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# Regression Model for Predicting Study Parameters of GFRP Strengthened Corrosion Damaged RC Columns

P.R.Dhevasenaa, K.Suguna and P.N.Raghunath

***Abstract*- This paper presents the prediction equations for study parameters of glass fibre reinforced polymers (GFRP) strengthened corrosion damaged reinforced concrete columns. A total of twenty one columns of size 150mm diameter and height of 600 mm were cast and tested to examine the effectiveness of GFRP on corrosion damaged reinforced concrete columns. Each of the seven specimens was given different level of corrosion as 0%, 15% and 30% level. CSM, UDC and WR were the different configuration of GFRP used in this study. The GFRP wrapping was done with 3 mm and 5 mm thickness for each configuration. All the test specimens were subjected to monotonic loading up to failure, in a loading frame of capacity 2000kN. Necessary measurements were taken for each load increment. The predictions from the regression equations were compared with those of the experimental values and the findings concluded that the predictions were made with reasonable accuracy.***

*Index Terms* - **Corrosion, GFRP, Regression, Wrapping.**

## I. INTRODUCTION

The direct consequences of reinforcement corrosion on the serviceability and structural integrity of reinforced concrete structures are cracking, spelling, and delamination of the concrete cover due to formation of expansive corrosion products; decrease in bonding at a steel concrete interface and decrease in the cross-sectional area of steel reinforcement. Some of the researchers also suggest that expansive corrosion products would exert a compressive softening effect on the concrete, which would influence the strength and ductility of an overall RC structure. Mangat and Elgarf (1999) investigated the residual flexural strength of concrete beams with corroding reinforcement. Different degrees of reinforcement corrosion were induced in increments varying from 1.25 to 10%. An accelerated corrosion technique was used by applying an external power supply. The results indicated that the reduction in reinforcing bar cross-section due to corrosion has an insignificant effect on the residual flexural strength of beams. The reduction in residual strength was due to the loss or breakdown of the steel/concrete interfacial bond.

Reinforced concrete column contains steel bars in the axial direction to take up compressive loads. Steel ties in the lateral direction resist the tendency of the core concrete to expand in the lateral direction and prevent the longitudinal reinforcing bars from buckling. This lateral tie mechanism already provides a level of confinement to the concrete core, which is further supplemented by the provision of FRP wrap. Hence, FRP confinement in a reinforced concrete column acts in tandem with the lateral steel ties to confine the core and thus improve the load-deflection performance, load carrying capacity, deflection ductility and energy ductility of the column.

The application of axial compressive force triggers shortening of the length of the reinforced concrete column. When the concrete core is not confined, lateral expansion takes place without restriction. When the column is confined using FRP wraps, the tendency of the concrete core to expand in the lateral direction is constrained, thus resulting in lower lateral strain and correspondingly lower axial strain. The stiffness of the concrete column in the axial direction increases due to FRP confinement. Toutanji (1999) conducted experimental and analytical studies on the performance of concrete columns externally wrapped with carbon and glass fibre reinforced polymer composite sheets. The stress-strain characteristics, ultimate strength, stiffness and ductility of the confined specimens were considered as the major study parameters. The results showed considerable enhancement in strength, ductility and energy absorption capacity for the externally confined concrete specimens. An analytical model was also proposed to predict the stress-strain relationship of FRP confined concrete specimens. The predicted results were in close agreement with the experimental results.

Slenderness ratio also influences the performance of FRP confined of reinforced concrete column. Columns with more slenderness perform poorly and fail at lower load levels. The application of FRP wraps improves the load carrying capacity, axial strain and lateral strain capacities even at high slenderness ratios thus offsetting the effects of slenderness (Mirmiran et al. (2001), Nagaradjane et al. (2007)).

American Concrete Institute (ACI) published report No. 440 in the year 2002, containing guidelines for the use of FRP as internal and external reinforcement in concrete construction. The committee was chaired by Sami H. Rizkalla and produced two separate reports, ACI 440.1R for internal FRP reinforcement and ACI 440.2R for externally bonded FRP reinforcement. The committee report No. 440.2R included comprehensive guidelines for strengthening in flexure, shear, axial tension and axial compression. The report also covered material properties of FRP and construction requirements related to installation, inspection and maintenance. The report presented equations for estimating the design strength of FRP confined reinforced concrete columns in compression based on the concrete confinement equation proposed by Mander et al. (1988).

