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# Nonlinear Finite Element Analysis of Corroded Reinforced Concrete Beams

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**Abstract**

Corrosion in reinforcing bars is a major cause of concern for sustainability of Reinforced Concrete (RC) structures exposed to extreme environmental conditions. Various RC structures, such as bridges and buildings are adversely affected due to the rebar corrosion, reducing its global load carrying capacity and ductility. In order to ensure an earthquake resistant design of any structure, the ductility of structural members is of chief concern. However, corrosion of reinforcing steel in RC members reduces its seismic performance. Thus, for safety and economic viability of any RC structure, an effective maintenance and repair work strategy is necessary. Based on the strong column - weak beam design concept of RC frames, the beams are the first structural members to absorb damage due to earthquake. Thus, to carry out maintenance and repair work, structural health assessment of RC beams considering the effect of reinforcement corrosion is of utmost importance. The present study aims at establishing a relation between the amount of corrosion induced and its effect on the ductility of an RC beam. A 3D Finite Element (FE) model of an RC beam including the effects of corrosion for nonlinear performance assessment has been modelled in ABAQUS. The FE model is validated with past experimental study including the effects of corrosion. Modelling of uniform corrosion in reinforcement bars involves defining the loss of bond between rebars and concrete, inducing spalling stresses on concrete and reduction in the cross-section area of the rebars. Bond-slip model between surface of concrete and reinforcement has been incorporated through cohesive surface. Spalling stress for uniform corrosion is applied in form of outward uniform pressure on the reinforcement and concrete interface. The cracking of cover concrete due to corrosion along with the flexural cracking in concrete due to incremental loading are implemented together in the present study. A comprehensive FE model is developed in order to obtain correct assessment of corroded beams. As observed from the FE model, the failure mechanism of the considered corroded RC beam is observed to be mostly shear failure as the corrosion level increases. Concrete crushing at the center of the RC beam is identified at the failure point of the beam due to corrosion induced damage. Evolution of displacement ductility index with respect to corrosion is determined for an RC beam based on the numerical study. It has been observed that the displacement ductility index of the beam is reduced significantly after considering a corrosion level of about 12%. Hence, the present study is an effort to establish a relation between structural performance of RC beams and level of reinforcement corrosion, which will be useful in proactive maintenance and repair work for corroded RC beams.

*Keywords*: *Numerical analysis, Corroded beams, bond – slip behaviour, spalling stresses, displacement ductility index.*

## 1. Introduction

Reinforced Concrete (RC) is a material which has been used extensively for construction of important infrastructure projects i.e. bridges, buildings etc. Exposure of RC structures to adverse environmental conditions like marine environment, dicing slat, carbon dioxide and chloride ions increase the rate of corrosion in reinforcement. As a result, durability of structure elements is substantially reduced by bond strength degradation, loss of concrete integrity and loss of cross-sectional area of steel. Reinforcement corrosion alter the failure mechanism of an RC beam from flexural to shear failure. The cost of maintenance and repair work of existing infrastructure is nearly same as construction of new infrastructure[1]. In order to adopt a cost-efficient maintenance and repair work policy, damage due to rebar corrosion is necessary to study systematically. Various experimental studies related to rebar corrosion have done to evaluate the residual strength of corroded beams[2], [3] and to quantify the damage due to reinforcement corrosion [4], [5]. Experimental studies of rebar corrosion are reliable to observe overall effect of corrosion.

However, comprehensive study of damage mechanism and parametric variation of corroded beams can be possible through a detail Finite Element (FE) model. Several past studies [6]–[8] proposed different techniques to include corrosion effects in a FE model of corroded RC beam. Most studies have included bond strength degradation and loss of steel cross section in a 2D Finite Element model. Few studies have included the effect of spalling stress by reducing compressive strength of concrete in a Finite Element model for simplicity [7]. Limited efforts have been put towards prediction of the failure point of corroded beams with FE analysis. Evolution of failure point with

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increase of corrosion level is an important relation in order to calculate reduction in ductility of corroded RC beam. An RC frame structure should be designed as per strong column and weak beam methodology. Essentially beams are useful to tie all columns together to resist earthquake force effectively. RC beams are the first structural members to absorb the damage due to earthquake. Whereas in long span bridges, bridge deck experience 20%-30% higher moments due to vertical component of earthquake vibrations[9]. Hence seismic performance of corroded RC beam is a crucial aspect to study, in order to avoid premature failure and heavy cost of maintenance and repair work.

