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Experimental investigation on effect of corrosion on curvature-ductility relationship of RCC member in flexure

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Abstract. Corrosion of reinforcement in concrete is the biggest concern when it comes to durability of concrete structure. It is not only detrimental to the health of the structure but also has economic implications with regard to the money and energy required for repair of concrete elements deteriorated by corrosion of steel. This study is dedicated to understand the effect of corrosion in concrete induced by chloride ingress using an accelerated technique involving the application of external voltage to laboratory cast RC beam specimens. All the specimens used in this study were cast in laboratory using M20 grade concrete using OPC (Ordinary Portland Cement). The diffusion coefficient of chloride ions into concrete was estimated using NT Build 492 test. Finally, the effect of corrosion on ductility, moment-curvature relationship and reduction in flexural strength of beams was measured using a two-point load flexural test. Reduction in strength and ductility was observed as the corrosion level increased.

Key words: Reinforced Concrete flexural member, accelerated chloride induced corrosion, corrosion level, moment-curvature relationship

1. Introduction

Cement is second most used material on Earth only next to water. Large portion of cement is used in RC which is used in infrastructure development of any nation. A good quality and durable construction is important not only for health of the structure and safety of people, but also in a greater sense for economic development of any nation. Achieving the desired durability in concrete is as important as achieving the desired strength. For many decades, the main focus of concrete design for any structure has been strength and workability; therefore, there is ample evidence of impulsive deterioration of recently built structures (Ahmad, 2003; Arora and Singh, 2016, Arora at al., 2016, 2019).

As per American Concrete report (ACI 201.2R-08, 2008) concrete durability can be defined as capability of concrete to resist, chemical attack, abrasion, weathering action or any other process of deterioration. Concrete is said to be durable if it can sustain its original form, quality as well as serviceability upon exposure to environment. RC chiefly consists of cement, aggregates and reinforcement mostly in form of steel bars (. Deterioration of concrete begins immediately after casting and is affected by a variety of internal and external factors which cause damage to either constituent, viz. hydrated cement paste, aggregates or reinforcement bars, by physical and/or chemical mechanisms. However, the biggest hurdle in achieving desired durability is due to deterioration of steel by means of corrosion. The reinforcement corrosion is a problem of serious concern. Significant proportion of a developed nation's GDP (Gross Domestic Product) is used for repair of corrosion related deterioration (Bhaskaran et al., 2014).

Concrete act as the environment for steel in Reinforced Concrete (RC) structure. Concrete provide alkaline medium to reinforcement owing to the presence of calcium hydroxide, a product of hydration of cement. In the range of pH of 12-13, a protective layer forms on the surface of rebar and prevents iron atoms from dissolving. Presence of oxygen, water, stray electric currents, foreign substances like chloride ion, acidic gas such as CO_2 etc. decreases the alkaline nature of concrete and break the passive layer of corrosion (Emmons, 1993). Corrosion causes deterioration in two ways. The products of corrosion occupy larger volume than the existing volume of steel. This reduces the operative area of reinforcement and causes tensile stresses in the concrete and reduction in structural capacity, cracking and cover spalling and delamination (Bossio et al., 2019).

Corrosion has potential to collapse the structure. (Webster and Clark, 2016; Ahmad, 2003; Bossio et al., 2019) studied the effect of corrosion on different diameter of rebar. The residual strength of flexure member was estimated at different level of corrosion and concluded that at 30% level of corrosion, flexure member lost its complete strength. (Cabrera and Ghoddoussi, 1992) Studied the impact of corrosion on flexure behavior RCC member and reported that bond strength reduced at 9% corrosion level and also showed that deflection also increase due to increase in corrosion level. Campione et al., (2016) studied the effect of corrosion on the flexure and shear strength and failure mode.

In the seismic design of RC beams of structures, the potential plastic hinge regions need to be carefully detailed for ductility in order to ensure that the shaking from large earthquakes will not cause collapse. Adequate ductility of members of RC frames is also necessary to ensure that moment redistribution can occur. Although adequate flexural ductility is essential for structures in high seismicity regions, many serious problems relating to the behavior of RC structures under severe seismic action can be traced due to the poor detailing of RC (Olivia 2005). Olivia et.al. (2005) concluded that the ductility of flexural element also has been reduced with increasing the corrosion level. The ductility of RC flexural members depends upon a number of factors, including percentage of tensile reinforcement, percentage of compressive reinforcement, percentage of lateral reinforcement and strength of concrete. Investigation regarding ductility of flexural members utilizing these factors has been explored in number of studies.

