Asian Journal of Engineering and Technology (ISSN: 2321 – 2462)
Volume 04 – Issue 04, August 2016

Static Response of Corrosion Damaged High Performance Concrete Beams Strengthened with Externally Bonded GFRP Laminates

N. Seshadrisekhar[1*], P. N. Raghunath[2] and K.Suguna[3]

[1] Research Scholar, Department of Civil & Structural Engineering
Annmalai University, India

[2,3] Professor, Department of Civil & Structural Engineering
Annmalai University, India

[*]*Corresponding author's email: seshadrisekhar456 [AT] gmail.com*

ABSTRACT---- ***This paper presents the results of an experimental study conducted to evaluate the static response of corrosion damaged High Performance Concrete (HPC) beams strengthened with externally bonded Glass Fibre Reinforced Polymer (GFRP) laminates at the soffit of beam. The experimental study was carried out on 9 Reinforced Concrete (RC) beams of size 3000mm x 150mm x 250 mm cast using high performance concrete. One beam specimen neither corroded nor strengthened to serve as reference beam. Two beams were corroded to serve as corroded control. A reinforcement mass loss of approximately 10% and 25% were used. Corrosion damage was induced on the beams by immersing them in salt solution and applying measured electric current through the reinforcing bars. Two beams were strengthened with UDCGFRP laminates having 3mm and 5mm thickness. Two beams were 10% corroded and strengthened with UDCGFRP laminates having 3mm and 5mm thickness. The remaining Two beams were 25% corroded and strengthened with UDCGFRP laminates having 3mm and 5mm thickness. In total 9 beams were tested under monotonically increasing load and 9 beams were tested under cyclic loading. The variables considered include level of corrosion, type of GFRP laminate and thicknesses of GFRP laminate. The static test results show that the beams strengthened with externally bonded UDCGFRP laminates exhibit increased strength, enhanced flexural stiffness and sufficient ductility.***

Keywords---- Corrosion damage, ductility, high performance concrete, strength, UDCGFRP

---

1. INTRODUCTION

Restoration of corroded bars in structural members to original or better level of performance is a necessity for keeping old structures in service. Although many techniques exist for repair and rehabilitation of corroded reinforced concrete structures, Fibre Reinforced Polymer (FRP) composite materials have been successfully used in new construction and for repair and rehabilitation of existing structures. Application of FRP plates at the soffit of corrosion damaged beams results in better performance of reinforced concrete beams with reference to strength, deformation and ductility. Since corrosion takes away much of the ductility and strength from affected members, improvement in these parameters will lead to better seismic behaviour of reinforced concrete members. Corrosion of high performance concrete beams still remains an area to be explored.

This study aims at subjecting high performance concrete beams to accelerated corrosion and then rehabilitating the beams by bonding glass fibre reinforced polymer sheets having various thicknesses and fibre configurations. This study was intended to evaluate the effect of Glass Fibre Reinforced Polymer (GFRP) laminates on the performance of corroded high performance concrete beams under static loading.

[1]Bencardino *et al* (2002) conducted an experimental investigation on reinforced concrete beams strengthened in flexure and shear using externally epoxy bonded bidirectional carbon fibre fabric to overcome the bond slip and plate separation at the ends. The authors concluded that CF fabrics provide an effective and efficient alternative to laminate strengthening of concrete structures. [2]Alagusundaramoorthy (2003) studied the flexural behaviour of RC beams strengthened with CFRP sheets or fabric with and without anchorages. Two types of CFRP materials (pultruded/fabric) were attempted. Two (106.4 mm2 and 487.6 mm2) pultruded CFRP areas were considered. The author reported that the increase was 49% and 40% for beams strengthened with CFRP sheet and fabric respectively. A 58% increase was achieved when anchorages were used. [3]Carlos and Maria (2006) conducted an experiment and found numerical results validated against