In the present study, a comprehensive 3D Finite Element model of uniformly corroded RC beam is developed in ABAQUS software. Results of FE analysis are validated with experimental results of Lee *et al.,*[3]. Spalling stress due to rebar corrosion is successfully implemented along with bending stress on the RC beam. Evolution in failure mechanism of the RC beam with increase of corrosion level is obtained and verified with past studies. Seismic performance of corroded beam is obtained by ductility index values of the beam at various corrosion level.

## 2. Corrosion induced damage

Corrosion is an environmental process on steel reinforcement which deteriorate RC structures over long period of time. In presence of water, oxygen and chloride ions, ferrous ion ($Fe^{2+}$) is oxidized to form corrosion products on surface of reinforcement. Formation of corrosion products on surface of reinforcement eventually deteriorate bond between reinforcement and concrete. Corrosion products consist of higher volume than same amount of steel material. It induces spalling stresses on concrete which is responsible for concrete cracking and delamination of concrete cover. Loss of cross sectional area of steel due to corrosion is directly reduce load carrying capacity of an RC beam. Hence, the corrosion induced damage mainly progresses in form of 1) bond strength degradation 2) loss of concrete integrity 3) loss of rebar cross section. In order to implement all form of damages in a numerical model, each damage is studied experimentally. Empirical models have been proposed to quantify each damage with respect to level of corrosion.

### *2.1 Bond strength degradation*

In order to quantify the bond strength degradation, evolution of bond slip behavior with increase of corrosion is important to study. It is observed that at initial level of corrosion bond strength between reinforcement and corrosion is increase and further increase of corrosion reduced bond strength significantly[5]. Initially, linear reduction of maximum bond strength with increase of corrosion level was proposed based on regression analysis [10] [11]. Later, [5] and [12] proposed constant maximum bond strength up to initial level of corrosion (1.5%-2%) and then reduced exponentially with further increase of corrosion level. Jiang *et al.,* [13] proposed a model which evolve whole bond slip curve instead of reducing maximum bond strength with increase of corrosion. It is implemented in the present FE model to modify bond slip behavior between rebar and concrete based on level of corrosion.

### *2.2 Loss of concrete integrity*

Spalling stress due to higher volume of corrosion products generate tensile stress on concrete around a corroded reinforcement bar. Since concrete is weak in tension, concrete cracks around corroded bar to release pressure of corrosion products. Eventually concrete cracking at reinforcement level leads to delamination of concrete cover. Maaddawy and Soudki [4] proposed analytical model to predict spalling pressure based on level of corrosion and various other parameters i.e. creep coefficient, diameter of bar, elastic modulus etc. It is implemented in the present FE model for spalling pressure due to rebar corrosion. Outward pressure is applied uniformly on the cylindrical concrete surface around rebar based on corrosion level.

### *2.3 Reduction of rebar area*

Instead of reducing area of reinforcement in the FE model, mechanical properties of corroded reinforcement are reduced based on level of corrosion. Yield strength, ultimate strength and elastic modulus of corroded bar are reduced with respect to level of corrosion as proposed by [3]. Table 1 presents the proposed equation for reduction of mechanical properties based on corrosion.

## 3 Finite Element model

Finite Element analysis results are validated with experimental study of Lee *et al.,*[3]. Material properties of concrete and reinforcement used in experimental investigation are reported in Table 2. Fig. 1 presents the FE model of experimental RC beam along with cross sectional detail. Symmetric boundary condition along the length of the beam is applied to model half beam along the length for computational efficiency. Bottom reinforcement bar of the RC beam are corroded through accelerated corrosion technique in experimental investigation. Experimental specimen was tested with 4 point bending up to failure point of each specimen. Corroded RC beams of 3.8%, 7.9% and 25.3% corrosion level were tested up to failure point along with healthy RC beam specimen.