To investigate the influence of the corrosion level on the beam ductility, an experimental program is conducted. The corrosion was induced using accelerated chloride induced corrosion technique and applied 30v DC (Direct Current) voltage. In this study the effect of corrosion on moment-curvature relationship and curvature ductility of flexure member was investigated to understand the failure mechanisms under seismic conditions where, higher ductility demands are placed on RC members.

Kashani et al., (2019) provided a comprehensive review of the experimental studies on the corrosion-damaged RC components and the residual flexural strength prediction capacity of the existing numerical model. Cross-sectional moment-curvature evaluations utilising cutting-edge corrosion damage models revealed a strong correlation between anticipated residual flexural capacity and experimental data.

Moment-curvature relationship characterizes the nonlinear behavior of critical section of RC beam. Moment-curvature relationship also represents the rotation or ductility capacity of flexure member. Moment-curvature diagram of flexure RCC member has been divided into three states as shown in 1 Moment-curvature relationship of RC as shown in Figure 1 (Baji and Ronagh, 2011).

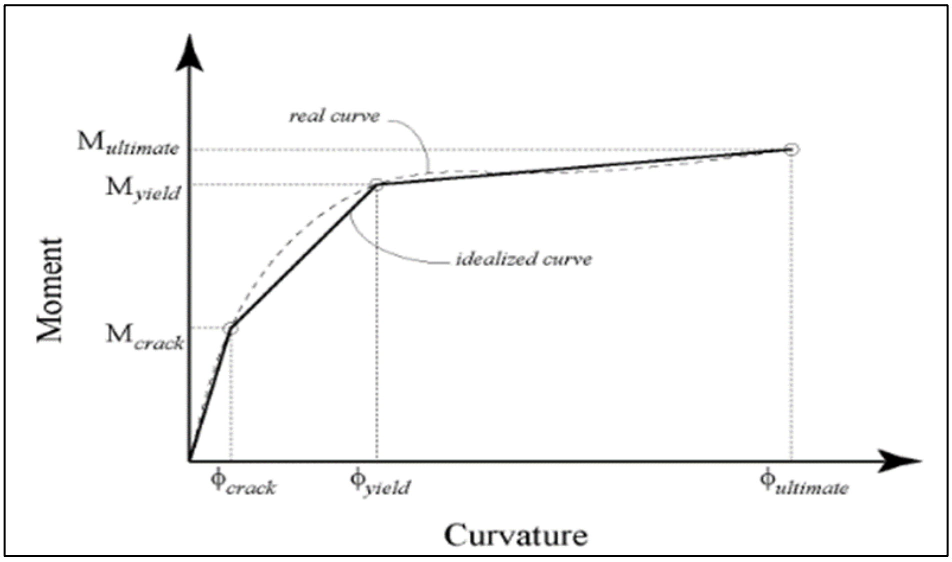

Fig. 1. Moment-curvature relationship of RC beam (Baji and Ronagh, 2011)

Moment of beam at critical section (at mid span of beam) is calculated from load using equation (1) at each time step during flexure test. At the same time the strain profile is also noted with the help of strain gauge using data logger. Curvature is calculated from equation (2)

$$M=(P*L)/6 \qquad (1)$$

$$\Phi=\varepsilon_C/X \qquad (2)$$

In the given equations, M is the Moment at mid span, P represents the Applied load, L is the Effective span of the beam, ε_C is the Compressive strain, Φ represents the Curvature and X is the Neutral axis depth.

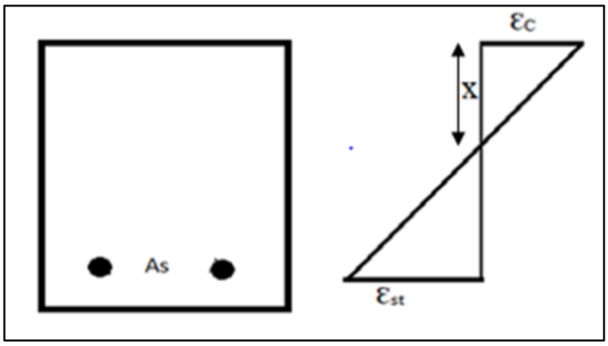

Fig. 2. Cross section of beam and strain profile of critical section

From moment-curvature relationship of the beams the yield curvature (Φ_Y) and ultimate curvature (Φ_U) were found with respect to yield moment and ultimate moment respectively. The ratio of ultimate curvature (Φ_U) to yield curvature (Φ_Y) is called ductility coefficient (μ) which characterizes the plastic region length and rotation capacity of the beam.

$$\mu=\Phi_u/\Phi_y \qquad (3)$$

In equation (3) μ is the Ductility coefficient, Φ_U is the Ultimate curvature and Φ_Y is Yield curvature.

