# Neuro-fuzzy network Prediction effective strain of FRP strips - strengthened RC beams

**Eng. Thara'a Mubarak** [1]

**Dr. Issam Nasser**[2] **Dr. Bassam Hwaija** [3]

[1] *Postgraduate Student, Department of Structural Engineering, Faculty of Civil Engineering, Tishreen University. tharaamub@yahoo.com*

[2,3] *Professor, Department of Structural Engineering, Faculty of Civil Engineering, Tishreen University. Syria*

# Content

- Introduction
- Adaptive neuro-fuzzy Inference System
- Results
- Failure modes prediction
- Conclusions

# Introduction

**Near Surface Mounted (NSM) strengthening technique, based on the concept of embedding glass or carbon FRP bars or strips into grooves made on the concrete cover of the elements to be strengthened**

## Why did we do this research?

**Experimental and analytical research on Near-surface mounted FRP has proven the importance and efficiency of this technique in strengthening RC beams but determining the effective strain for FRP strips is the main problem in this technique.**

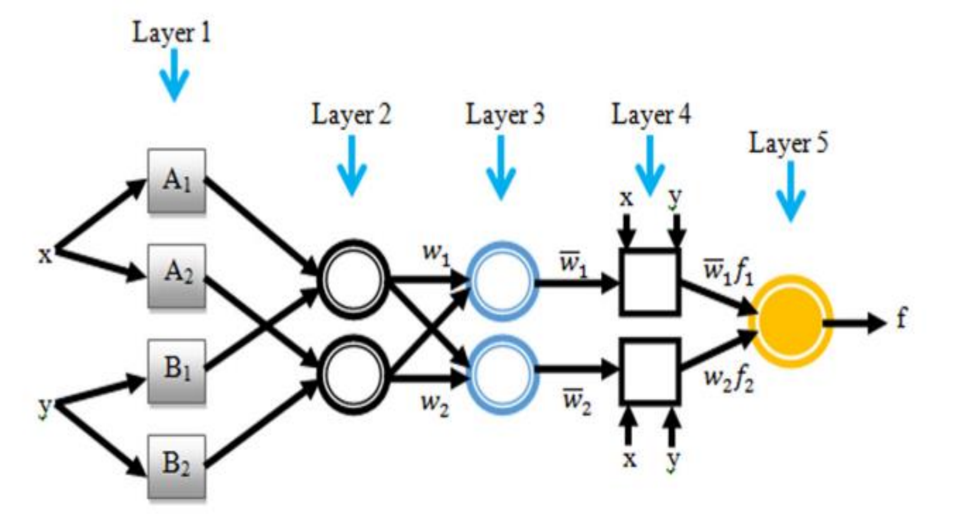
## Aim of research

**The present research has aimed to develop an accurate, yet rapid prediction model ANFIS for determining:**

- effective strain for NSM-FRP strips that strengthen RC beams
- Failure modes for RC beams strengthened with NSM.FRP strips

ANFIS is an intelligent system that integrates the learning power of artificial neural network technology and the knowledge of fuzzy logic. MATLAB toolbox was used to simulate the model.

ANFIS used a Sugeno-type fuzzy system in a five-layer network (the input layer not counted by Jang) for two inputs x and y, and one output z, as illustrated in Figure




ANFIS Structure with 2 inputs [1].

# Adaptive neuro-fuzzy Inference System (ANFIS)

**Database:**

The experimental data of 85 RC beams strengthened with the FRP strips by NSM technique that collected from published literature

**Inputs**

- strength of concrete (fc)
- length of the strengthened strip to the length of the beam ($L_b/L$)
- equivalent reinforcement ratio ($\rho_{l,eq}$)

**ANFIS models**

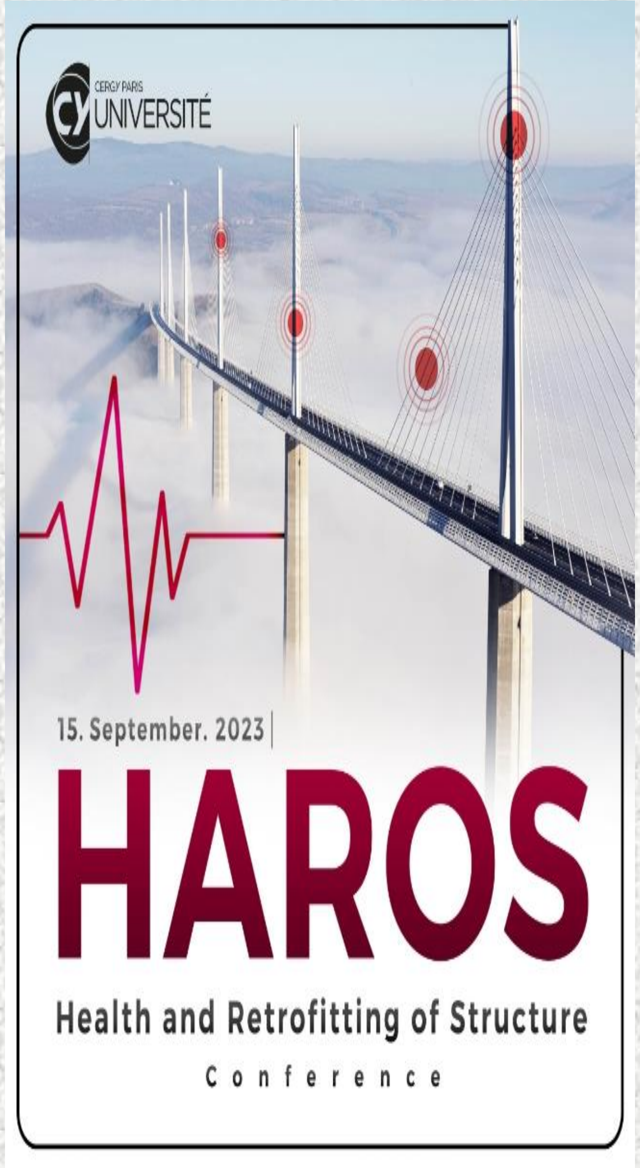
**Output**

effective strain of FRP strips ($\varepsilon_{fd}/\varepsilon_{fu}$)

