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Flexural bond strength behaviour in OPC concrete of NBS beam for various corrosion levels

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Abstract. Corrosion is one of the primary reasons why structures have limited durability. The present investigation is carried out to study the behavior of RC (Reinforced Concrete) structural members subjected to corrosion. Experimental investigations were carried out on National Bureau of Standard (NBS), RC beam specimens made of Ordinary Portland Cement (OPC) concrete. Load versus deflection behaviour was studied for different levels of corrosion i.e., 2.5%, 5%, 7.5% and 10%. It is observed that for every percentage increase in corrosion level, there is about 1.6% decrease in load carrying capacity. Also as the amount of corrosion increases there is a reduction in bond stress.

Keywords: bond stress; OPC concrete; corrosion rate; durability

1. Introduction

Concrete is a versatile material used extensively in construction industry. Its durability has an indirect effect on the economy and serviceability of concrete structures (Bondar *et al.* 2012). One of the factors by which structural failure can occur is due to reduction or total loss of rebar area by corrosion.

Corrosion of the steel mainly depends on its microstructure Kürklü *et al*. (2013). Corrosion consumes iron of the reinforcing bar progressively thereby reducing its cross sectional area. Corrosion increases its volume 2 to 6 times than that of the steel; it causes volume expansion developing tensile stresses in concrete (Bhaskar *et al.* 2010). This increased volume creates a bursting pressure which progressively leads to cracking and spalling of concrete. The degradation of bond results from the crushing of concrete keys near the bar lugs (Abdullah *et al.* 1996). The loss of steel-concrete bond and the reduction in cross section area of reinforcing bar has a negative effect on the load carrying capacity of structure. Therefore, corrosion affects both strength and serviceability of RC structures (Rajamane *et al.* 2011).

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2. Research significance

Reinforced steel bar can receive its external loads only from the surrounding concrete, because external loads are very rarely applied directly on it. One of the most important prerequisites of reinforced concrete construction is adequate bond between the reinforcement and the concrete.

Present study aims to investigate the effect of corrosion on performance of R.C beams, in particular on the bond strength and deflection characteristics. Following are the main points:

1. Accelerated corrosion using impressed current technique is adopted for achieving the desired corrosion level.
2. Load deflection behavior of RC beam subjected to different degree of corrosion levels is studied.
3. NBS beams have been cast and tested for bond strength by two-point loading flexural strength.
4. OPC concrete was used for preparing the beam specimens.

3. Experimental investigations

The details of experiments, materials used, and method of testing are explained below.

3.1 Materials

The materials used for the experimental investigation are as follows:

3.1.1 Fine aggregate

Physical tests on fine aggregates were conducted (Table 1).

3.1.2 Cement

Ordinary Portland cement (OPC) 43 Grade was used. It was tested as per IS: 8112- 1989 recommendations for the cement (Table 2).

3.1.3 Coarse aggregate

Size of aggregate used was 20mm downsize and 12.5mm down size angular type coarse aggregate. The results are tabulated in Table 3.

3.1.4 Reinforcing steel

Tensile strength of reinforcing steel bar was tested using Universal Testing Machine (UTM). Stress-strain curves for 25mm Thermo Mechanically Treated (TMT) Fe-415 reinforcing steel bar was obtained by plotting tension test data. Typical stress-strain curve for 25mm bar is shown in Fig. 1. The yield strength and ultimate strength are 485N/mm^2 and 589N/mm^2 respectively.

3.2 Preparation of test specimens

National Bureau of Standard (NBS) beam specimens of size 2.44 m × 0.457 m × 0.203 m were designed as under reinforced sections as per IS 456-2000 for the present study. A total of fifteen specimens were cast. Mass concreting was adopted as specimens were of large size. TMT rebar of 25mm diameter bar was placed at a cover depth of 50mm from bottom, 12mm hanger bar at top