2. Experimental program

A total of 19 specimens of varying dimensions has been used for performing various tests in the study. The specimen sets consisted of three 150 mm cubes for compressive strength estimation. Three cylinders of 150 mm diameter and 300 mm height were used for capturing the stress strain behavior of the hardened concrete. One cylinder of 100 mm dia. and 200 mm height was used for evaluating the diffusion coefficient of chloride. And 12 RC beams of size 150x150x700 mm were cast for flexure testing at different level of corrosion. As tension reinforcement, two 8 mm bars were used. The RC beams were designed as per IS :456 (2000) as shown in figure 3. Minimum reinforcement in compression zone was also provided to support the stirrups, and its contribution is resisting bending moment was neglected. The beam is designed with M20 grade concrete and as shown in the figure 3 the cross-sectional height and width of the beam was 150 mm. The section view of the beam shows the reinforcement used in the beam. All the reinforcement shown are 8 mm in diameter.

All the specimens were cast in single go to avoid influence of factors such as casting conditions, batch and age of cement, workmanship, quality control. Also, the specimens were cured for 28 days by keeping in water. The RC beams, cubes and cylinders were casted in laboratory and placed in moist curing room at 20°C and 95±5% relative humidity for 24 hours. The specimens demolded after 24 hour and placed in water curing tank for next 27 days. The cubes, cylinder and control beams (three) were tested at 28 days after removing from curing tank. The remaining beams (nine) are tested after inducing corrosion, these beams combination three of were placed into chloride solution for 24, 48 and 72 hours exposure period to induce different level of corrosion. The corrosion rate was measured for each exposure period and the level of induced corrosion was measured by equation (5). The duration of exposure period for beams is given in table 2.

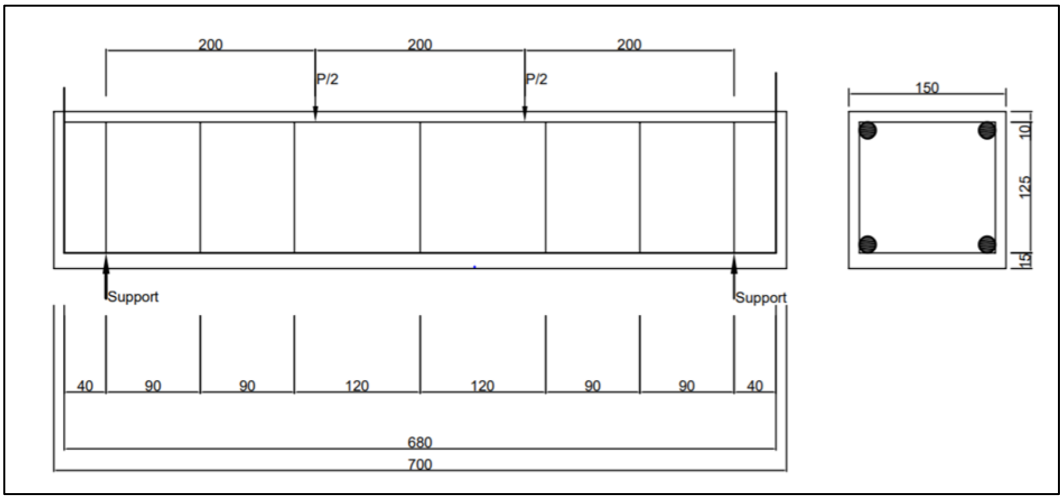

Fig. 3. Beam specimen details (All dimension in mm)

2.1. Concrete mix design

The M20 grade of concrete were used to cast the beams. The mix proportion of concrete was given in table 1.

