Proceedings of the 7th International Conference on Civil Structural and Transportation Engineering (ICCSTE'22)
Niagara Falls, Canada – June 05-07, 2022
Paper No. 225
DOI: 10.11159/iccste22.225

Effect of Corrosion and Transverse Reinforcement on Flexural Response of 3D Finite Element Reinforced Concrete Beams

Safdar Naveed Amini [1], Aditya Singh Rajput [2]
[1,2] Department of Civil Engineering, Indian Institute of Technology Ropar, Rupnagar, 140001 Punjab, India
First. 2018cez0001@iitrpr.ac.in; Second. aditya.rajput@iitrpr.ac.in

Abstract - Reinforced concrete structures positioned in coastal areas undergo durability related concerns due to early deterioration of reinforcing bars due to corrosion. This result in a reduction of load-carrying capacity and service life of the structure. This study aims to analyse the effect of varying corrosion percentages on the load-bearing ability of the structure. The idea pertinent to this study is to simulate various three-dimensional finite element beams in ABAQUS 6.14.1 and compare their results with the experimental data taken from the literature. The modelled beams are analysed with a four-point simply supported bending flexural test for validation. For concrete-steel interaction simulation, the cohesive surface interaction method proved to be most suitable as the results align with analytical results. Loss of bond in concrete-rebar interface due to decrease in mechanical interlock is calculated. Concrete Damage Plasticity model is adopted for calculating confined and unconfined strength of concrete in tension and compression. A parametric study is also performed to investigate varying corrosion percentages on residual capacity and behaviour of corroded beams. Flexural strength response due to spacing of transverse reinforcements as per different Indian standard codes is analysed. Spalling stress is calculated analytically and put into simulation data for more precise results. The results indicate a notable reduction in load-deflection behaviour due to concrete spalling, deterioration of rebars ribs, loss in mechanical interlock mechanism and yield strength. At very high corrosion, the structure undergoes an absolute brittle failure due to a complete steel-concrete bond loss. A good matching between finite element and experimental load-deflection curves is observed with variability in ultimate load-bearing capacities of less than 5% for all cases.

Keywords**:** bond slip, finite element, mechanical interlock, rebars corrosion, reinforced concrete.

1. Introduction

Reinforced concrete structures in marine and humid areas are prone to corrosive chloride media. It results in early deterioration of reinforcing bars due to corrosion. Corrosion of Reinforced Concrete (RC) bars is the most severe problem among the durability issues. World Corrosion Organization (WCO) states that every year, corrosion costs over 3% of the world's Gross Domestic Product (GDP). The main consequences of steel corrosion include a decrease in yield strength and cross-sectional area of rebars, generation of circumferential outward expansive pressure due to corrosion by-products causing cracking and spalling of concrete cover [1]. Various factors influence corrosion such as loss of alkalinity due to carbonation and chlorides, insufficient concrete cover, moisture pathways and construction variability in the mix design. These problems will ultimately affect the integrity and load-carrying capacity of the structure [2,3]. Thus, immediate attention is required towards analysing and quantification of this deterioration cause, loss of structural strength and thereby to device suitable ways for its prevention. The duration of initiation period is analysed by how swiftly the concrete cover is cracked or spalled. As a result, activating substances penetrate the steel, speeding up the corrosion process [4,5]. The literature study follows stepwise evaluation and these are discussed next,

a) Mechanical Experiments on Corroded Reinforcement Bars: Almusallam [6] explained a reduction in tensile strength reduction with increased corrosion resulting in brittle failure. Bossio et al. [7] experimentally studied a decrease in rebars elasticity due to increase in degree of corrosion and concluded with yield strength and elastic modulus reduction with increasing corrosion level. Similar kind of work has been done while comparing the effects of uniform and pitting corrosion on structural stability. It is concluded that pitting corrosion is found more hazardous by making the structure brittle [8].

b) Bond between Concrete and Reinforcement Steel Bars: Amausallam et al. [9] explained variation in bond stress at concrete-rebar interface due to expansive stress development. Amleh and Ghosh [10] modelled the effect of corrosion on bond strength and concluded a sharp decrease in concrete-steel bond strength with increasing corrosion. Ogura et al. [11] discovered reduction in pressure and friction, i.e., bond splitting failure between steel-rebar interface with varying corrosion.