Table 1 – Mechanical properties of rebar with percentage corrosion (δw)

| *Mechanical properties* | *Reduction due to percentage corrosion (δw)* |
|---|---|
| Yield Strength ($f_{cy}$) | $\left[1-1.24\left(\frac{\delta w}{100}\right)\right]\times f_y$ |
| Ultimate Strength ($f_u$) | $\left[1-1.24\left(\frac{\delta w}{100}\right)\right]\times f_u$ |
| Elastic Modulus ($E_s$) | $\left[1-1.24\left(\frac{\delta w}{100}\right)\right]\times E_s$ |

Table 2 – Properties of concrete and steel reinforcement

| *Concrete* | *Elastic Modulus (MPa)* | *Compressive strength (MPa)* | *Poisson's ratio* |
|---|---|---|---|
| | 29419 | 39.2 | 0.19 |
| Steel | Elastic Modulus (MPa) | Yield Strength (MPa) | Ultimate Strength (MPa) |
| Longitudinal bar (13mmϕ) | 182000 | 343 | 477 |
| Stirrups (6mmϕ) | 192000 | 226 | 415 |

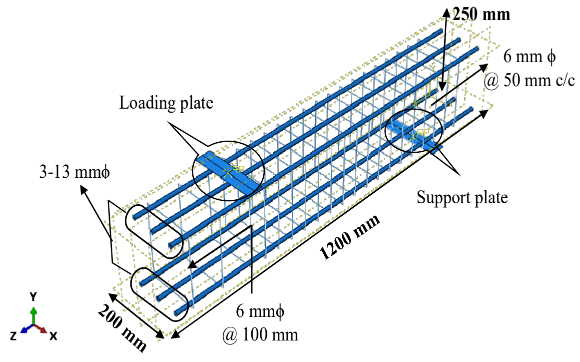



Fig. 1 – FE model of RC beam

3D brick element (C3D8R) is used for modelling the concrete and longitudinal reinforcement bars in ABAQUS. Whereas, 1D beam element (B31) is used for modelling the lateral ties or stirrups in the beams. Elements size of 30 mm is selected along the length of beam. Bond slip model between concrete and rebar surface is implemented using cohesive surface. In order to model the bond slip behaviour between concrete and rebar elements, the two surfaces should be in conctact initially. Hence minimum over closure as well as clearance are ensured at contact during meshing. Loading plate and support plate are modelled as a discrete rigid body. A displacement controlled FE analysis is carried out based on Newton-Raphson method with automatic time increament.

Concrete Damage Plasticity (CDP) model is implemented for nonlinear material behaviour of concrete. Parameters of CDP model are specified as per Table 3. Concrete behaviour in compression is defined based on [14] up to maximum compressive strength ($f_c$). Softening curve of concrete is defined based on[15]. Concrete behaviour in tension is defined as per proposed model of Hordijk[16]. Fig. 2 and 3 presents schematic curves of concrete behaviour in compression and tension respectively.

Table 3 – Parameters of CDP model

| *Dilation angle* | *Eccentricity* | *fb₀/fc₀* | *K* | *Viscosity parameter* |
|---|---|---|---|---|
| $31^0$ | 0.1 | 1.16 | 0.667 | 0.00001 |

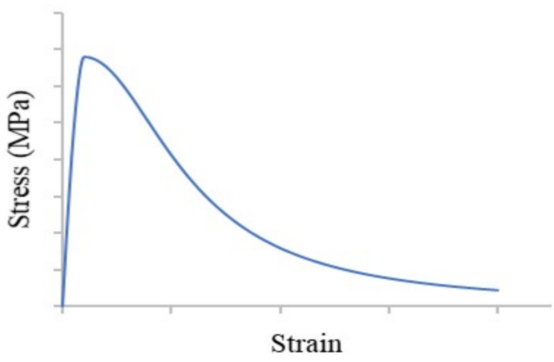



Fig. 2 Concrete behaviour in compression

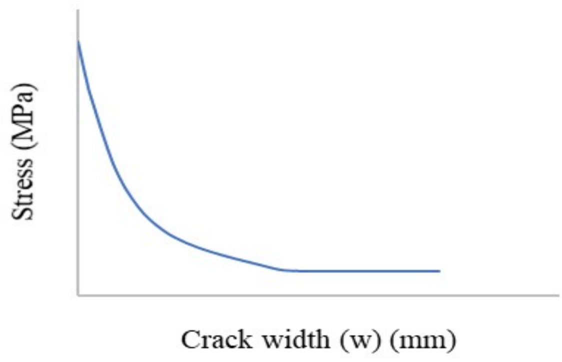



Fig. 3 Concrete behaviour in tension

Isotropic hardening followed by strain softening is implemented for steel reinforcement of Finite Element model. Ultimate strain for reinforcement is obtained by comparing the ultimate deflection point of experimental result to FE analysis results for healthy RC beams. As ultimate strain value of reinforcement governs the ultimate deflection point of an RC beam. Ultimate strain value in further analysis of corroded beams remain same as healthy beam.

