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Performance of Corrosion-Damaged HSC Beams Strengthened with GFRP Laminates

V.Balasubramaniam[#1], P.N. Raghunath[*2] and K. Suguna[#3]
[1,2,3]*Department of Civil and Structural Engineering,*
Annamalai University, Chidambaram-608 001, India
[2]pnr_ks@yahoo.com

***Abstract*—This paper presents the results of an experimental program conducted for evaluating the performance of corrosion damaged HSC beams strengthened with GFRP laminates. Five Beam specimens of size 150x250x3000 mm were caste and tested for the present investigation. One beam specimen was neither corroded nor strengthened to serve as reference. Two beams were corroded to serve as corroded control. A reinforcement mass loss of approximately 10 and 25% were used. The remaining two beams were corroded and strengthened with GFRP. The study parameters included first crack load, first crack deflection, yield load, yield load deflection, service load, service load deflection, ultimate load and ultimate deflection. Based on the results it was found that the UDCGFRP laminated beams showed distinct enhancement in ultimate strength and ductility.**

***Keywords*—Corrosion, high strength concrete, strengthening, UDCGFRP laminates**

I. Introduction

The problem of deterioration of concrete structures due to corrosion of steel reinforcement has received worldwide attention. Even though current codes of practice provide recommendations and precautions to avoid corrosion, evidence of corrosion of steel in concrete continues to be reported in the field situations. There are numerous references to studies carried out to investigate the structural strength of corrosion damaged RC beams[1-2]. Uomoto[3] subjected several small RC beams reinforced with a single 16mm rebar to accelerated corrosion using an impressed current and found that rebar corrosion has pronounced effect on the structural strength of RC beams than it does on the yield strength of the rebar. This result was attributed to the loss of bond between rebar and concrete due to cracking in concrete resulting from the expansive forces of the corrosion products. All the specimens were tested in flexure after corrosion and the results showed that un-corroded beams failed in flexure; while corroded beams exhibited a shear-bond failure at a load range of 67-95% as compared to un-corroded beams. It was concluded that the critical point in strength degradation occurs when longitudinal cracks form along the steel bars. Umoto[3] suggested that increasing the concrete cover decrease diffusion of chloride ions and prevents crack formation along the reinforcing bars.

Al-Sulaimani et al.[4] performed a total of 54 pull-out tests for 10, 14 and 20 mm bars which were corroded to various degrees ranging from 0-14% mass loss. The author concluded that bond strength increased up to 50, 33 and 25%, respectively, for 10, 14 and 20 mm rebar at about 1% corrosion. Beyond 1% corrosion, bond strength decreased, dropping below the bond strength of un-corroded rebar only when the first surface corrosion cracks were detected. The effects of rebar corrosion on the structural characteristics of RC beams are well documented[5,6,8].

Lee et al.[7] studied the characteristics of four RC beams subjected to accelerated corrosion and subsequently repaired with CFRP laminates externally bonded to the tension face. The Specimens were 200x250x2400 mm and were reinforced with three 13mm rebar at both top and bottom and with 6 mm stirrups at 50 mm spacing. The specimen with tension rebar corroded to 10% mass loss achieved an ultimate strength of 85% than that of un-corroded specimen and experienced failure due to loss of bond. Two corroded specimens were repaired with CFRP laminates after corrosion and showed an ultimate strength of 141 and 143% that of a un-corroded specimen and experienced failure due to tensile rupture of the CFRP laminates.

Many researchers have shown that concrete repair using FRP laminates is very successful in restoring or increasing the strength of concrete members. A further promising aspect of FRP repair is the prevention of deterioration due to rebar corrosion by confinement of the concrete member[7-9]. By strengthening concrete members with FRP laminates, concrete spalling and cracking caused by the expansive forces of the corrosion products may be delayed or even prevented.

The results of different studies discussed above strongly suggest that the corrosion cracking around the steel rebar is a fundamental component contributing to the loss of structural strength. This implies that if corrosion cracking can be prevented, or at least decreased, a certain degree of structural strength may be maintained in a corroding RC beam. This research derives such a relationship based on experimental data.

