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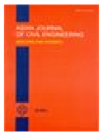

DUCTILITY BEHAVIOR OF COMPOSITE FIBRE REINFORCED POLYMER- HIGH STRENGTH CONCRETE COLUMNS UNDER COMPRESSION

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ABSTRACT

The paper presents the results of a study on the ductility behavior of composite fibre reinforced polymer- 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 deflection ductility and energy ductility capacity. Regression equation has been proposed for predicting the performance parameters. A better correlation has been observed between the test results and those predicted through the proposed equations.

Keywords: GFRP; ductility; high strength concrete; regression; strength

1. INTRODUCTION

Concrete with strengths higher than 40 MPa is generally referred to as high strength concrete. Some basic concepts relating to strength and ductility have been introduced in ACI code with respect to the compression member [1]. With developments in technology, the use of high strength concrete members has proved to be most promising in terms strength, stiffness, durability and economy [2,3]. As the strength of concrete increases, it becomes more brittle. The lack of ductility of high strength concrete columns can result in sudden failure. Several research works have proved use of spiral confinement, rectangular and circular lateral ties. In recent years, external wrapping has been identified as an

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effective method of confining concrete. Among the various materials available for the purpose, FRP has proved to be more beneficial. The application of FRP in the construction industry can eliminate some unwanted properties of high strength concrete, such as the brittle behavior of high strength concrete. FRP is particularly useful for strengthening columns and other unusual shapes. Several research studies have been reported an improving the strength and ductility of normal strength columns. Only limited literature is available on enhancing the ductility of high strength concrete column members. Hence an attempt has been made to investigate the strength and ductility performance of wrapping. Focusing attention on the behavior of compression members, the main parameters investigated in literature are the type of FRP material (carbon, glass, aramid,etc.) and its manufacture (unidirectional or bi-directional wraps), the shape of the transverse cross-section of the members, the dimensions and the shape of specimens, the strength of concrete, and the types and percentages of steel reinforcements [4–7].

The present paper deals with the analysis of experimental results, in terms of ductility capacity, obtained from tests on circular concrete columns, reinforced with external E-glass fiber composite. The principal study parameter was slenderness effect of ductility of FRP confined columns [8] and compared proposed regression equation and experimental data.

2. MATERIALS AND METHODS

An experimental investigation has been conducted on 28 column specimens having 150 mm diameter and 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 6 columns were wrapped with GFRP of varying configuration with different thickness for each slenderness ratio.

2.1 Material properties

The concrete used for casting the specimens was designed for a compressive strength 60 MPa. The mix ratio adopted was 1:1.73:2.51:0.34:0.8% (cement: Fine aggregate: Coarse aggregate: Water: Hyperplastizicer percentage by weight of binder). The characteristic compressive strength achieved was 63.64 MPa. The steel used for longitudinal reinforcement was ribbed steel with yield strength of 450 MPa and mild steel with yield strength of 300 MPa was used for the internal ties.

3. 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 and wrap details are provided in Table 1.

Table 1: Specimen details

Details of specimens	**Diameter (mm)**	**Height (mm)**	**Type of GFRP (mm)**	**Thickness of GFRP (mm)**
S8R0	150	300	-	0
S8CSM3	150	300	CSM	3
S8CSM5	150	300	CSM	5
S8UDC3	150	300	UDC	3
S8UDC5	150	300	UDC	5
S8WR3	150	300	WR	3
S8WR5	150	300	WR	5
S16R0	150	600	-	0
S16CSM3	150	600	CSM	3
S16CSM5	150	600	CSM	5
S16UDC3	150	600	UDC	3
S16UDC5	150	600	UDC	5
S16WR3	150	600	WR	3
S16WR5	150	600	WR	5
24R0	150	900	-	0
S24CSM3	150	900	CSM	3
S24CSM5	150	900	CSM	5
S24UDC3	150	900	UDC	3
S24UDC5	150	900	UDC	5
S24WR3	150	900	WR	3
S24WR5	150	900	WR	5
S32R0	150	1200	-	0
S32CSM3	150	1200	CSM	3
S32CSM5	150	1200	CSM	5
S32UDC3	150	1200	UDC	3
S32UDC5	150	1200	UDC	5
S32WR3	150	1200	WR	3
S32WR5	150	1200	WR	5

4. TEST SET-UP

Testing of specimens having heights of 300mm, 600mm, 900mm and 1200mm was carried out in a loading frame of 2000kN capacity. The instruments used for testing included deflectometer having a least count of 0.01mm and a lateral extensometer with a least count of 0.001mm. Figure1 shows the instrumentation adopted for the columns. The specimen was placed with capping at both ends. The load was applied in increments using the loading jack. Axial compression was measured using two dial gauges placed at top and bottom of the specimen.

