3rd Specialty Conference on Material Engineering & Applied Mechanics
3e Conférence spécialisée sur le génie des matériaux et mécanique appliquée

Montréal, Québec
May 29 to June 1, 2013 / *29 mai au 1 juin 2013*

Simplified Non-linear FE Model to Predict Staged Capacity Deterioration of RC Columns Subjected to Combined Ultimate or Seismic and Reinforcement Corrosion Loads

Amina M. Mohammed[1] and Husham H. Almansour[2]
[1]University of Ottawa, [2]National Research Council Canada, Canada

Abstract: The quasi-static and the low frequency cyclic loading-to-failure tests have shown that the stiffness degradation and strength of RC columns are reduced in a staged pattern. Although several studies have demonstrated this strength and stiffness degradation using complicated high-level 2D and 3D modeling approaches, a simplified numerical approach is required. Simplified non-linear finite element model developed by the authors is used in this paper to capture the staged damage and collapse of RC columns subjected to extreme loads. The model performs inelastic sectional and element analysis phases considering the instantaneous and successive changes of the sectional and element properties throughout the progress of the loading steps and the critical stages of corrosion-induced damages. The model considers all possible state of strain distributions on a concrete beam-column, and the nonlinear instantaneous sectional properties and the internal forces are calculated ensuring the equilibrium of all the internal and external forces in the section level. It is found that the proposed simplified nonlinear finite element model is numerically stable in all cases of strain distributions, both in static and dynamic analysis. The model shows that the load displacement curve of the columns subjected to quasi-static loading or the envelop of the load-displacement hysteretic relationship can be found using quasi-static analysis. The model can predict the nonlinear behavior of non-corroded and corroded specimens with high accuracy. Further research is required to accurately define the critical stages of damages incorporating field and experimental data of damaged RC columns and higher level non-linear finite element techniques.

1 Introduction

Thorough understanding of the deterioration mechanisms and identification of damage stages are essential base for any model simulating the behaviour of damaged structures. The effects of such damage stages on flexural and shear stiffness, ductility of materials and structural elements, progressive changes of internal forces and stress distributions due to spalling, mass losses, etc, could lead to identify threshold structural capacities for an efficient quantitative infrastructure management approach. Visual inspection is the most widely used method for the assessment of the physical condition of bridges; however, it is a subjective approach provides only qualitative condition assessment of bridge structures. The main objective of the development of a quantitative assessment approach is to minimize the risk of missing the detection of a critical and unsafe condition of a bridge element/system, or avoiding an over-conservative assessment that may result in unnecessary and costly repairs and/or replacement. The limits between different assessment rating categories based on visual inspection are not yet well separated. The wide transition zones between these assessment rating categories could lead to a contradictory in an inspector identification of critical distress symptoms of an important bridge in the transportation network. Yet, a fully time dependent quantitative assessment approach is far from realistically being available in the short term seen, but an integration of the visual inspection and a simplified quantitative assessment approach is proposed here as an effective transition step.

Consequently, establishing force-deformation characteristics of reinforced concrete columns subjected to extreme loads (axial, flexure and or seismic loads) combined with reinforcement corrosion are of major importance. Over the past four decades, the quasi-static and the low frequency cyclic loading-to-failure tests have been well-developed to evaluate the strength and stiffness degradation (together with the energy dissipation, in the case of cyclic loading) of non-corroded reinforced concrete columns. The results of these tests show that the stiffness and strength are reduced in a staged pattern. Experimental observations showed that typical sequence of damage stages of both quasi-static and cycle loading testes are starting with concrete cracking followed by longitudinal reinforcement yielding, spalling of the concrete cover, lateral reinforcement failure and local or global loose of confinement, and possible longitudinal reinforcement buckling and fracture.

Several analytical and numerical models have been proposed to capture one of these limit-cases of damage. Consequently, many researchers proposed advanced two-dimensional (2D) and three-dimensional (3D) models that capture such staged capacity deterioration of RC elements. Assimilating such models in a cost effective and numerically stable assessment approach is very challenging and could not be practical for field engineers. Furthermore, there is no simplified approach that accurately predicts stiffness, strength and hence residual load capacity of the structural element in these critical damage stages. Such a simplified approach may provide practical engineers with efficient quantifying evaluation management tool for better decisions on the operation status of RC bridges.

