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BEHAVIOR OF CORRODED RC BEAMS WITHOUT STIRRUPS REPAIRED WITH CFRP SHEETS

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In reinforced concrete structures located in hot and humid areas, steel reinforcement is generally vulnerable to deterioration due to corrosion. Corrosion of reinforcement in many cases is considered the main cause of concrete structures deterioration, which in turn requires large budgets for repair and maintenance. This paper presents the experimental results of damaged/repaired reinforced concrete beams. The experimental program consisted of testing reinforced concrete rectangular beam specimen's with/without shear reinforcement and exposed to accelerated corrosion of the longitudinal steel reinforcement on the tension side. Bonding external U-shaped CFRP sheets to restore the strength loss due to corrosion repaired corroded beams without shear reinforcement. The test results showed that corroded beams without stirrups failed in a brittle manner with drop in maximum deflection at failure of approximately 60% compared to the uncorroded beam. Corroded beams with stirrups lost some strength, but failed in ductile manner. Using externally bonded U-shaped CFRP sheets restored the ductility of corroded beams without stirrups and prevented bond failure at the steel concrete interface due to the absence of internal stirrups.

Keywords: Strengthening, Rehabilitation, Composite materials, Transvers steel, Corrosion, Repair.

1 INTRODUCTION

The deterioration of reinforced concrete structures resulting from corrosion of steel reinforcement is a worldwide problem, and the cost of repairs is substantial. While it is known that reinforcing steel provides strength and ductility only through bond and anchorage to the concrete, the effectiveness of such a bond mechanism can be reduced through deterioration of the steel, concrete or both (Umoto 1984, Okada *et al.* 1988, Katayama 1995, Almusallam *et al*. 1996, Carbera 1996, Morinaga 1996). Hence, the serviceability as well as the ultimate capacity of the damaged reinforced concrete member is affected.

The effect of corrosion of the longitudinal reinforcing steel on the strength and ductility of reinforced concrete beams is more critical if combined with corrosion of stirrups or if the beam is without stirrups. Researchers reported that the shear strength of members designed two to three decades ago was overestimated and the code conditions at that time for provisions of stirrups were not as stringent as codes today. As a result, a large number of structures in service are without stirrups, with minor margin of safety (Sherwood *et al.* 2006, Sneed 2007). In a recent study, Azam and Soudki (2013) presented the behavior of reinforced concrete slender beams without stirrups and with corroded longitudinal reinforcement anchored at the end with standard 90° hooks. They found that the absence of stirrups combined with loss of bond along the longitudinal reinforcement due to corrosion changed the mode of failure from beam action to arch action. There was an increase in failure load and deflections compared to the control uncorroded beams. The findings by Azam and Soudki (2013) are valid for properly anchored longitudinal reinforcement; but what if the corroded longitudinal reinforcement is not anchored.

This paper presents the research findings of an experimental study involving damage due to chloride induced corrosion in the flexural reinforcement of concrete beams without shear reinforcement and concrete beams with minimum shear reinforcement. The main objective is to evaluate the effect of corrosion of longitudinal reinforcement without anchorage on the structural behavior and the effectiveness of carbon fiber reinforced polymers (CFRP) in repair of corroded beams.

2 EXPERIMENTAL PROGRAM

2.1 Specimen Details

The experimental program consisted of testing reinforced concrete beams of 2.7 m long, 100 mm wide and 150 mm deep. The beams are divided into two groups summarized in Table 1. Group A consisted of rectangular beams without stirrups while Group B consisted of beam with stirrups as shown in Figure 1. Beam AC0 was a control beam with no corrosion, while beams AC5 and AC7.5 were subjected to accelerate corrosion with theoretical 5% and 7.5% corrosion (mass loss in reinforcement). Applying six U-shaped CFRP sheets repaired beams ARU5 and ARU7.5 were corroded beams with corrosion of 5% and 7.5%, respectively and then. For stirrups, 6-mm diameter epoxy coated plain bars spaced at 300 mm c/c were used within the shear span. The stirrups were epoxy coated to insure they will not get corroded during accelerated corrosion process of the tensile reinforcement. In Group B, Beam BC0 was a control beam with no corrosion, while beams BC5 and BC7.5 were subjected to accelerated corrosion with 5% and 7.5% corrosion (mass loss in tensile reinforcement).