Table 1. Concrete mix proportion

Sr no	w/c ratio	Mix Constituents		
		Cement (OPC) (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
1	0.60	300	721.24	1235.29

For the design of beam as per IS: 456 (2000) the characteristic strength of concrete was taken as 20 MPa, which represents the grade of concrete as M20.

2.2. NT Build 492

Diffusion coefficient or diffusivity, can be described as, the quantity of molecule of one substance that can diffuse into another substance through their unit contact surface area in unit time. In this case chloride ions are diffused into concrete by means of DC voltage. The rate of diffusion, which in turn depends on numerous factors like type of cement, w/c ratio, grade of concrete etc. is characterized by diffusion coefficient. For this study, the diffusion coefficient was found as per procedure given in NT Build 492 (1999) and it can be used to characterize the behavior of concrete against the chloride ion penetration.

The 100 mm diameter and 200 mm height cylinder was cut into three equal heighted 50 mm diameter specimen of height 50 mm each, and test was performed on each of these specimens. The non-steady diffusion coefficient is reported to be the average value of three specimens

2.3. Accelerated Chloride Induced Corrosion Test

In practice, the corrosion of steel rebar in concrete is very slow process and takes years and can be due to different agents such as chloride in case of chloride induced corrosion and carbon dioxide in case of carbonation corrosion (Belda et.al. 2018). In both the cases, the alkalinity of the concrete is reduced thus leading to corrosion (Ahmad, 2009).

For the purpose of study, accelerated corrosion chloride induced corrosion techniques was used as shown in figure 4. An external voltage is applied to penetrate chloride ion from electrolyte solution in which the cast specimens are kept immersed. Since corrosion is an electrolytic process, the steel reinforcement acts as anode electrode and stainless-steel plate, placed beneath the beam, as cathode electrode.

Fig. 4. Accelerated chloride induced corrosion setup

The beam and stainless-steel plate were placed into 16.5% NaCl solution and DC voltage of 30V was applied on the electrodes. NaCl solution acts as electrolyte which accelerates the corrosion process by breaking the passive layer of reinforcement. The beams were placed for certain duration period to induce different level of corrosion as shown in Table 2. The beams were designated based on exposure duration. Figure 5 shows the corroded beams after the test.

Table 2. Exposure duration of beams

No of beams	Sample Id	Duration (Hour)
3	CO	-
3	E1	24
3	E2	48
3	E3	72

Fig. 5. Corroded beam

2.4. Corrosion rate and corrosion level measurements

The rate of induced corrosion can be used to estimate the level of corrosion. The linear polarization resistance (LPR) technique was used to determine the rate of corrosion, which measures the corrosion current density (ICORR) as per ASTM G59 (2009) (Figure 6). The following equations were used to calculate the level of corrosion. (Andrade et al. 2004).

$$I_{corr} = \frac{\beta_a * \beta_c}{2.303 * R_P * (\beta_a + \beta_c)} \tag{4}$$

$$C_r = 11.56 * I_{corr} \left(\frac{m}{year}\right) \tag{5}$$

$$Corrosion\ level(\%\ reduction\ in\ dia\ of\ rebar) = \frac{2 * C_r * T}{D} * 100 \tag{6}$$

Here, $R_p$is Polarization resistance(Ohm), I_{corr} is Corrosion current density($\mu A/cm^2$), β_a & β_c represents Tafel's constants, C_r denotes Rate of corrosion(mm/Year), T is the Exposure period of beam(Year), and D is the Diameter of Rebar(mm).

Fig. 6. Current density measurement

2.5. Flexure Testing of Beams

Two-point load test was performed to estimate the flexural capacity of the RC beams (IS :516, 2021). The testing plan given in Table 3 Flexure testing plan. Three control beams were tested(C0) at 28 days after water curing. The remaining nine beams E1, E2 and E3 were tested in combination of three at three exposure regimes i.e. 24,48 and 72 hours in NaCl solutions. The specimens were tested after inducing corrosion to find out the effect of corrosion level on flexure performance of beams. Two strain gauges were installed at mid span of beam to record the strain at different time step of loading. The locations of strain gauges along the depth were, parallel to tensile reinforcement, along neutral axis depth and along compression reinforcement. The linear variable differential transferor (LVDT) device was also installed at mid-section of beam to measure the central deflection of beam (Arora et.al. 2018).

The flexure test was performed as displacement control mode at minimum rate of loading 0.01 mm/sec to examine the behavior of beam. The minimum rate of loading was applied to avoid the early damage of strain gauges and slow rate of loading gives more data points which helps better examination of the flexure behavior.