In this paper, a simplified yet efficient non-linear finite element model that simulates the staged failure and estimates the load capacity of the deteriorated RC elements in each critical stage is presented. The model is aimed at a capability to imitate the mechanical behaviour at the section level taking into account the boundary conditions and member geometry in the structural level. The corrosion-induced damage is established at the sectional level through the reduction of the reinforcing steel area, spalling of the concrete cover, loose of concrete confinement and possible buckling of deteriorated steel rebars.

2 Modeling Approach and Assumptions

The procedure to establish the load-deformation characteristics requires three basic steps: definition of constitutive material properties; performing inelastic sectional analysis; and performing a structural analysis. Of course, the effect of sectional geometry, steel reinforcement and confinement of core concrete, are considered in the sectional level while the effect of the boundary conditions and loading pattern are considered in the structure level modeling.

Several different approaches have been proposed to model the stress-strain relationship of concrete and reinforcing steel in compression and in tension. Kabaila 1964 and Basu1967 proposed a fourth-degree polynomial compressive stress-strain relationship followed by multi-linear post ultimate relationships with definite post-failure residual stress. This approach is apparently based on Hognestad second-order compressive stress-strain relationship of concrete up to ultimate stress followed by a linear stress drop up to failure, Figure 1. On the other hand, many researchers experimentally confirmed that the confinement can improve the stress-strain characteristics of the concrete as the lateral expansion of the concrete is restricted (Kent and Park 1970). In 1992, Saatcioglu and Razvi modified the stress-strain relationship of confined and unconfined concrete taking into account the reinforcement details. Their model assumed less strength and deformation capacity than those in Hognestad's model for unconfined cover concrete or the entire column section when the axial stress is low and the confinement of concrete core is negligible. In this paper, both models (a fourth-degree polynomial and Saatcioglu and Razvi models) are used according to the state of axial stress recognising to major element behaviours; flexural dominant or compression dominant behaviour. To represent the concrete stress-strain relationship in tension, Gilbert and Warner 1978 model has been used where tension softening, tension stiffening and local bond-slip effects are all taken into account. On the other hand, tri-linear stress-strain relationships is assumed for the reinforcing steel both in tension and in compression assuming no local rebar buckling is expected. More details of material models are provided by Mohammed et al. 2013a.

