. The number of rules used for processing the input data is a simple multiplication of the number rules in each input parameter. As the number of rules per input parameter is increased, the ANFIS object requires more data for training.

As the number of rules per input is decreased, ANFIS can train itself reasonably well even with limited amount of data. When the number of membership functions is very high and there is scarcity of data, the ANFIS object is inadequately trained and often predicts unreasonable values away from the training points. Hence, judicious choice of the type and number of membership functions is necessary for developing an effective ANFIS object.

4.2 Steps Involved in ANFIS Modelling

The various steps involved in ANFIS modelling is shown in figure 8.

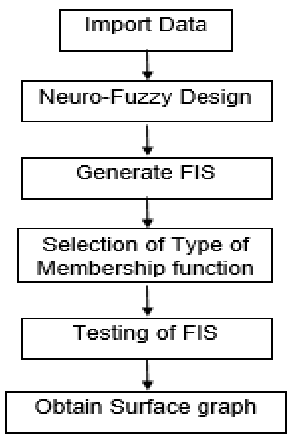

Figure 8: *Steps involved in ANFIS modelling*

4.3 Development of ANFIS Model

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 were grade of concrete, thickness of FRP plate, elastic modulus, composite ratio and they remain the same for all objects. ANFIS objects were produced at the rate of one object per parameter such as ultimate load and ultimate deflection. The training data and testing data were randomly chosen from the experimental values. Input data and target data was given in a training file to construct Neuro fuzzy design, then FIS was created as grid partition and appropriate membership function was chosen. 100 numbers of epochs was used, it was trained and tested, the surface graphs were plotted for various parameters.

The Trapezoidal membership function (trapmf) was chosen for training and testing data to run the ANFIS, the same procedure was followed for every parameter. Table 3 shows the RMS % errors in Training and testing Parameters and the ANFIS values where presented in table 4. These error values provide a means for validation of the performance of the ANFIS objects.

Table 3*: RMSPE in training and testing*

Parameters	RMS percentage Error
Ultimate Load	2.94538
Ultimate Deflection	4.5538

Table 4: *ANFIS Value*

Beam ID	P_u (kN)	Δ_u (mm)
A	51.5	65.2
AC1	64.8	48.6
AC2	74.8	57.6
AW1	64.8	48.6
AW2	74.1	57.1
AU1	85.2	68
AU2	97.3	75.3
B	70.5	72.4
BC1	80.2	60.6
BC2	84.2	66.4
BW1	80.2	60.6
BW2	83.4	65.8
BU1	88.6	78.5
BU2	109	86.4

The Root Mean Square Percentage Error (RMSPE) for training data was ranged from 2.92-4.50%. The errors in training data lie within reasonable small limits and hence the model performance was agreeable for prediction purposes.

4.4 3D Surface Model

The data generated was represented in the form of three-dimensional surfaces to enable visual examination of the functional form generated by the

ANFIS model for various parameters such as ultimate load and ultimate deflection are shown in figures 9 & 10.

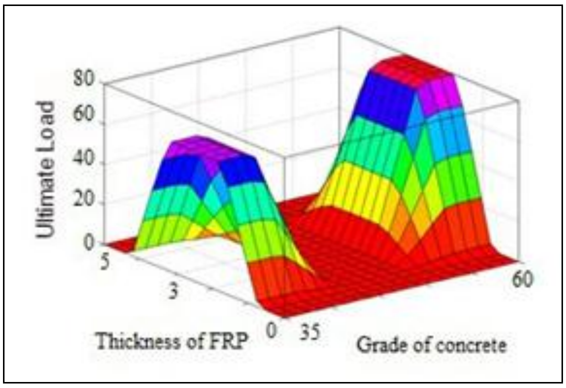

Figure 9: *3D surface model of ultimate load*

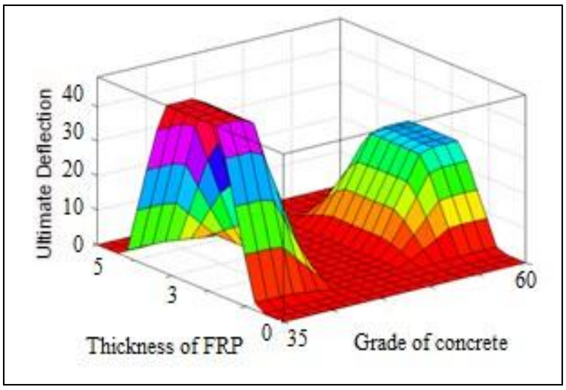

Figure 10: *3D surface model of ultimate deflection*

3.4 Performance of ANFIS model

The ANFIS objects developed for predicting the various parameters associated with the FRP strengthened PSC beam provided reasonable solutions. The errors were due to the limited number of data provided to the network. These error values provided a means for validation of the performance of the ANFIS objects. The errors in both training and testing data were within a reasonable limit and hence the model performance was agreeable for prediction purposes.