Note: the equivalent reinforcement ratio was suggested by Barros [3]

$$\rho_{l,\,eq} = A_{sl} / (b.d_s) + (A_f.E_f / E_s)/(b.d_f)$$

# Database:




| Table 1. Experimental data (database) | | input | | | output |
|---|---|---|---|---|---|
| Reference | Beam notation | f'c (MPa) | $\rho_{l,eq}$ | $l_b/L$ | $\varepsilon_{fd}/\varepsilon_{fu}$ |
| Barros 2010 [69] | VL1 | 31.1 | 0.5286 | 0.7647 | 0.4792 |
| | VL2 | 31.1 | 0.4889 | 0.8095 | 0.5124 |
| | VL3 | 31.1 | 0.4555 | 0.8333 | 0.4612 |
| Barros 2007 [38] | S1 | 44.2 | 0.2775 | 0.9000 | 0.9412 |
| | S2 | 44.2 | 0.4877 | 0.9000 | 0.7941 |
| | S3 | 44.2 | 0.7316 | 0.9000 | 0.6971 |
| Yost 2007 [39] | 6-1F | 37.2 | 1.9265 | 0.9500 | 0.5734 |
| | 6-2F | 37.2 | 2.0216 | 0.9500 | 0.4934 |
| | 9-2F | 37.2 | 1.3210 | 0.9500 | 0.8210 |
| | 12-1F | 37.2 | 0.9444 | 0.9500 | 0.9596 |
| | 12-2F | 37.2 | 0.9919 | 0.9500 | 0.8399 |
| Teng 2006 [26] | B500 | 35.2 | 0.6349 | 0.1563 | 0.1676 |
| | B1200 | 35.2 | 0.6349 | 0.3750 | 0.2679 |
| | B1800 | 35.2 | 0.6349 | 0.5625 | 0.5339 |
| | B2900 | 35.2 | 0.6349 | 0.9063 | 0.7103 |
| Kotynia 2006 [70] | p1 | 41.5 | 1.3657 | 0.9650 | 0.9200 |
| | p2 | 37.7 | 0.7909 | 0.9650 | 0.8100 |
| | p3 | 41.5 | 0.7788 | 0.9650 | 0.6600 |
| Barros 2005 [12] | V1R1 | 45.3 | 0.4541 | 0.9330 | 0.9118 |
| | V2R2 | 48.9 | 0.6826 | 0.9330 | 0.7529 |
| | V3R2 | 42.8 | 0.9021 | 0.9330 | 0.7529 |
| | V4R3 | 46.4 | 1.2957 | 0.9330 | 0.6235 |
| Täljsten 2003 [71] | E4 | 60.7 | 0.9638 | 1.0000 | 0.6389 |
| | E5 | 60.7 | 0.9638 | 0.8333 | 0.6222 |
| Hassan and Rizkalla 2003 [36] | B1 | 48 | 1.0544 | 0.12 | 0.0968 |
| | B2 | 48 | 1.0544 | 0.20 | 0.1278 |
| | B3 | 48 | 1.0544 | 0.40 | 0.5338 |
| | B4 | 48 | 1.0544 | 0.60 | 0.8872 |
| | B5 | 48 | 1.0544 | 0.68 | 0.9549 |
| | B6 | 48 | 1.0544 | 0.76 | 0.9624 |
| | B7 | 48 | 1.0544 | 0.84 | 0.9699 |
| | B8 | 48 | 1.0544 | 0.96 | 0.9850 |

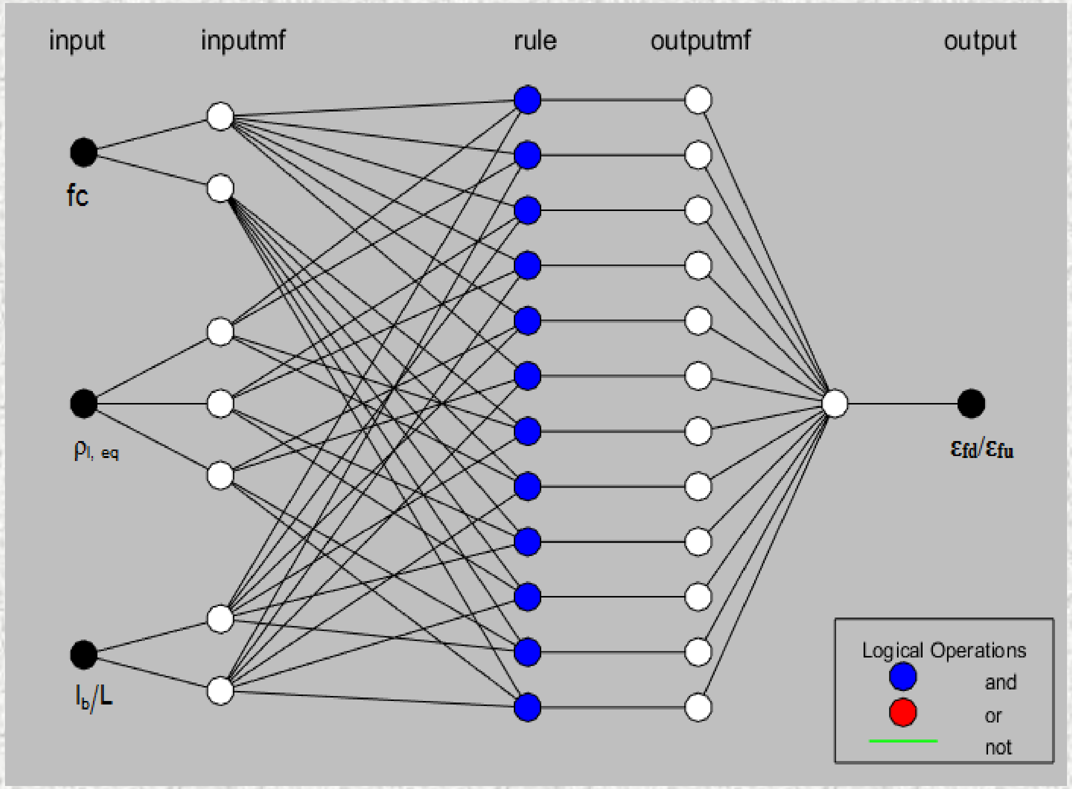
# Analysis of the ANFIS model:

**Initially, the ANFIS network was trained with the 80% experimental data collected within the database shown in table1**

**To fuzzify the ANFIS inputs three bell-shaped membership functions to model the second input and two relationships to model the first and third inputs.**

