International Journal of Engineering Sciences Paradigms and Researches (IJESPR)
(Vol. 47, Issue 04) and (Publishing Date: 10th December, 2018)
(An Indexed, Referred and Impact Factor Journal)
ISSN: 2319-6564
www.ijesonline.com

Strength and Ductility Test of GFRP Strengthened Corrosion Damaged RC Columns

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ABSTRACT---- ***This paper presents the results of an experimental investigation to examine the effectiveness of Glass Fibre Reinforced Polymer (GFRP) wraps on corrosion damaged high strength concrete columns. A total of fourteen specimens of 150mm diameter and height of 600 mm were cast and tested. Each of the seven specimens were subjected to 0%, 15% and 30% level of corrosion-damage and in that one column specimen were used as corroded control. Glass fibre reinforced polymer wraps were used with different configurations such as CSM, UDC and WR. The wrapping was done with 3 mm and 5 mm thickness for each material. All the columns were tested under monotonic loading up to failure, in a loading frame of capacity 2000 kN. Necessary measurements were taken for each load increment. The findings concluded that GFRP wrapped corrosion-damaged concrete columns showed considerable enhancement in the load carrying capacity, deflection and ductility than the control concrete columns.***

Keywords – Corrosion, Ductility, GFRP, Wrap

1. INTRODUCTION

An increasing number of reinforced concrete structures have reached the end of their service life, either due to deterioration of concrete and reinforcements caused by environmental factors and the widespread application of deicing salts, or due to increase in applied loads. These deteriorated structures may be structurally deficient or functionally obsolete, and most are now in serious need of extensive rehabilitation or replacement. Strengthening can be used as a cost-effective alternative to the replacement of these structures and is often the only feasible solution. Fibre Reinforced Polymers (FRP) wraps or laminates are well suited to this application because of their high strength-to weight ratio, good fatigue properties, and excellent resistance to corrosion. Their application in civil engineering structures has been growing rapidly in recent years, and is becoming an effective and promising solution for strengthening deteriorated concrete members.

The application of FRP poses minimal modification to the geometry, aesthetics and utility of the structure. Installation of externally bonded up gradation systems using FRP is fast and intensive less labour. Several studies on the behavior of reinforced concrete beams strengthened with FRP composite sheets provided valuable information regarding the strength, deformation, ductility and long-term performance of FRP strengthening systems.

The present research work has been undertaken for evaluating the performance of glass fibre reinforced polymer (GFRP) wrapped corrosion damaged high strength concrete columns. Emphasis has been given to the strength and deformation properties of GFRP wrapped corrosion damaged high strength concrete columns. Comparison has been made between the un-strengthened and strengthened beams and appropriate conclusions are drawn based on the results of investigation carried out.

Hadi and Li (2004) 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.

Lam and Kwan (2010) investigated the restoration of the flexural ductility by using HSC. The effect of adding confinement on the flexural ductility of HSC columns were studied by a nonlinear moment-curvature analysis taking into account the stress-path dependence of the steel reinforcement. Their analytical results proved that the addition of confinement would enhance the flexural ductility of columns by increasing the balanced steel ratio and balanced axial load level. The authors concluded that the effectiveness of adding confinement to improve the flexural ductility of columns decreased as the compressive strength of concrete in column increases.

Liu (2002) studied the compressive strength of concrete cylinders exposed to sea water. The cylinders were reinforced with non-adhesive wound hybrid polymer composites separated from the concrete surface by aluminium foil. The wraps included GFRP cloth, glass fibre filament winding, hybrid glass-kevlar-glass fibre filament winding and glass-carbon-glass filament winding. Some of the specimens were soaked in live sea water and another portion was soaked in dead sea water (water brought from sea and kept in laboratory, which meant most of the organisms were dead) for a duration of 180 days. The specimens with glass-kevlar-glass filament winding absorbed the maximum amount of water at 7.73% and showed the maximum reduction in compressive strength at 26.6% after 180 days of exposure to live sea water. The effect of live sea water was similar to the effect of dead sea water. Air ageing was less harmful to the specimens. Carbon fibre was good in resisting the effect of sea water.