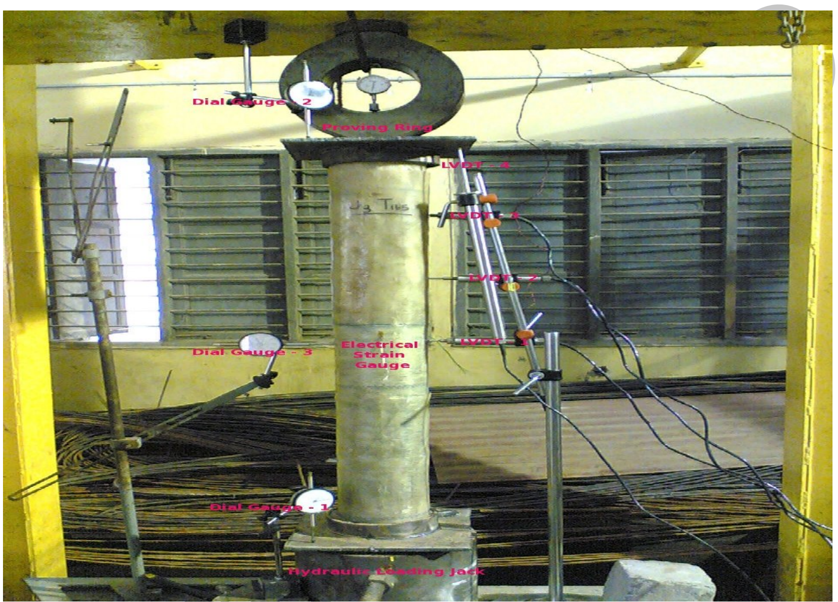

Figure 1. Test set-up with instruments

5. RESULTS AND DISCUSSION

The ultimate loads and deflection experienced by the test specimens are presented in Table 2.

5.1 Stress-strain behaviour of GFRP wrapped RC columns

The stress-strain curves for the concrete columns (with and without GFRP wrapping) grouped by slenderness ratio are presented in Figures 2 to 5.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 stress, although the differences are not as high as those for ultimate stress. 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.

Table 2: Ultimate loads and deflection for tested columns

Specimen designation	Ultimate load (kN)	Ultimate deflection (mm)	Deflection ductility	Energy ductility
S8R0	1150	2.93	1.47	1.74
S16R0	1080	3.01	1.43	1.66
S24R0	1000	3.29	2.01	3.23
S32R0	900	3.45	1.99	3.42
S8CSM3	1220	3.02	1.67	1.99
S16CSM3	1140	3.16	1.90	2.43
S24CSM3	1050	3.56	2.43	3.84
S32CSM3	990	3.62	2.46	4.26
S8CSM5	1300	3.32	1.79	2.17
S16CSM5	1200	3.46	2.12	3.05
S24CSM5	1175	3.89	2.76	4.48
S32CSM5	1025	4.02	3.02	5.50
S8UDC3	1370	4.70	2.51	3.05
S16UDC3	1300	4.82	2.32	3.19
S24UDC3	1275	4.90	4.95	7.96
S32UDC3	1190	5.04	4.71	7.61
S8UDC5	1450	4.83	3.77	5.22
S16UDC5	1375	4.94	3.86	5.22
S24UDC5	1330	5.04	6.72	11.04
S32UDC5	1225	5.35	6.69	12.19
S8WR3	1270	3.92	1.75	1.96
S16WR3	1170	4.23	2.21	2.84
S24WR3	1120	4.17	3.50	5.75
S32WR3	1050	4.35	3.37	5.89
S8WR5	1320	4.28	3.29	4.32
S16WR5	1225	4.33	3.23	4.62
S24WR5	1185	4.33	4.33	7.25
S32WR5	1090	4.90	4.30	7.46