c) Experimental works on Corroded Beams: Lachemi et al. [12] experimented with levels of corrosion and analysed reduction in load-bearing capacity and increase in displacement with increasing corrosion. Bhargava and Ghosh [13] examined that lateral load-carrying capacity, strength and stiffness reduces with increasing corrosion. Rajput and Sharma [14,15] analysed that an inadequate confinement reinforcement in corroded structures significantly reduces ductility, strength and energy absorption. The performance is deteriorated by increased crack widths and deflections at service loads.

d) Modelling of Corroded Beams: Maaddawy et al. [16] explained an analytical model for calculating maximum slip at the maximum stress for calculating bond stiffness and spalling stresses due to increased corrosion. [17,18] formulated an analytical model for calculating the variation of a cross-sectional area, increased crack spacing and width for pitting and uniform corrosion. Kalias and Rafiq [19] formulated a finite element (FE) way for corroded structures and formulated a bond deterioration model and local stress-slip law for determining stresses and strains acting on RC beams subjected to flexure.

A lot of research efforts has been done in the past years by various researchers for experimentally analysing corrosion-induced damages in rebars. However, none of the studies presented a finite element analysis approach to model the corrosion in rebars embedded in concrete. Since the experimental research is time-consuming, the purpose of this study includes analytical calculations of various reduced properties of steel and concrete and applying them in FE model to validate the experimental data taken from literature. In this study, a corroded concrete-rebar interface is modelled separately along with spalling stresses and then applied in FE model for precise results. A parametric study is also performed to analyse the behavioural response, structural integrity and capacity of the corroded Beam under different cases.

2. Research Methodology

2.1. Finite Element Modelling

The main objective of the present research work is to develop a comprehensive 3D FE model for corroded and uncorroded RC beams. A non-linear FE model is developed to predict the behavioural response of both types of structures i.e. (corroded and un-corroded) under flexure using ABAQUS 6.14.1. Due to high non-linearity in FE model, a Dynamic Explicit analysis is opted for simulation as it overcomes the problem of convergence [20]. Three-dimensional 8-noded linear brick reduced integrated elements (C3D8R) are used for describing longitudinal reinforcements, steel plates and concrete. A 2-noded linear 3D truss element (T3D2) is used for the stirrups. Steel plates are used to apply loads on the Beam. Boundary conditions, i.e., fixed and roller supports are applied for the calculation of deflections and reaction forces. Concrete and corroded steel are connected using the master-slave interactions. A concrete-rebar slip phenomenon is explained using normal and shear stiffness of the structure.

2.2. Concrete Behaviour Model

Concrete Damage plasticity (CDP) model is found to be more stable for modelling the concrete behaviour under failure. Inelastic strain, damage and cracking strain related to tension and compression members are calculated analytically along with the softening behaviour. This model was developed by Lubliner et al. [21] and was extended by Lee and Fenves [22].

2.3. Concrete Zones

Reinforced concrete is divided into three zones, i.e., confined, unconfined and core concrete [23], Fig. 1(a), (b). It is quite admissible that the inclusion of transverse reinforcements improves the structural integrity and resilience. It safeguards the structure especially under earthquake forces and lateral loads. Stirrups resist shear forces, prevent buckling of longitudinal bars thus improving the ductility of structure [24].

2.4. Confined Concrete Strength

Concrete behaviour under tension is assumed to be linear by resisting tensile stresses caused by bending forces due to applied loads until concrete cracking initiates at concrete's modulus of rupture [25]. CDP values, damage parameter, inelastic confinement effectiveness coefficient, lateral effective confining pressure and cracking strains are calculated using the following equations in stress-strain model for confined Concrete [26].