**To determine the effective strain of FRP strips the ANFIS networks were tested after the training process**

**The final structure of ANFIS is illustrated in adjacent figure.**



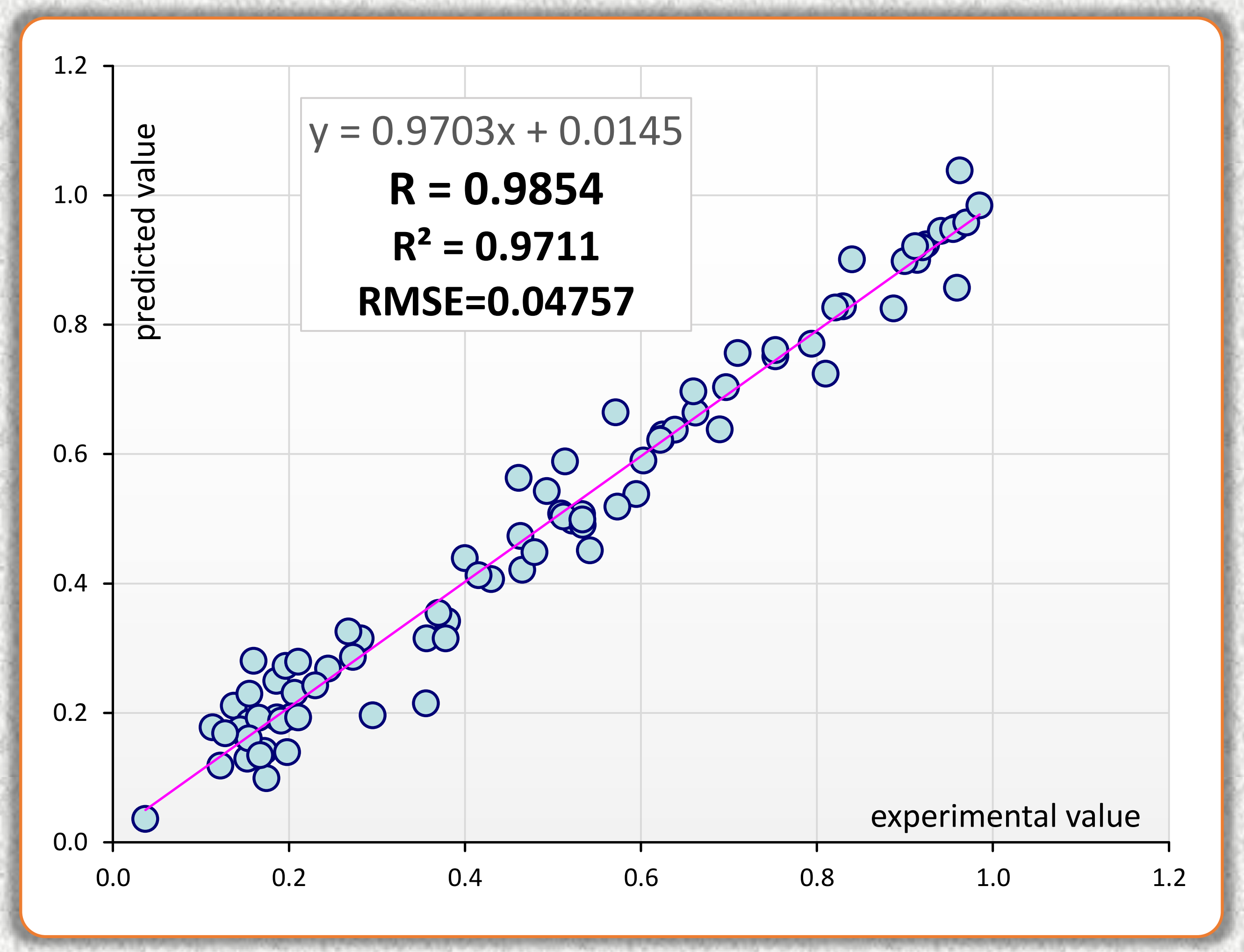

**Structure of the proposed (ANFIS) to predict effective strain**

# Results

The predicted values of the ANFIS model are shown in following figure as a scatter plot.

most points are located near the diagonal line of the ANFIS prediction model.

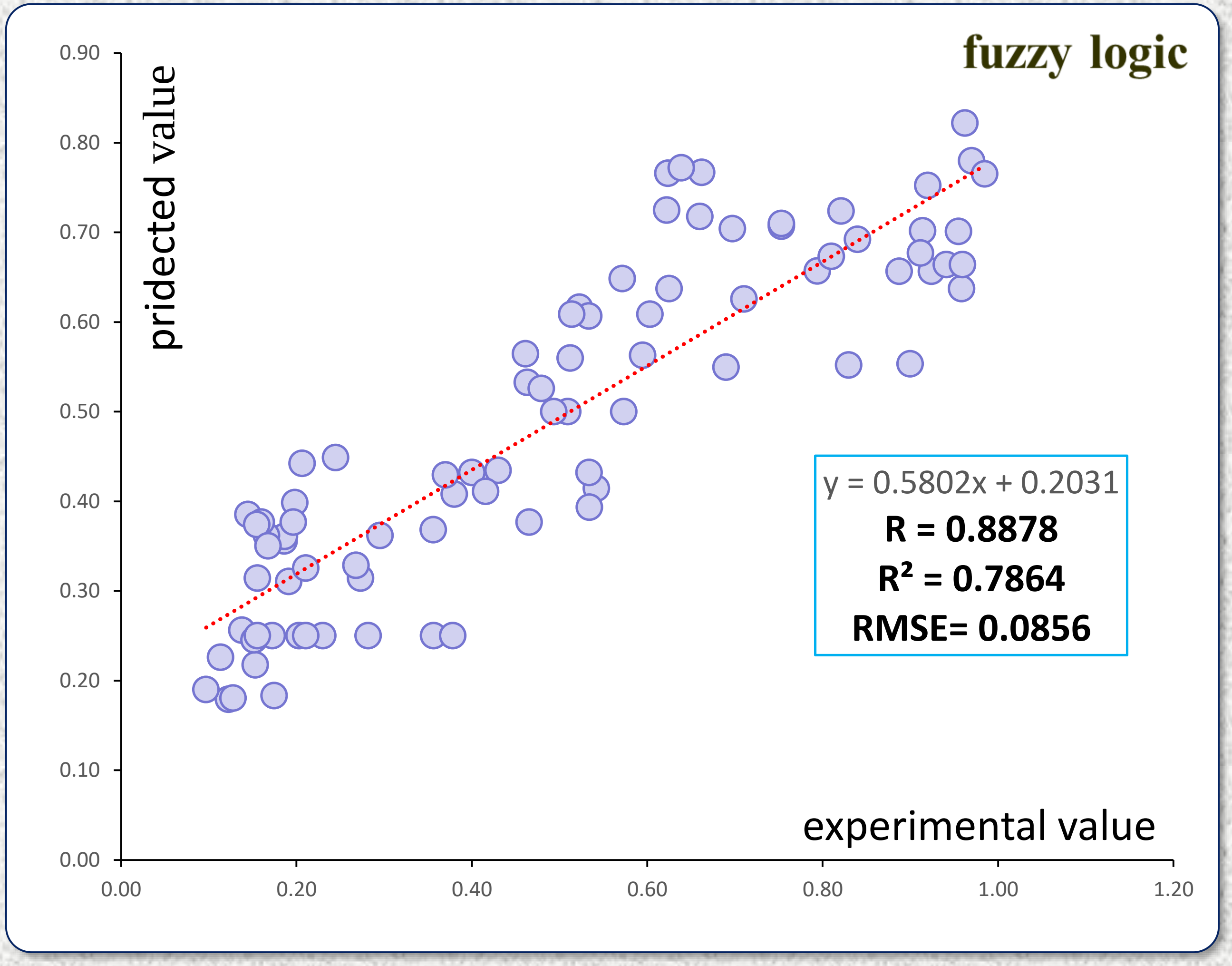
the values of the prediction results are in good agreement with the experimental values