Wooten et al. (2003) investigated the effect of FRP confinement on corrosion of steel rod embedded into concrete. A total of 13 specimens with varying number of plies, different types of epoxy resin and varying fibre orientations of wrap were tested. Corrosion was induced by immersing the specimens in a tank containing 5% sodium chloride salt solution and impressing 12 V electric supply. Specimens were removed from the tank when concrete cracked or wrap failed or electric flow increased. The rebar was immersed in muriatic acid for one week to remove rust and loose materials. The study concluded that confining with CFRP increased corrosion resistance of rebar under submerged and accelerated conditions. This resulted in prolonged life, lower corrosion potential, reduced rate of mass loss and reduction in chloride content of concrete. The mass loss in FRP confined concrete was half of that in unconfined specimens. Increasing the number of layers from 1 to 2 showed measurable increase in corrosion resistance, while increasing the number of layers from 2 to 3 showed no improvement.

Neale (2000) presented an overview on the strengthening and rehabilitation of civil engineering structures using FRP. He addressed the repair techniques on column strengthening, seismic applications using FRP wraps, beams strengthening bonded with laminates and applications to masonry structures. He also discussed the durability aspects when using FRP for rehabilitation. The progress regarding field executions and assessments was also reviewed.

Lee and Bonnaci (2000) conducted an investigation in corrosion-damaged reinforced concrete column externally bonded with CFRP. Seven columns were subjected to accelerated corrosion regime and wrapped with CFRP sheets. They were also subjected to further post-repair accelerated corrosion. The authors showed that FRP jacketing of corrosion damaged columns markedly improved the strength of the column. The FRP-repaired columns subjected to post-repair corrosion showed a slight reduction in ductility.

Belarbi and Bae (2009) studied the effect of corrosion of steel reinforcement on RC columns wrapped with FRP sheets. The authors also studied the effects of strengthening RC columns with CFRP and GFRP sheets. The columns were subjected to uni-axial compression test. The results revealed that the combined environmental cycle used in this study does not show any significant effects on CFRP wrapped RC columns. While the GFRP wrapped columns were affected with decrease in their load. They also indicated that corrosion of test columns wrapped with CFRP sheets continued even after the corrosion source has been removed.

Neale, Demers and Labossiere (2005) investigated the use of FRP wraps for the protection and rehabilitation of RC columns. In the first part of the study, the main reinforcement used was alone subjected to accelerated corrosion. Three types of FRP wraps (glass, carbon and aramid) and two conventional waterproofing systems were used to protect the columns. The results showed that the FRP wrapped specimens provided an excellent protection. In the second part of the study, the columns with both axial and spiral reinforcement were used. The specimens were subjected to realistic corrosion and rehabilitated with FRP. It has been showed that the repaired specimens were stronger than the non-corroded unstrengthened specimen. It was also observed that the FRP wrapping increased the column ductility considerably when compared to the conventional column.

2. RESEARCH SIGNIFICANCE

In recent years repair and strengthening of reinforced concrete columns plays a vital role of structural rehabilitation in order to ensure that the columns have adequate capacity to perform against corrosion, seismic and other loading patterns. The research work is significant in that the behaviour of GFRP confined reinforced concrete column wrapped with three types of GFRP at two different thicknesses will be investigated. The investigation will provide an understanding on the relationship between level of corrosion and external GFRP confinement in the form of adhesive bonded wraps.

3. MATERIAL AND METHODS

The mix proportions of concrete are given in Table 1. The characteristic strength attained from the test was 64 MPa. The dosage of hyper plasticizer Glenium B233 was 0.8% by weight of binder. The test specimens were provided with longitudinal reinforcement of high yield strength deformed bars of characteristic strength 450.67 MPa. The lateral ties consisted of mild steel bars of yield strength 300.82 MPa.

Table 1: Details of Concrete Mix

Material	Quantity in Kg/m^3
Cement	450
River Sand	780
Coarse Aggregate 20mm	680
Coarse Aggregate 10mm	450
Hyper Plasticizer – Glenium B233	0.8 % by weight of binder
Silica Fume	25
Water	160
Water to Cement Ratio	0.36

Glass fibres used for the study have various fibre configurations.
1. Chopped Strand Mat (CSM)
2. Uni-directional Cloth (UDC)
3. Woven Rovings (WR)
The glass fibres used for the study are shown in Figures 1 to 3.

Figure. 1 Chopped Strand Mat Fabric

Figure. 2 Uni-Directional Cloth Fabric

Figure. 3 Woven Rovings Fabric

All the specimens were 150 mm in diameter and 900 mm in height. The specimens were provided with six bars of 8 mm diameter as longitudinal reinforcement. Each specimen also contained 6 mm diameter ties at a spacing of 115 mm c/c. The longitudinal bars were kept protruded from the column face to accommodate the electrical connections for accelerated corrosion. The details of specimens are shown Figure. 4.