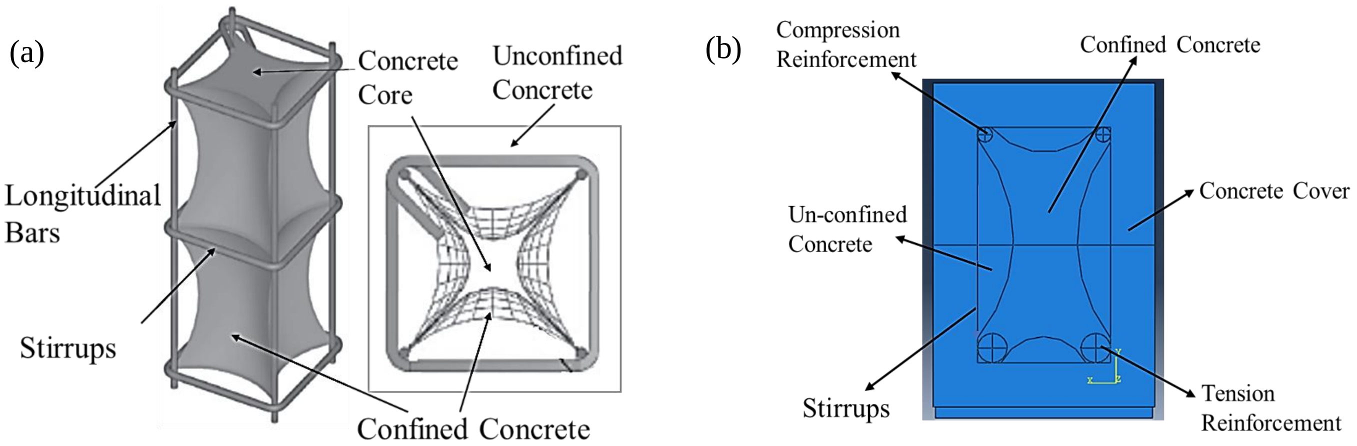


Fig. 1(a) Different Concrete Zones in a rectangular Beam [23] and (b) Reinforced concrete zoning of modelled FE beam

$$f'_{cc} = (-1.254 + 2.254\sqrt{1 + 7.94\frac{f'_l}{f'_c}} - 2\frac{f'_l}{f'_c}) \tag{1}$$

$$\varepsilon_{cc} = \epsilon_{co} \, [\, 1+5\frac{f'_{cc}}{f'_c} -1] \tag{2}$$

$$k_e = \frac{\left(1-\frac{s'}{2d_s}\right)}{1-p_{cc}} \tag{3}$$

$$f'_l = 0.5\times k_e \times \rho_s \times f_{yh} \tag{4}$$

2.5. Bond Stress and Slip Calculation

Concrete-rebar bond stress is calculated for beams with different percentages of corrosion [19]. A reasonable valid result is expected since many parameters are included in bond stress τ_{max} and rebar-slip (S_1) calculation.

$$\tau_{max} = R\,(0.55+ 0.24\frac{C_c}{d_b})\sqrt{f_c} + 0.191\frac{A_{tf}f_{yt}}{S_s\,d_b} \tag{5}$$

$$R = [A_1+ A_2X] \tag{6}$$

$$S_1 = S_{max} = 0.15\,C_o\frac{10}{3}\ln(\frac{\tau_{max}}{\tau 1}) + S_o\ln(\frac{\tau 1}{\tau_{max}}) \tag{7}$$

$$\tau_1 = 2.57\sqrt{f_c} \tag{8}$$

2.6. Degraded Properties of Concrete and Steel

Circumferential expansive pressure due to corrosion by-products reduces the concrete strength in cover region. Since, chlorides and CO_2 ingress reduces the cross-sectional area of rebars, the residual yield strength (f_{yc}) and reduced modulus of elasticity (E_{sc}) of rebars are calculated as follows [27].

$$f_{cc} = \frac{f_c}{1+k\frac{\varepsilon 1}{\varepsilon c}} \tag{9}$$

$$f_{tt} = \frac{f_{cc}}{f_c} \times f_t \tag{10}$$

$$\epsilon_1 = \frac{n_{bar} w_{cr}}{b_o} \tag{11}$$

$$f_{yc} = (1\text{- } 0.011X_p)f_y \tag{12}$$

$$E_{sc} = (1\text{-}0.007X_p)E_s \tag{13}$$

2.7. Spalling Stresses Calculation

Increased corrosion in rebars result in an enlarged circumferential net outward pressure due to corrosion by-products. Since, concrete cover is in an unconfined zone, there is an increase in uniform radial outward pressure (P_{cor}) around the cover zone resulting in spalling of concrete cover which is calculated as follows [28].