Scatter plots of predicted values by ANFIS

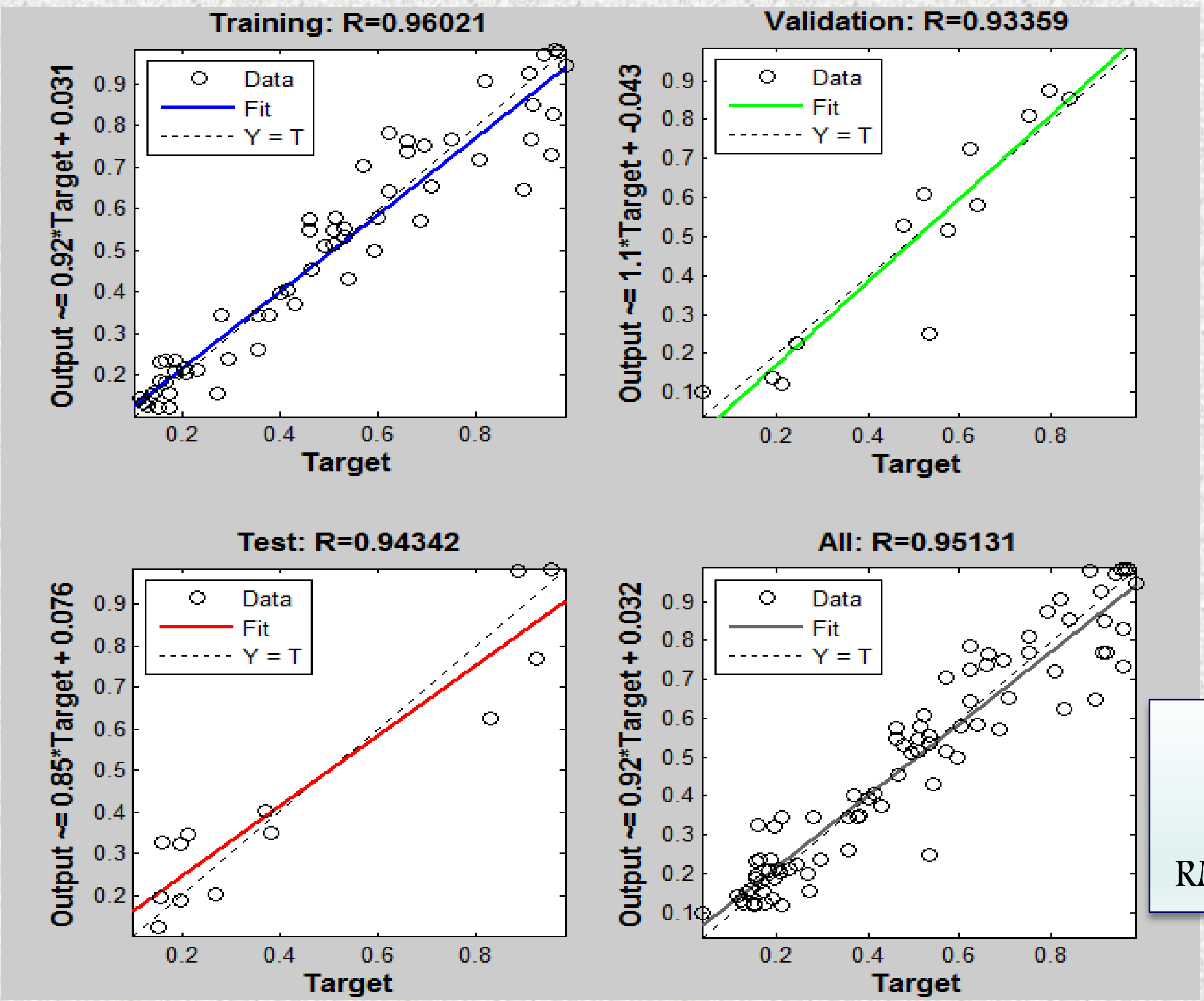
# Results

To ensure that the proposed ANFIS method was valid as a confirmed method, the expected results were compared to the expected results using fuzzy logic and ANN neural network method




Scatter plots of predicted values by FIS

# Results




R = 0.9513

$R^2$ = 0.905

RMSE= 0.0852

**Scatter plots of predicted values by ANN**

# Results

**Table 2 summarizes the accuracy results of prediction by ANFIS, ANN, and fuzzy, for the experimental database.**

**Table 2. Performance statistics of the ANFIS, FIS, ANN models**

| ANFIS model | | ANN model | | FIS model | |
|---|---|---|---|---|---|
| $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE |
| 0.971 | 0.04757 | 0.905 | 0.8526 | 0.786 | 0.08566 |

**From Table 2, the results of the proposed ANFIS method are more accurate than the traditional methods and this is due to the higher adaptation of the ANFIS network to find the ideal values for relationships on the one hand and the type of relationship on the other hand, the bell-shaped membership has been used in the ANFIS method.**

The confirmation of the high accuracy of ANFIS was also verified by comparing its expected results with the results of the formula proposed by Barros [3] and modified by Khalifa [4] using RSME, and $R^2$ as stated in its references.

Table 3 summarizes the accuracy results for these equations.

**Barros's formula [2]**

$$\frac{\varepsilon_{fe}}{\varepsilon_{fu}} = -32.648\rho_{l,eq} + 0.9606$$

**Khalifa's formula [4]**

$$\frac{\varepsilon_{fe}}{\varepsilon_{fu}} = -27.37\rho_{l,eq} + 0.9174$$

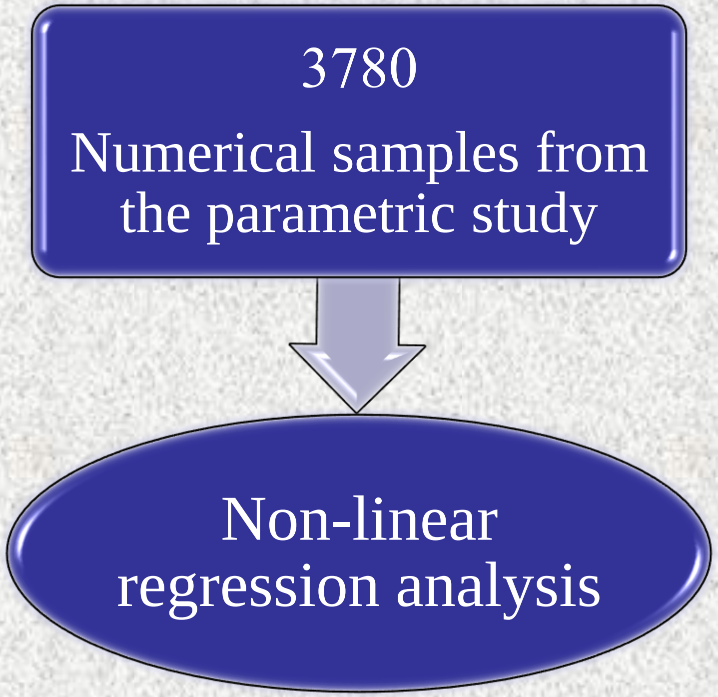
Table 3. Performance statistics of the Barros, Khalifa's formula

| Barros's formula | | Khalifa's formula | |
|---|---|---|---|
| [3] $R^2$ | RMSE | [4] $R^2$ | RMSE |
| 0.5106 | 0.155 | 0.5286 | 0.133 |

# Results

**The confirmation of the high accuracy of ANFIS was also verified by comparing its expected results with the results of a formula proposed by us, which**

**took the effort of three years of continuous work**




$$\varepsilon_{fe} = 12\left(\frac{f_c}{nE_fA_f}\right)^{0.35} \times (-183\rho_s^2 + 2.84\rho_s + 0.051) < 0.9\varepsilon_{fu}$$

$$\rho_s \geq \rho_{smin} \qquad \text{(I)}$$

$$\varepsilon_{fe} = \sqrt{\frac{f_c}{\sqrt{n}}} \times \frac{53}{\left(E_fA_f\right)^{0.7}} < 0.9\varepsilon_{fu}$$