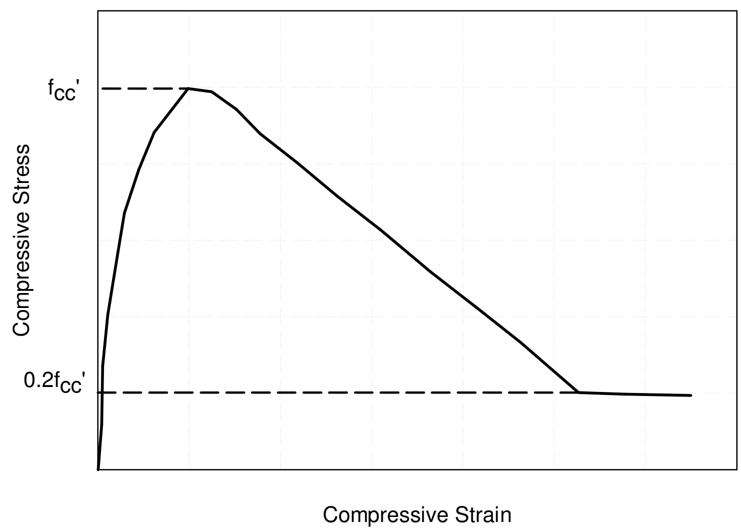

Figure1: Stress-strain relation for compressive concrete

Sectional analysis is an essential step to consider the elasto-plastic development of concrete stresses and the variation of sectional characteristics throughout the crack propagation and the changes in the stress distributions in the section level. The concrete and the steel are assumed in a full composite action and the effects of shear deformations are neglected. Based on the strain distribution over the section, an iterative nonlinear process is conducted to satisfy the equilibrium of the forces on the section in every step of the load increment (axial, moment or both). If the section is subjected to only flexural stresses, the strain distribution is variable from extreme tensile strain at one end to extreme compressive strain on the other end (see Figure 2-b). As the cracks initiated and propagated, the neutral axis migrates toward the extreme compression fiber with further increase of the strain level. If the section is subjected to axial stresses only, the strain distribution is constant compression (see Figure 2-c). On the other hand, if a combination of axial stress and flexural stress is applied on the section, then the strain will be one of two cases: (i) pure compression (see Figure 2-d); (ii) variable high compressive strain to low tensile strain (see Figure 2-e). The most popular state of strain distribution for beam columns is case (ii), while case c is for typical beams, and case d is for typical columns with low eccentricity. The nonlinear stress distribution is shown in Figure 2-f. In the FEM model (Mohammed, et al, 2013a) and to integrate the nonlinear stresses over the concrete and the steel, the section is divided into number of strips, where the stresses at the center of these strips are determined from the material nonlinear stress-strain relationships. It is found that this approach is numerically stable in all cases of strain distributions shown in Figure 2. The nonlinear instantaneous sectional properties (EA_i and EI_i) and the internal forces are then calculated ensuring the equilibrium of all the internal and external forces in the section level.

Depending on the assumption of the number of sections per element and the instantaneous nonlinear sectional properties, the stiffness, mass and dumping matrices are derived for each element and assembled over the structure for each load step. In the structure level of nonlinear modelling, it is assumed that: (i) all deformations (displacements, rotations, etc.) are continues functions over the structural element throughout all the load increment steps; and (ii) the equilibrium has to be satisfied in the section and structure levels. More details of inelastic sectional and member analysis can be found in Mohammed et al. 2013a &b.

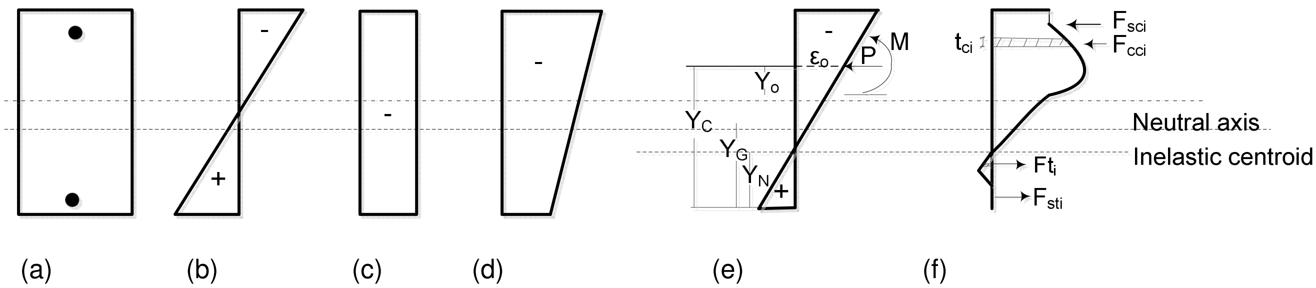

Figure 2: Stress-strain distribution; (a) cross section; (b) strain distribution due to flexural; (c) strain distribution due to axial load; (d) strain distribution due to flexural & axial load; (e) depths distribution; (f) concrete & steel stresses

3 Modeling Effects of Corrosion

As the change in RC section properties (area and moment of inertia) leads to a reduction in elements stiffness, the effect of reinforcement corrosion is modelled here by reducing the rebar cross-sectional area and its ductility. Removing concrete cover may also result in increased eccentricity of the applied axial load (Rodríguez et al, 1996). It has been observed that losing stirrups/ties can be more vulnerable to corrosion than longitudinal bars as they are usually closer to the external surface of the structure, and they have greater perimeter/cross-sectional area ratio. Partial loss of bond at the steel-to-concrete interface is one of the important effects of corrosion. Depending on the affected length of the bars, loose of bond could lead to increase the deformations of RC element (El Maaddawy et al, 2005). Bond failure could occur in severely large corrosion affected RC members of when the joints of framed structures are severely damaged. In addition, the degradation of bond-slip relationships as consequence of corrosion effects causes increases in the global drift ratio of RC structures due to increases in lateral displacement, (Yalciner et al, 2012). In this study, concrete is assumed to be compositely connected to steel at the section level prior to corrosion and when the corrosion takes place, the bond is assumed to be fully lost in the affected zones. Based on field observations, it is assumed, in this study, that localized corrosion damages occur in critical zones of the bridge where the salty water splashed on the column surface or the bridge top where the salty water leaks from the expansion/ construction joints of the superstructure (Mohammed et al, 2013a &b). This will only result in local loose of bond. The damaged material models are integrated in the sectional level modeling for different deterioration stages and/or corrosion amounts.