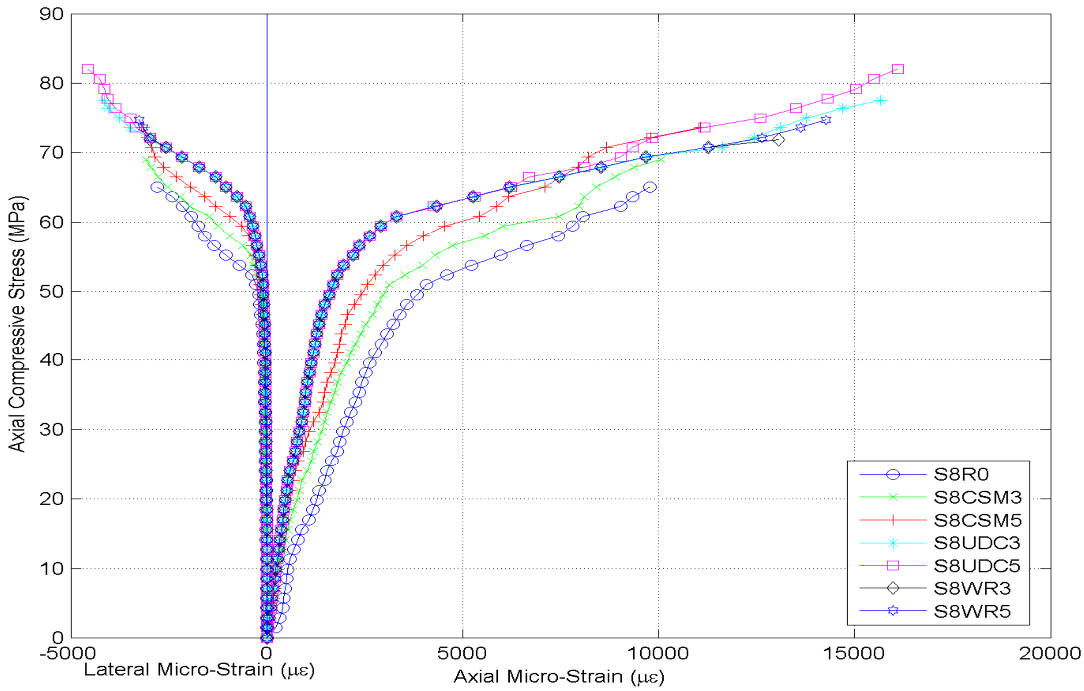

Figure 2. Stress-strain curves for columns S 8

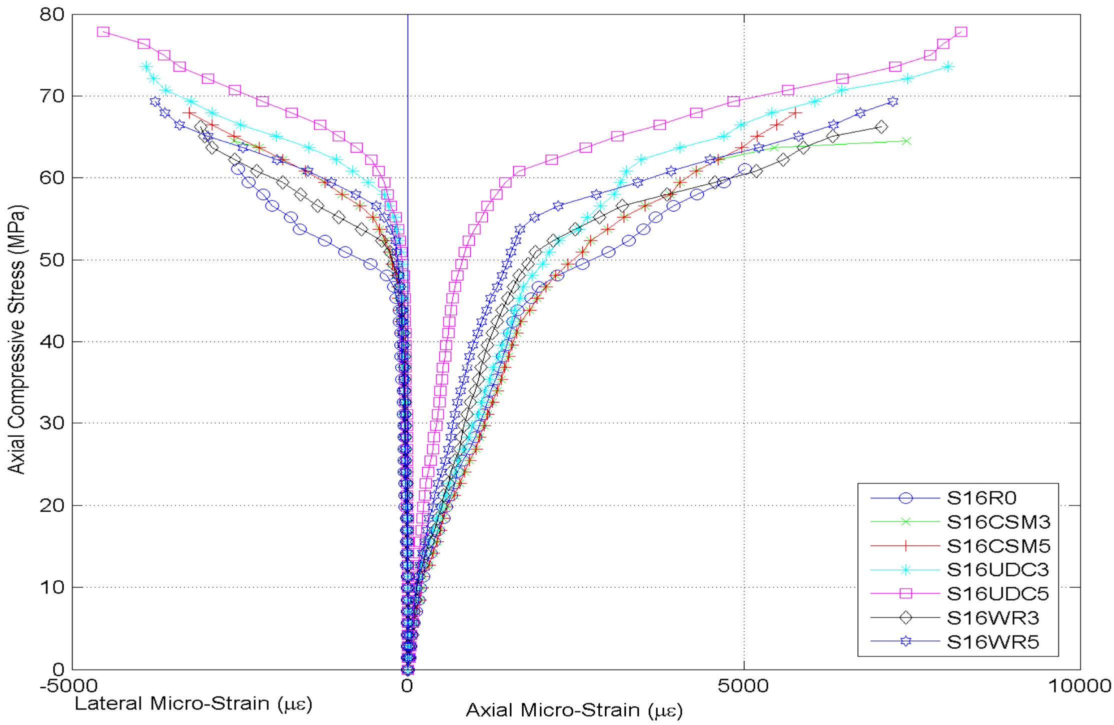

Figure 3. Stress-strain curves for columns S 16

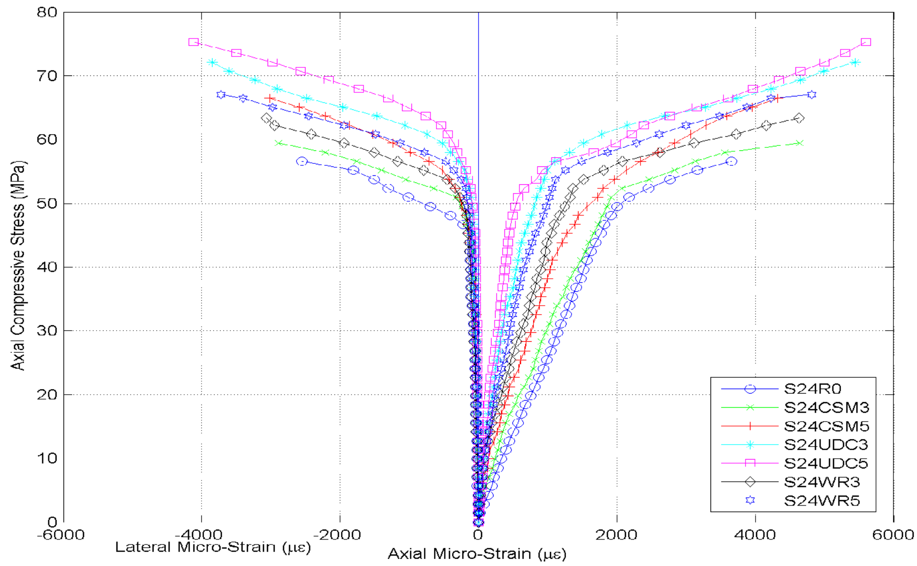

Figure 4. Stress-strain curves for columns S 24

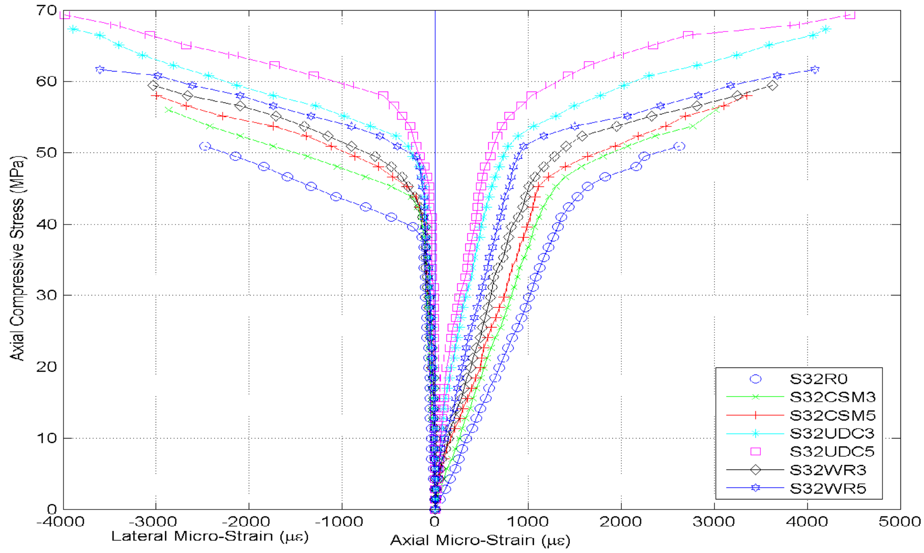

Figure 5. Stress-strain curves for columns S 32

The columns with UDCGFRP wrapping normally showed better stress-strain behaviour. The stress 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 trend 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 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 5mm 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.