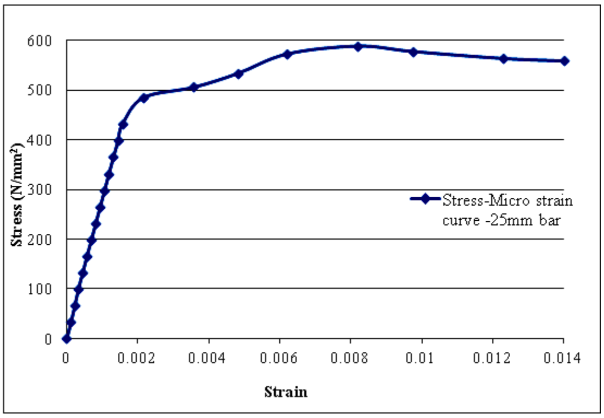


Fig. 1 Stress-strain curve for 25 mm diameter TMT Fe-415 reinforcing steel bar

Table 1 Characteristics of fine aggregate used for concrete mix

Sl No	Test Parameters	Results
1	Specific gravity	2.6
2	Water absorption	2.0%
3	Moisture content	5.0%
4	Grading	Zone I

Table 2 Test results on characteristics of OPC

Sl No	Test Parameters	Results	As per IS 8112:1989 (Specifications of 43 Grade OPC)
1	Initial setting and final setting time	75 min and 260 min	Not less than 30 min. and not more than 600 min
2	Specific gravity	3.1	
3	Compressive strength:		
	3 Days	24.09N/mm^2	Not less than 23 N/mm^2
	7 Days	34.48N/mm^2	Not less than 33 N/mm^2
	28 Days	46.85N/mm^2	Not less than 43 N/mm^2

Table 3 Characteristics of coarse aggregate of 20mm downsize used for concrete mix

Sl No	Test Parameters	Results
1	Specific gravity	2.8
2	Water absorption	0.5%
3	Moisture content	Nil
4	Shape	Angular

and side bars were provided with a stirrups of 8mm diameter (Fig. 2).

Concrete mix for M30 Grade was prepared using Ordinary Portland Cement (OPC) Concrete, fine sand and aggregate (20mm & 12.5mm) as per IS 10262:2009. Mix proportion of 1: 1.77: 2.87 was used. Water cement ratio of 0.45, with an addition of 2ml/kg of a commercially available chemical admixture was used. Slump obtained was 58mm. Specimens were kept in water for 28

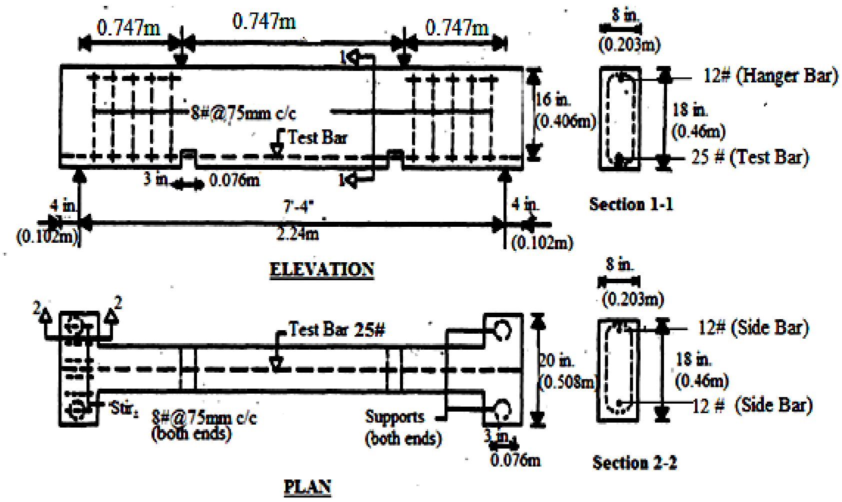


Fig. 2 Reinforcement details of NBS beam specimen (Paul 1978)

days of curing. Compressive strength of 34.44N/mm^2 was achieved at the end of 28days.

Before placing of concrete in beam moulds, one blue colour multi-strand copper wire of 4cm^2 cross sectional area was connected at one end of rebar, and soldered to reinforcement bar and also covered with M-seal to prevent corrosion at that area. This wire is protruded to the surface level to induce electric current. Similar steps were followed at the other end and one black colour, multi-strand copper wire of 2cm^2 cross sectional area was connected to reinforcement bar, which helps in the monitoring process of corrosion rate.