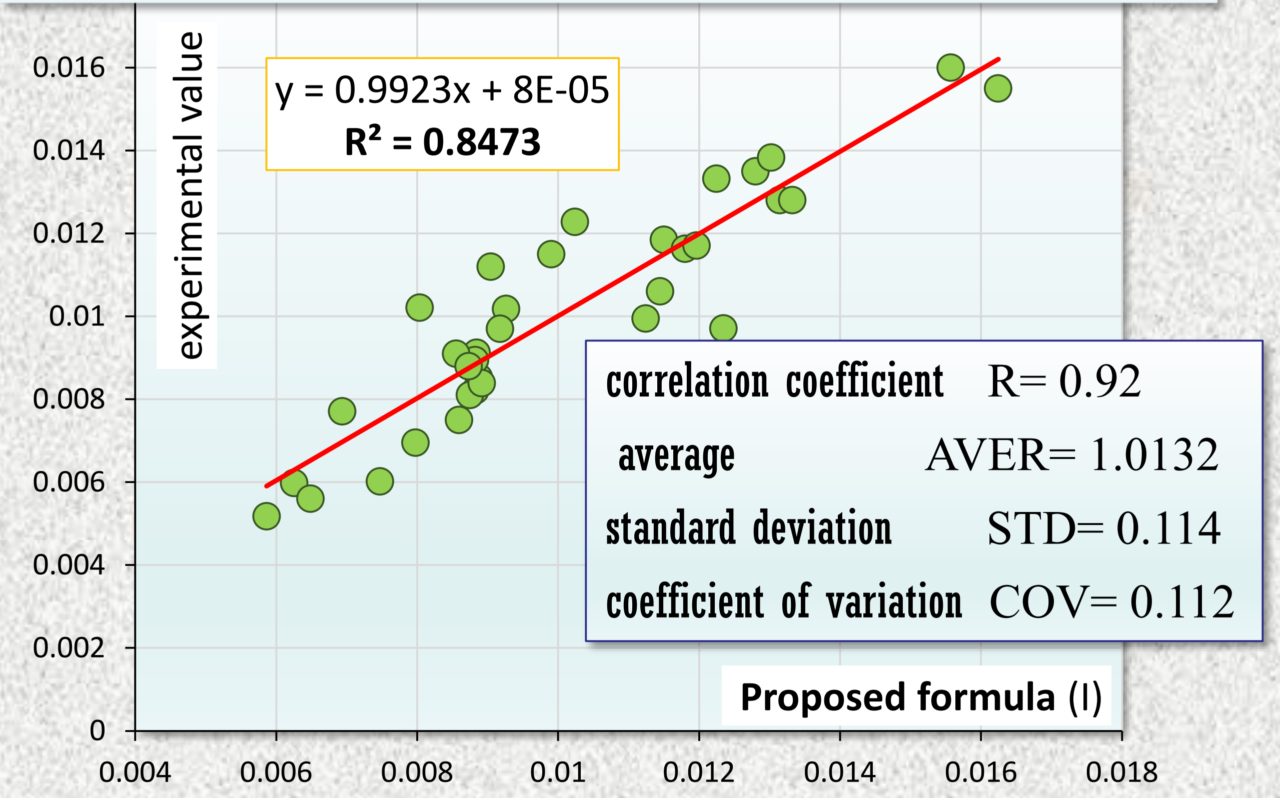
$$\rho_s < \rho_{smin} \qquad \text{(II)}$$

# Results

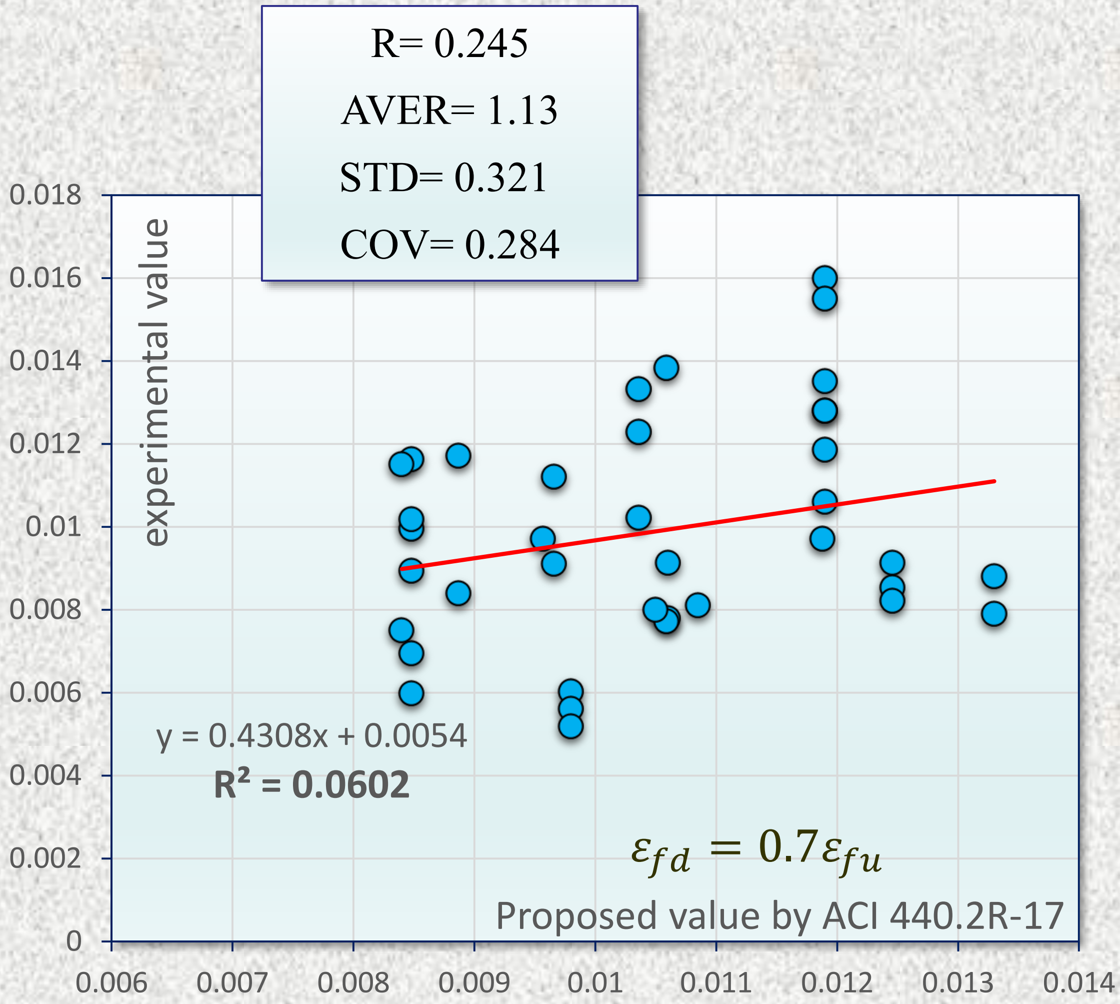
$$\varepsilon_{fe} = 12\left(\frac{f_c}{nE_fA_f}\right)^{0.35} \times (-183\rho_s^2 + 2.84\rho_s + 0.051) < 0.9\varepsilon_{fu}$$

$$\rho_s \geq \rho_{smin}$$

$L_b$= (0.85−1)L (I)