$$P_{cor} = \frac{m\ E_{ef}\ D}{90.9\ (1+\vartheta+\psi)\ (D+2\delta 0)} - \frac{2\delta 0\ E_{ef}}{(1+\vartheta+\psi)\ (D+2\delta 0)} \tag{14}$$

$$\psi = \frac{(D+2\delta 0)2}{2C\ [C+(D+2\delta 0)]} \tag{15}$$

$$E_{ef} = \frac{E}{1+\theta} \tag{16}$$

3. Experimental Data considered for FE Models Validation

The experimental data related to the flexural and shear behaviour of a rectangular beam is obtained by load-deflection graphs [12]. These beams are considered for validation of corroded and non-corroded FE model beams. Four levels of reinforcement corrosion percentages i.e., 5, 10, 15, and 20 are subjected in beams to induce mass losses in bottom rebars and stirrups. Calculated concrete and steel residual strength of corroded rebars with varying corrosion as explained in Table 1.

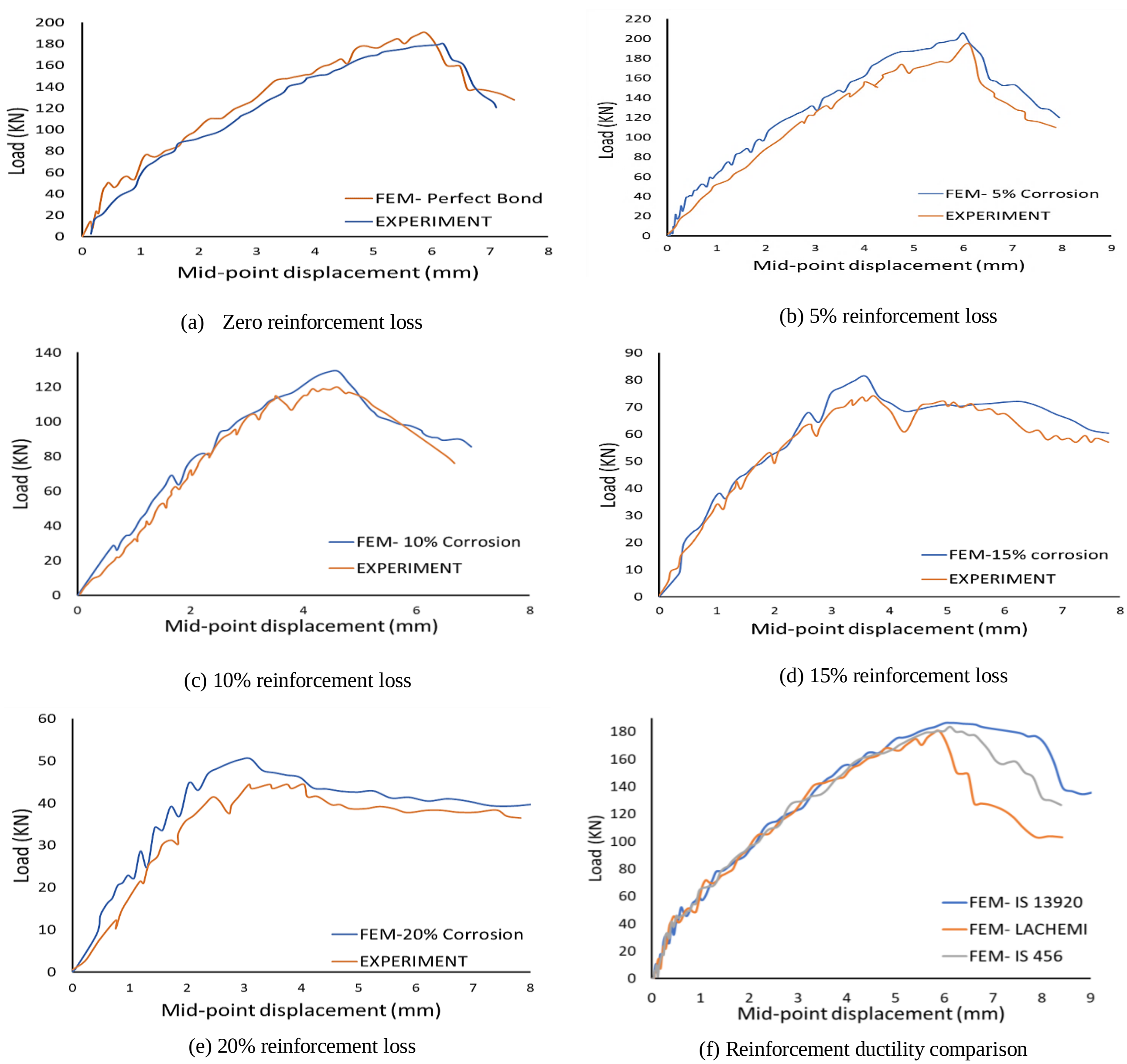
Moment of resistance of this Beam is calculated analytically. It is analysed that the moment of resistance of beam is greater than its limiting moment of resistance i.e., ($Mu > Mu_{lim}$). Since, there are depth restrictions, thus compression reinforcement is also provided in beams by calculating its factored shear load and shear resistance capacity.