3.3 Accelerated corrosion technique

Electrochemical corrosion technique was used to accelerate the corrosion of steel bars embedded in beam specimens. Specimens were partially immersed in a 5% NaC1 solution for duration of 8 days; direction of current was arranged such that, rebars embedded inside the concrete specimens served as anode. The steel plate which was placed along the length of beam functions as cathode. Current required to achieve different corrosion levels can be obtained using Faraday's law (Eq. 3) (Ahmad 2009). The amount of current equal to 2.5A, 5A, 7.5A and 10A were applied to obtain the required degree of corrosion level i.e., 2.5%, 5%, 7.5%, and 10%. For each trial, three specimens were considered. A Schematic representation of corrosion test set-up used for accelerated corrosion process is shown in Fig. 3.

3.3.1 Calculation of amount of current required to obtain different corrosion levels

From Faraday's law

$$i_{corr} = \frac{(w_i - w_f)F}{\pi \times D \times L \times W \times T} \tag{1}$$

$$\rho = \frac{(w_i - w_f)}{w_i} \times 100 \tag{2}$$

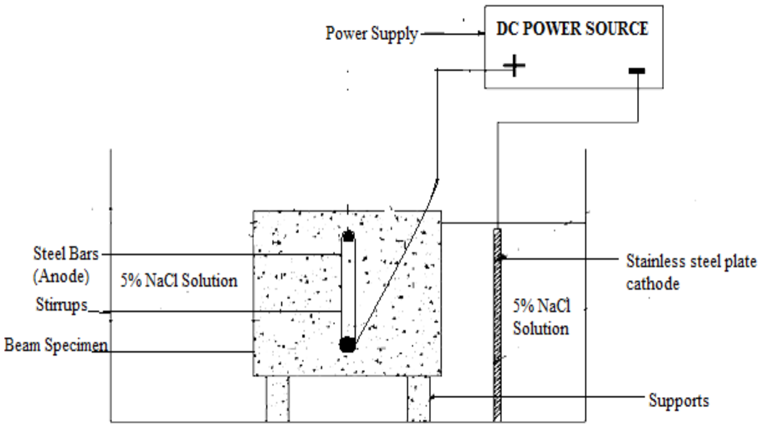


Fig. 3 Schematic representation of accelerated corrosion of beam specimen

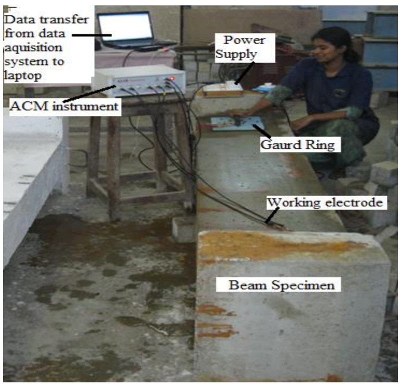


Fig. 4 Corrosion monitoring set up

Fig. 5 Corrosion monitoring instrument

$$i_{app} = i_{corr} = \frac{(\rho \times w_i \times F)}{100 \times \pi \times D \times L \times W \times T} \tag{3}$$

where; *ρ=degree of corrosion, T=time in seconds,* i_{corr}*=corrosion current density, Initial weight of steel* W_i*= 20,000g;* W_i*=final weight; F=96487 Amp-sec; W (equivalent weight of steel)= 27.925g,* i_{app}*=Applied Current*