2.2 Material Properties

Ordinary Portland cement was used for the concrete mix along with a maximum aggregate size of 10 mm. The concrete mix was proportioned by weight as follows, aggregate: sand: water: cement = 60: 67: 16: 25, with a water to cement ratio of 0.64. The concrete had an average 28-day compressive strength of 35 ± 1.5 MPa. The average yield strength of the 10 mm diameter reinforcing bars was measured as 420 MPa with Modulus of Elasticity of 200 GPa. Unidirectional carbon fiber sheets were used for the U-Shaped CFRP strips. The CFRP sheets had tensile strength of 3800 MPa, Modulus of Elasticity of 240 GPa. A two-part epoxy was used to bond the CFRP sheet to the concrete surface. One coat of epoxy was first applied to the concrete surface, then the CFRP sheet was attached to the epoxy coated concrete and a second coat of epoxy was applied to the CFRP sheet. The composite laminate (fiber + epoxy) had an average thickness of 1 mm.

2.3 Preparing the Specimens

Casting of each beam was done in two layers; the first layer of concrete contained salt approximately 1% by weight of cement in the mix which covered up to one third of the section height (above the tensile steel bars). This was done to simulate chloride ions (Cl^-) contamination and to accelerate corrosion. The second layer of concrete was poured up to the top of the beam containing no salt of the first layer.

Table 1. Details of test specimens and test result.

Beam designation	Theoretical mass loss (%)	Stirrups	CFRP U-strips	P_u (kN)	D_u (mm)	V_u (kN)	V_n (kN)	Mode of failure
AC0	0.0	----	----	15.8	66	7.9	11.9	CC
AC5	5.0	----	----	14.6	23	7.3	11.9	BF
AC7.5	7.5	----	----	14.8	56	7.4	11.9	CC
ARU5	5.0	----	√	12	25	6	11.9	BF
ARU7.5	7.5	----	√	14	48	7.0	11.9	CC
BC0	0.0	√	----	17	43	8.5	17.6	CC
BC5	5.0	√	----	16.3	40	8.15	17.6	CC
BC7.5	7.5	√	----	14	32	7	17.6	CC

P_u = Ultimate Load
D_u = Max. Deflection
V_u = Ultimate shear force= $P_u/2$
V_n= Nominal shear strength(analytical)
CC = Concrete Crushing.
BF = Bond Failure at Steel Concrete Interface.

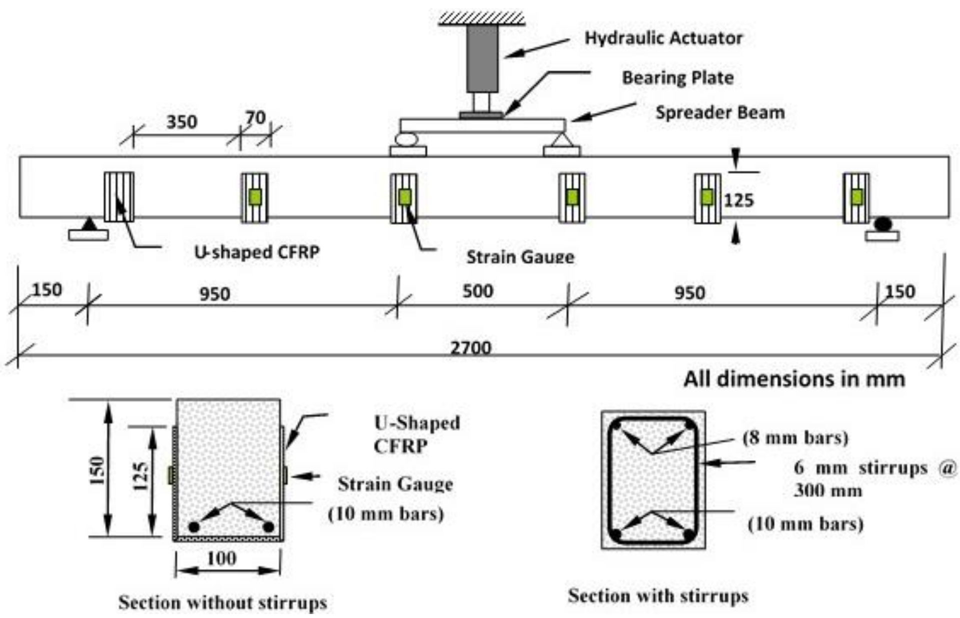


Figure 1. Test setup for beams and cross section details.