4. Conclusions

The following conclusion were drawn from the study are as follows.

1) FRP laminated post-tensioned concrete beams was found to be very effective in the ultimate load carrying capacity, and stiffness when compared to the control beam specimen.
2) From the experimental results it is clearly showed that uni-directional cloth FRP type of orientation has increased its load carrying capacity and stiffness.
3) In the high strength PSC beams, the ultimate load and its deflection was appreciably improved when compared to the normal strength PSC beams.
4) The unbonded post-tensioned concrete beam specimen was failed by yielding of tension steel reinforcement followed by the crushing of concrete.
5) The failure of strengthened PSC beam specimens occurred by rupture and delamination of GFRP.
6) The developed ANFIS model by using the trapezoidal membership function (trapmf) as demonstrated its ability in training provided in the given input and output data sets.
7) ANFIS model predicts the ultimate load and ultimate deflection with reasonable accuracy.
8) ANFIS model provided the root mean square percentage error for the various parameters were ranged from 2.92-4.5%.

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References

[1] Jun Y. Cha, P. Balaguru and L. Chung, Experimental and Analytical Investigation of Partially prestressed concrete beams strengthened with Carbon Reinforcement, SP 188-55, 1998.

[2] Y.J. Kim, Modeling of concrete beams prestressed with AFRP tendons, Challenges, Opportunities and Solutions in Structural Engineeringand Construction, ISBN 978-0-415-56809-8.

[3] Kyle H. Larson, Robert J. Peterman, and Hayder A. Rasheed, "Strengthfatigue behavior of fiber reinforced polymer strengthened prestressed concrete T-beams," ASCE J of Composites for Construction, 9(3), 313-326, 2005.

[4] Ross A, David M. J, Tedesco J. W, Hughes M. L., "Strengthening of reinforced concrete beams with externally bonded composites Laminates," ACI Struct. J., vol. 96, pp. 212–220, 1999.

[5] F. EI Meski and M. Harajli. Flexural behaviour of unbonded post tensioned concrete members strengthed using external FRP composites, journal of composites for construction 2013.17:197-207. 2013.

[6] O.F. Hussien, T.H.K.Elafandy, A.A.Abdelrahman, S.A.AbdelBaky, E.A. Nasr. "Behavior of bonded and unbonded prestressed normal and high strength concrete beams", HBRC Journal 8, 239–251. 2012.

[7] S.J.S. Hakim, H. Abdul Razak, S.A. Ravanfar, "Structural damage identification using Artificial Neural Networks (ANNs) and Adaptive NeuroFuzzy Interface System (ANFIS)", ISSN: 2311-9020; ISBN: 978-972-752-165-4. 2013.

[8] Kh Mahfuz ud Darain, Sahaboddin Shamshirband , Mohd Zamin Jumaat, M. Obaydullah, "Adaptive neuro fuzzy prediction of deflection and cracking behaviour of NSM strengthened RC beams",

Construction and Building Materials 98 276–285, 2015.

[9] Mohammad Mohammadhassani, Hossein Nezamabadi-Pour, MohdZamin Jumaat, Mohammed Jameel, S.J.S.Hakim and Majid Zargar, "Application of the ANFIS model in deflection prediction of concrete deep beam", Structural Engineering and Mechanics, Vol. 45, No.3, 319-332, 2013.

[10] Jiin-Po Yeh, Ren-Pei Yang, "Application of the Adaptive Neuro-Fuzzy Inference System for Optimal Design ofReinforced Concrete Beams", Journal of Intelligent Learning Systems and Applications, 6, 162-175., 2014.

[11] IS 4031-2 (1999): Methods of physical tests for hydraulic cement, Part 2: Determination of fineness by specific surface by Blaine air permeability method.

[12] IS 4031-1 (1996): Methods of physical tests for hydraulic cement, Part 1: Determination of fineness by dry sieving.

[13] IS 4031-4 (1988): Methods of physical tests for hydraulic cement, Part 4: Determination of consistency of standard cement paste.

[14] IS 2386-3 (1963): Methods of test for aggregates for concrete, Part 3: Specific gravity, density, voids, absorption and bulking

[15] IS 456 (2000): Plain and Reinforced Concrete - Code of Practice.

[16] IS 1786 (2008): High strength deformed steel bars and wires for concrete reinforcement