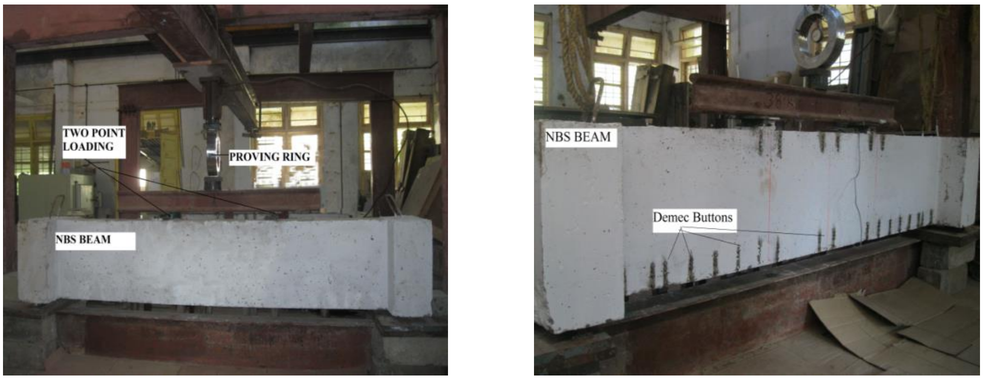
3.4 Corrosion rate measurements

After completion of accelerated corrosion, corrosion rate was monitored with applied corrosion monitoring instrument (Figs. 4-5) based on linear polarization resistance (LPR) method.

The corrosion current density was calculated by using the Stern-Geary formula.

$$i_{corr} = \frac{B}{R_p} \tag{4}$$

where, i_{corr} = corrosion current density (μA/cm^2); R_p = polarization resistance (kΩ cm^2); B= 26 mV



(a) (b)

Fig. 6 Test set up of NBS beam Specimen

(for steel in active condition this value is normally used).

Corrosion rate was calculated using the following equation given in ASTM G1 (Beaudoin *et al.* 2001, Pradahan and Bhattacharjee 2009)

$$Corrosion\ \ Rate\ (mm/year) = \frac{0.0327 \times a \times i_{corr}}{n \times D} \tag{5}$$

where; α=atomic weight of iron, i.e., 55.84 amu; n= no. of electrons exchanged in corrosion reaction, i.e., 2 for iron and D=density of rebar (7.85g/cm^3).

3.5 Test setup

The beam specimens were tested under two point loading condition (Fig. 6). Dial gauges were fixed at the top side as shown in Fig. 7 (two at load points and one at centre) to measure the deflection for each load increment.

Demec buttons were glued at a distance of 100mm c/c (Fig. 8) in the tension side surface of concrete at reinforcement level. Demec gauges were used to determine strain values between demec buttons (Fig. 9). Initial strain values were noted before application of load. The load was applied at15kN increments. Proving ring of 50 tonne capacity was used to note the applied load.

Maximum crack widths for different degrees of corrosion levels were measured. Crack width was assessed using Concrete Crack Microscope instrument, shown in Fig. 10. The least count of the crack microscope is 0.02 mm.

3.6 Determination of bond stress

For analysis purpose critical average strain values of two-point loading points (Right and Left) were taken. Since load distribution was at a distance of 747mm (Fig. 2). After obtaining the critical average strain values at tension side reinforcement level, the corresponding stress values were noted from stress strain curve of steel bar (Fig. 1). After obtaining the bar stress (f_s), and embedment length of 747mm from critical section (Fig. 2) and diameter of rebar 25mm for controlled beam and reduced diameter values for different degree of corrosion levels (2.5%, 5%, 7.5% and 10%) were used for the determination of bond stress values attained from Eq. (6).

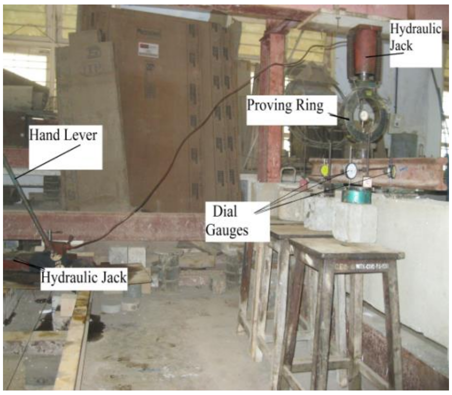


Fig. 7 Position of dial gauges

Fig. 8 Measurement of strain values using demec gauge

Fig. 9 Mechanical (Demec) strain gauge

Fig. 10 Concrete crack microscope

Table 4 Reduced bar diameter for different levels of corrosion

Corrosion level (%)	Bar diameter (mm)
0	25.00
2.5	24.69
5	24.37
7.5	24.04
10	23.72

$$\tau_{bd} = \frac{\phi \times f_s}{4 \times l_d} \tag{6}$$

where, τ_{bd}=Average bond stress (N/mm^2); fs=Bar stress (N/mm^2); l_d=Embedment length (747mm); ϕ=Diameter of rebar (mm)