experimental data obtained from 19 beams strengthened with different types of FRP. They derived the numerical simulation which indicated that the concrete tensile strength does not constitute the unique failure criterion for predicting plate debonding failure of strengthened RC beams. [4]Maaddawy *et al* (2005) investigated the combined effect of corrosion and sustained loads on the structural performance of reinforced concrete beams. A total of nine beams, each measuring 152 x 254 x 3200 mm, were tested. One beam was tested as a virgin while eight beams were exposed to accelerated corrosion for up to 310 days using an impressed current technique. Four beams were corroded under sustained load that corresponded to approximately 60% of the yield load of the virgin beam. The remaining four beams were kept unloaded during the corrosion exposure. Test results showed that the presence of sustained load and associated flexural cracks during corrosion exposure significantly reduced the time to corrosion cracking and slightly increased the crack width. The presence of flexural cracks during corrosion exposure initially increased the steel mass loss rate and, consequently, reduction in beam strength. As time progressed, no correlation between the reduction in the beam strength and the presence of flexural cracks was observed. [5]Esfahani *et al* (2007) carried out an investigation on the flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. 12 concrete beam specimens with dimensions of 150 x 250 x 2000 mm length were cast and tested. Beam sections with three different reinforcing ratios (ρ) were used. Nine specimens were strengthened in flexure by CFRP sheets. The other three specimens were considered as control specimens. The length, width and number of layers of CFRP sheets were varied in different specimens. The flexural strength and stiffness of the strengthened beams increased compared to the control specimens. The authors concluded that the design guidelines of ACI 440.2R-02 and ISIS Canada overestimate the effect of CFRP sheets in increasing the flexural strength of beams with small ρ values compared to the maximum value, $\rho_{max,}$ specified in these two guidelines. [6]Almusallam *et al* (2014) investigated the effect of longitudinal steel ratio on the flexural performance of RC beams externally strengthened with fiber-reinforced polymer (FRP) composites experimentally and numerically. The experimental programme consisted of testing 11 beams under four-point bending until failure. Each beam was duplicated to verify the repeatability of the results. Three beams were tested as control specimens; the remaining eight beams were externally strengthened in flexure with FRP composites. The primary experimentally studied parameters were longitudinal steel ratio and axial FRP stiffness. Three different steel ratios were examined. For the lowest steel ratio, four different FRP systems with six axial stiffness values were investigated. However, for the other two steel ratios, only one FRP system was studied. [7]Heffernan and Erki (2004) investigated the fatigue behavior of reinforced concrete beams strengthened with carbon fibre reinforced plastic laminates. Twenty 3 m and six 5 m beams were loaded monotonically and cyclically for this study. The beams were of size 150 x 300 mm. Two beams, without and with CFRP strengthening were loaded monotonically to failure at a rate of 1 mm/min stroke rate. The remaining beams were loaded cyclically to failure. These beams were loaded by applying a sinusoidal loading pattern at a rate of 3 Hz. Three ranges of stress were applied, low stress 84.1 kN, medium stress 98.00 kN and high stress 112.00 kN. The authors concluded that beams strengthened with CFRP sheets exhibit enhanced fatigue life at all stress levels. [8]Mahjoub *et al* (2010) presented experimental and analytical studies concerning the flexural strengthening of HSC beams by external bonding of FRP sheets. 6 concrete beam specimens with dimensions of 150 x 250 x 3000mm were cast and tested under two - point loading. The principal variables included in their study were different layouts of CFRP sheets and tensile steel reinforcement ratio. They concluded that as the amount of tensile steel reinforcement was increased, the additional strength provided by the carbon FRP external reinforcement got reduced. Also their finite element model results showed good agreement with the experimental results. [9]Ferrier *et al* (2011) investigated reinforced concrete beams with externally bonded FRP subjected to fatigue loading. The results showed that the strengthening improves the fatigue behaviour of RC beams. With a load corresponding to 84% of the carrying capacity of RC beam, the fatigue behaviour of the beam was much improved. Further the results for the larger beams showed that the overall behaviour of RC beams was improved with the use of external FRP strengthening: a better fatigue behaviour was obtained, with a 40% increase in service load. [10]Yu *et al.*, (2011) investigated the fatigue behaviour of concrete beams strengthened with glass-fibre composite under flexure. Seven beams of size150 x 250 x 2500 mm were used for this study, one beam was tested under monotonic loading, six beams were tested under cyclic loading. One beam was non-strengthened and five beams were strengthened with two layers of GFC sheet. The authors concluded that the failure mode of reinforced concrete beams strengthened with GFC under fatigue loading followed reinforcing steel fracture. Bonded GFC sheets reduce the stress in reinforcing steel and contribute to bridging the cracks in concrete. [11]Ravikant *et al* (2013) studied the effect of cyclic loading on the flexural behaviour of FRP strengthened RC beams. 12 RC beams of size 120 x 240 x 1900mm were cast. 9 beams were strengthened with FRP and the remaining 3 beams were un-strengthened. Three tensile steel ratios (0.545%, 0.818% and 1.09%) were considered for this study. The authors concluded that flexural strengthening of RC Beams using FRP exhibit additional strength and ductility. Failure of FRP strengthened under-reinforced RC beams initiated with yielding of steel followed by sudden FRP rupture.