Richard et al (2003) 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.

Nagaradjane, Rajasekaran, Raghunath and Suguna (2007) investigated the effect of slenderness on the performance of concentrically loaded plain concrete cylinders confined by GFRP wrap. The compressive strength of the concrete cylinders increased in the range of 39.49% to 56.20% due to 3 mm thick GFRP wrapping and by 60.53% due to reduction of slenderness ratio from 24 to 8. A General Regression Neural Network (GRNN) model was proposed in the study for predicting the compressive strength, ultimate axial compressive strain and ultimate lateral compressive strain of GFRP wrapped cylinders. The predictions of the GRNN model agreed well with experimental results.

The research study is intended to evaluate the effect of glass fibre reinforced polymer wrapping on the performance of corrosion-damaged concrete columns. A regression based models have also been developed for estimating the strength, deformation and ductility performance of GFRP confined corrosion-damaged concrete columns.

Regression analysis is a mathematical measure of the average relationship between two or more variables in terms of the original units of the data. In regression analysis, there are two types of variables. The variable whose value in influenced or is to be predicted is called dependent variable. The variable, which influences the values or is used for prediction, is called independent variables or predictor.

Multiple linear regression analysis was carried out in this study to determine the relations between the dependent variable of compressive strength, ultimate axial compressive strain, ductility and energy absorption and the independent variables such as level of corrosion damage, type of GFRP wrap material, thickness of GFRP wrap.

## II. TERMINOLOGY USED IN REGRESSION ANALYSIS

### *A. Regression Co-efficient*

The unknown factor introduced into a regression equation. This factor suitably modifies the input parameters and tends to make the predictions closer to the observed results

### *B. Sum of Squared Errors*

The square of error values after adding to represent the total numerical error level associated with the predictions of the regression equation.

### *C. Mean Squared Error*

Mean Squared Error (MSE) is the sum of squared errors divided by the number of samples in hand. Mean Squared Error is superior to Sum of Squared Errors since MSE indicates the squared error per sample while SSE simply gives the sum, irrespective of the number of samples involved.

### D. *Root Mean Squared Error*

Root Mean Squared Error (RMSE) is the square root of Mean Squared Error. Hence, this represents the numerical value by which the prediction might deviate from the actual value. The deviation might be negative or positive, thus making the predictions bit lower or higher than the actual values.

### E. *Fitness of Function*

The fitness of function is measured as the ratio between variance for the predicted values and the variance for the actual values. The fitness value lies between 0 and 1.

### F. *Multiple Linear Regression*

The general purpose of multiple linear regressions (the term was first used by Pearson, 1908) is an extension of the simple linear regression where multiple independent variables exist. When there are $i$ independent variables $x1$, $x2$,…., $xi$, the linear multiple regression equation is in the general form of,

$$y = a_0 + a_1\ x_1 + a_2\ x_2 + \dots\dots\dots. + a_i\ x_i \qquad \text{(Eq. 1)}$$

where $y$ is the dependent variable, $x1$, $x2$, …, $xi$ are the independent variables (explanatory variables) and ***a*** denotes coefficient vector.

## III. MODELLING OF REGRESSION EQUATIONS

The regression equations for the various parameters such as axial compressive strength, ultimate compressive strain, deflection ductility, energy ductility and energy absorption were modeled for the present study by using the multiple regression analysis, which was carried out by a statistical software Origin Pro 8.0 version.

### A. *Regression Equation for Compressive Strength*

The regression equation for estimating the compressive strength for FRP wrapped corrosion-damaged columns was obtained with the aid of ACI 440.2R equation. The general form of the equation proposed for the compressive strength is,

$$f''_{cc} = a_0 + a_1\ f'_{cc} + a_2\ \frac{f_l}{f'_{co}} + a_3\ C_d + \frac{f_y\ A_{st}}{A_g} \qquad \text{(Eq. 2)}$$

Using the regression equation 2 and the data used for the regression analysis summarized in Table 1, the regression co-efficients $a_0$ to $a_3$ can be determined.

