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Ductility Performance of Corrosion-Damaged Reinforced Concrete Beams

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Abstract: This paper presents the results of an experimental study to investigate the corrosion activity in reinforced concrete beams. All specimens 150X250X3000mm in size were cast and tested for the present investigation. One beam was tested as a virgin while two beams were exposed to accelerated corrosion damage of 10% and 25%. The deflection got reduced by 27.58% and 34.49% due to corrosion reinforcement.

Key words: Corrosion, Ductility, Reinforced Concrete, Ultimate strength

INTRODUCTION

The problem of deterioration of concrete structures due to corrosion of steel reinforcement has received worldwide attention. Whereas current codes of practice adopt recommendations and precautions to avoid corrosion of steel in concrete continues to be reported in the field situations. There are numerous references to studies carried out to investigate the corrosion mechanism, corrosion prevention, and corrosion rate measurements [Schiecl,et al.1997; Hussain et al.1995; Andrade et al. 1990].

Corrosion of reinforcement steel used in concrete leads to formation of rust. As the steel corrodes, the volume of rust also increases and at one stage, the force induced by the corrosion products may exceed the tensile strength of concrete and because of this, cracking of concrete

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will occur. These corrosion products would exert enormous stress on the surrounding concrete promoting the deterioration of concrete structures. Corrosion of steel reinforcement is the most common durability problem of reinforced concrete structures.

Steel in concrete is normally protected from corrosion by a passive film of iron oxides on the steel surface resulting from the natural alkaline environment of concrete. The passive film is chemically stable in the absence of carbonation and chloride ions (Bentur et al.1997; Broomfield 1997).The ingress of chloride irons, Cl^- , to the level of steel reinforcing bars destroys the passive film and initiates corrosion [American Concrete Institute (ACI) 2002; Comite Euro-International du Beton (CEB) 1992]. This makes reinforced concrete structures in coastal areas and marine environments vulnerable to damage by corrosion of steel reinforcement.

Reinforced concrete infrastructures located in cold environments are also susceptible to corrosion damage due to the use of deicing salts. Once corrosion is initiated, electrochemical reactions occur, leading to the formation of expansive corrosion products that create tensile stresses in concrete surrounding the corroding steel reinforcing bar. This results in concrete cracking and spalling, which aggravates the progressive damage, thus affecting the durability of the structure. The corrosion rate is a key element in determining the time from corrosion initiation to corrosion cracking, which is usually used to predict the functional service life of a corroded RC structure [Tutti 1982; Weyers 1998]. After corrosion initiation, the corrosion rate depends mainly on the availability of oxygen and moisture at the cathode and on the concrete resistivity. This is mainly affected by the internal moisture content and concrete porosity [Bentur et al;]. The results of different studies discussed above strongly suggest that corrosion cracking around the steel rebar is a fundamental component contributing to the loss of structural strength.

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Hence research is needed to clarify the interaction between the degrees of corrosion, load carrying capacity and the ductility in RC beams having well anchored steel reinforcement. This research paper derives such a relationship based on experimental data.

EXPERIMENTAL PROGRAMME

A total of three beam specimens 150 × 250 × 3000 mm were cast. Two beams were subjected to accelerated corrosion at 10% and at 25%. One of the specimens was kept as a control specimen (with out corrosion).

MATERIAL PROPERTIES

The mix proportion used was 1:1.39:3.08 with a maximum aggregate size of 20mm, and a w/c ratio of 0.48. The specified 28-day compressive strength concrete used was 29.7 MPa. HYSD bars of yield strength 450.67MPa and 300.82MPa were used for tension and shear reinforcements respectively.

SPECIMEN DETAILS

Fig.1 shows the reinforcement details of the beam specimens. It consisted of two 10mm diameter bars at top. The tension reinforcement consisted of 2 bars 12mm diameter and the Shear reinforcement consisted of 8mm diameter stirrups at 150mm 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.

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ACCELERATED CORROSION

The specimens were subjected to accelerated corrosion. Fig.2 represents the accelerated corrosion setup. The beam 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 of11Amps; thereby achieving theoretical steel weight loss of 10% and 25%.

According to Faraday's law,

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

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* = 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)] Thus, by knowing the original mass of the rebar and the total current of the mass loss, the duration of corrosion activity can be determined.

TEST PROCEDURE

The beams were tested under two point loading in a loading frame capacity of 750KN. The deflections were measured at midspan and load points using mechanical dial gauges of 0.01mm accuracy. The crack widths were measured using crack deflection microscope with a least count of 0.02. 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.

TEST RESULTS AND DISCUSSION

The test results on the load and deflection properties of the specimens are reported in Table 1. The first crack loads were obtained on visual examination only. At this load level, the load carrying capacity of Corrosion damaged RC beams (A10% andA25%) decreased by an average of 54.55% with respect to the control specimen. The service loads were obtained from the ultimate loads with the usual partial safety factors. At this stage, the load carrying capacity of the corroded beam specimens reduced by 27.56% and 34.42% for 10% and 25% degrees corrosion damage respectively, compared to the control beam. The yield loads were obtained corresponding to the stage of loading beyond which the load - deflection response was not linear. At this load level, the strength decreased by an average of 37% for corroded specimen. 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. At this load level, the corroded un strengthened specimens decreased by an average of 27.58% at 10% mass loss and 34.49% at 25% mass loss respectively, compared to the control specimen.