2. MATERIALS AND METHODS

The concrete used for all beam specimens had a compressive strength of 67MPa. The concrete consisted of 450 kg/m^3 of ordinary Portland cement, 25 kg/m^3 of silica fume, 780 kg/m^3 of fine aggregate, 1130 kg/m^3 of coarse aggregate, 0.36 water/cement ratio and 0.8% of hyperplasticizer (Glenium B233). HYSD bars of characteristic strength 466MPa were used for the longitudinal reinforcement. The specimens were provided with 8mm diameter stirrups at 100 mm spacing. Unidirectional Cloth (UDC) GFRP laminates of 3mm and 5mm thickness were used for the study.

A total of nine beam specimens of 150 x 250 x 3000 mm were cast and tested for the present investigation. Fig.1 shows the reinforcement details of the beam specimens. The tension reinforcement consisted of 2 bars 12mm diameter and the shear reinforcement consisted of 8mm diameter stirrups at 100mm spacing. The bottom reinforcing steel was extended 50mm beyond the end concrete face for the purpose of making necessary external electrical connections towards inducing accelerated corrosion.

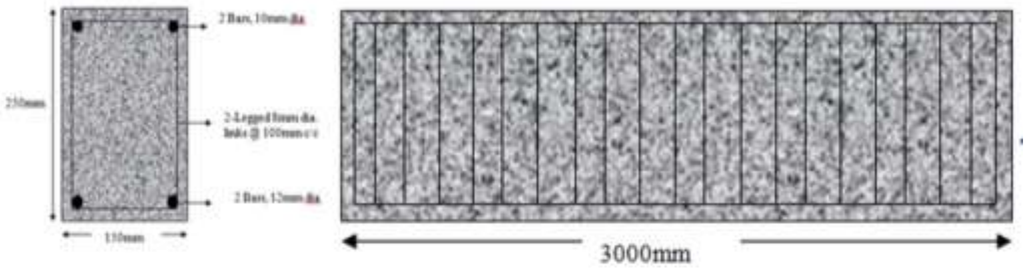

Fig. 1 Reinforcement Details of the Beam Specimen

One beam specimens were neither corroded nor strengthened to serve as reference. Two beams were corroded to serve as corroded control. A reinforcement mass loss of 10% and 25% were used. Two beams were strengthened with UDCGFRP laminates having 3mm and 5mm thickness. . The UDCGFRP fibre configuration used for the study is shown in Fig. 2. Two beams were 10% corroded and strengthened with UDCGFRP laminates having 3mm and 5mm thickness. The remaining two beams were 25% corroded and strengthened with UDCGFRP laminates having 3mm and 5mm thickness. The properties of UDCGFRP are shown in Table 1.

Fig.2 Uni-Directional Cloth

Table 1 Properties of Glass Fibre Reinforced Polymer (GFRP)

Sl. No.	Type of GFRP	Thickness (mm)	Tensile Strength (MPa)	Ultimate Elongation (%)	Elasticity Modulus (MPa)
1.	Uni-Directional Cloth	3	446.90	3.02	13965.63
2.	Uni-Directional Cloth	5	451.50	2.60	17365.38

The specimen were prepared for GFRP lamination by removing all loose materials on the soffit of the beam using wire brush and roughening with a surface grinding machine. Two- component room temperature curing epoxy adhesive was used for bonding the laminates. The laminated specimens were cured for a period of 7 days.The process of GFRP strengthening of all test specimens is presented in Figs.3 to 6.

Fig.3 Surface Preparation at Soffit of Beam

Fig.4 Application of Epoxy Adhesive on Beam Soffits

Fig.5 Placing of Laminate over the Beam Soffit

Fig.6 Application of Weight on Laminate

Fig.7 shows the accelerated corrosion set-up. The specimens were placed in a tank with 3.5% NaCl solution used as an electrolyte. The solution level in the tank was adjusted to slightly exceed the concrete cover plus reinforcing bar diameter to ensure adequate submersion of the longitudinal reinforcement. The specimens were provided with a direct current power supply with an output of11Amps thereby achieving theoretical steel mass loss of 10% and 25%. Fig.3.10 shows beam specimens subjected to corrosion.