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II. MATERIALS AND METHODS

The specified 28day compressive strength of concrete used was 62 MPa with a maximum aggregate size of 20 mm and a w/c ratio of 0.48. 12 mm diameter bars having an yield strength of 456.51MPa were used for the longitudinal reinforcement and Uni-directional cloth glass fiber reinforced polymer (GFRP) sheets with 3 mm thickness used for this investigation had a elastic modulus of 17365.38 MPa and an ultimate elongation of 2.6%.

Figure 1 shows the reinforcement details of the beam specimen. It consisted of two 10 mm diameter bars at top and two 12 mm diameter bars at bottom. Shear reinforcement consisted of 8 mm diameter stirrups at 150 mm spacing. The bottom reinforcing steel was extended 50 mm beyond the end of concrete face for the purpose of making external electrical connections.

Details of the test specimens are given in Table 1. A total of four beams were subjected to accelerated corrosion (10% and 25%).

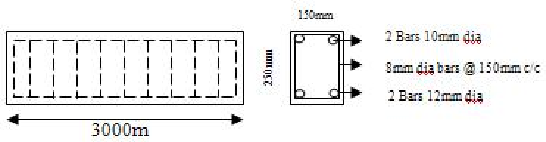

Fig.1 Reinforcement details of the beam specimen

Following the corrosion phase, UDCGFRP laminates having 3 mm thickness were bonded to the tension face, with the fiber orientation in the longitudinal direction. One of the specimens was kept as a control specimen and was neither strengthened nor corroded (virgin).

Accelerated corrosion: All the specimens were subjected to accelerated corrosion. Figure 2 shows the accelerated corrosion setup. The four specimens were placed in a tank where 3.5% NaCl solution was 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 incorporated with a direct current power supply with an output of 11 amps thereby achieving theoretical steel weight loss of 10% and 25%. According to Faraday's law:

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

Where

Δw = Mass loss due to corrosion

A_m = Atomic mass of iron (55.85 g)

I = Corrosion current in amps

t = time since corrosion initiation (sec)

Z = valence(assuming that most of rust product is due to Fe $(OH)_2$, Z is taken as 2)

F = Faraday's constant [96487 coulombs (g/equivalent)]

TABLE 1

Details of the Test Specimens

Specimen	Specimen details	Level of Corrosion	Type of GFRP	Thickness of GFRP (mm)
RO	Virgin	-	-	0
AO	Corroded-Unstrengthened	10	-	0
AUDC3	Corroded-Strengthened	10	UDC	3
BO	Corroded-Unstrengthened	25	-	0
BUDC3	Corroded-Strengthened	25	UDC	3

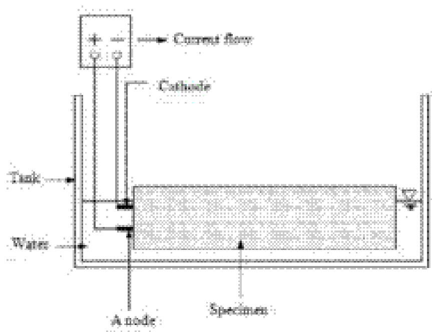

Fig. 2 Schematic of Accelerated Corrosion Set-up

By knowing the original mass of the rebar and the total current of the mass loss, the duration of corrosion activity can be determined. The specimens were prepared for GFRP lamination by removing all loose materials on the soffit of the rectangular beam by applying wire brush and roughened 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.

III. TEST SET-UP AND PROCEDURE

The beams were tested under two-point loading in a loading frame capacity of 750 KN. The deflections were measured at mid-span and load points using mechanical dial gauges of 0.01 mm accuracy. The crack widths were measured using crack deflection microscope with a least count of 0.02mm. The curvature measurement was also done using dial gauges placed over the compression face of the beam at and near to the support points. The deflections, curvature and crack width were measured at each load stage. The loading was continued until failure. The details of test set up are shown in Fig. 3.

Fig.3 Experimental Test Set-up

IV. TEST RESULTS AND DISCUSSION

The test results on the load and deflection properties of the specimens are reported in Table 2. The ductility indices of test beams are presented in Table 3. The first crack loads were obtained by visual examination. The service loads were obtained from the ultimate loads with the usual partial safety factors. 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. The deflection capacity is defined as the deflection of the beam at failure.