Cohesive surface is modelled to define bond slip behaviour between corroded bar and concrete. General contact interaction is assigned on surface of reinforcement and concrete. Linear elastic traction separation behaviour is defined using cohesive behaviour as per Eq. (1)[17]. The traction vector t consists of one normal stress and two shear stress components and δ vector represent the separation (slip) corresponding to traction vector. Stiffness value along length of beam ( $K_{tt}$ ) is obtained as per bond model [13]. Maximum stress criteria are selected to define damage in bond slip behaviour based on maximum bond stress.

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{pmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{pmatrix} \begin{pmatrix} \delta_n \\ \delta_s \\ \delta_t \end{pmatrix} = K\delta \qquad (1)$$

## 4 Results and Discussion

A Finite Element model validated with experimental results is a reliable and cost-effective method to obtain solution of practical problems. As it would be difficult to achieve boundary conditions, material properties, geometry and loading conditions same as practical condition for experimental investigation. In order to validate present FE model, a healthy RC beam model is considered as per the experimental detail [3]. FE analysis for healthy beam is performed considering bond slip behaviour at 0% corrosion as per [13]. Numerical analysis for corroded beams is performed by inclusion of respective corrosion damages in the FE model. Bond-slip behavior, spalling stress and loss of mechanical properties are incorporated based on level of corrosion. Table – 3 shows comparison between outcome of Finite Element analysis and Experimental procedure. Experimental values of yield load, ultimate load and ultimate deflection are in closely match with FEM results. Thus, reduction in load carrying capacity as well as ultimate deflection is accurately obtained with the numerical model of corroded RC beam.

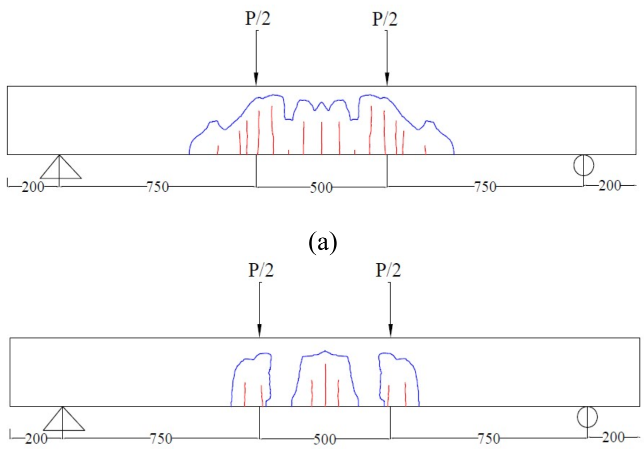
Table-3 Comparison between FEM and Experimental results

| *Level of Corrosion* | *Properties* | *Experimental* | *FEM* |
|---|---|---|---|
| 0% | Yield Load (KN) | 75.5 | 74.4 |
| | Ultimate Load (KN) | 88.9 | 94.58 |
| | Ultimate Deflection(mm) | 88.1 | 90.7 |
| 3.8% | Yield Load (KN) | 71.1 | 71.4 |
| | Ultimate Load (KN) | 85.4 | 91.45 |
| | Ultimate Deflection(mm) | 82 | 83.66 |
| 7.9% | Yield Load (KN) | 69.6 | 69.27 |
| | Ultimate Load (KN) | 78.8 | 88.6 |
| | Ultimate Deflection(mm) | 63.4 | 83.91 |
| 25.3% | Yield Load (KN) | 51.5 | 53.4 |
| | Ultimate Load (KN) | 67.3 | 68.26 |
| | Ultimate Deflection(mm) | 52.3 | 52 |

Flexural cracks and principal strain distribution of corroded beam further illustrates the effect of reinforcement corrosion as compared in Fig. 4a and 4b. Flexural cracks are depicted along with principal strain distribution for healthy beam and 25.3% corroded beam. Principal strain distribution presents flexural crack region for an RC beam. As it is clearly observed that flexural cracking region is clearly reduced with increase of corrosion level. Generally, it is noticed that reinforcement corrosion alters the failure mechanism from flexural failure to shear failure for corroded RC beams. The same mechanism is observed with present numerical analysis.

Loss of bond strength degradation due to corrosion on bottom reinforcement, reduces flexural crack region in case of 25.3% corroded RC beam as shown in Fig. 4b. However, it also leads to brittle failure due to concrete crushing and increase of width of flexural crack. Hence, brittle failure of corroded beams is mainly caused by bond strength degradation between corroded bar and concrete.