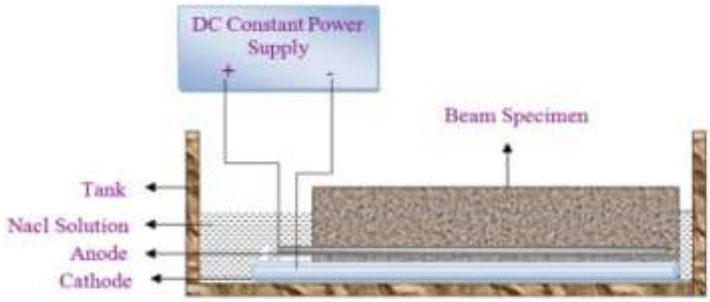

Fig.7 Schematic of Accelerated Corrosion Set-up

The beams were tested to failure under two-point loading system. Sufficient data was obtained on the strength, deformation, ductility and failure characteristics of corroded high performance concrete beams with GFRP laminates as well as control beams tested under monotonic loading. Sufficient data was obtained on the strength, deformation, fatigue life and failure characteristics of corroded high performance concrete beams with GFRP laminates as well as control beams tested under cyclic loading. The details of test specimen are presented in Table 2.

Table 2 Specimen Details

Sl. No.	Beam Designation	% Steel Reinforcement	Corrosion Damage (%)	GFRP		Type of Loading
				Type	Thickness	
1	NCB-S	0.603	0	-	0	Static
2	NCBU3- S	0.603	0	UDC	3	Static
3	NCBU5- S	0.603	0	UDC	5	Static
4	10CB-S	0.603	10	-	0	Static
5	10CBU3-S	0.603	10	UDC	3	Static
6	10CBU5-S	0.603	10	UDC	5	Static
7	25CB-S	0.603	25	-	0	Static
8	25CBU3-S	0.603	25	UDC	3	Static
9	25CBU5-S	0.603	25	UDC	5	Static

The details of static test set-up and the associated instrumentation is shown in Fig. 8.

Fig.8 Test Set-up for Static Loading

3. RESULTS AND DISCUSSION

3.1 Static Response of Tested Beams

The static test results of experimental investigation carried out on nine beams which included three control beams and six GFRP strengthened high performance concrete beams are presented and discussed in this chapter The study parameters considered for this research work included first crack load, deflection at first crack load, yield load, deflection at yield load, ultimate load, deflection at ultimate load, deflection ductility, deflection ductility ratio, energy ductility, energy ductility ratio, number of cracks and average spacing of cracks.
The test results on the strength and deformation properties of the control beams and GFRP strengthened high performance concrete beams at different load levels are presented in Table 3.
The effect of corrosion damage was evaluated by comparing the performance of corroded- strengthened specimens with the virgin (un-corroded – un-strengthened) beam. The effect of thickness of GFRP plate on performance parameters was measured by comparing the performance of corroded-strengthened beams with that of corroded control beams (A10%, A25%).

Table 3 Strength and Deformation Properties Pertaining to various Load Levels

Sl. No.	Beam Designation	First Crack Load (kN)	Deflection at First Crack Load (mm)	Yield Load (kN)	Deflection at Yield Load (mm)	Ultimate Load (kN)	Deflection at Ultimate Load (mm)
1	NCB-S	16.24	1.63	47.73	19.09	57.82	40.97
2	NCBU3-S	34.61	5.69	63.77	28.14	86.71	88.28
3	NCBU5-S	38.36	7.52	76.03	25.38	97.09	94.23
4	10CB-S	14.62	1.23	43.94	13.04	48.53	19.29
5	10CBU3-S	28.97	4.09	56.41	19.26	76.69	58.23
6	10CBU5-S	35.39	4.81	71.12	13.72	89.57	66.52
7	25CB-S	10.58	3.29	38.58	16.36	44.26	22.96
8	25CBU3-S	25.21	6.14	49.05	21.83	58.34	51.22
9	25CBU5-S	32.49	6.86	53.96	22.52	72.71	68.12

3.2 Effect of GFRP Plating on Strength and Deflection
The loads carried by all the test beams at first crack stage, yield stage and ultimate stage were obtained experimentally. The first crack loads were obtained by visual examination. The yield loads were obtained (by inspection) corresponding to the stage of loading beyond which the load- deflection response was not linear. The ultimate loads were obtained corresponding to the stage of loading beyond which the beam would not sustain additional deformation at the same load intensity.
Figs. 9 to 11 shows the effect of GFRP laminates on various load levels. The beams strengthened with 3mm and 5mm thick UDCGFRP exhibit an increase of 112.93% and 136.02% respectively in first crack load when compared to control beam (NCB-S), 98.15% and 142.06% when compared to 10% corroded control beam (10CB-S) and 138.27% and 207.08% when compared to 25% corroded control beam (25CB-S).
The beams strengthened with 3mm and 5mm thick UDCGFRP exhibit an increase of 33.60% and 59.29% respectively in yield load when compared to control beam (NCB-S), 28.37% and 61.85% when compared to 10% corroded control beam (10CB-S) and 27.18% and 38.86% when compared to 25% corroded control beam (25CB-S).
The beams strengthened with 3mm and 5mm thick UDCGFRP exhibit an increase of 49.96% and 67.91% respectively in ultimate load when compared to control beam (NCB-S), 58.02% and 84.56% when compared to 10% corroded control beam (10CB-S) and 31.81% and 64.27% when compared to 25% corroded control beam (25CB-S).