## ACI 440.2R−17

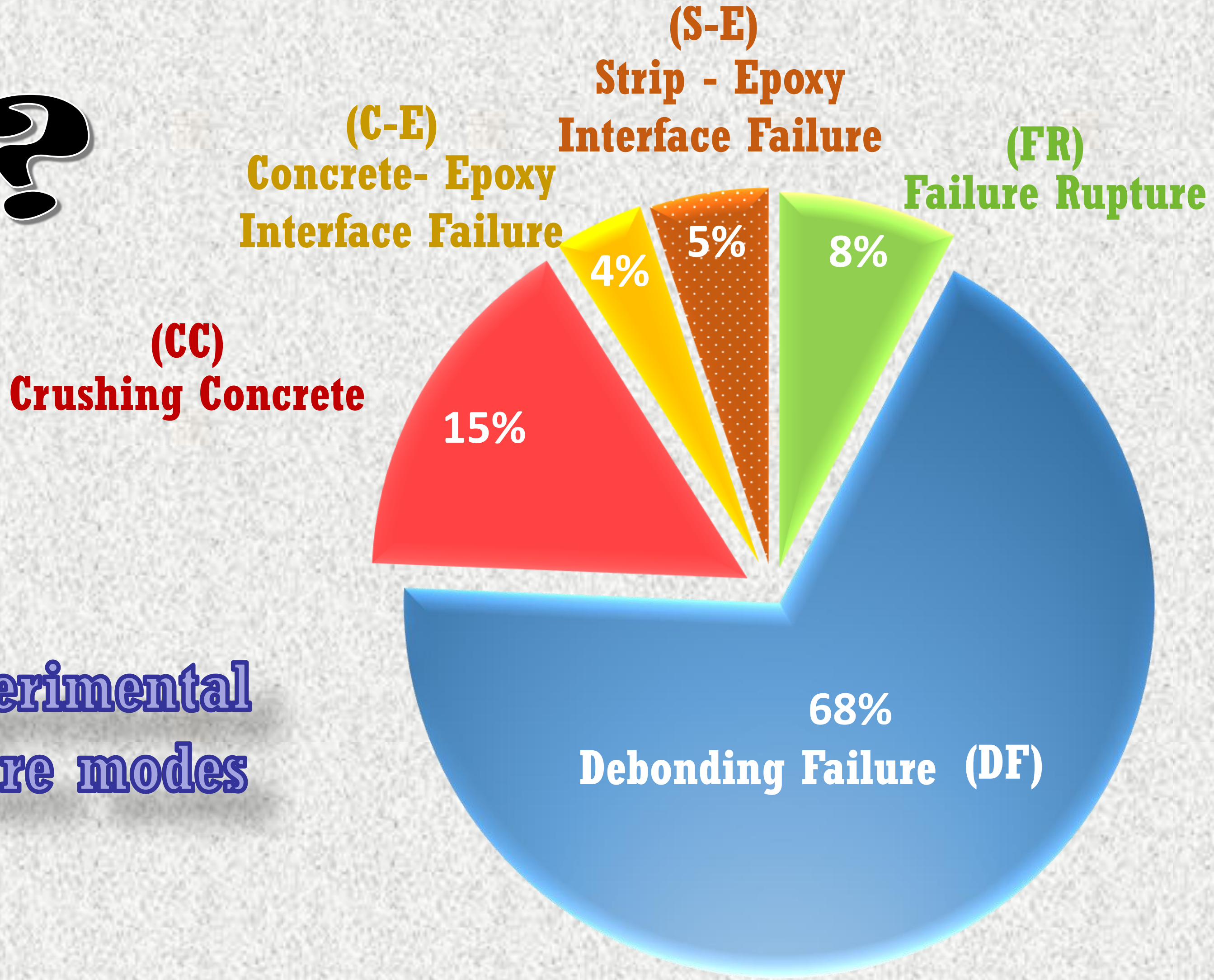


# Failure modes prediction for strengthened RC beams

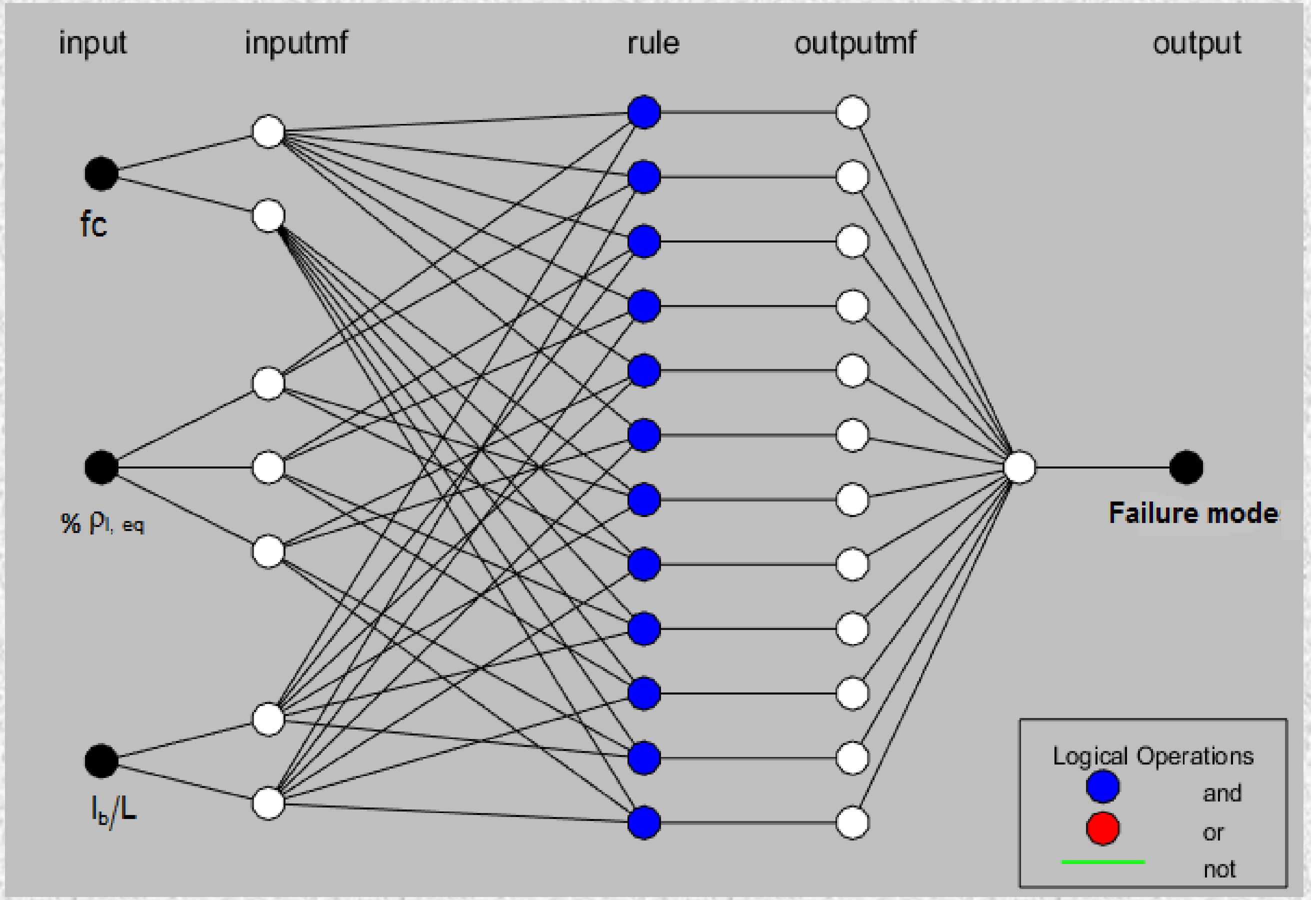
**Can we predict the failure modes of RC beams strengthened with FRP strips using ANFIS ?**

