NONLINEAR BEHAVIOUR OF CORRODE RC COLUMNS UNDER CYCLIC LOADING

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ABSTRACT

A new modelling technique is developed to model the nonlinear behaviour of corrosion damaged reinforced concrete (RC) bridge piers subject to cyclic loading. The model employs a nonlinear beam-column element with multi-mechanical fibre section using OpenSees. The nonlinear uniaxial material models used in the fibre section account for the effect of corrosion damage on vertical reinforcing, cracked cover concrete due to corrosion of vertical bars and damaged confined concrete due to corrosion of horizontal tie reinforcement. An advanced material model is used to simulate the nonlinear behaviour of vertical reinforcing bars that accounts for combined impact of inelastic buckling and low-cycle fatigue degradation. The basic uncorroded model is verified by comparison of the computation and observed response of RC columns with uncorroded reinforcement. This model is used in an exploration study of recently tested reinforced concrete components to investigate the impact of different corrosion models on the inelastic response of corrosion damaged RC column.

INTRODUCTION

Many structures in regions of high seismicity are also exposed to corrosive environments. Corrosion of reinforcing steel is the most common reason for the premature deterioration of RC structures. In the recent years several researchers have put significant efforts to study the seismic vulnerability and fragility analysis of corroded RC bridges (Gosh and Padgett 2010, Alipour et al. 2011). They have investigated the effect of reinforcement corrosion on the behaviour and response of RC bridges subject to seismic loading through nonlinear fibre-based finite element analysis. However, they have used very simple uniaxial material models to model the impact of corrosion on stress-strain behaviour of reinforcing steel. Moreover, in most cases the corrosion damages has only been limited to the reinforcing bars (only considering an average reduced area or reduced yield strength) and the impact of corrosion on confined concrete, ductility and reduced low-cycle fatigue life is ignored. Recent experimental testing (Ou et al. 2011, Ma et al. 2012) shows that corrosion can significantly diminish the strength and drift capacity of RC elements (e.g. beams and columns). Therefore, material deterioration due to corrosion must be considered in assessing the earthquake vulnerability of existing RC structures in corrosive environments.

To address these issues, there have been a series of comprehensive experimental investigations conducted to explore the impact of corrosion on nonlinear behaviour of reinforcing bars at the Earthquake Engineering Research Centre (EERC) of the University of Bristol. In these experiments the nonlinear constitutive behaviour of corroded reinforcing bars subject to monotonic (tension and compression) and cyclic loading with the effect of buckling have been investigated. The experimental results showed that corrosion has a substantial influence on the ultimate capacity and ductility of corroded bars in tension and significantly reduces the buckling capacity of corroded bars in compression. It was also observed that corrosion has a significant influence on low-cycle high amplitude fatigue degradation of corroded bars under cyclic load history.

Here a numerical model is presented that enables simulation of the nonlinear flexural response of RC components with corroded reinforcement. The model employs the force-based beam-column element and the fibre-type section model that are available in OpenSees. A new phenomenological hysteretic model that simulates the buckling of longitudinal reinforcement under cyclic loading, the impact of corrosion on buckling strength and low-cycle high amplitude fatigue degradation is used.

This phenomenological hysteretic model is validated through comparison of simulated and observed response for RC columns with uncorroded reinforcement. Typical concrete constitutive models are employed to simulate the response of components with corroded reinforcement; cover concrete strength is adjusted to account for corrosion induced damage and core concrete strength and ductility adjusted to account for corrosion induced damage to transverse reinforcement. The model is used to simulate the response of several recently tested reinforced concrete components with corroded reinforcement and to investigate the impact of corrosion on the nonlinear behaviour of RC columns.

Furthermore, an advanced 3D optical measurement technique has been employed to measure the non-uniform pitting corrosion along the length of corroded bars. Using the data from optical measurement, a simple methodology has been developed for calculation of the residual diameter of corroded bars. This approach provides a more realistic estimate of residual diameter of corroded bars compare to the earlier models based on uniform mass loss.

This paper summarises the results of this research project which are crucial input parameters for probabilistic spatial-time-variant seismic reliability analysis of deteriorating systems.

PROPOSED FINITE ELEMENT MODEL

In this research a force-based nonlinear fibre beam-column element (distributed plasticity model) with Gauss-Labotto integration scheme available in the OpenSees is employed (OpenSees 2012). To avoid any localisation effect due to softening behaviour of vertical reinforcement in post-buckling region; the column is modelled using two force-based elements. The first element has three integration points and second element has five integration points. The length of the first element is taken to be $6L_{eff}$ where L_{eff} is the calculated buckling length of vertical reinforcing bars (Figure 1). L_{eff} is defined in the following sections. This allows controlling the length of the first integration point to be equal to the buckling length of reinforcement that is used to define the material model of reinforcing bars. To model the slippage of reinforcement at the column-foundation interface, a zero-length section element is used at the base.