6. DUCTILITY OF GFRP WRAPPED RC COLUMNS

The ductility for the columns was calculated based on deflection and energy absorption. The deflection ductility was calculated as the ratio between the deflection at ultimate point and the deflection at yield point. The energy ductility was calculated as the ratio of the cumulative energy absorption at ultimate point to the cumulative energy absorption at yield point.

In symbolic terms, the deflection ductility (Δ_d) may be represented by

$$\Delta_d = \frac{\delta_u}{\delta_y} \tag{1}$$

and the energy ductility (Δ_e) may be represented by

$$\Delta_e = \frac{\int_0^{x_u} \sigma \quad d\varepsilon}{\int_0^{x_y} \sigma \quad d\varepsilon} \tag{2}$$

But, the integral form is not readily applicable for experimental stress-strain curves which consist of discrete number of points instead of a function representing the stress-strain behaviour. Hence, the equation may be rewritten in a form suitable for numerical computation as follows:

$$\Delta_e = \frac{\sum_{i=1}^{N_u - 1} \frac{(\sigma_i + \sigma_{i+1})}{2} (\varepsilon_{i+1} - \varepsilon_i)}{\sum_{i=1}^{N_y - 1} \frac{(\sigma_i + \sigma_{i+1})}{2} (\varepsilon_{i+1} - \varepsilon_i)} \tag{3}$$

where, the Δ_d is the deflection ductility, Δ_e is the energy ductility, δ_y is the deflection at yield point, δ_u is the deflection at ultimate point, N_u is the reading number at ultimate point, N_y is the reading number at yield point, σ_i is the stress at i^{eth} point, ε_i is the strain value at i^{eth} point, σ is stress at a point, $d\varepsilon$ is a small interval in the strain axis.

The ductility ratios were calculated as the ratio between the ductility of the column and the ductility of unwrapped column having the same slenderness ratio. The deflection and energy ductility values so calculated for the experimental results using the equations 1 and 3 are presented in Table 2 and Figures 6 and 7.

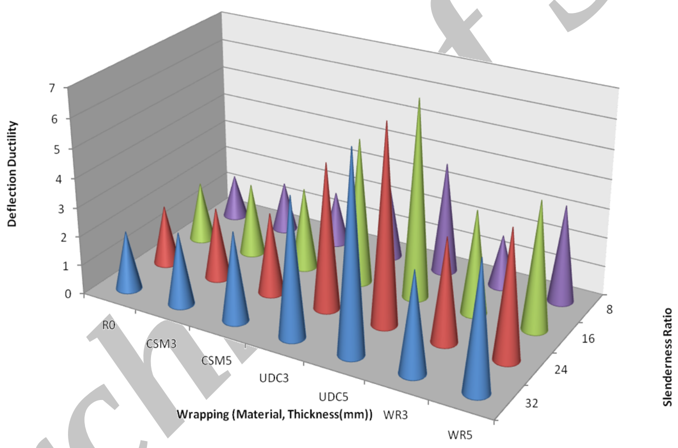

Figure 7. Deflection ductility for GFRP columns

Figure 8. Energy ductility for GFRP columns

6.1 Effect of slenderness ratio on deflection ductility

The unwrapped columns showed sensitively to slenderness ratio on deflection ductility, the decrease in 28.14% and 26.13% for the columns S16R0 and S8R0, the increase in 1.00% for the column S24R0 compared to the column S32R0. The columns exhibited decrease in deflection ductility up to 31.28% for 3mm thick CSMGFRP wrap, decrease in deflection ductility up to 50.74% for 3mm thick UDCGFRP wrap and decrease in deflection ductility up to 34.42% for 3mm thick WRGFRP wrap from base of 32. The columns decrease in deflection ductility up to 46.71% for 5mm thick CSMGFRP wrap, decrease in deflection ductility up to 43.65% for 5mm thick UDCGFRP wrap and decrease in deflection ductility up to 23.49% for 5mm thick WRGFRP wrap from base of 32.