**Table 1. Data Used for Determination of Regression Co-efficient for Compressive Strength**

| Sl. No. | Specimen Designation | Compressive Stress from Mander et al. (1988) Model | Confinement Coefficient $\left(\frac{2E_f \varepsilon_{fu} nt}{f'_{co} D}\right)$ | Level of Corrosion Damage | Compressive Strength from Experiment (minus strength of steel) |
|---|---|---|---|---|---|
| 1 | NC CON | 57.84 | 0.00000 | 0 | 42.44 |
| 2 | NC CSM 3 | 86.75 | 0.03966 | 0 | 45.27 |
| 3 | NC CSM 5 | 109.36 | 0.08171 | 0 | 48.10 |
| 4 | NC UDC 3 | 130.52 | 0.14045 | 0 | 67.91 |
| 5 | NC UDC 5 | 161.71 | 0.23649 | 0 | 72.15 |
| 6 | NC WR 3 | 90.76 | 0.04632 | 0 | 60.83 |
| 7 | NC WR 5 | 114.66 | 0.09328 | 0 | 63.66 |
| 8 | CD 15 CON | 57.84 | 0.00000 | 15 | 41.03 |
| 9 | CD 15 CSM 3 | 86.75 | 0.03966 | 15 | 43.86 |
| 10 | CD 15 CSM 5 | 109.36 | 0.08171 | 15 | 46.69 |

| Sl. No. | Specimen Designation | Compressive Stress from Mander et al. (1988) Model | Confinement Coefficient $\left(\frac{2E_f \varepsilon_{fu} nt}{f'_{co} D}\right)$ | Level of Corrosion Damage | Compressive Strength from Experiment (minus strength of steel) |
|---|---|---|---|---|---|
| 11 | CD 15 UDC 3 | 130.52 | 0.14045 | 15 | 66.49 |
| 12 | CD 15 UDC 5 | 161.71 | 0.23649 | 15 | 69.32 |
| 13 | CD 15 WR 3 | 90.76 | 0.04632 | 15 | 58.00 |
| 14 | CD 15 WR 5 | 114.66 | 0.09328 | 15 | 60.83 |
| 15 | CD 30 CON | 57.84 | 0.00000 | 30 | 39.61 |
| 16 | CD 30 CSM 3 | 86.75 | 0.03966 | 30 | 42.44 |
| 17 | CD 30 CSM 5 | 109.36 | 0.08171 | 30 | 45.27 |
| 18 | CD 30 UDC 3 | 130.52 | 0.14045 | 30 | 63.66 |
| 19 | CD 30 UDC 5 | 161.71 | 0.23649 | 30 | 67.91 |
| 20 | CD 30 WR 3 | 90.76 | 0.04632 | 30 | 55.17 |
| 21 | CD 30 WR 5 | 114.66 | 0.09328 | 30 | 58.00 |

### *B. Regression Equation for Ultimate Axial Compressive Strain*

The regression equation for ultimate axial compressive strain was used with one of the proposed modelled by Karbhari and Gao (1997). The regression equation for the ultimate axial compressive strain was modelled with the unknown regression co- effiecient presented in equation 3. The data used for the regression analysis is presented in Table 8.2 and the regression co-efficient fitted in equation 2 is shown in Table 4.

$$\epsilon_{cc} = a_0 + a_1 \left(\epsilon_{co} + 0.001\left(\frac{E_f\, n\, t}{f'_{co}\, D}\right)\right) + a_3\, C_d$$

(Eq. 3)

**Table 2. Data Used for Determination of Regression Co-efficient for Ultimate Axial Compressive Strain**

| Sl.No. | Specimen Designation | Karbhari and Gao Model (1997) | Confinement Co-efficient | Levels of Corrosion Damage | Experimental Ultimate Strain |
|---|---|---|---|---|---|
| 1 | NC CON | 0.003500 | 0.00 | 0 | 0.009767 |
| 2 | NC CSM 3 | 0.004373 | 0.08 | 0 | 0.010067 |
| 3 | NC CSM 5 | 0.005298 | 0.16 | 0 | 0.011067 |
| 4 | NC UDC 3 | 0.006417 | 0.27 | 0 | 0.015667 |
| 5 | NC UDC 5 | 0.008704 | 0.48 | 0 | 0.016100 |
| 6 | NC WR 3 | 0.004519 | 0.09 | 0 | 0.013067 |
| 7 | NC WR 5 | 0.005553 | 0.19 | 0 | 0.014267 |
| 8 | CD 15 CON | 0.003500 | 0.00 | 15 | 0.005017 |
| 9 | CD 15 CSM 3 | 0.004373 | 0.08 | 15 | 0.005267 |