Reduced bar diameter after induced corrosion level

Reduced diameter values are determined using Eq. (7) and are presented in Table 4.

$$\phi_1 = \phi\sqrt{(1-p)} \tag{7}$$

where; ϕ=*initial diameter* and ϕ_1=*reduced diameter*, ρ=weight loss in percetage

4. Results and discussion

4.1 Measurement of corrosion current density

The corrosion rate is measured in terms of corrosion current density, i_{corr}, and is a quantitative index, which represents an overall estimate of the corrosion attack on reinforcement. The i_{corr} is measured electrochemically.

Corrosion current densities were calculated for each specimen for different grids and average was considered to calculate the weight loss (%). Obtained corrosion levels (%) for applied current are shown in Fig. 11. Average values of corrosion current densities are given in Table 5.

From Fig. 11 obtained corrosion levels for the applied current (A) can be calculated as

$$y = 0.98x - 0.54 \quad R^2=0.998 \tag{8}$$

where; x=applied current (A) and y= obtained corrosion level (%)

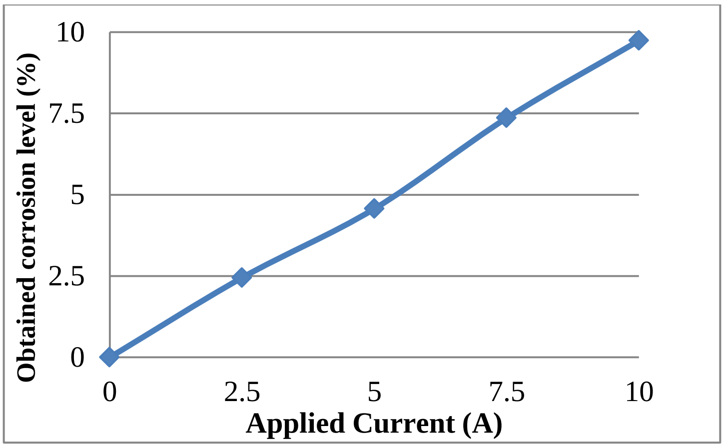
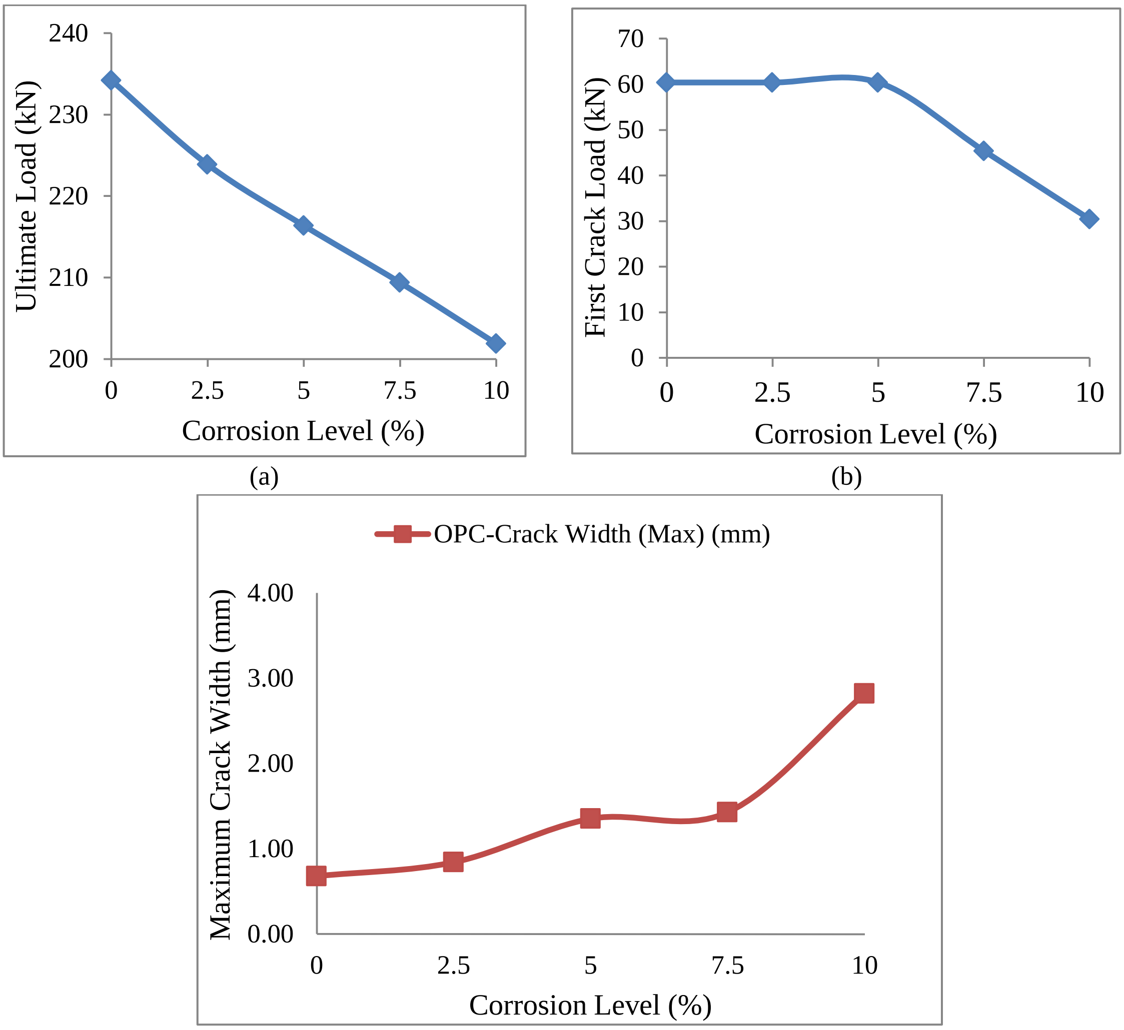