3. Results and discussion

3.1. Stress-Strain Behaviour of Concrete

The stress-strain curve of concrete was made to characterize the behavior of concrete in compression zone, throughout flexure testing (Singh et.al 2018). Three number of concrete cubes of size, 150 mm side, were used to determine the stress strain curve of concrete. The maximum compressive strain of concrete was found 0.003711 and corresponding stress in concrete was found to be 22.7 MPa.

3.2. Diffusion Coefficient of Chloride Ion

In general range chloride diffusivity found in the range of 6.4*10-12 m^2/s – 12.4*10-12 m^2/s for concrete exposed to seawater (Erdogdu et al., 2004). In this study, the diffusion coefficient (D) was found to be 8.87 *10-12 m^2/s. This value is relatively higher diffusivity of chloride ion into concrete.

3.3. Corrosion level measurement

This may be attributed to relatively higher w/c ratio i.e. 0.6 and OPC as binder. The higher value of diffusion coefficient helped accelerate chloride induction for testing purpose but is not suitable for real concrete. The corrosion rate was measured using linear polarization resistance technique. The corrosion current density was calculated using Stern Geary equation by measuring the polarization resistance and Tafel's constant. In order to acquire uniformity in the test, influencing parameter in test like applied voltage, electrolyte solution (16.5 % NaCl solution), cover depth, diameter of rebar (i.e. grade of the rebar and diameter of rebar) and grade of concrete remains the same for each beam. The average corrosion current density of three beams for each exposure condition was estimated using equation (5). The average level of corrosion of three beams was estimated using equation (6) for each exposure condition. The average results of corrosion current density and level of corrosion was given in Table 3. The average level of corrosion in the terms of % reduction in diameter was induced 2.27%, 4.93% and 9.24% for exposure regimes i.e. 24, 48- and 72-hours exposure period respectively.

The corrosion level characterizes the loss in the diameter with respect to 8 mm diameter of rebars. The corrosion rates represent the penetration of depth in per unit time. The total penetration represents the loss in diameter of rebar which is determined using equation (5).

Table 3. Duration, current intensity and corrosion level for different beams

No of beams	Sample ID	Average Corrosion current density (I_{CORR} in mA/cm^2)	Corrosion rate (m/year)	Duration (Hour)	Corrosion level (based on reduction in diameter of rebar)
3	C0	-	-	-	0%
3	E1	2.87	0.033	24	2.27%
3	E2	3.12	0.036	48	4.93%
3	E3	3.89	0.045	72	9.24%

3.4. Flexural strength of beams

The flexure strength is maximum load that can be sustained by beam before failure in bending. Two-point load test was used, in which two equal points loads were applied gradually at one third length of the beam so that the middle third portion of beam is subjected to pure bending (Arora et.al. 2016, Arora et.al. 2018) as shown in figure (7). The adopted testing plan is given in table 4. The ultimate flexure load and corresponding maximum deflection at mid span are shown in Table 5 Flexure test results.

It can be observed that average ultimate failure load and corresponding deflection of control beams and 2.27% corroded beams (E1) is comparable. However, significant reduction is failure load and maximum deflection is seen when corrosion level is increased beyond 2.27%. It is also observed that, the relation between corrosion level and ultimate failure load was found non-linear. Increase of the degree of corrosion leads to beam moment capacity reduction. This reduction can be more attributed to the reduction of area of reinforcements than the decline in the bond due to the change in the surface characteristics of bars.