The deflection capacity is defined as the deflection of the beam at failure. It is clear that as the corrosion intensity increases, there is a corresponding decrease in the ultimate deflection of the beams. This implies that the area under the load-deflection curves decreases with an increase in the corrosion intensity.

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The load deflection responses of the specimens are shown in Fig.4. The effects of corrosion on flexural behavior were: The deflection at first crack load level of corroded specimens decreased by an average of 64% at 10% mass loss and 21% at 25% mass loss, respectively compared to the control specimens, the yield load level of the corroded specimens reduced by an average of 8% at 10% mass loss and 13% at 25% mass loss respectively; the service load level of the corroded specimens exhibited a decrease of 27.58% and 34.49% at ultimate load level of the corroded beams compared to the control beam.

The area under the load-deflection curve is an indication of the absorbed energy and ductility, the increase in the corrosion intensity decreases the absorbed energy and hence the ductility of the beams. It is clear from Table 2 that the control specimen had lesser width when compared to the corroded specimens.

CONCLUSIONS

Based on the test results the following conclusions are drawn.

1. Both strength and serviceability, major concern for a corroding beam, get progressively impaired with increasing corrosion intensity.

2. The degree of corrosion has a marked influence on the load carrying capacity of the beam specimens. There is a relatively sharp reduction in the load carrying capacity of a beam with increasing weight loss.

3. The increase in corrosion intensity decreases the absorbed energy and hence the ductility of the beams. This indicates that the corrosion not only affects the strength of the beams but also induces brittleness in their behavior.

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Table-1 Test Results

Specimen	First Crack Stage		Yield Stage		Service Load Stage		Ultimate Stage	
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
Virgin	26.98	2.36	51.50	8.43	47.41	6.50	71.12	40
A10%	19.62	0.83	34.34	7.75	34.34	7.75	51.5	36
A25%	12.26	2.20	29.43	7.25	31.09	10.56	46.59	32

Note: A10%, A25%, refers to degrees of corrosion damage at 10%, 25%

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Table -2 Ductility Indices

Specimen	Deflection Ductility	Curvature Ductility	Energy Ductility	Maximum Crack width (mm)
Control	4.74	7.87	7.87	1.20
A10%	4.41	6.64	6.64	1.24
A25%	4.64	8.40	8.40	1.30

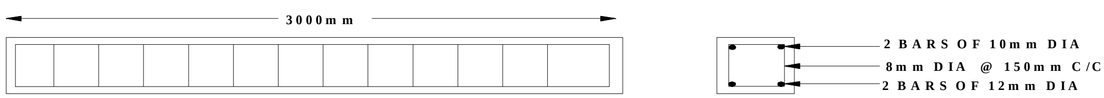

Fig.1Reinforcement Details of the Beam Specimen

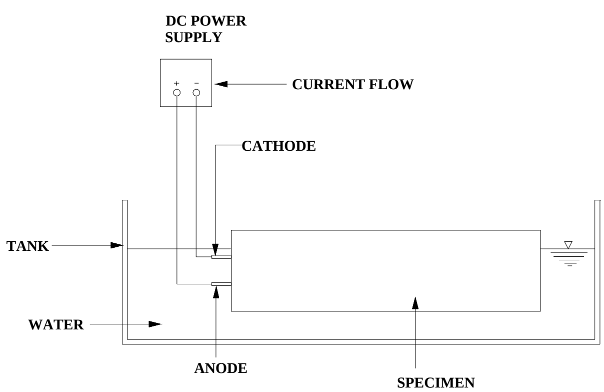

Fig.2. Schematic of Accelerated Corrosion Set-up

Fig.3. Test Set-up

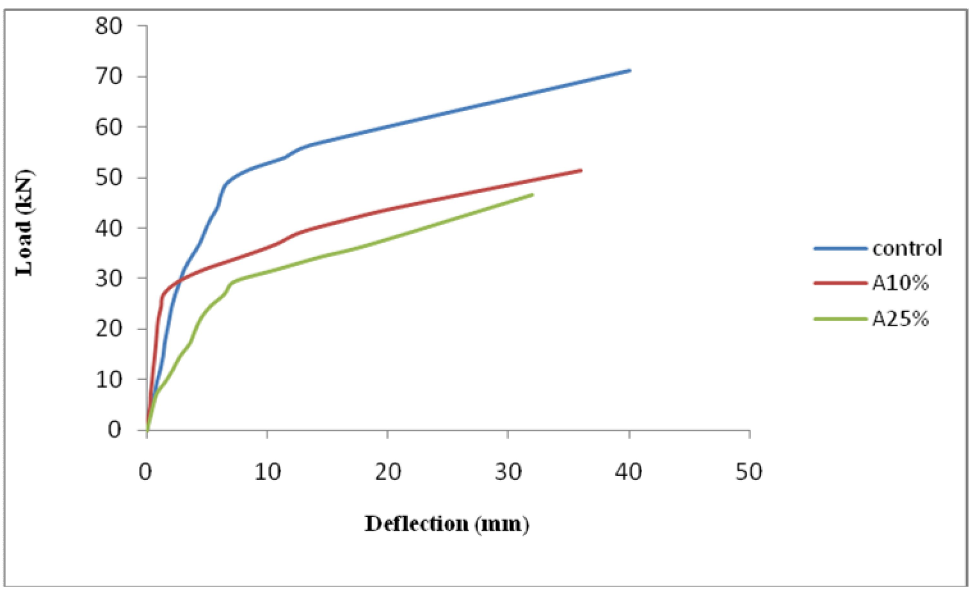

Fig.4 Load- Deflection Response