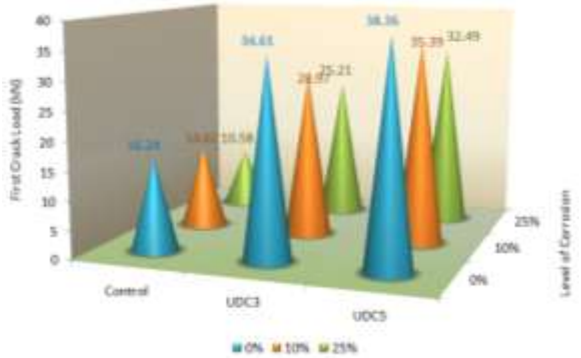

Fig.9 Effect of GFRP on First Crack Load

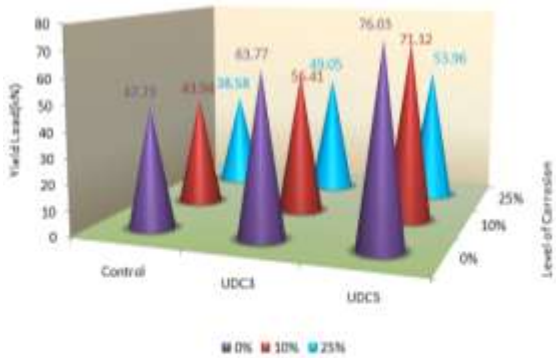

Fig.11 Effect of GFRP on Yield Load

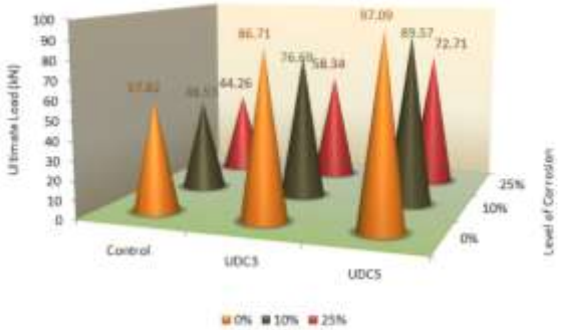

Fig. 11 Effect of GFRP on Ultimate Load

Deflection of a beam primarily depends on the loading, span, moment of inertia of the section and elasticity modulus of concrete. Bonding of GFRP laminates to the soffit of a beam results in an increase in cross-sectional area and stiffness. This increase in stiffness influences the deflection behaviour of the plated beams during pre-cracking, cracking and post-cracking stages. Figs. 12 to 14 show the effect of GFRP laminates on deflection at various load levels.

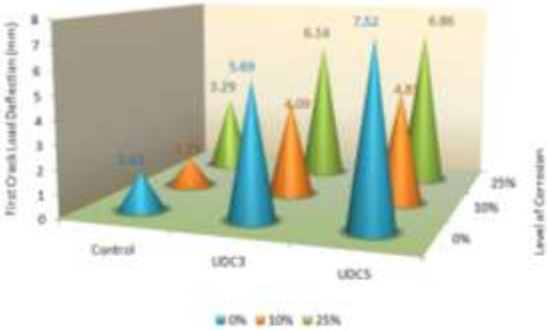

Fig.12 Effect of GFRP on Deflection at First Crack Deflection

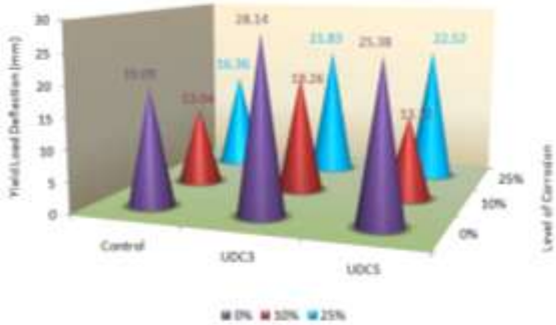

Fig.13Effect of GFRP on Deflection at Yield Deflection

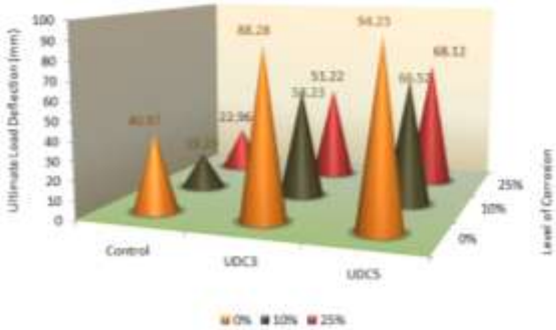

Fig.14 Effect of GFRP on Deflection at Ultimate Deflection

The beams strengthened with 3mm and 5mm thick UDCGFRP exhibit a decrease in deflection of 51.18% and 72.42% respectively at ultimate load when compared to control beam (NCB-S), 77.33% and 87.64% when compared to 10% corroded control beam (10CB-S) and 63.85% and 72.89% when compared to 25% corroded control beam (25CB-S).