Fig. 11 Variation of Applied current with corrosion level

Table 5 Corrosion current density ($\mu A/cm^2$)

	Corrosion current density ($\mu A/cm^2$)					
Corrosion Level (%)	grid-1	grid-2	grid-3	grid-4	grid-5	Average
2.5	130.67	128.57	129.09	128.04	128.04	128.88
5	248.70	244.49	240.79	236.06	232.89	240.59
7.5	389.92	386.23	383.59	390.97	387.81	387.70
10	517.43	514.79	507.42	515.85	510.05	513.11



(c)

Fig. 12 Effect of different corrosion levels on (a) First Crack load (b) Ultimate load carrying capacity (c) Maximum crack width

4.2 Experimental investigation on load deflection behaviour of RC concrete

In the present study, 3 control specimens and 12 corroded specimens (3 sets each for 2.5%, 5%, 7.5% and 10% of corrosion) were tested using two-point loading to determine the flexural bond stress capacity.

4.3 Ultimate load carrying capacity and crack width of NBS beams

Results of ultimate load, maximum crack width and first crack load are shown in Fig. 12. As the degree of corrosion level increases load carrying capacity decreases (Fig. 12(a)). From Fig.

12(a) it is observed that for every percentage increase in corrosion level there is about 1.6% decrease in load carrying capacity. As the degree of corrosion level increases first crack load decreases for 7.5% and 10% corrosion level (Fig. 12(b)).

From Fig. 12(c) it is observed that difference in crack width with corrosion level is small in the initial stages. After 7.5% corrosion level, crack width increases in its size.

4.4 Load deflection behaviour of NBS beam

As degree of corrosion level increases deflection also increases. This may be due to change in material property of corroded reinforcement. Load deflection behavior is given in Fig. 13.