**YES, We can.**

**Experimental failure modes**



**YES, We can.**




**Structure of the proposed (ANFIS) to predict failure mode**

# Failure modes prediction for strengthened RC beams

| Beam notation | Inputs: f'c (MPa) | $\rho_{l,\,eq}$% | $l_b$/L | Failure Mode Output: Experimental Failure Mode | ANFIS Failure Mode |
|---|---|---|---|---|---|
| AD1sh | 33 | 0.9481 | 0.857 | DF | DF |
| AS2sh | 33 | 2.0585 | 0.857 | DF | DF |
| BS3sh | 42.77 | 0.8599 | 0.857 | DF | DF |
| BT3sh | 42.77 | 1.0379 | 0.857 | DF | DF |
| S-212-25-2NSM | 33.1 | 0.6723 | 0.915 | CC | CC |
| R-PL-15 | 31.3 | 0.4415 | 0.9 | RF | CC |
| R-PL-25 | 31.3 | 0.4624 | 0.9 | DF | CC |
| R-PL-25-2-S | 31.3 | 0.5132 | 0.9 | DF | DF |
| B-N-2-2 | 35 | 0.8038 | 0.955 | C-E | C-E |
| NSM_c_2*1.4*10_1 | 21 | 1.081 | 0.905 | DF | DF |
| NSM_c_3*1.4*10_1 | 21 | 1.1462 | 0.905 | DF | DF |
| M2S1 | 30.5 | 0.6326 | 0.653 | S-E | S-E |
| F2S1 | 30.5 | 0.6326 | 0.833 | [illegible] | [illegible] |
| B2 | 25 | 0.2949 | 1 | [illegible] | [illegible] |
| B3 | 25 | 0.3284 | 1 | DF | DF |
| B4 | 25 | 0.363 | 1 | DF | DF |
| LB2S1 | 31.4 | 0.6316 | 0.833 | S-E | S-E |
| LB2S2 | 31.4 | 0.6326 | 0.833 | S-E | S-E |
| NSM2-32 | 30 | 0.486 | 0.32 | DF | DF |
| NSM2-48 | 30 | 0.486 | 0.48 | CC | CC |
| NSM1-70 | 30 | 0.315 | 0.7 | CC | CC |
| NSM2-70 | 30 | 0.486 | 0.7 | CC | CC |
| NSM2-80 | 30 | 0.486 | 0.8 | CC | CC |
| NSM2-96 | 30 | 0.486 | 0.96 | CC | CC |
| NISA/20/85 | 22.3 | 0.5263 | 0.507 | DF | DF |
| NISA/20/130 | 23.5 | 0.5263 | 0.541 | DF | DF |
| NISA/20/170 | 23.5 | 0.5263 | 0.57 | DF | DF |
| NISA/20/85P | 21.3 | 0.5263 | 0.507 | DF | DF |
| NISA/20/130P | 21.3 | 0.5263 | 0.533 | DF | DF |
| NISA/20/160P | 21.3 | 0.5263 | 0.563 | DF | DF |
| NISA/30/80 | 32.5 | 0.5263 | 0.504 | DF | DF |
| NISA/30/120 | 32.5 | 0.5263 | 0.533 | DF | DF |
| NISB/20/85 | 19.85 | 1.8413 | 0.507 | DF | DF |
| NISB/20/130 | 19.85 | 1.8413 | 0.541 | DF | DF |
| NIISB/40/80 | 41.58 | 0.7392 | 0.504 | DF | DF |
| NIISB/40/2*80 | 41.19 | 0.7941 | 0.504 | DF | DF |
| NIISB/40/120 | 41.19 | 0.7392 | 0.533 | DF | DF |
| NIISB/40/160 | 41.19 | 0.7392 | 0.563 | DF | DF |

**Error percentage 6.4%**

| Beam notation | Inputs: f'c (MPa) | $\rho_{l,\,eq}$% | $l_b$/L | Failure Mode Output: Experimental Failure Mode | ANFIS Failure Mode |
|---|---|---|---|---|---|
| NILA/40/100 | 41.75 | 0.5253 | 0.35 | DF | DF |
| NILA/40/120 | 41.75 | 0.5253 | 0.36 | DF | DF |
| NILA/50/2*80 | 41.75 | 0.6266 | 0.34 | DF | DF |
| NILB/40/90 | 37.67 | 1.8413 | 0.345 | DF | DF |
| NILB/40/120 | 37.67 | 1.8413 | 0.36 | DF | DF |
| NILB/40/120p | 43.7 | 1.8413 | 0.36 | DF | DF |
| NILB/40/130pp | 43.7 | 1.8413 | 0.365 | DF | DF |
| NIILB/40/80p | 34.32 | 0.8065 | 0.34 | DF | DF |
| NIILB/40/2*80 | 34.32 | 0.8561 | 0.34 | DF | DF |
| NIILB/40/120 | 38.8 | 0.8065 | 0.36 | DF | DF |
| S1 | 44.2 | 0.2775 | 0.9 | DF | DF |
| [illegible] | 44.2 | 0.4877 | 0.9 | DF | DF |
| [illegible] | 44.2 | 0.7316 | 0.9 | DF | DF |
| [illegible] | 37.2 | 1.9265 | 0.95 | cc | CC |
| [illegible] | 37.2 | 2.0216 | 0.95 | cc | CC |
| [illegible] | 37.2 | 1.321 | 0.95 | cc | CC |
| [illegible] | 37.2 | 0.9444 | 0.95 | RF | CC |
| 12-2F | 37.2 | 0.9919 | 0.95 | CC | RF |
| B500 | 35.2 | 0.6349 | 0.156 | DF | DF |
| B1200 | 35.2 | 0.6349 | 0.375 | DF | DF |
| B1800 | 35.2 | 0.6349 | 0.563 | DF | DF |
| B2900 | 35.2 | 0.6349 | 0.906 | CC | CC |
| p1 | 41.5 | 1.3657 | 0.965 | CC | CC |
| p2 | 37.7 | 0.7909 | 0.965 | DF | DF |
| p3 | 41.5 | 0.7788 | 0.965 | DF | DF |
| V2R2 | 48.9 | 0.6826 | 0.933 | DF | DF |
| V3R2 | 42.8 | 0.9021 | 0.933 | DF | DF |
| V4R3 | 46.4 | 1.2957 | 0.933 | DF | DF |
| E4 | 60.7 | 0.9638 | 1 | DF | DF |
| B1 | 48 | 1.0544 | 0.12 | C-E | C-E |
| B2 | 48 | 1.0544 | 0.2 | C-E | RF |
| B3 | 48 | 1.0544 | 0.4 | DF | DF |
| B4 | 48 | 1.0544 | 0.6 | DF | DF |
| B5 | 48 | 1.0544 | 0.68 | RF | RF |
| B6 | 48 | 1.0544 | 0.76 | RF | RF |
| B7 | 48 | 1.0544 | 0.84 | RF | RF |
| B8 | 48 | 1.0544 | 0.96 | RF | RF |