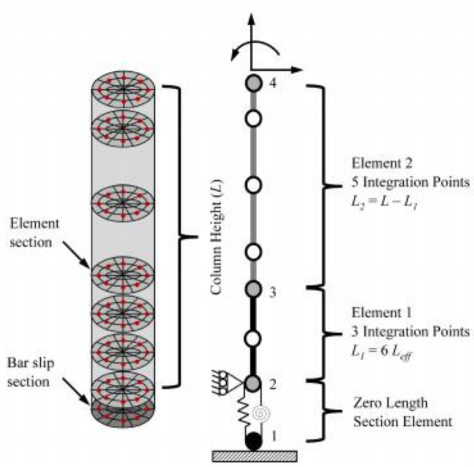


Figure 1. Proposed nonlinear fibre beam-column finite element model

MODELLING CROSS SECTIONAL PROPERTIES OF CORRODED REINFROCEMENT

Twenty three corroded reinforcing bars were taken from a total of 120 samples for refined geometrical surface analysis of corrosion patterns. The reinforcing bars varied in length (from 220mm to 400mm) and had a range of mass loss ratios (8.93% to 55.94%). The surface pitting pattern of the corroded bars was measured using a structured light scanner with 5.0 MP resolution. The outcome of the scanning process was a set of 3D solid models of the corroded bars that were identical to the real bars including the very fine details of pitting pattern. Further detail is available in Kashani et al. (2013c). For each bar cross sections were taken through the 3D model at 0.5mm intervals over the whole length. The cross sections were transformed to data points (x, y, z coordinates) and each cross section included data points every 0.03mm around the perimeter. To better understand the corrosion patterns, the cross section of the bars can be unwrapped ($-\pi \le \theta \le \pi$) and the data presented in the format of r and θ in polar coordinates (Figure 2).

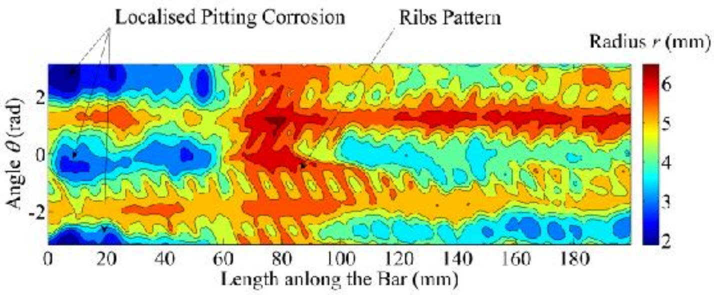


Figure 2. Contour plot of corrosion patter of a corroded bar with 36.40% mass loss

A set of probabilistic models are developed that account for: a) the change of cross section area over the length of corroded bars, b) the change in second moment of area of cross sections over the length of corroded bars. Equation (1) can be used to calculate the average reduced cross section area of reinforcement considering a linear reduction in area as function of percentage mass loss ψ.

$$A_{ave} = A_0\left(1 - 0.01 \cdot \ \right) \tag{1}$$

where, A_{ave} is the average reduced cross section area of corroded reinforcement and A_0 is the corresponding original uncorroded cross section area.

Once the average reduced cross section area is calculated, the cross section area considering pitting effect (A') can be calculated using the Equation (2).

$$A' = ¥ A_{ave} \tag{2}$$

where, γ is the mean value of area pitting coefficient that is derived by assuming a lognormal distribution. Further detail is available in (Kashani et al. 2013c).

Kashani et al. (2013c) found that the irregular cross section shape of corroded bars results in axis rotation. Therefore, in probabilistic models they considered the minimum principal second moment of area. The minimum second moment of area of corroded bars (I'_{min}) can be calculated by introducing a pitting coefficient for second moment of area as defined in Equation (3) below:

$$I'_{\min} = \mathrm{K} I_0 \tag{3}$$

where, K is the mean value of pitting coefficient of minimum second moment of area of corrode bars considering lognormal distribution, I_0 is the second moment of area the original uncorroded bar.

The mean values of the pitting coefficients (γ and K) can be calculated using the Equation (4).

$$M_{(¥ \text{ or } \mathrm{K})} = \exp\left(« + \frac{\pm^2}{2} \right) \tag{4}$$

where, μ and σ are defined in Equations (5) and (6) below:

$$\text{«} = a \cdot {}^{b} \tag{5}$$

$$\pm = c \cdot {}^{d} \tag{6}$$

The coefficients *a*,*b*,*c*, and *d* and further detail are available in Kashani et al. (2013c).