However, beams AC0 and BC0 were cast without the addition of salt to concrete, as these beams were control specimens with no corrosion. After 28 days curing in room conditions at 25^o C temperature and 60% humidity, the beams to be subjected to accelerated corrosion were placed inside a tank which has salted water with a concentration of about 3% by weight of water. To induce corrosion in the reinforcement, the rebar was connected to a power (voltage) source where a current was applied to accelerate the corrosion process. Accelerated corrosion was carried out by impressing an electric current through the main longitudinal bottom reinforcing bars of about 488 mA, which corresponds to approximate current density of 281 μA/cm². Following the accelerated corrosion phase, the beams were left for two days to dry. The beams were then repaired with CFRP and were left for a week for the CFRP to cure under room temperature.

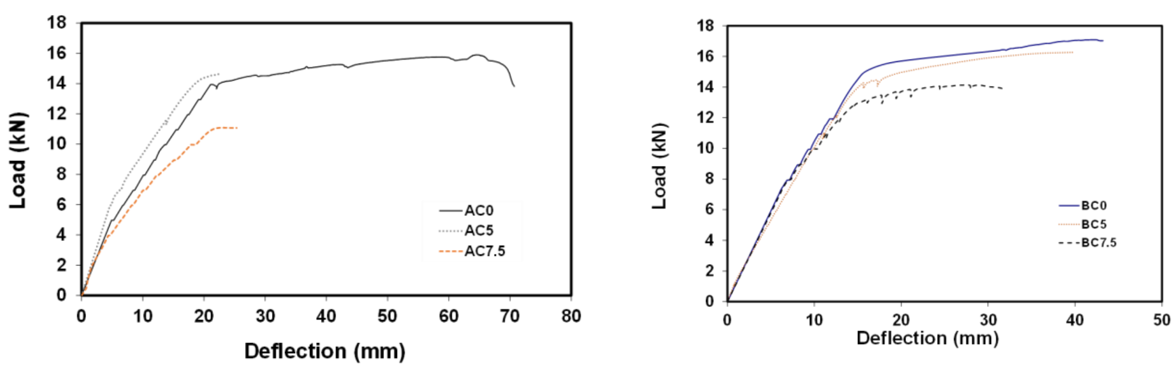
2.4 Test Setup and Instrumentation

All specimens were loaded in four-point loading (see Figure 1). The load was applied using a 250 kN hydraulic actuator through a spreader steel beam to the specimen. Linear variable displacement transducers (LVDTs) with a range capacity of 100mm were used to measure the mid-span deflections of the beam. All beams were tested to failure using displacement control with a rate of 0.3 mm/min.

3 RESULTS AND DISCUSSION

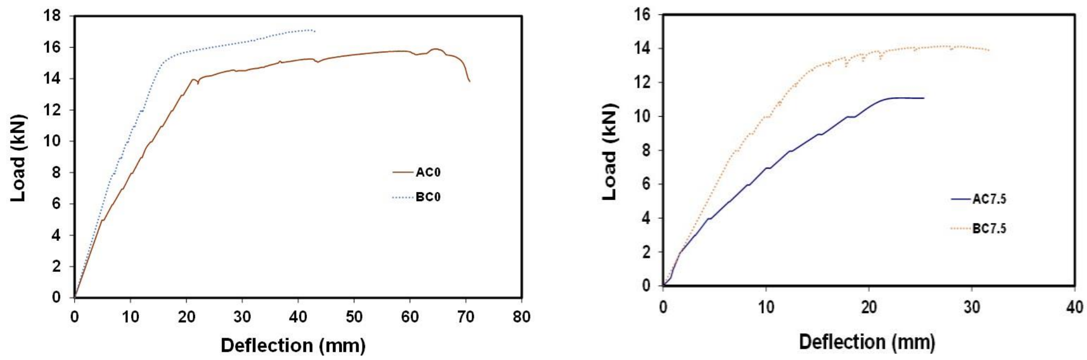
3.1 Effect of Corrosion

The test results of all tested beams are summarized it Table 1. The load vs. mid-span deflections is shown in Figure 2. Figure 5a shows that the behavior of beam AC0 (without stirrups and with 0% corrosion) is of a typical under-reinforced beam exhibiting large deformation beyond the yield point before it failed by crushing of concrete. However, corroded beams without stirrups (AC5 and AC7.5) failed in a brittle manner due to debonding between reinforcement and concrete. The beam literally split into two pieces longitudinally at the level of the corroded rebars. The maximum deflections at failure were 66 mm, 23 mm and 25 mm for beams AC0, AC5 and AC7.5, respectively. The ultimate deflection was reduced due to corrosion by approximately 63% compared to the control uncorroded beam (beam AC0). On the other hand, beams with stirrups (Fig. 2b) lost some strength due to corrosion, but failed in a ductile manner. The maximum deflections were 43 mm, 40 mm and 32 mm for beams BC0, BC5 and BC7.5, respectively. This indicates a reduction in deflection of 1% and 25% in beams BC5 and BC7.5 relative to the control uncorroded beam (beam BC0). All beams with stirrups failed by crushing of concrete after steel has yielded.