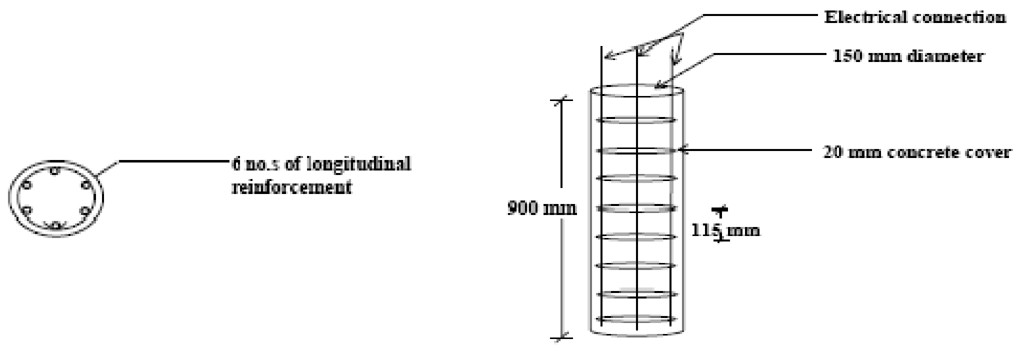

Figure 4: Column Details

The column specimens were grouped under various levels of corrosion damage. The specimen designation, level of corrosion damage and GFRP wrapping are summarized in Table 2. The properties of fibres used in the experimental work are shown in Table 3.

Table 2: Specimen Details

Specimen Designation	Level of Corrosion (%)	Type of GFRP	Thickness of GFRP (mm)
NC CON	No Corrosion	---	0
NC CSM 3	No Corrosion	CSM	3
NC CSM 5	No Corrosion	CSM	5
NC UDC 3	No Corrosion	UDC	3
NC UDC 5	No Corrosion	UDC	5
NC WR 3	No Corrosion	WR	3
NC WR 5	No Corrosion	WR	5
CD 15 CON	15	---	0
CD 15 CSM 3	15	CSM	3
CD 15 CSM 5	15	CSM	5
CD 15 UDC 3	15	UDC	3
CD 15 UDC 5	15	UDC	5
CD 15 WR 3	15	WR	3
CD 15 WR 5	15	WR	5
CD 30 CON	30	---	0
CD 30 CSM 3	30	CSM	3
CD 30 CSM 5	30	CSM	5
CD 30 UDC 3	30	UDC	3
CD 30 UDC 5	30	UDC	5
CD 30 WR 3	30	WR	3
CD 30 WR 5	30	WR	5

Table 3: Properties of Glass Fibre Reinforced Polymer

Sl. No.	Type of Fibre in GFRP	Thickness (mm)	Elasticity Modulus (MPa)	Ultimate Elongation (%)	Tensile Strength (MPa)
			ASTM D 638	ASTM D 638	ASTM D 638
1.	Chopped Strand Mat	3	7467.46	1.69	126.20
		5	11386.86	1.37	156.00
2.	Uni-Directional Cloth	3	13965.63	3.02	446.90
		5	17365.38	2.60	451.50
3.	Woven Rovings	3	6855.81	2.15	147.40
		5	8994.44	1.98	178.09

4. ACCELERATED CORROSION PROCESS

A schematic representation of the corrosion testing is shown in Figure.5. The columns were subjected to accelerated corrosion. The columns were kept immersed in 3.5% NaCl solution in a high-density polyethylene tank. The columns were immersed for a day to ensure full saturation condition. The direction of the current was arranged so that the reinforcement cage served as the anode while stainless steel perforated cylinders, acted as counter electrode. The accelerated corrosion process was achieved by applying a power supply with an output of 32 V and 11 amps. High voltage was used to accelerate the corrosion and shorten the test period. Two levels of corrosion damage, 15% and 30% were induced. The time for corrosion can be estimated by the Faraday's equation,

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$$\Delta w = \frac{A_m . I . t}{Z . F}$$

where Δw = mass loss due to corrosion, Am = atomic mass of iron (55.85 g), *I* = corrosion current in amps, *t* = time since corrosion initiation (sec), *Z* = valency (assuming that most of rust product is due to Fe (OH) 2, *Z* is taken as 2), F = Faraday's constant [96487coulombs (g/equivalent)]. The corrosion activity was monitored for the columns by measuring the corrosion potential in accordance with the ASTM procedure.