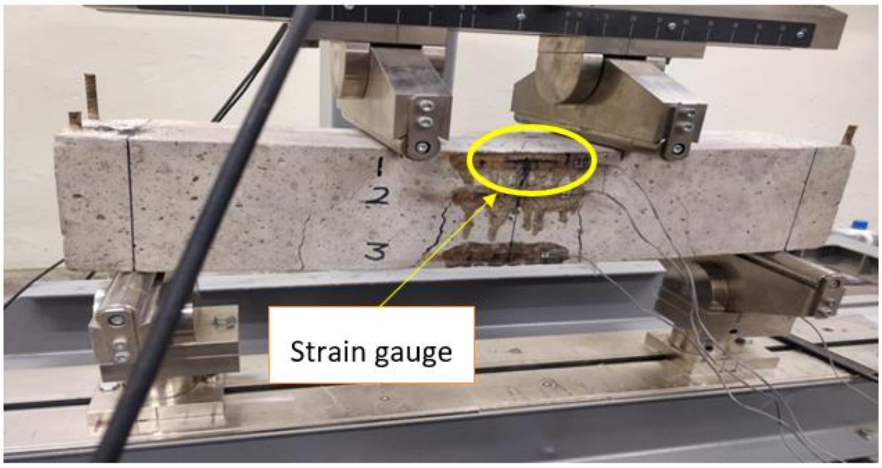

Fig. 7. Flexure testing of beam

Table 4. Flexure testing plan

No. of beams	Sample ID	Exposure period (Hours)	Level of corrosion (%)	Remarks
3	C0	-	0	Three beams are tested at zero corrosion level as control specimen after 28 days curing
3	E1	24	2.27	These beams were placed for 28-day water curing, then placed for accelerated induced corrosion and after measurement of corrosion level, flexure tests were performed.
3	E2	48	4.93	
3	E3	72	9.24	

Table 5. Flexure Test Results

S. No.	Sample ID	Corrosion level (%)	Ultimate flexure strength (KN)	Average value of flexure load (KN)	Maximum deflection (mm)	Average of maximum deflection (mm)
1	C0	0	88.48	85.30	15.13	14.98
			83.26		14.63	
			84.18		15.19	
2	E1	2.27	84.06	81.01	14.28	13.68
			78.26		13.35	
			80.72		13.42	
3	E2	4.93	76.42	73.94	12.91	12.14
			71.56		11.14	
			73.84		12.37	
4	E3	9.24	63.45	61.44	10.82	10.48
			59.23		10.24	
			61.65		10.36	

3.5. Moment-curvature of Beams

The maximum bending moment at middle third span at each load increment was calculated using equation (1) and the curvature at mid-span was calculated using equation (2). The moment-curvature relationship was found by mapping the strain profile of mid-section beam and shown in Figure 8 Moment-curvature relationship at different level of corrosion.

Corrosion reduced the cross section of rebar which lead to reduction in cross section area of the rebars, which in turn reduced the flexural performance of the RC beam. It was observed that as the level of corrosion increased the ultimate moment taking capacity of beams decreased. The yield moment when there is no corrosion and 2.27% is comparable. However, notable reduction in yield moment of beam corroded by 4.93% and 9.24% was observed with respect to control beam. Curvature also significantly reduced as the level of corrosion increased with respect to the control beam. The reduction in curvature will be caused in reduction of the rotation capacity and ductility of the beam.