6.2 Effect of thickness of wrap on deflection ductility

The columns wrapped with 3mm thick CSMGFRP exhibited increase in the range of 13.61% to 32.87% over the corresponding unwrapped column. The columns wrapped with 5mm thick CSMGFRP exhibited increase in the range of 21.77% to 51.76% over the corresponding unwrapped columns. The columns wrapped with 3mm thick WRGFRP exhibited increase in the range of 19.05% to 74.13% over the corresponding unwrapped columns. The columns wrapped with 5mm thick WRGFRP showed 115.42 % to 125.87% increase in deflection ductility compared to the corresponding unwrapped columns. The columns wrapped with UDCGFRP showed increase in ductility in the range of 62.24% to 146.27% for 3mm thick wrap and 156.46% to 236.18% for 5mm thick wrap, when compared to the corresponding wrapped columns.

6.3 Effect of wrap material on deflection ductility

The columns wrapped with 3mm thick UDCGFRP exhibited increases in 50.30%, 22.11%, 103.70% and 91.46% for S8UDCGFRP, S16UDCGFRP, S24UDCGFRP and S32UDCGFRP, when compared to the corresponding CSMGFRP wrapped columns. The columns wrapped with 5mm thick UDCGFRP showed 82.08% to 143.48%, when compared to the corresponding CSMGFRP wrapped columns. The columns wrapped with 3mm thick WRGFRP exhibited increase in the range of 4.79% to 44.03%, when compared to the corresponding CSMGFRP wrapped columns. The columns wrapped with 5mm thick WRGFRP showed 42.38% to 83.79%, when compared to the corresponding CSMGFRP wrapped columns.

6.4 Effect of slenderness ratio on energy ductility

Energy ductility for 3mm thick GFRP wrapped columns were lower for slenderness ratios of 24, 16and 8 compared to the columns having slenderness ratio of 32. Among the GFRP wrapped columns, the maximum increase in energy ductility as a result of decrease in slenderness ratio was observed in the range of 2.38% to 66.72% for 3mm thick WRGFRP wrapped columns. Columns wrapped with 3mm thick UDCGFRP showed up to 59.92% increase in energy ductility. Columns wrapped with 3mm thick CSMGFRP showed increase in energy ductility at 9.86% to 52.29% due to decrease in slenderness ratio.Columns wrapped with 5mm thick UDCGFRP showed 2.48 % to 57.18% increase in energy ductility for decrease in slenderness ratio from 32. Columns wrapped with 5mm thick CSMGFRP showed increase in energy ductility at18.55% to 60.54% due to the decrease in slenderness ratio. Columns wrapped with 5mm thick WRGFRP showed increase in energy ductility at 2.82% to 46.16% due to the decrease in slenderness ratio.

6.5 Effect of thickness of wrap on energy ductility

The columns wrapped with 3mm thick CSMGFRP exhibited increase in the range of 14.37% to 46.39% over the corresponding unwrapped columns. The columns wrapped with 5mm thick CSMGFRP exhibited increase in the range of 24.71% to 83.73% over the corresponding unwrapped column. The columns wrapped with 3mm thick WRGFRP exhibited increase in the range of 12.64% to 78.02% over the corresponding unwrapped column. The columns wrapped with 5mm thick WRGFRP showed 118.13% to 178.31% increase in deflection ductility compared to the corresponding unwrapped column. The columns wrapped with UDCGFRP showed increase in ductility in the range of 75.28% to 146.44% for 3mm thick wrap and 200.00% to 256.43% for 5mm thick wrap, when compared to the corresponding wrapped column.

6.6 Effect of wrap material on energy ductility

The wrapped columns with 3mm thick WRGFRP wrapping showed up to 107.29% increase, the 5mm thick WRGFRP wrapped columns showed increase in energy ductility up to 99.78 % over the corresponding CSMGFRP wrapped column Columns having 3mm thick UDCGFRP showed increase in energy ductility in the range of 31.28 % to 78.64% and those with 5mm thick UDCGFRP showed 71.15% to 146.43% increase in energy ductility compared to the corresponding 3mm and 5mm thick CSMGFRP wrapped columns.