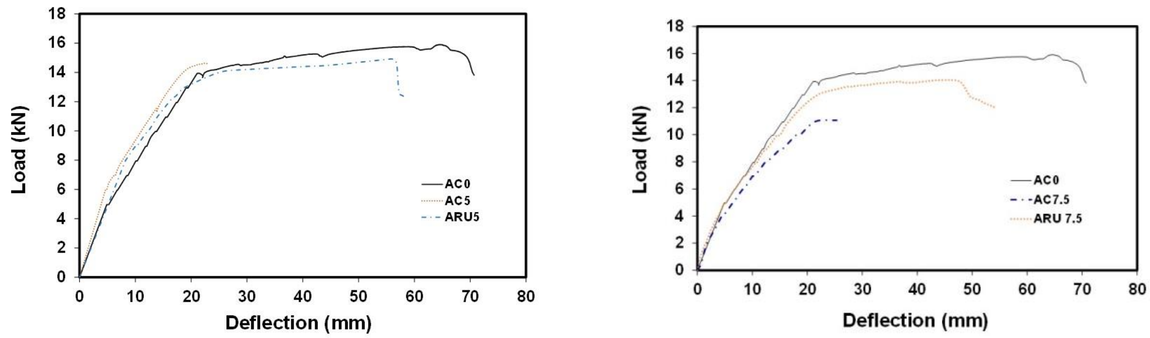
(a) (b)

Figure 2. Effect of corrosion (a) Beams without stirrups; (b) Beams with stirrups.



(a) (b)

Figure 3. Effect of stirrups on beams (a) control; (b) corroded.



(a) (b)

Figure 4. Effect of CFRP U-wrap strips on beams without stirrups (a) Beams with 5% corrosion; (b) Beams with 7.5% corrosion.

3.2 Effect of Stirrups on Load Deflection Behavior

Beams with stirrups showed higher stiffness and resisted slightly higher loads (see Fig.3). The control beam without stirrups failed at a load of 15.8 kN and a deflection of 66 mm, while the control beam with stirrups failed at a load of 17 kN and a deflection of 43 mm. The control beams with/without stirrups showed a ductile behavior. However, the presence of stirrups increased the stiffness by approximately 17%. The effect of stirrups is more prominent in the corroded beams as shown in Figure 3b. The corroded beam without stirrups failed at a load of 12 kN and a deflection of 25 mm, while the corroded beam with stirrups failed at a load of 14 kN and a deflection of 32 mm. It is also noted that the existence of stirrups increased the deflection at ultimate load by 22% and stiffness by 32% of the corroded beams. The increase in stiffness was mainly due to the confinement provided by the stirrups. The presence of stirrups provides the confinement needed such that the flexural steel will act compositely with concrete in compression as one unit.

3.2 Effect of U-Shaped CFRP Strips Repair

Attaching U-shaped CFRP strips on corroded beams without stirrups changed the mode of failure of the repaired beams. Adding U-shaped sheets improved the strength by attaining higher ultimate load and improved ductility indicated by higher maximum deflection at failure (see

Figure 4). This is observed from the response of beams ARU5 and ARU7.5, which failed by crushing of concrete, compared to a brittle failure observed in beams AC5 and AC7.5. The maximum deflections were increased by 59% and by 48% in beams ARU5 and ARU7.5 compared to beams AC5 and AC7.5, respectively due to the CFRP repair.

4 CONCLUSIONS

Based on the experimental results, the following conclusions are drawn:

- Corroded beams without stirrups failed in a brittle manner with drop in maximum deflection at failure of approximately 60% compared to the uncorroded beam.
- Corroded beams with stirrups lost some strength, but failed in ductile manner. The reduction in maximum deflection due corrosion ranged between 1% to 25% for 5% mass loss and 7.5% mass loss, respectively compared to the uncorroded beam.
- Corroded beams without stirrups repaired by U-shape CFRP strips effectively confined the corroded beams and changed the mode of failure to a ductile failure. The maximum deflection of repaired beams increased by 59% in beam with 5% mass loss and by 48% in beam with 7.5% mass loss compared to the unrepaired corroded beams with the same mass loss.

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