Table 1: Calculated concrete and steel residual strength of corroded rebars (MPa)

Beam Type	Corrosion Degree (%)	Steel Yield Strength	Stirrups Yield Strength	Reduced Elasticity of Steel	Reduced Elasticity of Concrete	Concrete cover strength	Bottom rebars Bond Stress	Bottom rebars Spalling stress	Top rebars Bond stress	Top rebars Spalling stress
BM-0	0	550	400	200000	26100	31	23	0	21	0
BM-1	5	520	380	193000	22800	23.5	21.11	0.36	19.53	0.38
BM-2	10	490	356	186900	19300	19	19.76	0.72	18.2	0.77
BM-3	15	460	334	179000	12950	12.2	18.44	1.12	17.2	1.22
BM-4	20	425	310	172000	6080	6.32	16.81	1.45	15.67	1.55
BM-5	30	360	265	158000	3320	3.44	14.13	2.17	13.24	2.30
BM-6	40	308	224	144000	1550	1.63	11.32	2.90	10.7	3.10
BM-7	50	240	180	130000	831	0.87	8.5	3.60	8.2	3.80

4. Results and Discussions

The aim of this work is to compare and quantify the load-deflection (L-D) curves obtained from experimental data and FE modelling. Beam model with no corrosion is modelled using a perfect bond case. Different beams for corrosion are modelled to analyse the four levels of corrosion percentages i.e., 5, 10, 15, and 20. Simulations were performed and the obtained results are discussed in Fig.2 (a) to Fig.2 (e). The graphs explain the mid-span load-displacement reactions of beams with varying corrosion. The experimental results are compared with the simulation results. It is clearly evident that increasing corrosion is inversely proportional to the stiffness and load-bearing capacity of structure. A good matching between finite element and experimental load-deflection curves is observed with variability in ultimate load-bearing capacities of less than 5% for all cases.



(a) Zero reinforcement loss

(b) 5% reinforcement loss

(c) 10% reinforcement loss

(d) 15% reinforcement loss

(e) 20% reinforcement loss

(f) Reinforcement ductility comparison

Fig. 2 Mid-span Load-Displacement curves for Experimental and FE Beams with Varying Corrosion

4.1. Parametric Study

To further enhance the understanding on behaviour of corrosion on different areas of structure, an elaborative study is conducted. A total of Nineteen 3D FE models are modelled out of which seven beams are utilized for the validation process and the remaining for parametric study. In all beam models, the dimensions are kept the same as previous model but the material properties and corrosion location is changed as described in Table 2.