Also, it was observed that corrosion pressure has limited effect on softening of concrete through the concrete core as the corrosion level increases. After formulation of longitudinal crack along the height of corroded reinforcing bar, the bar deflects by corrosion pressure towards the weakest part and concrete cover spall off (Rodríguez et al. 1996 and Oyado et al. 2007).

Since bridge columns usually subjected to a high axial load and low eccentricity; therefore, the main concern of simulating corrosion effects on the RC bridge columns are loss stirrups, confinement and buckle the reinforcement bars. In some cases and with severe localized corrosion, the behavior bridge columns could switch from compression to flexural depending on the level of applied load and the level and location of corrosion.

4 Estimation of Staged Deterioration of Ultimate and Seismic Capacity

In order to simulate the failure mechanism of RC elements when subjected to ultimate or seismic load, it is essential to capture all stages of damage and the structural behaviour and capacity with high accuracy. The characteristics and capabilities of the proposed simplified nonlinear FEM model such as its accuracy, applicability, versatility, and its efficiency are demonstrated in the following sections in comparison with available experimental results. The main focus in this paper is on the effectiveness of the model to simulate the force-deformation relationship of different RC element subjected to extreme loads (ultimate or seismic loads). More details of numerical validations and comparisons can be found in Mohammed et al.2013a & b.

4.1 Validation of the Proposed Model

The proposed model is validated though its two modeling levels; sectional level and element (structure) level. The convergence of the model depends on the optimum selection of three major parameters: (i) the load step; (ii) element size ;(iii) number of section per element. The convergence should be achieved in each load step where slow convergence or divergence categorized as numerical instability.

The preliminary validity of the proposed model is performed by investigating a simply supported beam subjected to uniform distributed load. The experimental load-deflection curve of this beam is originally presented by De Cossio-Siess 1960. A numerical simulation based on closed form derivation of the beam nonlinear stiffness from the flexibility matrix is proposed by Rasheed and Dinno 1994. The load deflection relationship estimated by the proposed model compared to experimental results and Rasheed and Dinno model result are shown in Figure 3. The results of both models, the proposed and Rasheed and Dinno, are almost identical and underestimate the experimental results.

This example shows that the model is capable to safely simulate the section mechanical behaviour with high numerical stability. Conversely, the use of the other model requires intensive time and large number of trials to reach a numerical stability, and tuning the convergence is a case by case problem. Rasheed and Dinno model requires satisfying a normalized convergence criterion for the moment of the axial rigidity about the inelastic centroid, which is very sensitive criterion and can be satisfied only for very limited cases.

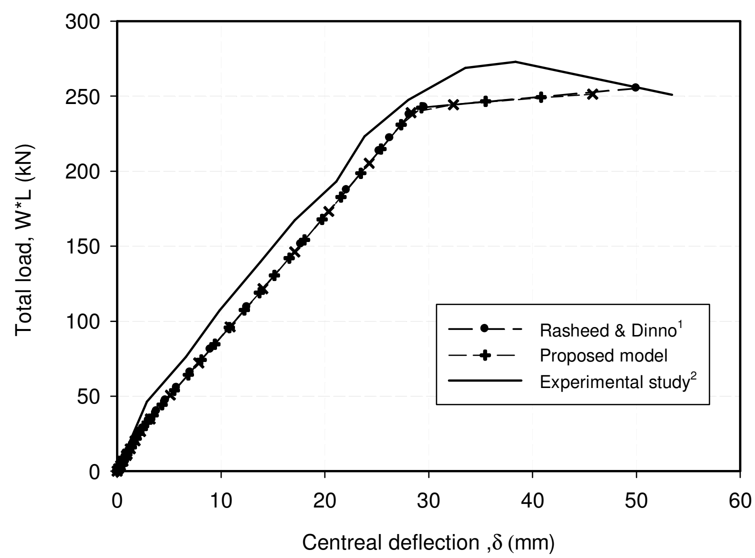

Figure 3: Load-central deflection response of simply supported beam subjected to uniform distributed load; [1] Rasheed and Dinno 1994 ; [2] De Cossio-Siess1960.