| | | | | | |
|---|---|---|---|---|---|
| 10 | CD 15 CSM 5 | 0.005298 | 0.16 | 15 | 0.005767 |
| 11 | CD 15 UDC 3 | 0.006417 | 0.27 | 15 | 0.008033 |
| 12 | CD 15 UDC 5 | 0.008704 | 0.48 | 15 | 0.008233 |
| 13 | CD 15 WR 3 | 0.004519 | 0.09 | 15 | 0.007050 |
| 14 | CD 15 WR 5 | 0.005553 | 0.19 | 15 | 0.007217 |
| 15 | CD 30 CON | 0.003500 | 0.00 | 30 | 0.003656 |
| 16 | CD 30 CSM 3 | 0.004373 | 0.08 | 30 | 0.003956 |
| 17 | CD 30 CSM 5 | 0.005298 | 0.16 | 30 | 0.004322 |
| 18 | CD 30 UDC 3 | 0.006417 | 0.27 | 30 | 0.005444 |
| 19 | CD 30 UDC 5 | 0.008704 | 0.48 | 30 | 0.005600 |
| 20 | CD 30 WR 3 | 0.004519 | 0.09 | 30 | 0.004633 |
| 21 | CD 30 WR 5 | 0.005553 | 0.19 | 30 | 0.004811 |

### C. *Regression Equation for Other Parameters*

The regression equation for other parameters such as deflection ductility, energy ductility and energy absorption were modelled with two regression co-efficients. The general form of the equation is as follows,

$$P_P = a_0 + a_1 \frac{f_l}{f'_{co}} + a_3 C_d \qquad \text{(Eq. 4)}$$

Here $P_p$ denotes for the predicted parameters. The data used to model the regression equation for various parameters are presented in Table 3 and the results of those predicted parameters are shown in Table 4.

**Table 3. Data Used for Estimating Regression Equation for Other Parameter**

| Specimen Designation | Deflection Ductility | Confinement Co-efficient | Levels of Corrosion Damage | Energy Ductility |
|---|---|---|---|---|
| NC CON | 3.53 | 0.00 | 0 | 2.15 |
| NC CSM 3 | 4.66 | 0.08 | 0 | 2.42 |
| NC CSM 5 | 4.68 | 0.16 | 0 | 3.83 |
| NC UDC 3 | 5.65 | 0.27 | 0 | 3.41 |
| NC UDC 5 | 6.17 | 0.48 | 0 | 4.36 |
| NC WR 3 | 5.41 | 0.09 | 0 | 2.51 |
| NC WR 5 | 5.62 | 0.19 | 0 | 3.92 |

| | | | | |
|---|---|---|---|---|
| CD 15 CON | 3.59 | 0.00 | 15 | 1.99 |
| CD 15 CSM 3 | 4.20 | 0.08 | 15 | 2.13 |
| CD 15 CSM 5 | 4.87 | 0.16 | 15 | 3.31 |
| CD 15 UDC 3 | 6.35 | 0.27 | 15 | 3.18 |
| CD 15 UDC 5 | 6.85 | 0.48 | 15 | 4.13 |
| CD 15 WR 3 | 5.41 | 0.09 | 15 | 2.39 |
| CD 15 WR 5 | 6.56 | 0.19 | 15 | 3.20 |
| CD 30 CON | 4.27 | 0.00 | 30 | 1.77 |
| CD 30 CSM 3 | 5.39 | 0.08 | 30 | 1.95 |
| CD 30 CSM 5 | 5.15 | 0.16 | 30 | 2.81 |
| CD 30 UDC 3 | 6.61 | 0.27 | 30 | 3.06 |
| CD 30 UDC 5 | 6.99 | 0.48 | 30 | 4.06 |
| CD 30 WR 3 | 5.64 | 0.09 | 30 | 2.10 |
| CD 30 WR 5 | 5.96 | 0.19 | 30 | 2.92 |

## IV. RESULTS OF REGRESSION EQUATIONS

In this study, multiple linear regression analysis was carried out to determine the relations between the dependent variable of compressive strength or ultimate axial compressive strain and the independent variables, i.e., level of corrosion damage, type of GFRP wrap material and thickness of GFRP wrap. The results of regression equation for various parameters associated with GFRP wrapped corrosion-damaged concrete columns are presented in Table 4. The proposed regression equations enabled the predictions to be made with reasonable accuracy. The predictions from the regression equations were compared with those of the experimental values and are presented through Figs. 1 to 4.