4.5 Load strain behavior of NBS beam

From Fig. 14 it is seen that as the corrosion level increases strain value increases linearly in the initial stage. Then at higher corrosion levels, rate of increase of strain is higher for the same increment of load level compared to lower levels of corrosion. Controlled beam specimen performs better at increased corrosion levels. Present investigation is to study bond characteristic which is dependent on characteristics of steel at interface and not in the body of reinforcement. From the stress strain curves it is clear that the sudden increase in strain levels without increase in stress is indicative of slip characteristics owing to drop in bond. Higher the accelerated corrosion at surface lower is the stress level at which such slip occurs and is consistent with infusive judgment.

4.6 Bar force and bond stress performance of NBS beam

From Table 7 it is observed that as the corrosion level increases bond stress value decreases.

Percentage reduction in bond stress for different levels of corrosion i.e. 2.5%, 5%, 7.5% and

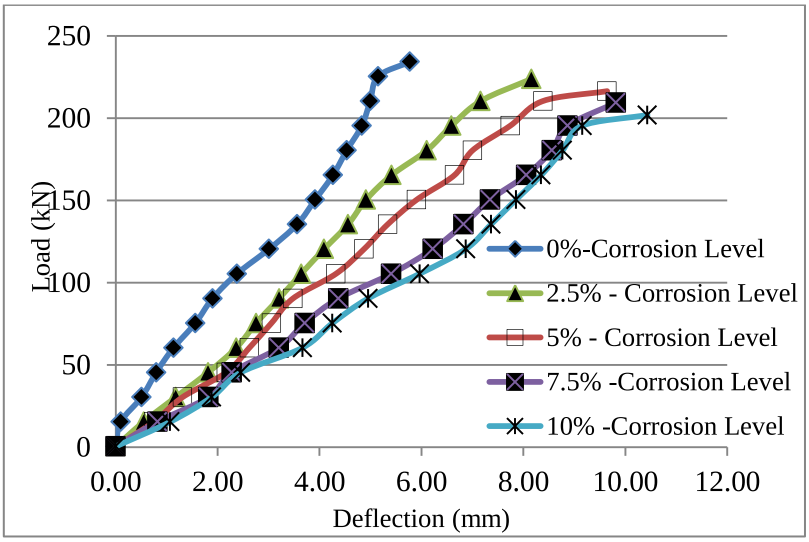
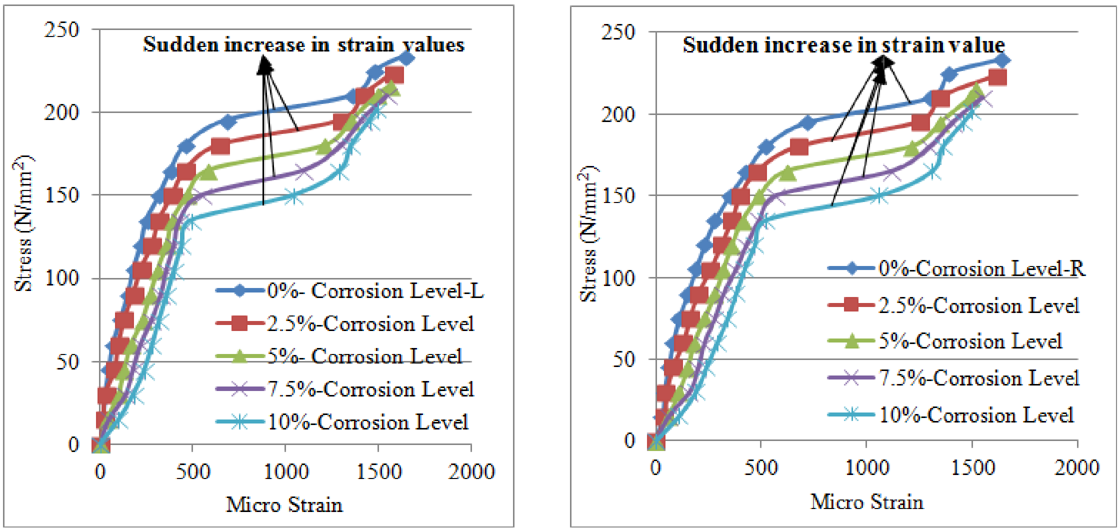