1. EXPERIMENTAL TEST SET-UP

All the specimens were tested in a loading frame of capacity 2000 kN. To measure the axial compression of the column specimen, two deflectometers with a least count of 0.01mm were fitted at top and bottom of the specimen. A lateral extensometer was provided at mid-height of the column to measure the lateral strain. Figure 6 shows the experimental test set up and instrumentation provided for the test specimens.

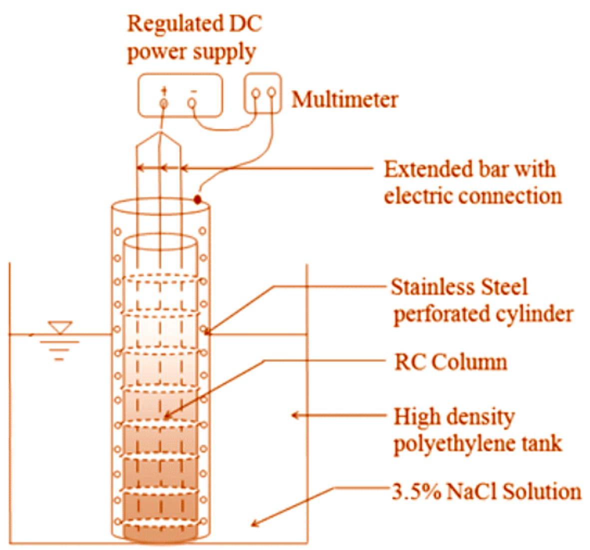

Figure.5: Schematic View of Accelerated Corrosion Set-up

Figure 6: Test Set-up

2. TEST RESULTS AND DISCUSSION

The performance of unwrapped and wrapped corrosion-damaged columns was evaluated by considering the non- corroded unwrapped specimen as reference. The effect of fibre wrap thickness was evaluated by taking the corroded control column as reference. The influence of wrap material corresponding to their thickness was calculated by considering CSMGFRP wrapped specimen as reference. The experimental results of column specimens at ultimate stage are presented in Table 4.

Table 4. Summary of Test Results at Ultimate Stage

Specimen Designation	Ultimate Load (kN)	Ultimate Stress (MPa)	Ultimate Deformation (mm)	Ultimate Axial Micro Strain	Ultimate Lateral Deformation (mm)	Ultimate Lateral Micro Strain
NC CON	750	42.44	3.14	2767	0.32	2404
NC CSM 3	800	45.27	3.24	3324	0.33	2520
NC CSM 5	850	48.10	3.56	3955	0.37	2731
NC UDC 3	1200	67.91	4.57	5288	0.46	3526
NC UDC 5	1275	72.15	4.96	5700	0.52	3750
NC WR 3	1075	60.83	4.34	4700	0.40	3180
NC WR 5	1125	63.66	4.52	4900	0.44	3487

CD 30 CON	700	39.61	3.76	2189	0.23	2150
CD 30 CSM 3	750	42.44	3.32	2651	0.26	2421
CD 30 CSM 5	800	45.27	3.36	3225	0.29	2613
CD 30 UDC 3	1125	63.66	4.29	4767	0.34	3149
CD 30 UDC 5	1200	67.91	4.75	5277	0.45	3692
CD 30 WR 3	975	55.17	3.24	4400	0.31	2975
CD 30 WR 5	1025	58.00	3.82	4654	0.39	3127

Effect of GFRP Wrapping on Load Carrying Capacity

The level of corrosion-damaged columns was compared with the non-corroded unwrapped control specimen. The ultimate load capacity for a corroded unwrapped column dropped to 6.67% for 30% level of corrosion damage respectively. The axial compression capacity was significantly decreased due to the corrosion damages such as cracking and cross-sectional loss of steel reinforcement.

CSMGFRP, UDCGFRP and WRGFRP increased the axial strength in the range of 0.49% to 9.76%, 16.10% to 26.83% and 3.41% to 12.20% when compared to the unwrapped column. It was observed that GFRP wrapped corrosion-damaged columns provided enhanced strength levels than the non-corroded unwrapped column. It was observed that GFRP wrapped corrosion-damaged columns provided enhanced strength levels than the non-corroded unwrapped column.

The effect of GFRP wrap material corresponding to their thickness was calculated by considering CSMGFRP wrapped columns as reference specimen and is presented in Figure.7.