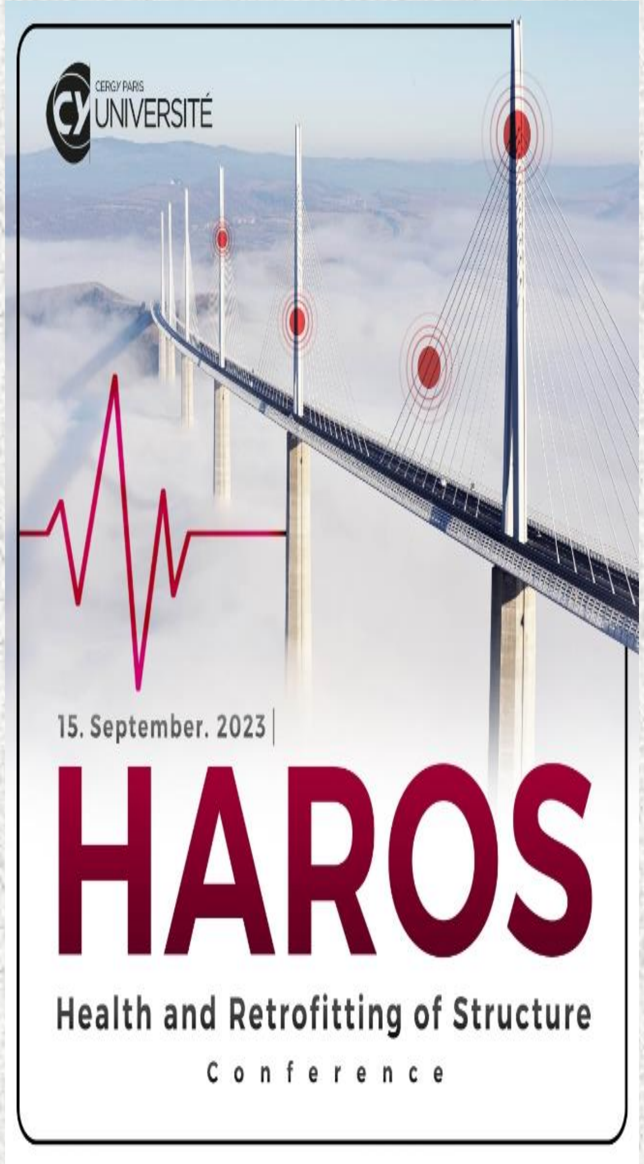
# Conclusions

1. The study revealed that the predicted effective strain of FRP strips closely conforms to the experimental results, which confirms the efficiency of the ANFIS model. The ANFIS system showed superior predictive accuracy and high generalizability compared to the fuzzy logic and neural networking method (ANN), The level of accuracy with ANFIS was achieved at RMSE = 0.0475.
   The main benefits of the ANFIS model are an effective, highly adaptable calculation with optimization and adaptation techniques.

2. A comparison of the collecting experimental data with Barros's formula and Khalifa's formula Where the highest accuracy of these equations reached RMSE=0.1333.

3. Thus, statistical indicators gave ANFIS a preference in predicting effective strain for FRP strips of RC beams flexurally-strengthened with NSM FRP strips.

# Conclusions




## The main conclusions

**It is possible to use the proposed ANFIS model to predict the value of the effective strain for FRP strips of RC beams flexurally-strengthened with NSM FRP strips and the failure modes of these beams, which saves us the high cost of experimental testing as well as time-saving which is valuable in the end.**

# References

Jang, ANFIS: adaptive-network-based fuzzy inference system, IEEE Trans. Syst. Man Cybern. 23 (3) (1993) 665–685.

Barros, Fortes. Flexural strengthening of concrete beams with CFRP laminates bonded into slits. Cement & Concrete Composite 2005, 27(4), 471–480.

Barros, Dias, Lima. Efficacy of CFRP-based techniques for the flexural and shear strengthening of concrete beams, Cement & Concrete Composite 2007, 29(3), 203-217.

Khalifa, Flexural Performance of R.C Beams Strengthened with Near Surface Mounted CFRP Strips, Alexandria Engineering Journal, 2016

Teng, Delorenzis, Wang, Wong, Lam. Debonding failures of RC beams strengthened with near surface mounted CFRP strips. Journal of composites for construction, 10 (2) (2006), 92-105.

Kotynia, (2012) Bond between FRP and concrete in reinforced concrete beams strengthened with near surface mounted and externally bounded reinforcement. Construction and building materials, 32, 41-54

Moawad, Flexural Behavior of NSM FRP Strengthened Reinforced Concrete Beams under Sustained Loading, PhD thesis, The University of Girona, 2020.

Barris, Sala, Gómez, Torres, Flexural behavior of FRP reinforced concrete beams strengthened with NSM CFRP strips, Composite Structures 241 (2020).

Jung, Park, Kang, and Keum, Flexural Behavior of Concrete Beam Strengthened by Near-Surface Mounted CFRP Reinforcement Using Equivalent Section Model, Advances in Materials Science and Engineering Volume 2017, Article ID 9180624

Bilotta, Ceroni, Nigro, Pecce, Efficiency of CFRP NSM strips and EBR plates for flexural strengthening of RC beams and loading pattern influence, Composite Structures 124 (2015)

# References


**Sharaky, Torres, Sallam, Experimental and analytical investigation into the flexural performance of RC beams with partially and fully bonded NSM FRP bars/strips, Composite Structures 122 (2015) 113–126.**

**Ibrahim, Fattah, Kotb, Mjeed, Flexural Behavior of RC Beams Strengthened with CFRP Strips, The 7th International Conference on FRP Composites in Civil Engineering International Institute for FRP in Construction (CICE 2014), Canada.**

**Sharaky, A Study of the Bond and Flexural Behavior of Reinforced Concrete Elements Strengthened with Near Surface Mounted (NSM) FRP Reinforcement, PhD thesis, The University of Girona, 2013.**

**Young, Seup, Assessment of Flexural Strengthening Behavior Using the Stirrup-Cutting Near Surface Mounted(CNSM) CFRP strip, Journal of the Korea Institute for Structural Maintenance and Inspection Vol. 16, No. 6 (2012)102-112.**

**[15] Barros, Costa, Flexural and Shear Strengthening of RC Beams with Composites Material – The Influence of Cutting Steel Stirrups to Install CFRP Strips, Cement and concrete composites,**

**Yost, Gross, Dinehart, Mildenberg, Flexural Behavior of Concrete Beams Strengthened with Near-Surface-Mounted CFRP Strips. ACI-Structural Journal, 104 (S41) (2007), 430-437.**

**Kotynia, Flexural behavior of Reinforced Concrete Beams Strengthened with near Surface Mounted CFRP Strips, Third International Conference on FRP Composites in Civil Engineering (CICE 2006), Miami, Florida, USA**

**Täljsten, Carolin, Nordin, Concrete Structures Strengthened with Near Surface Mounted Reinforcement of CFRP, Sweden (2003).**


Thank you