Fig. 13 Effect of corrosion on central deflection behavior of OPC concrete



(a) at left side loading point (b) at right side loading point

Fig. 14 Effect of corrosion on stress strain behavior

Table 7 Bar force, reduced diameter and bond stress performance for different degree of corrosion in NBS beam

Bar force and Bond Stress values at slip region in strain values								
	Initial strain values				Final strain values			
Corrosion Level (%)	Micro Strain	f_s -Stress in bar (N/mm^2)	Reduced Diameter (mm)	Bond Stress (N/mm^2)	Micro Strain	f_S-Stress in bar (N/mm^2)	Reduced Diameter (mm)	Bond Stress (N/mm^2)
0	700	199.21	25.00	1.67	1330	367.96	25.00	3.08
2.5	660	188.85	24.69	1.56	1275	353.58	24.69	2.92
5	600	177.59	24.37	1.45	1210	337.08	24.37	2.75
7.5	560	163.25	24.04	1.31	1110	310.00	24.04	2.49
10	505	148.13	23.72	1.18	1050	293.93	23.72	2.33

10% with respect to controlled specimen were 6.59%, 13.17%, 21.56% and 29.34% respectively.

From Fig. 15 it is observed that slope approximately drops for about 2.64% and 2.1% for initial and final bond stress values for every percentage increase in corrosion level.

Bond stress values for different degree of corrosion can be calculated from following equations obtained from Fig. 15, where x=corrosion levels (%) and y= bond stress (N/mm^2)

For even region at initial strain values

$$y = -0.049x + 1.678 \qquad R^2 = 0.996 \tag{9}$$

For even region at final strain values

$$y = -0.076x + 3.099 \qquad R^2 = 0.992 \tag{10}$$

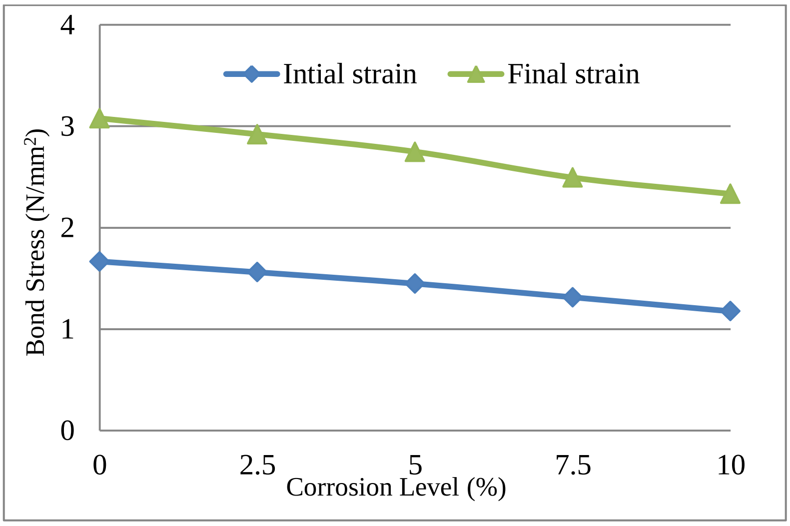


Fig. 15 Effect of variation of different degree of corrosion on bond stress at slip region strain values

5. Conclusions

• For every percentage increase in corrosion level, there is about 1.6% decrease in load carrying capacity.

• The effect of reinforcement corrosion in crack width is small at small level of corrosion. Above 7.5% corrosion level crack width rapidly increases in its size.

• For increasing corrosion level, strain values increase in the initial stages. Then at higher corrosion levels rate of increase of strain is higher for the same increment of load level, compared to the lower levels of corrosion.

• As the corrosion level increases, value of bond stress decreases. Percentage reduction in bond stress for different levels of corrosion i.e., 2.5%, 5%, 7.5% and 10% with respect to controlled specimen were 6.59%, 13.17%, 21.56% and 29.34% respectively.

• Effect of corrosion in RC member affects on reduction in cross sectional areas, bond stress and load carrying capacity as well as crack width. Hence, present research enhances its significance in assessment and better understanding of RC structures exposed to corrosive environment.

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