Finite Element analysis for various level of corrosion on bottom reinforcement are performed based on validated FE model. Evolution of yield load, ultimate load and ultimate deflection is observed in form of ratio of corroded to non-corroded values for the RC beam as shown in Fig. 5. Ultimate deflection is noticed to be around 40% of healthy RC beam, a highest reduction compared to other properties i.e. yield load and ultimate load at 28% corrosion level.




(b)

Fig. 4 – Flexural cracks and principal strain distribution in (a) healthy beam (b) 25.3% corroded beam

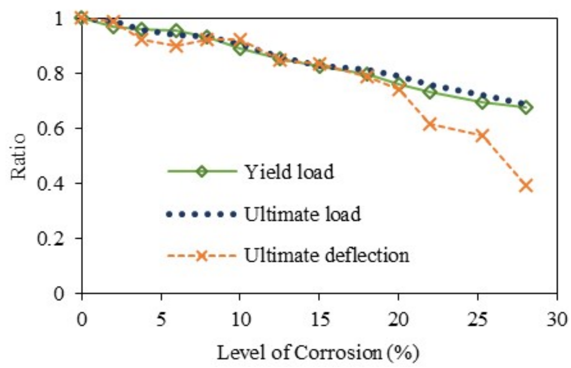



Fig. 5 Ratio of Yield load $(fy_n/fy)$, Ulimate load $(fu_n/fu)$ and ultimate deflection $(\delta u_n/\delta u)$ Vs level of corrosion (%)

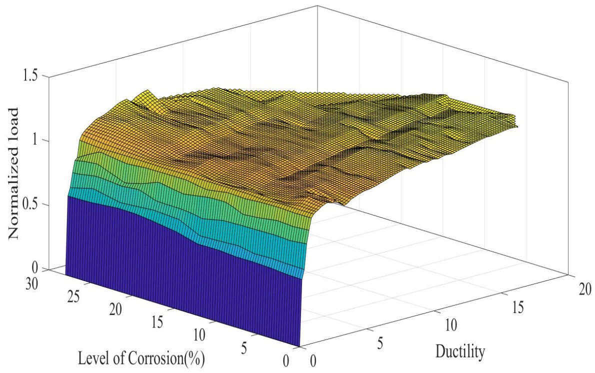



Fig. 6 Ductility vs Normalized Load vs Corrosion level(%)

In order to further study the effect of corrosion on the ductility of an RC beam, Ductility vs Normalized load is plotted along with increase of corrosion level as shown in Fig. 6. Ductility and normalized load are obtained as ratio of displacement to displacement at yield load ($\delta/\delta y$) and load to yield load ($f/f_y$) respectively. Distance between yield point and failure point termed as the plastic property of an RC beam. It is observed to reduce 65.5% with increase of corrosion level from 0 to 28%. As corrosion reduces ductility of an RC beam, its structural performance during seismic loads is surely an important safety concern. In order to avoid any chances of catastrophic collapse due to corrosion, a proactive maintenance and repair work policy is an effective way forward. The edge of failure points in Fig. 6 is observed, which is also termed as displacement ductility index. Displacement ductility index is defined as ratio of ultimate deflection ($\delta u$) to the deflection at yield load ($\delta y$) as per Eq. (2). It is reduced significantly after 12.5% of corrosion level. Hence it is advisable to do necessary maintenance and repair work due to corrosion damage before 12.5% level of corrosion.

$$\mu_u = \frac{\delta u}{\delta y} \qquad (2)$$

## 5 Conclusion

The present study is an attempt to rigorously model a corroded RC beam and study its performance, as well as the effect of corrosion on the ductility capacity. Both the reduction in ultimate deflection load bearing is observed. However, the reduction in ultimate deflection of the RC beam is significant, amounting to nearly 61%, as compared to the non-corroded RC beam. The displacement ductility as obtained from numerical analysis of the corroded RC beams also demonstrates the fact. Based on the study, it is suggested that any maintenance or repair work of the corroded RC beams should be scheduled before corrosion level reaches to about 12%. This will ensure safety of the RC structure during seismic activity along with economical maintenance and repair work of corroded RC beams. The considered modelling strategy for the corroded RC beam can be further extended for studying the effective maintenance and repair work of such RC beams in RC buildings and bridges.

**Disclosures**

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