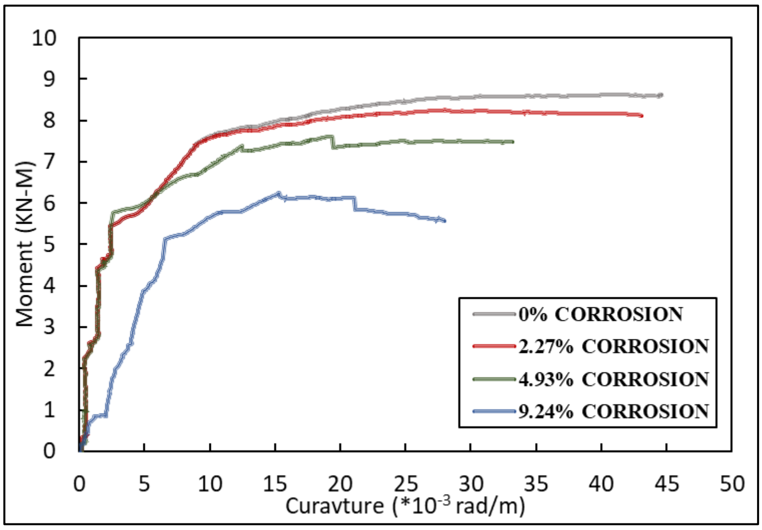

Fig. 8. Moment-curvature relationship at different level of corrosion

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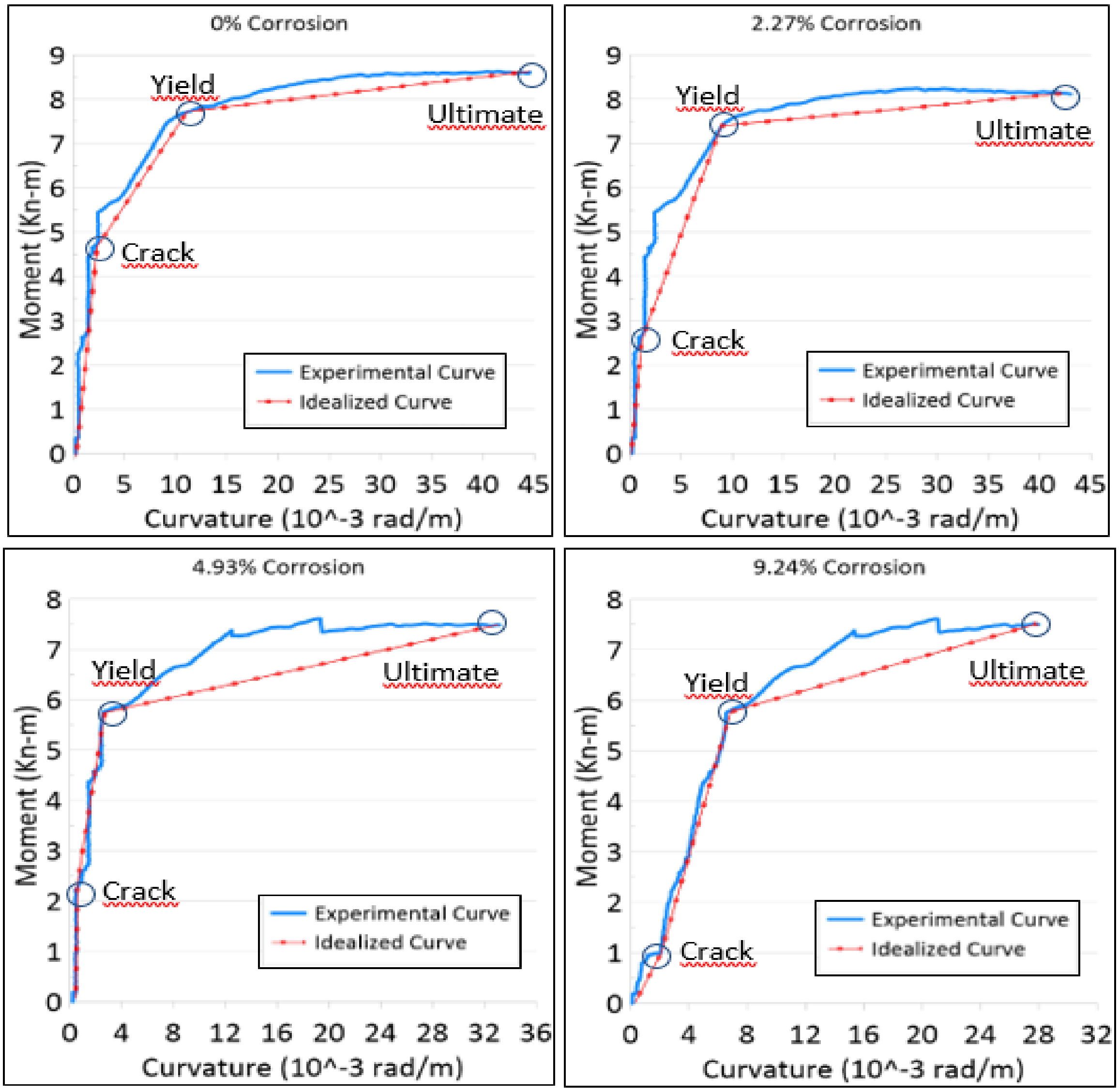

Fig. 9. Experimental and Idealized curves obtained for different levels of corrosion of reinforcement

Figure 9 shows individual Moment curvature curves for the tested beams. For each of the experimentally obtained curves an idealized curve is drawn. Based on sudden change in the slope. Idealized curve is divided into three points, marked by the points named as, crack, yield and ultimate. Table 6 shows the values of Moment and curvature at three demarcated points on the idealized curve.

Reduction in ultimate deflection signifies loss in ductility of the corroded beams and the failure of the corroded beams indicates transfer from ductile failure mode with a large mid-span deflection to a brittle failure mode with only a few limited deflections gradually (Peng et al.,, 2019; Yuksel and Sakcalı, 2022). Thus, it can be said that, corrosion of rebars is likely to make the real structures brittle and may cause sudden failure, which can be even more detrimental.