The UDCGFRP wrapped corrosion-damaged columns resulted in higher ultimate load carrying when compared with CSMGFRP of same thickness. The UDCGFRP wrapped corrosion-damaged columns showed an increase in ultimate axial strength in the range of 15.54% to 19.62%. For columns subjected to 30% level of corrosion damage, UDCGFRP wrapped column showed an increase in load carrying capacity in the range of 15.54% and 19.62%.

The columns wrapped with WRGFRP showed a minimal increase in the range of 2.22% to 4.30% in compressive strength when compared to CSMGFRP wrapped columns. For columns subjected to 30% level of corrosion damage, WRGFRP of 3mm and 5mm thickness showed a marginal improvement in ultimate strength by 2.91% and 4.32% respectively. From the results, it is obvious that UDCGFRP provided the most effective confinement to corrosion-damaged concrete columns.

The columns wrapped with 3mm thick CSMGFRP, UDCGFRP and WRGFRP showed an increase in load carrying capacity by 14.5%, 32.2% and 17.8% respectively and those with 5 mm thick CSMGFRP, UDCGFRP and WRGFRP wrap column exhibited an increase of 16.2%, 38.9% and 21.1% respectively for 30% level of corrosion damage.

The axial compression capacity of corrosion-damaged columns was found to restore the ultimate strength by GFRP wrapping, to some extent. On overall observations the corroded and then repaired columns were about 30% stronger than the non-corroded un-strengthened columns.

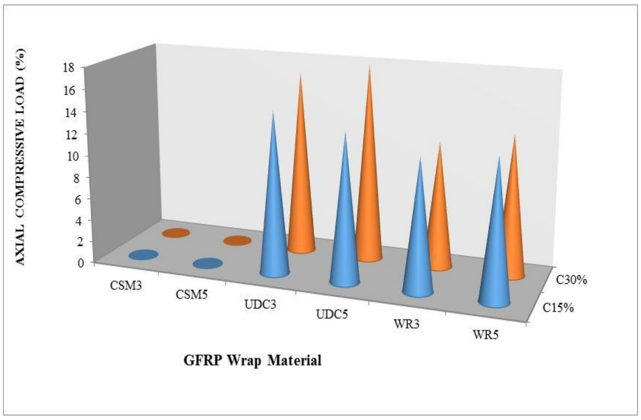

Figure 7. Effect of GFRP Wrap Material on Load Carrying Capacity of Corrosion-Damaged Columns

Effect of GFRP Wrapping on Ultimate Axial Deformation

The effect of axial deformation on various levels of corrosion-damage is shown in Figure.8. The ultimate axial deformation was decreased due to the corrosion damage induced in the columns. The ultimate axial deformation of column CD 15 CON and CD 30 CON were reduced by 1.59 % and 2.54 % respectively when compared to the non- corroded unwrapped control column NC CON. The specimens with CSMGFRP, UDCGFRP and WRGFRP wrapping showed a decrease in axial deformation by 4.14% to 10.19%, 12.10% to 22.92% and 20.38% to 35.98% in comparison with control column.

The effect of GFRP wrap material on ultimate axial deformation is shown in Figure.9. The columns wrapped with WRGFRP showed a nominal decrease in the range of 10.80% to 11.92% in axial deformation in comparison with CSMGFRP wrapped columns. For columns with 15% level of corrosion damage, WRGFRP showed a decrease in ultimate axial deformation in the range of 16.94% to 23.34% in comparison with CSMGFRP wrapped columns. For columns subjected to 30% level of corrosion damage, WRGFRP showed a decrease in axial deformation in the range of 23.44% and 28.72% in comparison with CSMGFRP wrapped columns.

The UDCGFRP wrapped corrosion-damaged columns showed an decrease in ultimate axial deformation by 5.96% to 6.08%. The UDCGFRP wrapped column exhibit an decrease in axial deformation by 8.30% to 8.71 for 15% level of corrosion damage. For columns subjected to 30% level of corrosion-damage, the GFRP wrapping decrease the ultimate axial deformation in the range of 8.62% to 14.18%.

A noteworthy behaviour was found in UDCGFRP material over other materials. This was because fibres in UDCGFRP where so oriented as to effectively confine the concrete.

An appreciable decrease in ultimate axial deformation of corroded and wrapped column was observed.