Table 2: Finite element 3d models used in parametric study

Beam Notation	Cross-section	Description
BM 8-12	Corrosion in Top bars only	Reduced steel and concrete properties only in compression bars.
BM 13-17	Corrosion in Bottom bars only	Reduced steel and concrete properties only in tension bars.
BM 18	Ductile detailing (IS-456)	Spacing of stirrups as per IS-456:2016
BM 19	Ductile detailing (IS-13920)	Ductile reinforcement detailing as per IS 13920:2016

4.1.1. Effect of Corrosion Degree in Compression and Tension Zone

Five FE beams (BM 8-12) are modelled to analyse corrosion effect only in the compression rebars. As anticipated, compression rebars resulted in a slight reduction in the flexural capacity of beam as shown in Fig. 3(a). It is estimated that this reduction could be due to concrete cover cracks in compressive zone and half the cross-sectional area as compared to bottom bars. In the similar manner, Five FE beams (BM 13-17) are modelled to analyse the corrosion effect in tension rebars [29]. Since, a four-point bending test is performed in this study for flexural strength of structure, it is observed that there is a sharp decrease in strength of corroded beams with increase in corrosion due to reduction in rebars cross-sectional area as shown in Fig. 3(b). It is also analysed that after 20% corrosion, the load bearing capacity of structure reduces to almost one-third and the structure lacks its structural integrity and ductility showing a brittle failure.

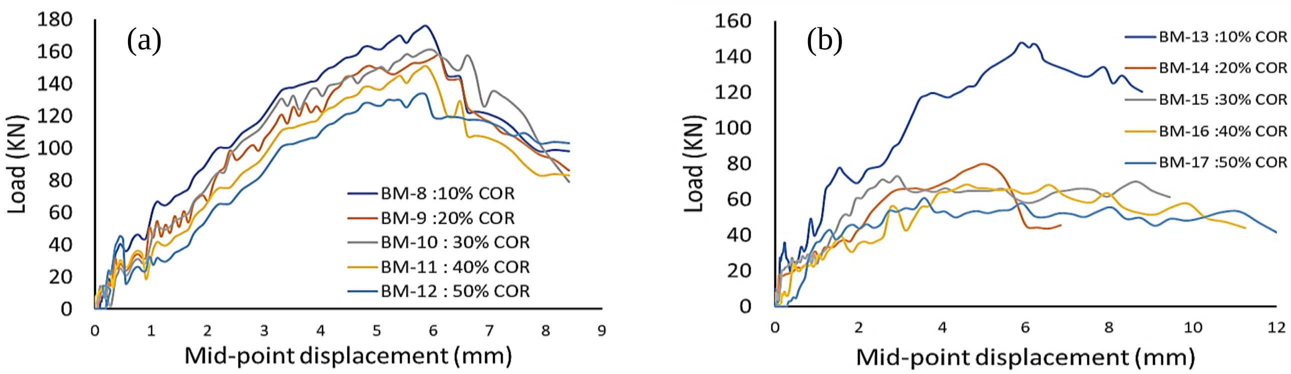


Fig.3 (a) Variation of Corrosion in Compression Zone and (b) Variation of Corrosion in Tension Zone

4.1.2. Ductile Detailing of Stirrups

Ductile detailing on RC beams at different seismic zones were done as per the available Indian standard (IS) codes i.e., IS-13920 and IS-456. Spacing of stirrups and beams are modelled accordingly. The purpose is to understand the structure's ductile response at various seismic zones by varying stirrups spacings. BM-18 is modelled as per IS-456 [30] and BM-19 as per IS-13920 [31]. Fig.2 (f) explain the comparison of experimental results with various IS codes. It is interesting to observe that the structure's ductility improves when reinforcement is designed as per IS codes. It is evident that by increasing number of transverse reinforcements and reducing stirrups spacings, ductility improves. Thus, the structure behaves more resilient under lateral and earthquake forces.

5. Conclusion

In this work, a comparative assessment is done by modelling a 3D FE simulation for corroded and un-corroded RC beams and comparing their results with the experimental work which were taken from the literature. A dynamic explicit technique along with CDP model is used for modelling of beams. Perfect bond method is adopted for non-corroded beam modelling. A Cohesive surface technique along with master-slave interactions are utilized for corroded beams for connection of steel with concrete. Concrete-rebar slip phenomenon is explained and used in model using normal and shear stiffness between steel and concrete It is analysed that increasing corrosion is inversely proportional to stiffness and load-bearing capacity of structure. Also, presence of corrosion only in the compression zone reduces the load-bearing ability of a structure to less extent but the structural strength reduces severely when corrosion is present in the tension zone. Furthermore, spacing of stirrups designed as per Indian standard codes increased the structure's ductility, making it resilient under seismic and lateral forces. A good correlation between finite element and experimental load-deflection curves is observed with variability in ultimate load-bearing capacities of less than 5% for all cases.