Table 6 Moment (Kn-m)-curvature (10^-3 * rad/m) relationship at different level of corrosion

Points	0% Corrosion		2.27% Corrosion		4.93% Corrosion		9.24% Corrosion	
	Moment	Curvature	Moment	Curvature	Moment	Curvature	Moment	Curvature
Crack	4.3	1.45	2.67	1.2	2.11	0.48	0.84	2.07
Yield	7.50	9.3	7.40	4.0	5.78	2.75	5.13	6.57
Ultimate	8.6	44.48	8.11	43.0	7.48	33.19	5.57	27.99

3.6. Ductility coefficient

From moment-curvature relationship of the beams the yield curvature(Φ_Y) and ultimate curvature(Φ_U) calculated corresponds to yield moment and ultimate moment respectively. The ratio of ultimate curvature(Φ_U) to yield curvature (Φ_Y) is called ductility coefficient(μ) which characterizes the plastic region length and rotation capacity of the beam.

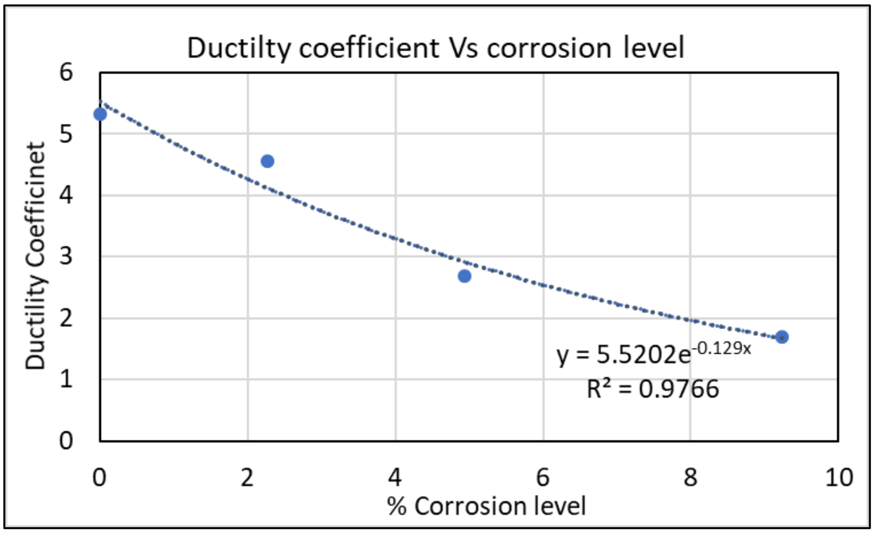

Fig. 10. Ductility coefficient Vs corrosion level (%) relationship curve

The relationship between ductility coefficient of RC flexural member and corrosion level (%), using curve fitting method is found to be

$$y = 5.5202e^{-0.129x} \tag{6}$$

This result of the ductility coefficient of the control beam obtained in our study was found to be in line with the (Rao et al., 2017; Kwan et al., 2002). The section ductility of RC beams exponential reduced with increased in corrosion level in the tensile reinforcement. For severe corrosion cases, reductions in moment and curvature capacities lead to shifting in the structural behaviour of the load-bearing members from ductile to brittle as suggested by past researchers (Yuksel and Sakcalı, 2022).

4. Conclusions

Impact of corrosion on curvature ductility RC beams which was designed as per IS: 456 (2000) code was subject of this study and significant effect of corrosion on the flexure behavior of RC beam was observed. Corrosion to a certain level (2.27%) does not cause any significant reduction in load carrying capacity of RC members. However, with further increase in the corrosion level, the load carrying capacity reduced upto 28 % at the 9.24 % corrosion level. The curvature ductility exponentially decreased with increased in the corrosion level. The lower curvature ductility leads to brittle failure of the flexure member, which is not desirable for seismic performance of any structural element. Curvature ductility coefficient of beam corroded at 9.24% corrosion level obtained 5 times lower as compare to control RC beam. Reduction in ultimate deflection signifies loss in ductility of the corroded beams and the failure of the corroded beams indicates transfer from ductile failure mode with a large mid-span deflection to a brittle failure mode with only a few limited deflections gradually. Thus, it can be said that, corrosion of rebars is likely to make the real structures brittle and may cause sudden failure, which can be even more detrimental.

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