For 15% level of corrosion-damage, the columns wrapped with CSMGFRP, UDCGFRP and WRGFRP showed an decrease in ultimate axial deformation in the range of 0.33% to 3.04%, 2.81% to 5.75% and 6.01% to 16.66% respectively. For column specimens subjected to 30% level of corrosion-damage, FRP wrapping decreased the ultimate axial deformation in the range of 3.97% to 4.73% for CSMGFRP, 6.70% to 12.95% for UDCGFRP and 16.54% to 23.88% for WRGFRP.

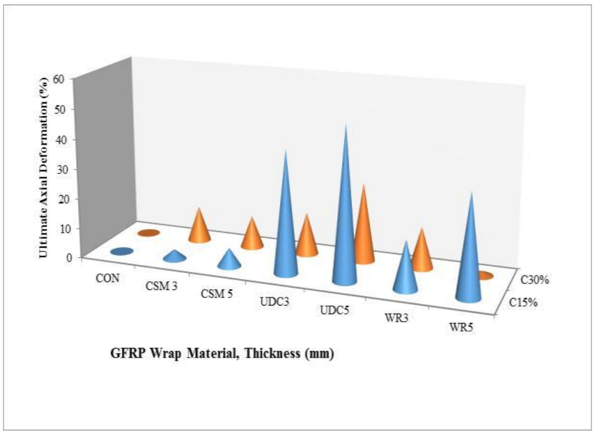

Figure 8. Effect of Various Levels of Corrosion-Damage on Axial Deformation of GFRP Wrapped Columns

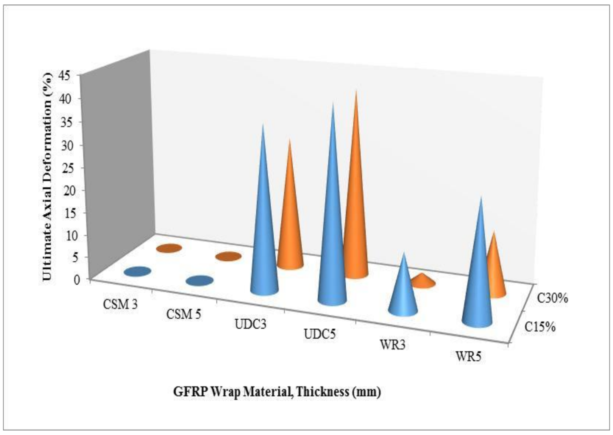

Figure 9. Effect of GFRP Wrap Material on Axial Deformation of Corrosion-Damaged Columns

Effect of GFRP Wrapping on Ultimate Lateral Deformation

The effect of GFRP wrapping on ultimate lateral deformation for various levels of corrosion damage is shown in Figure. 10.The ultimate lateral deformation in corroded column was decreased by 9.68% and 21.94% for 15% and 30% level of corrosion damage.

For 15% level of corrosion-damage, the columns wrapped with CSMGFRP, UDCGFRP and WRGFRP exhibit an decrease in lateral deformation by a maximum of 10.97%, 54.84% and 26.45% respectively when compared with the control column.

The influence of GFRP wrap material on ultimate lateral deformation is presented in Figure.11.

The columns wrapped with WRGFRP showed a decreased in the range of 6.92% to 13.96% in lateral deformation when compared to CSMGFRP wrapped columns. For columns subjected to 15% level of corrosion damage, WRGFRP showed a decreased in ultimate lateral deformation by 13.95%. For columns subjected to 30% level of corrosion damage, WRGFRP showed decrease in lateral deformation in the range of 6.92% to 9.64%. For columns subjected to 15% and 30% level of corrosion damage, UDCGFRP wrapping decreased the ultimate lateral deformation by 39.53% and 39.15%.

The influence of GFRP wrap thickness on lateral deformation is presented in Figures. 12 and 13.

For test specimens subjected to 15% corrosion damage level, 3 mm thick CSMGFRP, UDCGFRP and WRGFRP showed a decrease in lateral deformation by 14.29%, 52.86% and 30%. For specimens subjected to 15% level of corrosion damage, 5 mm thick CSMGFRP, UDCGFRP and WRGFRP showed a decrease in lateral deformation by 22.85%, 71.43% and 40%.