Nomenclature			
A_1, A_2	0.861, -0.014: for 1 Amp current	K_{nn}	Stiffness in normal direction
A_t	Total cross-sect. area of stirrup within S_S	K_{ss}, K_{tt}	Stiffness in shear direction
c_C	One-half clear spacing between rebar	m	Corrosion percentage
D	Diameter of steel bar (tension and compression) mm	n_{bar}	Number of bars (in compression and tension zones)
d_b	Diameter of the rebar	R	Bond loss reduction factor, 1 for non-corroded case
E_s	Modulus of elasticity of rebar	RC	Reinforced concrete
E_{ef}	Effective elastic modulus, MPa	S`	Centre to centre stirrups spacing
E	Elastic modulus of concrete, MPa	S_S	Spacing of the stirrup
f'_{cc}	compressive strength of confined concrete	S_o	0.15, 0.4 for plain and reinforced concrete.
f_y	Yield strength of rebar, MPa	w_{cr}	Width of crack (cover region crack)
f'_l	Effective lateral confining pressure	ε_{co}	Strain at max. compr. strength (unconfined concrete)
f_{yh}	Yield strength of rebars, MPa	ε_{cc}	Strain values Increase with confined concrete
f_{yt}	Yield stress of the stirrup.	τ_{max}	Bond stress
f_{cc}	Reduced compressive concrete cover strength	ε_c	Strain at maximum compressive strength i.e. (0.002)
f_{tt}	Reduced tensile strength of cover	ε_1	Strain based on corrosion percentage and crack width
f_c	Concrete compressive strength	δ_0	Thickness of porous zone i.e., 0.001 (mm)
FE	Finite element	θ	Creep coefficient (2.35) (as per CSA standard)
GDP	Gross Domestic Product	ν	Poisson's ratio (0.2)
k	Constant = 0.1 (for ribbed medium diameter bars)	X_p	Corrosion percentage
k_e	Confinement effectiveness coefficient	WCO	World Corrosion Organization

References

[1] A. L. Sakkaf, "Modelling of corroded reinforced concrete beams," Ph.D. dissertation, Dept. Civil Eng., King Fahd Univ., Dhahran, Saudi Arabia.

[2] M. Sompura, M. and N. Kwatra, "Finite element analysis of corroded RC beams," Ph.D. dissertation, Dept. Civil Eng., Thapar Univ., Patiala, India.

[3] H.M. Noh and Noor, N.M., "Structural Effects of Reinforced Concrete Beam Due to Corrosion," in *Proceedings of the E3S Web of Conferences*, Poland, 2018, vol. 34, 01024.

[4] J.M. Wachira, "Effects of chlorides on corrosion of simulated reinforced blended cement mortars," Int. J. Corrosion., vol. 13, pp.1-7, 2019.

[5] A.A Abouhussien and A.A. Hassan., "Experimental and empirical time to corrosion of reinforced concrete structures under different curing conditions,". Advances in Civil Eng., vol. 2014, pp. 1-9, 2019.

[6] A.A. Almusallam, “Effect of degree of corrosion on the properties of reinforcing steel bars,”. Constr. Building material, vol. 15, Issue 8, pp. 361-368, 2001.

[7] Bossio et al. “Modeling of concrete cracking due to corrosion process of reinforcement bars,”. Cement and Concrete Research, vol. 71, pp. 78-92, 2015.

[8] H.S. Lee and Y.S. Cho, “Evaluation of the mechanical properties of steel reinforcement embedded in concrete specimen as a function of the degree of reinforcement corrosion,”. Int. J. of Fracture, vol. 157, pp.81-88. 2009.