7.1 Regression

The mathematical technique used for fitting curves, whether linear or non-linear, of the predetermined shape. The purpose of regression is to evaluate the unknown coefficients in an equation. The form of the equation is assumed a priori in such a way that it might best suite the anticipated relationship between the input and the output.

7.2 Multivariate linear regression

Multivariate linear regression helps to construct first order equations involving more than one independent variable. The basic formulation for multivariate linear regression is,

$$\begin{Bmatrix} \frac{\partial}{\partial a_0} \\ \frac{\partial}{\partial a_1} \\ \frac{\partial}{\partial a_2} \\ \frac{\partial}{\partial a_3} \\ \vdots \\ \frac{\partial}{\partial a_n} \end{Bmatrix} \sum_{i=1}^{K} \left(P_i - \left(a_0 + a_1 x_{1i} + a_2 x_{2i} + a_3 x_{3i} + \cdots + a_n x_{ni}\right)\right)^2 = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \qquad \text{Eq. (2.a)}$$

where, $a_0 \cdots a_n$ are the coefficients to be determined, $x_1 \cdots x_n$ are the independent variables, P is the dependent variable or the actual result value for the set of ith input data and K is the number data sets available for regression. On executing the partial derivative operators, equation 2.a reduces to,

$$\sum_{i=1}^{K} \begin{bmatrix} 1 & x_{1i} & x_{2i} & x_{3i} & \cdots & x_{ni} \\ x_{1i} & x_{1i}^2 & x_{1i}x_{2i} & x_{1i}x_{3i} & \cdots & x_{1i}x_{ni} \\ x_{2i} & x_{2i}x_{1i} & x_{2i}^2 & x_{2i}x_{3i} & \cdots & x_{2i}x_{ni} \\ x_{3i} & x_{3i}x_{1i} & x_{3i}x_{2i} & x_{3i}^2 & \cdots & x_{3i}x_{ni} \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ x_{ni} & x_{ni}x_{1i} & x_{ni}x_{2i} & x_{ni}x_{3i} & \cdots & x_{ni}x_{ni} \end{bmatrix} \begin{Bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_n \end{Bmatrix} = \sum_{i=1}^{K} \begin{Bmatrix} P_i \\ P_1P_i \\ P_2P_i \\ P_3P_i \\ \vdots \\ P_nP_i \end{Bmatrix} \tag{2.b}$$

The above equation can be solved by summing up the values of independent and dependent variables after carrying out the required operations. The logic presented in equation 2.b was implemented in MATLAB source file named regression.m.

7.3 Regression equations for ductility parameters

The regression equations for parameters other than the ultimate compressive stress and ultimate axial strain were modelled with just two coefficients of regression, one for the inverse of slenderness ratio and the other for the ratio between FRP confining pressure and the unconfined compressive strength of concrete. The basic equation used for determination of the regression coefficients was,

$$P = a_0 + \frac{a_1}{\lambda} + a_2 \frac{f_l}{f'_{co}} \tag{3}$$

where, P stands the parameter to be predicted and a_0, a_1 and a_2 are the regression coefficients. This equation was used for predicting the parameters deflection ductility and energy ductility. The regression equations are presented in Table 3.

Table 3: Regression equations

Sl. No.	Parameter	Regression equation	RMS error	RMSPE	Fitness
1.	Deflection ductility	$\eta_d=0.1973+0.0587\lambda+0.2080F+0.3903t_{frp}$	0.564	22.693	0.635
2.	Energy ductility	$\eta_e=-1.091+0.1496\lambda+0.3233F+0.6626t_{frp}$	0.949	24.941	0.611

Predictions from the regression equations were compared against experimental values and presented in Figures 9 and 10.