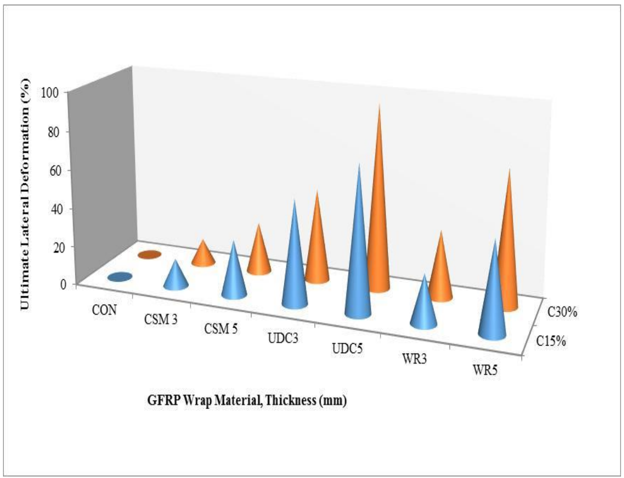

Figure 10. Effect of Various Levels of Corrosion-Damage on Lateral Deformation of GFRP Wrapped Columns

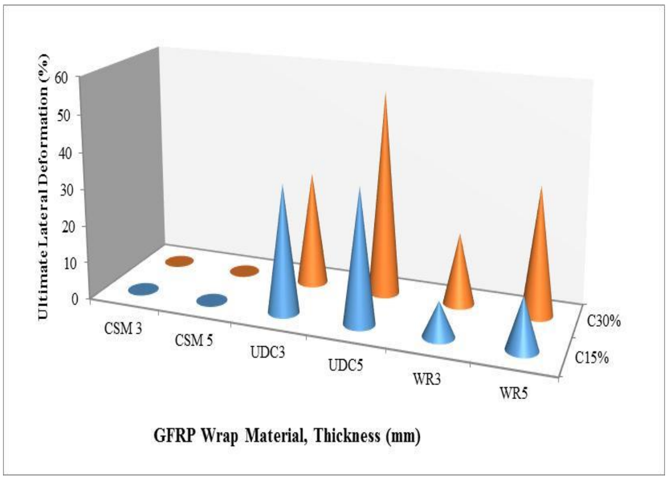

Figure 11. Effect of GFRP Wrap Material on Lateral Deformation of Corrosion-Damaged Columns

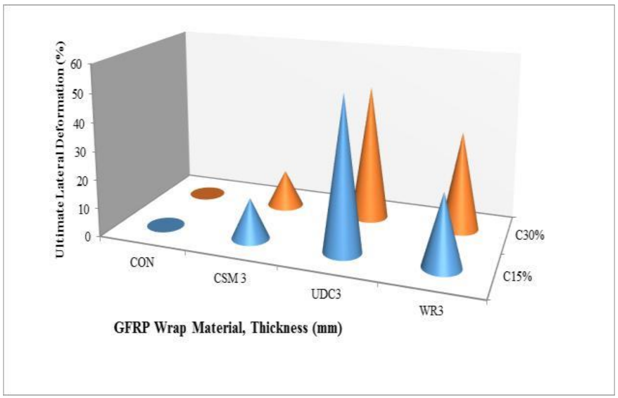

Figure 12. Effect of 3 mm Thick GFRP Wrap on Lateral Deformation of Corrosion-Damaged Columns

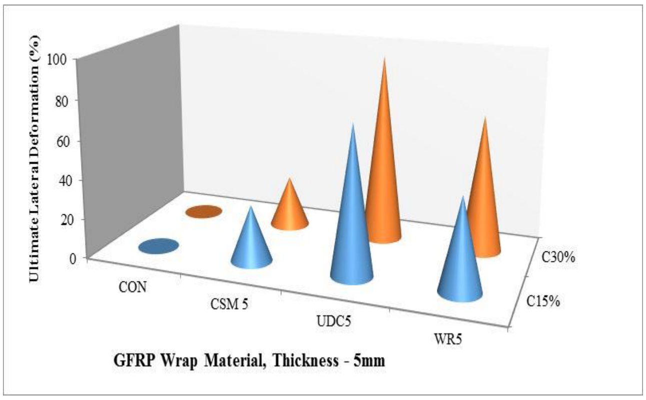

Figure 13. Effect of 5 mm Thick GFRP Wrap on Lateral Deformation of Corrosion-Damaged Columns

For 30% level of corrosion damage, the columns with 3mm thick GFRP wrapping showed a decrease in ultimate lateral deformation by 32% for CSMGFRP, 66.94% for UDCGFRP and 40.5% for WRGFRP and those with 5mm thick GFRP wrapping exhibit a decrease in lateral deformation by 37.10% for CSMGFRP, 90.90% for UDCGFRP and 50.41% for WRGFRP.