**Table 4. Results of Regression Equation**

| SI. No | Parameter | Regression Equation | Adj. $R^2$ |
|---|---|---|---|
| 1 | Ultimate axial compressive strength | $27.12 – 0.1347\ c_d + \frac{f_y\ A_{st}}{A_g} + 0.273\ \{f'_{co}\ [2.25\sqrt{1 + 7.9\ \frac{f_l}{f'_{co}}} - 2\frac{f_l}{f'_{co}} - 1.25]\} + 8.312\ (\frac{2f_{fu}nt}{f'_{co}\ D})$ | 0.7005 |
| **2** | Ultimate axial compressive strain | $0.033 – 0.00027\ c_d - 6.38\{\epsilon_{co} + 0.01(\frac{f_l}{f'_{co}})\} + 0.077(\frac{2f_{fu}nt}{f'_{co}\ D})$ | 0.8369 |
| **3** | Deflection Ductility | $4.10 + 0.0204\ c_d + 5.469\ (\frac{2f_{fu}nt}{f'_{co}\ D})$ | 0.69266 |
| **4** | Energy Ductiltiy | $2.3609 - 0.01871\ c_d + 4.702(\frac{2f_{fu}nt}{f'_{co}\ D})$ | 0.8322 |

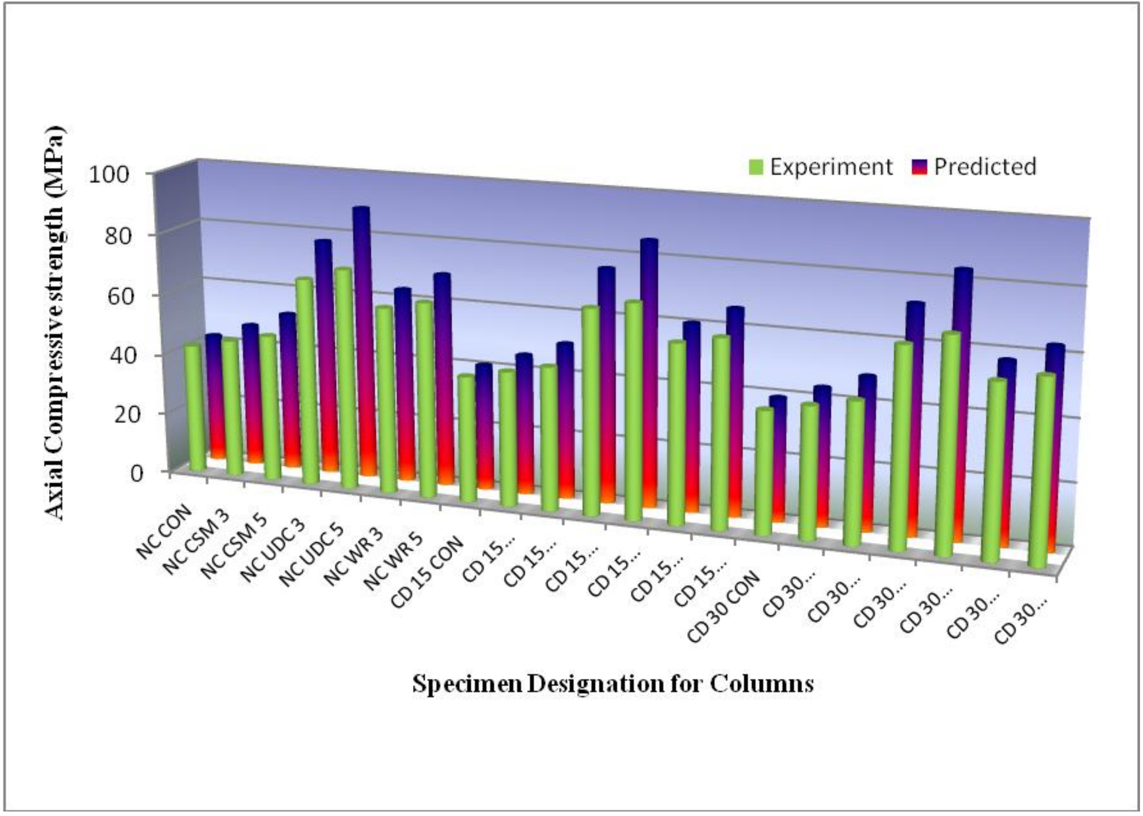