TABLE 2 Test results

Specimen	First Crack Stage		Yield Stage		Service Stage		Ultimate Stage		
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Maximum crack width (mm)
RO	17.17	1.32	49.05	20.34	37.60	10.35	56.41	39.97	1.14
AO	14.72	1.37	44.15	12.78	32.70	8.19	49.05	20.29	1.16
BO	9.81	3.32	39.24	15.80	29.43	7.56	44.15	21.96	1.50
AUDC3	29.43	4.18	56.41	19.31	50.68	11.59	76.03	58.23	0.98
BUDC3	24.53	6.09	49.05	22.91	39.24	13.37	58.86	53.22	1.24

TABLE 3 Ductility indices

Specimen	Deflection ductility	Energy Ductility
RO	1.97	2.34
AO	1.59	1.88
BO	1.39	1.76
AUDC3	3.02	4.30
BUDC3	2.32	3.16

At the first crack stage, the corroded - strengthened specimens exhibit an increase up to 71.40% at 10% and 42.86% at 25% mass loss respectively compared to the virgin beam. However the strength decreased by an average of 14.26 and 42.86% for 10 and 25% degree corrosion damage respectively, for corroded un-strengthened specimens.

At the yield load level, the corroded - strengthened specimens exhibit an increase up to 15% at 10% and 0% at 25% mass loss respectively compared to the virgin beam. However the strength decreased by an average of 9.98% and 20% for 10 and 25% degree corrosion damage respectively, for corroded un-strengthened specimens.

At the service load stage, the corroded - strengthened specimens exhibit an increase up to 79.35% at 10% and 65.53% at 25% mass loss respectively compared to the virgin beam. However the strength decreased by an average of 27.56 and 34.42% for 10 and 25% degree corrosion damage respectively, for corroded un-strengthened specimens.

At the ultimate load level, the corroded - strengthened specimens exhibit an increase up to 34.78% at 10% and 4.34% at 25% mass loss respectively compared the virgin beam. However the strength decreased by an average of 13.04% and 21.73% for 10% and 25% degree corrosion damage respectively, for corroded un-strengthened specimens. Based on the test results, it was found that GFRP laminates imparted beneficial effects even at the corrosion-damaged stage.

The deflection got reduced at all load levels in UDGGFRP strengthened beams, The deflection at yield load stage decreased by 30.19% and 2.8% at 10% & 25% level of corrosion damage when compared to the virgin specimen. For beams with 3mm thick UDCGFRP laminates at the same level of corrosion damage, the deflections decreased by 15% and 13.79% when compared to the corroded control beam specimen.

The deflection at ultimate load stage decreased by 41.61% and 29.79% at 10% and 25% level of corrosion damage when compared to the virgin specimen. For beams with 3mm thick UDCGFRP laminates at the same level of corrosion damage, the deflections decreased by 35.48% and 24.97% when compared to the corroded control beam specimen.

The ductility indices of the tested beams are provided in Table3. The GFRP strengthened corrosion damaged concrete beams showed an increase in the deflection ductility upto 66% and an increase in the energy ductility was 89% at 10% level of corrosion damage. For the beam specimens subjected to 25% level of corrosion damage, the increase in deflection ductility was found to be 128% and the increase in energy ductility was found to be 79%.

V. CONCLUSION

Based on the test results the following conclusions are drawn:

- GFRP laminates properly bonded to the tension face of RC beams enhance the Ultimate strength substantially. The UDCGFRP strengthened beams exhibit an increase of 34.78% in Ultimate strength at 10% steel mass loss and 4.34% at 25% steel mass loss when compared to the control specimen.
- The deflection got reduced at all load levels inGFRP strengthened beams. At the ultimate stage,UDCGFRP laminated beams exhibit a decrease of 35.48% at 10% mass loss and 24.97% at 25% mass loss when compared to the corroded control beam
- UDCGFRP laminated beams show enhanced ductility. The increase in deflection ductility was found to be 66% at 10% mass loss and 128% at 25% mass loss.

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