3. STRESS-STRAIN RESPONSE OF GFRP WRAPPED CORROSION- DAMAGED COLUMNS

The stress-strain curves for columns with 0% and 30% level of corrosion damage is shown in Figures. 14 to 16.

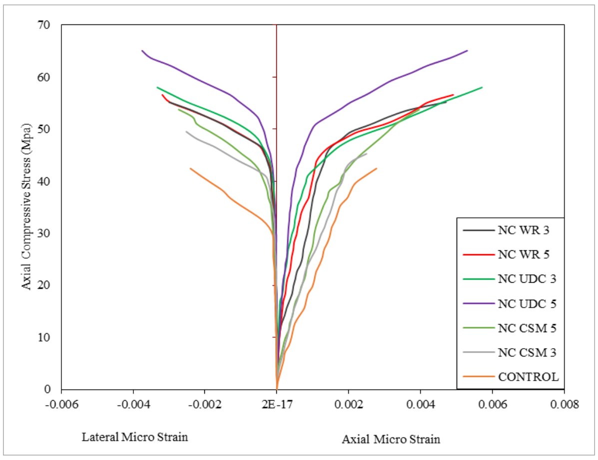

Figure 14. Stress-Strain Response for 0% Level of Corrosion-Damaged Columns

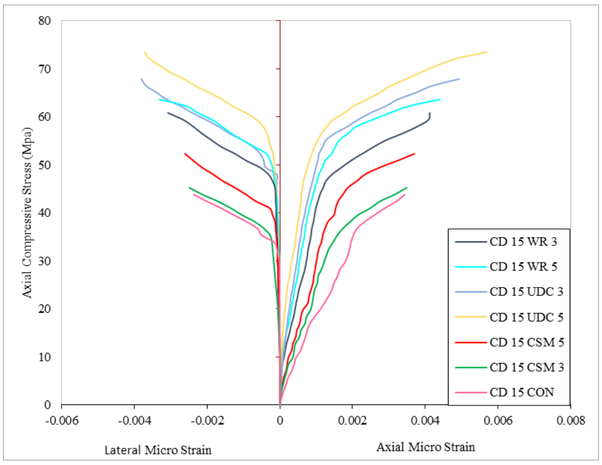

Figure 15. Stress-Strain Response for 15% Level of Corrosion-Damaged Columns

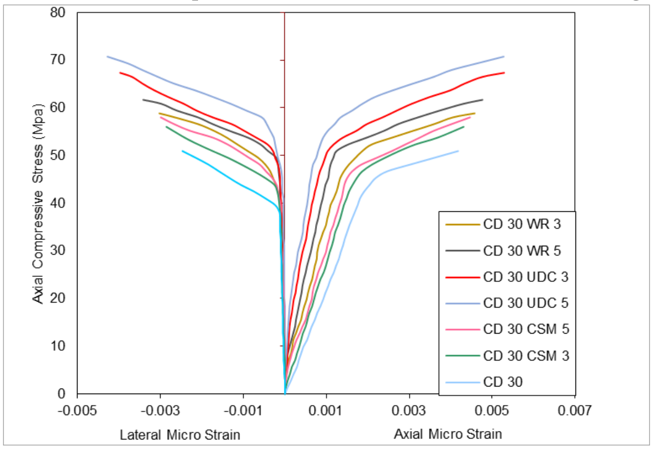

Figure 16. Stress-Strain Response for 30% Level of Corrosion-Damaged Columns

The corroded wrapped columns experienced a large strain value. The corroded control column failed at reduced stress with increase in level of corrosion damage. On increasing the thickness of GFRP wrapping, the stress level moved up to a certain extent. The UDCGFRP wrapping performed well in both corroded and non-corroded columns.

4. CONCLUSIONS

Based on the experimental results, the following conclusions are drawn

1. GFRP wrapped corrosion-damaged concrete columns show a considerable enhancement in the load carrying capacity, deflection and ductility than the control concrete columns.
2. UDCGFRP wrapped corrosion-damaged concrete column exhibit a better performance when compared to CSMGFRP and WRGFRP.
3. The GFRP wrapped corrosion-damaged column showed an increase in ultimate load by 30% when compared to the corroded - unwrapped column.
4. The GFRP confined corrosion-damaged columns exhibit a maximum increase in ultimate axial deformation by 38% when compared with the corroded- unwrapped column.
5. The GFRP wrapped corrosion-damaged concrete columns exhibit a maximum increase of 125% in ductility.

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