3.3 Effect of GFRP Plating on Ductility

The ductility indices and ductility ratios of the tested beams are shown in Figs. 15 to 18. Ductility of reinforced concrete beams is essentially a measure of their energy absorption capacity. Ductility of a beam is its ability to sustain inelastic deformation without any loss in its load carrying capacity, prior to failure. Ductility can be expressed in terms of deformation or energy. The deformation can be deflection, strain or curvature.

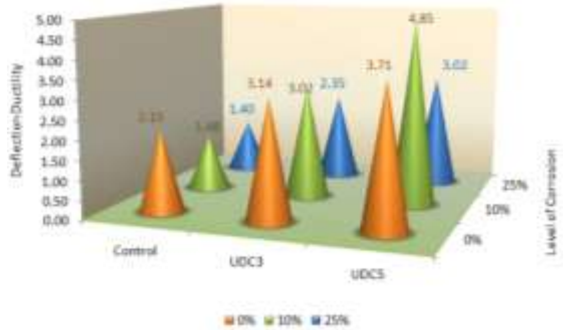

Fig.15 Effect of GFRP on Deflection Ductility

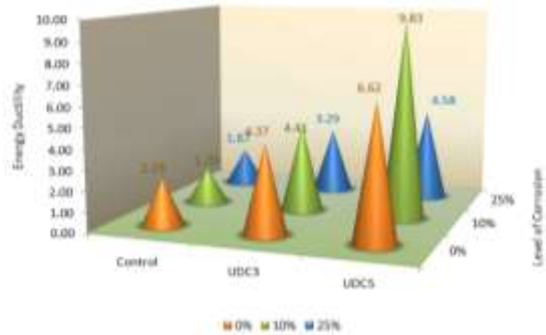

Fig.16 Effect of GFRP on Energy Ductility

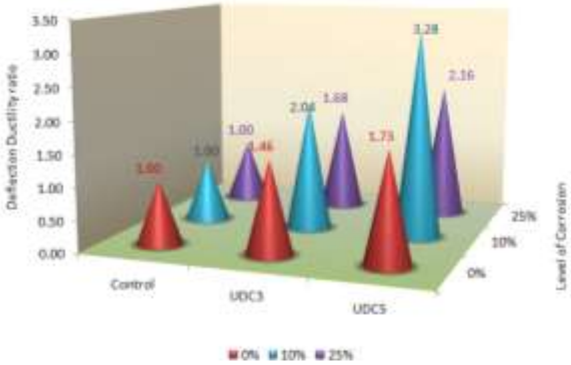

Fig.17 Deflection Ductility Ratios

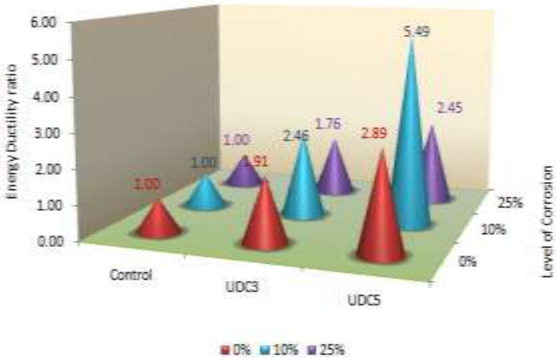

Fig. 18 Energy Ductility Ratios

The load-deflection curves shown in Fig.19 reveal that strengthening by bonding GFRP laminates positively influence the overall structural ductility of the strengthened beams.

The ductility ratios of the strengthened beams to those of the corresponding reference specimens inferred that strengthening with GFRP laminates has appreciable effect on the structural ductility. The deflection ductility of reinforced concrete beams strengthened with 5mmUDCGFRP exhibit an increase of 72.56% with respect to the control specimen. The energy ductility of reinforced concrete beams strengthened with 5mmUDCGFRP exhibit an increase of 189.08% with respect to the control specimen. It can be inferred from the results presented in Figs. 15 to 18 that GFRP has noticeable effect on the beam ductilities.