**Fig. 1 Regression Prediction for Ultimate Axial Compressive Strength**

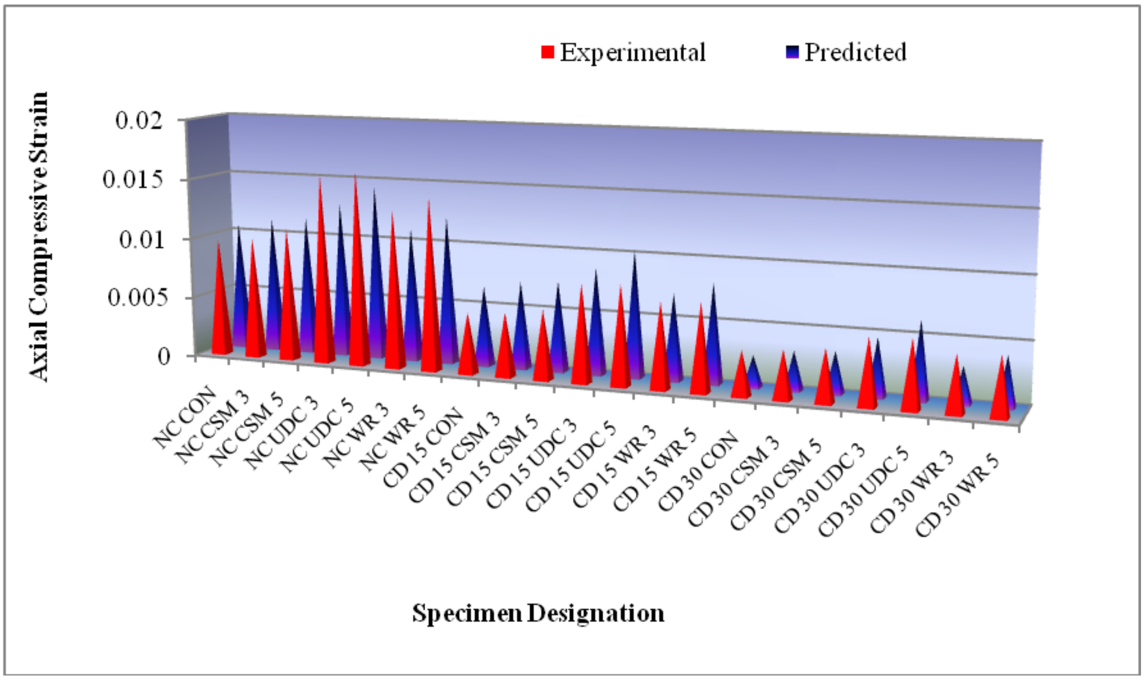

**Fig. 2 Regression Prediction for Ultimate Axial Compressive Strain**

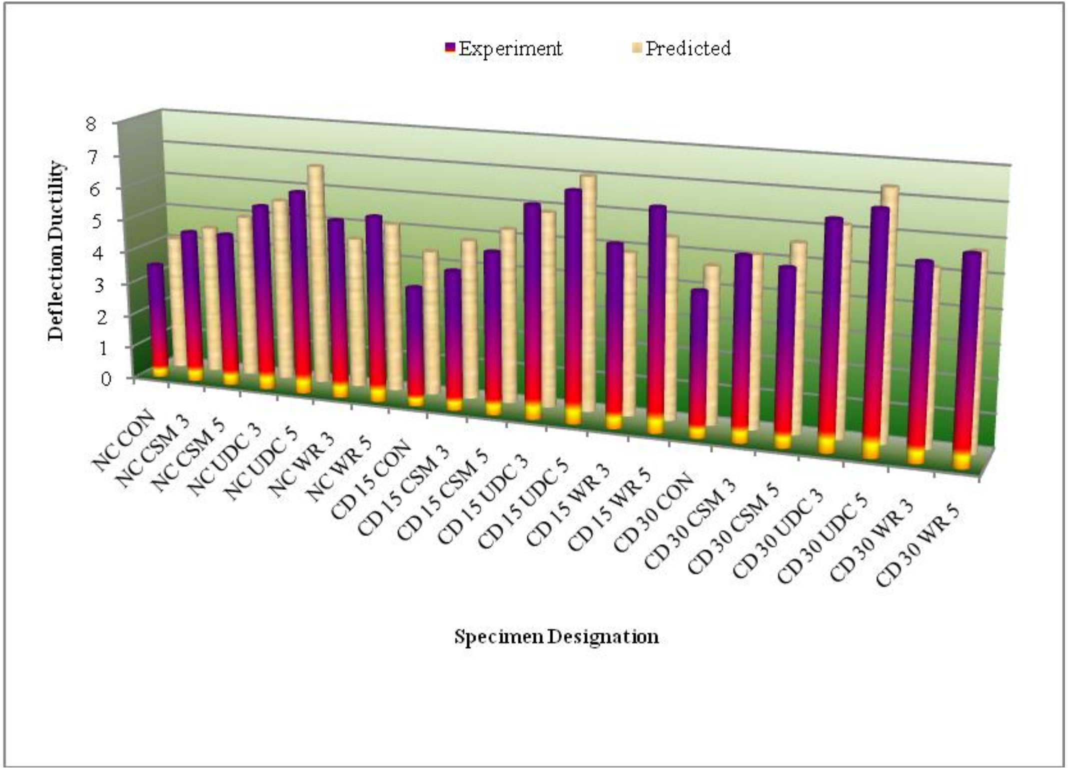

Fig. 3 Regression Prediction for Deflection Ductility

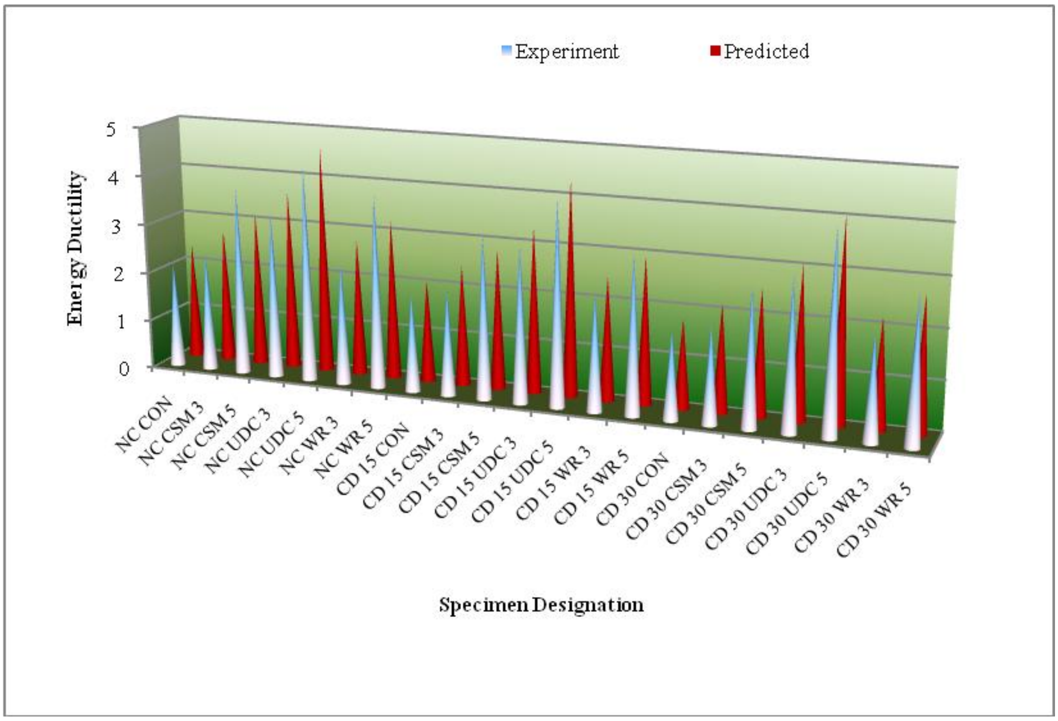

Fig. 4 Regression Prediction for Energy Ductility

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