[9] A.A. Almusallam et al, “Effect of reinforcement corrosion on bond strength,”. Construction and Building Material, vol.10, pp.123-129, 1996.

[10] L. Amleh and A.Ghosh, “Modeling the effect of corrosion on bond strength at the steel–concrete interface with finite-element analysis,”. Can. J. Civ. Eng., vol. 33(6), pp. 673-682, 2006

[11] N. Ogura et al. “Analysis of bond splitting failure of deformed bars within structural concrete,”. Eng. Structures., vol. 30 (2), pp. 428–435, 2008.

[12] M. Lachemi et al, “The effect of corrosion on shear behavior of reinforced self-consolidating concrete beams,”. Eng. Structures, vol.79, pp.1-12, 2014.

[13] K. Bhargava et al, “Models for corrosion-induced bond strength degradation in reinforced concrete- Analytical and empirical models,” Nuclear Eng. And Design., vol. 237(11), pp.1140-1157, 2007.

[14] A.S. Rajput and U.K. Sharma, “Corroded reinforced concrete columns under simulated seismic loading,” Eng. Structures, vol. 171, pp. 453-463, 2018.

[15] A.S. Rajput and U.K. Sharma, “Performance of aged reinforced concrete columns under simulated seismic loading,”. Eng. Structures, vol. 20(3), pp. 453-463, 2019.

[16] El. Maaddawy et al., “Analytical model to predict nonlinear flexural behaviour of corroded reinforced concrete beams,” ACI Struct. J., vol.102(4), pp. 550-559, 2005.

[17] D. Coronelli and P. Gambarova, “Structural assessment of corroded reinforced concrete beams: modelling guidelines,” J. Struct. Eng., vol. 130(8), pp. 1214-1224, 2004.

[18] F. Biondini and M. Vergani, “Deteriorating beam finite element for nonlinear analysis of concrete structures under corrosion,”. Struct. Infrastructural. Eng., vol. 11(4), pp. 519-532, 2015.

[19] A.N. Kallias and M.I. Rafiq, “Finite element investigation of the structural response of corroded RC beams,”. Eng. Structures, vol. 32(9), pp. 2984-2994, 2010.

[20] Abaqus 6.14 Documentation. Providence, RI: Dassault Systems. (Accessed: 25 March 2022)

[21] J. Lubliner et al., “A plastic-damage model for concrete,”. Int. J. Solids Struct., vol. 25(3), pp. 299-326 1989.

[22] J. Lee and G.L. Fenves, “Plastic-damage model for cyclic loading of concrete structures,” J. Eng. Mechanics., vol. 124(8), pp. 892-900, 1998.

[23] N. Subramanian, “Design of confinement reinforcement for RC columns,”. Indian Concr. J., vol. 85(6), pp. 19-29, 2011.

[24] D.C. Kent and R. Park, “Flexural members with confined concrete,” J. Struct. Eng., vol. 97(7), pp. 1969-1990, 1971.

[25] B. Mander and R. Park, “Theoretical stress-strain model for confined concrete,” J. Struct. Eng., vol. 114(8), pp. 1804-1826, 1988.

[26] El Maaddawy et al., “Analytical model to predict nonlinear flexural behaviour of corroded reinforced concrete beams,”. ACI Struct. J., vol. 102(4), pp. 550-559, 2005.

[27] P.S. Mangat and M.S. Elgarf, “Flexural strength of concrete beams with corroding reinforcement,” Str. Journal, vol. 96(1), pp. 149-158, 1999.

[28] El Maaddawy and K. Soudki, “A model for prediction of time from corrosion initiation to corrosion cracking,”. Cem. Concr. Composition., vol. 29(3), pp.168-175, 2007.

[29] S.M. Allam et al., “Evaluation of tension stiffening effect on the crack width calculation of flexural RC members,” Alex. Eng. J., vol. 52(2), pp. 163-173, 2013.

[30] BIS 456:2016, Plain and reinforced concrete-Code of Practice. Bureau of Indian Standards, New Delhi, India,2016.

[31] BIS 13920:2016, Ductile Detailing of Reinforced Concrete-Code of Practice. Bureau of Indian Standards, New Delhi, India, 2016.