A careful examination of the ductility ratios presented in Figs. 15 to 18 indicates that the ductility definitions based on deflection and energy reflects the actual physical behaviour of the beams. Hence they can be presumed to give a reasonable and valid representation of the ductility of reinforced high performance concrete beams strengthened with GFRP laminates.

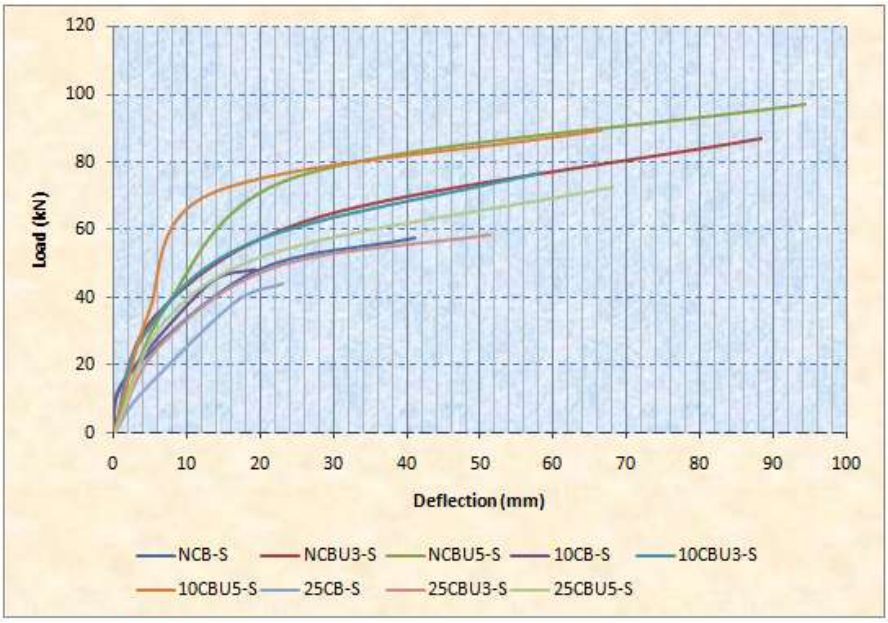

Fig. 19 Load-Deflection Response of Control and Corroded - Strengthened HPC Beams

The load-deflection response of all specimens as shown in Fig.19 exhibit three regions of behaviour. At low load levels, the reinforced high performance concrete beam stiffness is relatively high indicating that the concrete behaves in a linear elastic manner. As the load increases, the extreme fibre stresses in bending increase until the tensile strength of concrete is reached. This causes flexural cracking initially in the constant moment region. Flexural cracking causes a marked reduction in stiffness as shown by a sudden change of gradient in the response. Flexural cracks formed in the constant moment zone extend vertically upwards and become progressively wide as the load is increased. Cracks are also initiated in the shear spans of the beam with increased loads. The final failure of the beam is characterized by large strains in the steel reinforcement and substantial deflection near collapse accompanied by extensive cracking.

The load-deflection response of the GFRP strengthened beams is similar to that of control beam but with several significant differences. The pre-cracking stiffness is identical for both strengthened and control beams. This is to be expected as the entire section is effective and the GFRP laminate has relatively little effect on the moment of inertia and hence the flexural rigidity of the section.The post-cracking stiffness of the GFRP strengthened beams is significantly higher than that of the control beams. After cracking, when the concrete beneath the neutral axis becomes ineffective, the addition of the plate causes a significant increase in the moment of inertia and hence the flexural rigidity of the strengthened beam.
It can be inferred from the test results that change in GFRP thickness and level of corrosion has noticeable effect on the beam deflections at all load levels.

3.4 Effect of GFRP Plating on Failure Modes

Beams tested for this research work failed in different mechanisms. The various failure mechanisms are listed in Table 4. In this study the specimens failed in flexure mode only. The test beams experienced considerable flexural cracking and vertical deflection near to failure. Well distributed closely spaced cracking was observed. The failure modes observed in this experimental study are similar to that mentioned in ACI 440.2R-02 in section 9.2.1 (2002).

Table 4 Failure Modes and Crack Patterns of Tested Beams

Sl. No.	Beam Designation	Type of Failure
1	NCB-S	Flexural Failure
2	NCBU3-S	Flexural Failure
3	NCBU5-S	Flexural Failure
4	10CB-S	Flexural Failure
5	10CBU3-S	Flexural Failure
6	10CBU5-S	Flexural Failure
7	25CB-S	Flexural Failure
8	25CBU3-S	Flexural Failure
9	25CBU5-S	Flexural Failure

Flexural cracks are initiated in the constant moment region as the tensile strength of concrete is reached. The cracks propagate upwards as loading progresses but remain very narrow throughout the loading history and significantly smaller than those in the control beams. This demonstrates the restraining effect caused by the plate on crack openings. Further flexural cracks initiate at locations along the shear spans of the beam as the load level increases. Inclined cracks propagate towards the loading points. These cracks widen as the applied load increases but remain narrow at the base of the beam, demonstrating the confining effect of the external strengthening.