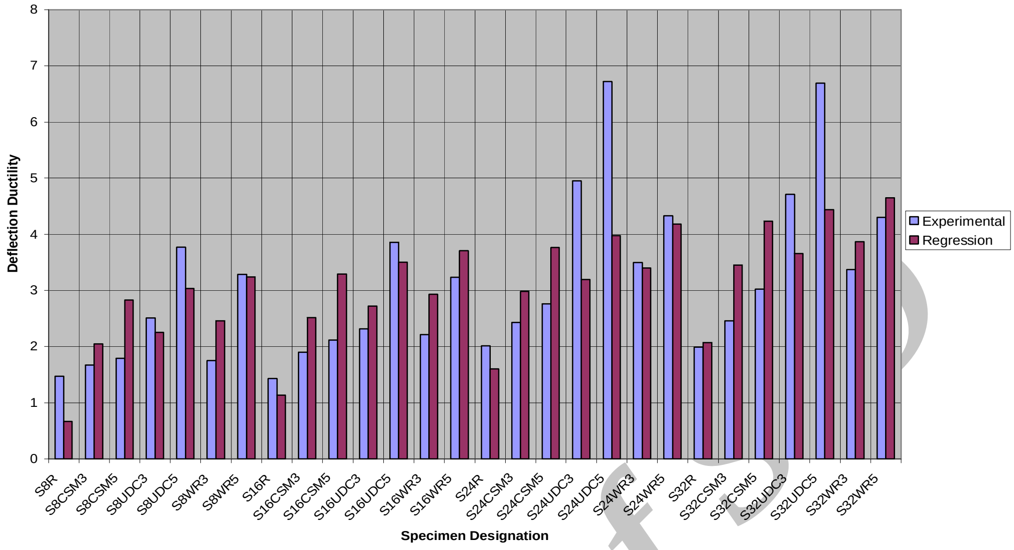

Figure 9. Comparison of predictions of regression equation with experimental data – deflection ductility

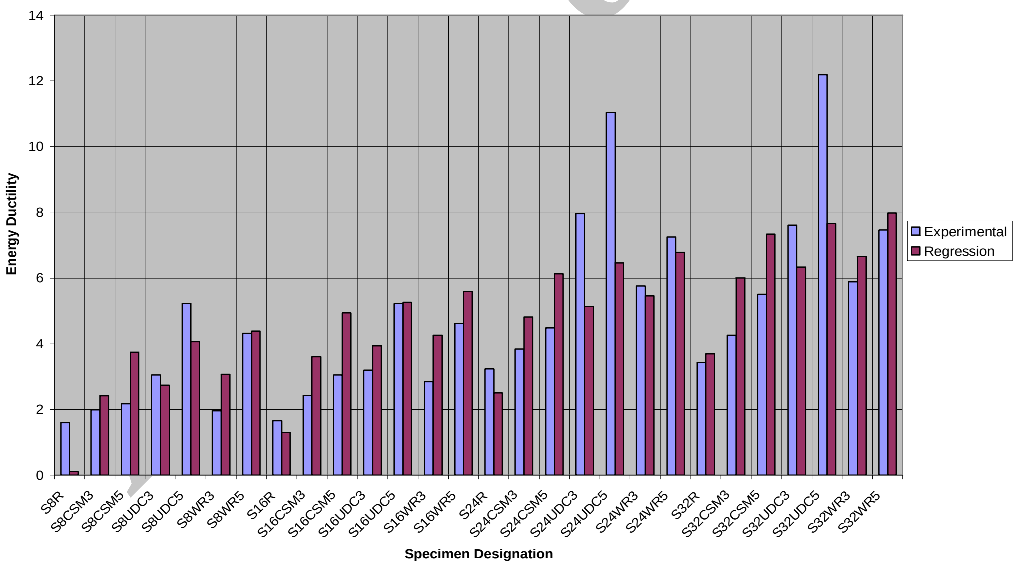

Figure 10. Comparison of predictions of regression equation with experimental data – energy ductility

7. CONCLUSIONS

Based on the results obtained through the experimental investigation and the regression analysis, the following conclusion are made

- Deflection ductility increased by a maximum of 146.27% and 236.17% for 3 mm and 5 mm thick wrapping when compared to the unwrapped columns.
- Energy ductility increased by a maximum of 146.44% and 256.43% for 3 mm and 5 mm thick GFRP wrapped column when compared to the unwrapped column.
- The regression equations were proposed as part of this study can be used for predicting the performance of GFRP wrapped columns. The regression analysis consider slenderness ratio as a parameter, which makes predictions more accurate for given column geometry.

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