4.2 Case Study I: RC Column under Compression Loads

Saatcioglu and Razvi 1992 investigated the behaviour and design of normal-strength and high-strength concrete columns subjected to earthquake loads. One of their study specimens is selected for the comparison with the proposed model results. The specimen is a square column of 250 mm X 250 mm cross section, and 1500 mm height; a clear concrete cover of 10 mm is provided; the concrete compressive strengths was established by standard cylinder tests with concrete compressive strength $f_c' = 60\ \mathrm{MPa}$; the longitudinal bars were 16mm in diameter (No15), and had yield strength of 450 MPa; the volumetric rations (ρ_s) of the lateral reinforcement is 1.4 %; the spacing of transverse reinforcement is 85 mm; the specimen was tested under monotonically increasing. Figure 4 shows axial load-axial strain relationships established from the experimental test of the column compared to the stress-strain relationship from the proposed model. The model results match the experimental results in the elastic range and underestimate the stress after the yield where the predicted collapse strain is also less than that in the test.

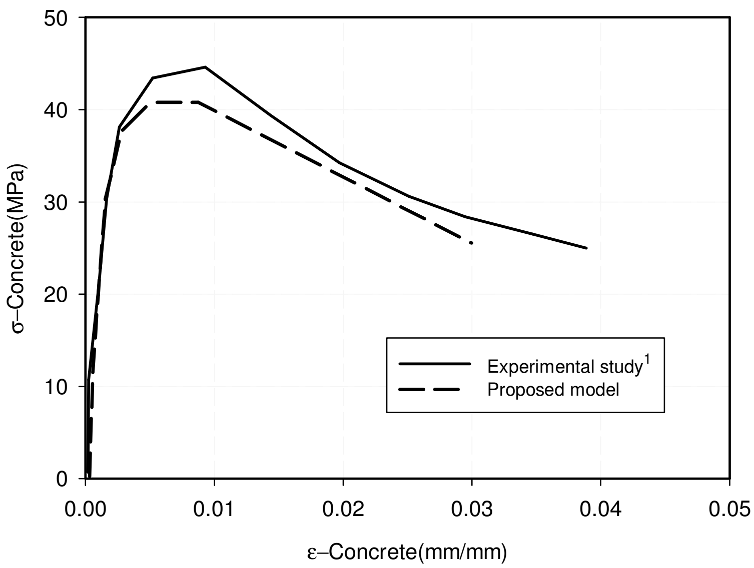

Figure 4-: Stress-strain of extreme fiber of confined zone of the selected specimen; [1] Saatcioglu & Razvi 1992.

4.3 Case Study II: RC Column under Cyclic Loading

In this case study, an RC column tested by Saatcioglu and Ozcebe 1989 is investigated. The column represents part of a first-story column in-between the foundation and the inflection point the column is designed as an earthquake-resistant. The test results show the effects of axial load, transverse reinforcement, and bidirectional loading on column ductility. The column is square with 350 mm X 350 mm cross-section and 900 mm height. The concrete compressive strength is 37.3 MPa; the longitudinal rebars diameter is 25 mm with yield strength of 425 MPa and the longitudinal reinforcement ratio is 3.27%; and the spacing of ϕ 10 transverse reinforcement was 65 mm center to center. The proposed model is used to predict the load-deformation curve of the column and its load-displacement hysteretic relationship. The model use Takeda's approach to establish the load-displacement hysteretic relationship.

Figure 5-a shows a good match of the model results and the experimental results in the elastic range and again the model underestimates the stresses after the yield point. Figure 5-b shows

the predicted envelop of the hysteretic relationship plotted on the experimental results, which shows very good match.