4. CONCLUSIONS

The epoxy bonding of GFRP laminates offers an attractive means of strengthening corroded beams in flexure. An overall evaluation of test results indicates that corroded high performance concrete beams strengthened with UDCGFRP laminates exhibit higher load carrying capacity and ductility. The high performance concrete beams strengthened with 5mmUDCGFRP laminate exhibit an increase of 67.91% in ultimate load when compared to the control beam.The high performance concrete beams strengthened with 5mmUDCGFRP laminate exhibit decrease of 72.42% in deflection at ultimate load when compared to the control beam.The high performance concrete beams with 10% level of corrosion strengthened with 5mmUDCGFRP laminate exhibit a increase of 84.56% in ultimate load and exhibit a decrease of 87.64% in deflection at ultimate load when compared to the 10% corroded control beam. The high performance concrete beams with 25% level of corrosion strengthened with 5mmUDCGFRP laminate exhibit a increase of 64.27% in ultimate load exhibit a decrease of 72.89% in deflection at ultimate load when compared to the 25% corroded control beam. The deflection ductility for 5mm UDCGFRP strengthened beam showed maximum increase of 72.86%. The energy ductility for 5mm UDCGFRP strengthened beam showed maximum increase of 189.08%. All the beam specimens failed in flexure mode only.

5. REFERENCES

[1] Alagusundaramoorthy, P., I. E. Harik, and C. C. Choo. (2003), Flexural Behavior of RC Beams Strengthened with Carbon Fiber Reinforced Polymer Sheets or Fabric, *Journal of composites for Construction*, 7(4), 292-301.

[2] Almusallam, T. H., H. M. Elsanadedy, and Y. A. Al-Salloum. (2014), Effect of Longitudinal Steel Ratio on Behavior of RC Beams Strengthened with FRP Composites: Experimental and FE Study, *Journal of Composites for Construction*, 19(1) 0401- 4028.

[3] Bencardino, Francesco, Giuseppe Spadea, and R. Narayan Swamy (2002), Strength and Ductility of Reinforced Concrete Beams Externally Reinforced with Carbon Fiber Fabric, *Structural Journal* 99(2), 163-171.

[4] Carlos A., and Maria M. Lopez.(2006), Sensitivity Analysis of Reinforced Concrete Beams Strengthened with FRP Laminates, *Cement and Concrete Composites*, 28(1), 102-114.

[5] Esfahani, Mohammad Reza, M. R. Kianoush, and A. R. Tajari.(2007), Flexural Behaviour of Reinforced Concrete Beams Strengthened by CFRP Sheets, *Engineering Structures*, 29(10), 2428-2444.

[6] Ferrier, E., Bigaud, D., Clement, J. C., & Hamelin, P. (2011), Fatigue-Loading Effect on RC Beams Strengthened with Externally Bonded FRP, *Construction and Building Materials*, *25*(2), 539-546.

[7] Heffernan, P. J. and Erki, M.A. (2004), Fatigue Behavior of Reinforced Concrete Beams Strengthened with Carbon Fiber Reinforced Plastic Laminates, *Journal of Composites for Construction*, 8(2), 132-140.

[8] Maaddawy, T., Soudki, K. and Topper, T., (2005). Long-term Performance of Corrosion-Damaged Reinforced Concrete Beams, *ACI Structural Journal*, *102*(5), 649.

[9] Mahjoub, Reza, and Seyed Hamid Hashemi.(2010), Finite Element Analysis of RC Beams Strengthened with FRP Sheets Under Bending, *Australian Journal of Basic and Applied Sciences*, 4(5), 773-778.

[10] Ravikant, Shrivastava, Uttamasha Gupta, and U. B. Choubey. (2013), Effect Of Cyclic Loading on Flexural Behaviour of FRP Strengthened RC Beams: A Stability Point Approach. *International Journal of Advanced Research in Engineering and Applied Sciences*, 2(6), 9-26.

[11] Yu, T., Li, C., Lei, J., and Zhang, H. (2011), Fatigue of Concrete Beams Strengthened With Glass-Fiber Composite Under Flexure, *Journal of Composites for Construction*, 15(4), 557-564.