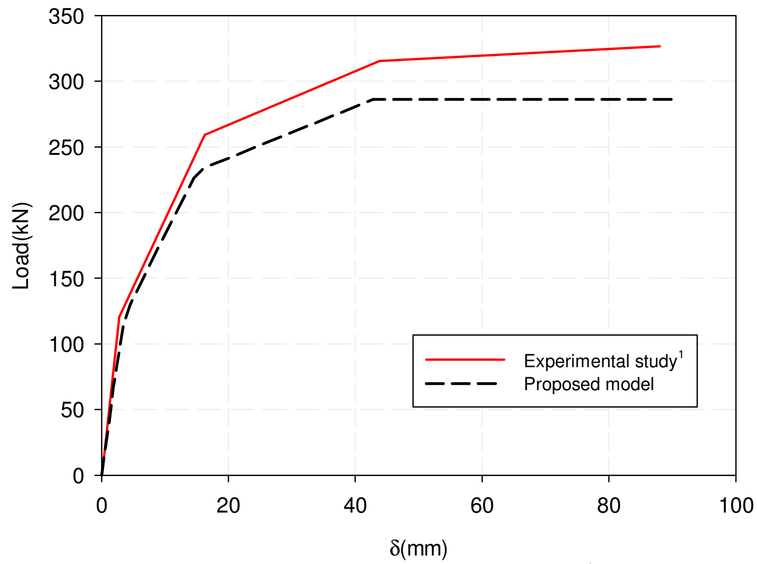

Figure 5-a: Lateral load-top deflection of the selected specimen; [1]Saatcioglu & Ozcebe 1989.

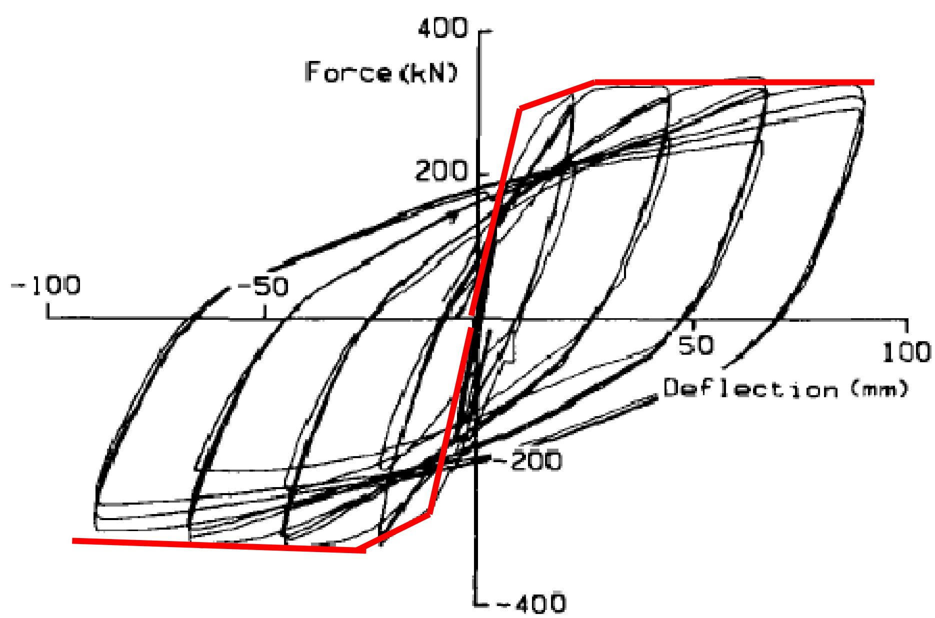

Figure 5-b: Lateral load-top deflection hysteretic relationships, after Saatcioglu & Ozcebe 1989.

4.4 Case Study III: RC Column Subjected to Cyclic Load and Reinforcement Corrosion

In this case study, two RC columns subjected to combined cyclic load and reinforcement corrosion are investigated. The columns investigated in this paper are Column No1 and Column

No 4 out of the eleven cantilever column specimens tested by Oyado et al, 2007.The columns were exposed to different levels of corrosion then subjected to the cyclic load. The columns are 1650 mm long and square cross sectional dimensions of a 450 X 450 mm. The mechanical properties of the concrete of both columns are: (i) compressive strength: 30.5 MPa; (ii) tensile strength: 2.64 MPa (from tensile splitting test); and (iii) modulus of elasticity: 25.5 GPa. Column No1 is the control specimen while Column No4 is made with the scraped bars at the loading side. It is observed that throughout the application of the cyclic load, the concrete cover close to the column support damaged and split in parts gradually the case of the control specimen, Column No1. Conversely, in the case of testing Column No4 under cyclic loading, the concrete cover at the zones affected by the reinforcement corrosion splits in one piece. Figures 6-a and 6-b show the envelop of hysteretic response of the control and the corroded specimen, as collected from the tests and as predicted by the proposed model. It is observed that the decline of the maximum lateral resistance force of the corroded specimen is only 10% compared to the control specimen; however, significant reduction of the displacement at maximum lateral load capacity reaches 50 % in the corroded specimen. The lateral load capacity of the last loading cycle of the corroded specimen is also decline to half of the related capacity of the control specimen, while the maximum displacement at the last loading cycle decline by 40 %.

The load-displacement envelops curves for non-corroded and corroded specimens are simulated with reasonable accuracy where most of the critical characteristics are captured. The model identify all critical damage stages where the load resistance capacity decreased, namely: cover spalling; one stirrup failure; two stirrups failure; and complete loss of confinement of the core concrete as shown in Figures 6-a and 6-b. It is important to mention that the model can estimate accurately the envelop curves of both columns either by conducting the hysteretic load-displacement analysis or by conducting static non-linear analysis for each of the damage stages, then the final load displacement envelop curve is plotted through defining the displacement at each damage stage.

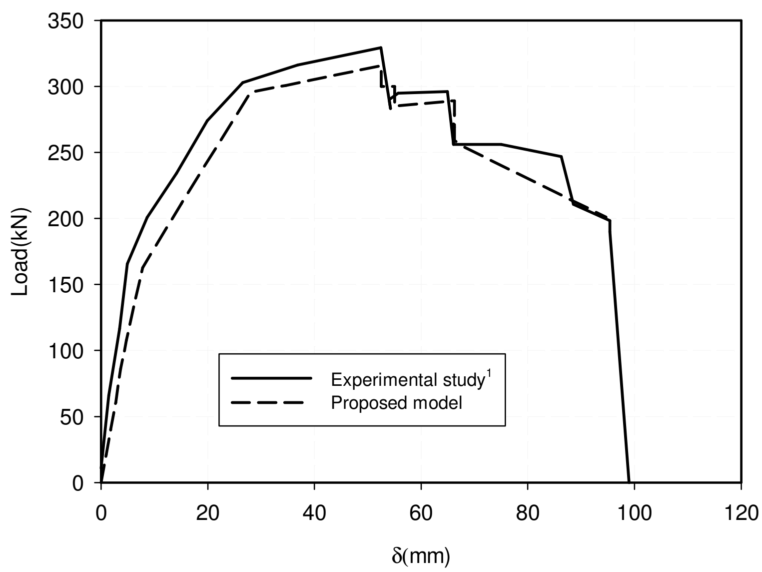

Figure 6-a: Envelope curve of load-displacement relationship of control specimen, Column No 1 ([1]Oyado et al.2007)

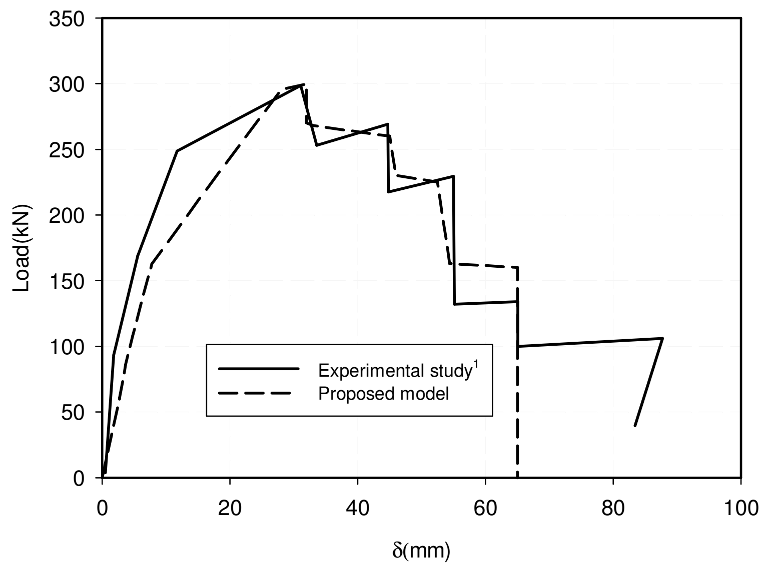

Figure 6-b: Envelope curve of load-displacement relationship of the specimen subjected to reinforcement corrosion, Column No 4 ([1]Oyado et al.2007)

5 Summary and Conclusion

Several studies have demonstrated the strength and stiffness degradation of RC columns using quasi-static and the low frequency cyclic loading-to-failure tests or using complicated 2D and 3D modeling approaches. However, a simplified numerical approach is required to predict stiffness and strength deterioration of RC columns subjected to extreme loads (ultimate or seismic). Simplified nonlinear finite element model of RC elements subjected to any combination of axial, flexure, and lateral static or cyclic loads is developed by the authors (see Mohammed et al 2013a & b). The capabilities to capture the staged collapse of such RC element are investigated in this paper. The model employs nonlinear constitutive material properties, performs inelastic sectional analysis considering the instantaneous and successive changes of the sectional and element properties throughout the progress of the loading steps and the critical stages of corrosion-induced damages. The model considers all possible state of strain distributions on a reinforced concrete beam-column element and the nonlinear instantaneous sectional properties and internal forces are calculated ensuring the equilibrium of all the internal and external forces in the section level. Depending on the assumption of the number of sections per element and instantaneous nonlinear sectional properties, the stiffness, mass and dumping matrices are derived for each element and assembled over the structure for each load step.

It is found that the proposed simplified nonlinear finite element model is numerically stable in all cases of strain distributions, both in dynamic and static analysis. The model shows that the load displacement curve of the columns subjected to quasi-static loading or the envelop of the load-displacement hysteretic relationship can be found using quasi-static analysis. The model can predict the nonlinear behavior of non-corroded and corroded specimens with high accuracy.

6 Future Work

The simplified nonlinear finite element model developed by the authors together with the capability to model staged deterioration of structural capacity open the research in three major areas:

(i) Assessment of bridge elements current capacity where the accurate identification of the critical stages of damages is required. Incorporating field and experimental data on the damaged RC bridge elements could result in practical approach for engineers.
(ii) Modeling the behaviour of RC frame bridge, RC continuous bridge, or RC multi-story frame elements subjected to combined ultimate loads or seismic load and reinforcement corrosion;
(iii) Development of non-linear finite element model based on two-dimensional finite elements (plane stress/plane strain, or shell elements) would be important to capture the shear, shear-flexural, and time dependent bond lose effects on the staged damage mechanism.

7 References

Basu. K., 1967. Computation of failure loads of composite column. *Inst. Civ. Engrs, London*, 36: 557-578.

De. Cossio R. D. and Siess C. R., 1960. Behaviour and strength in shear of beams and frames without web reinforcement. Journal-American Concrete Institute,(56):695-735.

El Maaddawy, T., Soudki, K., and Topper, T.,2005a. Long-term performance of corrosion-damaged reinforced concrete beams. *ACI Structural Journal*,102(66),649-656.

Gilbert, R. and Warner R.,1978. Tension stiffening in reinforced concrete slabs. *J. Strcut. Div. ASCE* .104(ST12),1885-1900.

Kabalia, A., 1964. Disc. of equation of the stress-strain curve of concrete. P. Desayi and S. Krishnana, *J. Am. Concr. Inst*. 61,1227-1229.

Mohammed, A., Almansour, H., and Martín-Pérez, B., 2013a.Nonlinear sectional analysis of RC section subjected to ultimate loads and reinforcement corrosion, (to be submitted shortly to *Computer and Structures*).

Mohammed, A., Almansour, H., and Martín-Pérez, B., 2013b. Nonlinear flexural analysis of RC beam-column subjected to ultimate loads and reinforcement corrosion, (to be submitted shortly to *Computer and Structures*).

Oyado, M., Saito, Y., Yasojima, A., and Kanakubo, T. 2007.Structural Performance of corroded RC column under seismic Load. *First International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading*, Whistler, Canada.

Rasheed, H., and Dinno, K., 1994. An improved nonlinear analysis of reinforced concrete frames. *Computer and structures*. 53(3)625-636.

Rodríguez, J., Ortega, L. M. and Casal, J.,1996. Load bearing capacity of concrete columns with corroded reinforcement. *Corrosion of Reinforcement in Concrete Construction*, Royal Society of Chemistry: 220-230.

Saatcioglu, M., and Ozcebe, G., 1989. Response of reinforced concrete columns to simulated seismic loading. *ACI Structural Journal*, 86-(1): 3-12.

Saatcioglu, M., and Razvi, S., 1992. Strength and ductility of confined concrete. *Journal of Structural Engineering*, 118(6): 1590-1607.

Yalciner H., Sensoys., and Eren O., 2012. Time-dependent seismic performance assessment of a single-degree-of-freedom frame subject to corrosion. *Engineering Failure Analysis*,(19):109-122.