NONLINEAR UNIALXIAL MODEL OF CORRODED REINFORCEMENT

The mechanical properties and cross sectional area of longitudinal reinforcement in tension have been modified using existing mathematical models available in the literature and experimental data (Kashani et al. 2013a, b). Kashani (2014) conducted a comprehensive nonlinear finite element analysis to investigate the impact of corrosion pattern on nonlinear cyclic repose of corroded reinforcing bars. Using the data generated from the nonlinear finite element analysis and experimental data (Kashani et al. 2013a, b) a new phenomenological hysteretic model for corroded reinforcing bars was developed. The features included in the new model include the inelastic buckling and post-buckling, reduced yield strength and ductility and low-cycle fatigue degradation due to corrosion. Once the model was validated against the experimental data of isolated corroded bars, it has been implemented in the OpenSees (Figure 3). To account for the influence of tie stiffness on cyclic behaviour of vertical reinforcement a parametric study has been conducted using UW-PEER (Berry et al. 2004) experimental column database. Using the parametric study data the unloading-reloading and pinching parameters of the proposed model are optimised. Further details are available in (Kashani 2014).

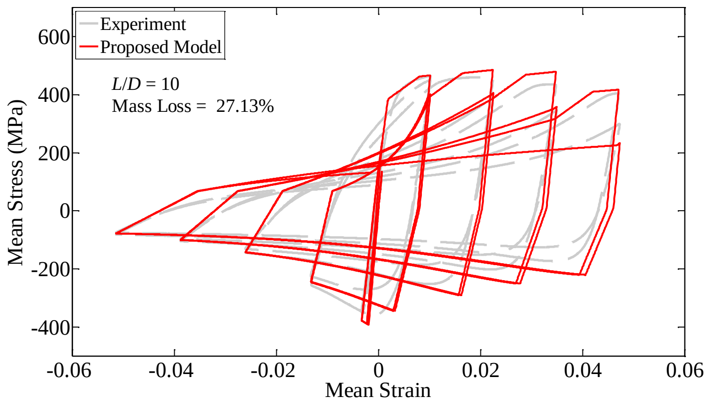


Figure 3. Example of the new phenomenological hysteretic model implemented in the OpenSees

NONLINEAR UNIALXIAL MODEL OF DAMAGED CONCRETE

An unconfined concrete model is used for cover concrete and a confined concrete model is used for the core concrete. The Concrete04 available in the OpenSees is used to model both confined and unconfined concrete. Mander's equations (Mander et al. 1988) are used to define the confinement parameters. The model suggested by Scott et al. (1982) is used to define the maximum strain in confined concrete which is associated with the fracture of first hoop reinforcement in the column. The effect of corrosion induced cracking of cover concrete in the compression zone is considered in the analysis using the model suggested by Coronelli and Gambarova (2004). The effect of corrosion on confined concrete is considered by reducing the volumetric ratio and yield strength of the confinement reinforcement as a function of steel mass loss due to corrosion. The influence of corrosion on reduced ductility is also considered by limiting the maximum strain in the confined concrete as a function of reduced ductility of hoop reinforcement. The unconfined and confined concrete models used in the analysis are shown in Figure 4.

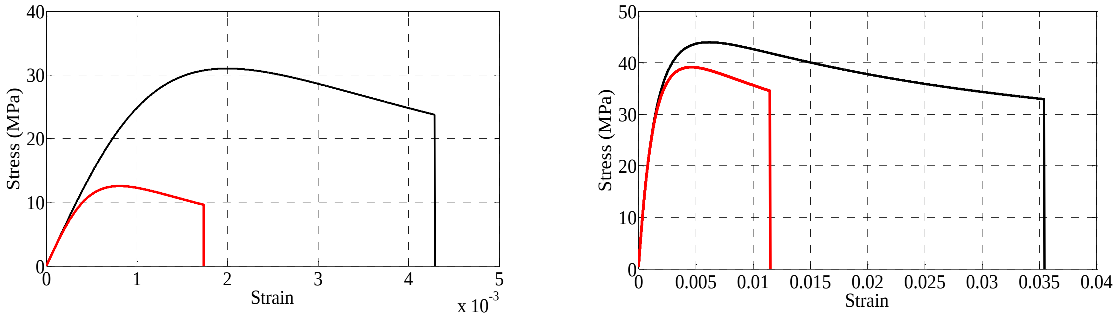


Figure 4. Material model of concrete: (a) unconfined cover concrete (b) confined core concrete

BOND-SLIP MODEL AND ZERO LENGTH ELEMENT

Lowes and Altoontash (2003) adopted a bar-slip model for the end slip of longitudinal reinforcement in beam-column joints. This model has been employed by here to model the bond-slip behaviour of RC columns.

It is known that corrosion affects the reinforcing bars near the surface of concrete due to diffusion of chloride ions from the surface and/or carbonation of cover concrete. In bridge piers, the longitudinal bars are anchored to the foundation well below the foundation surface. Therefore, the longitudinal bars don't corrode at this depth and the bar-slip behaviour of bars at the anchorage zone remains the same as uncorroded column. This has been observed experimentally (Ou et al. 2011, Ma et al. 2012).

NONLINEAR ANALYSIS OF CORRODED BRIDGE PIERS

The basic un-corroded model was validated against the UW-PEER RC column database (Berry et al. 2004). The corrosion damaged models are separately validated against the material test dataset as explained in previous sections. One of the columns in UW-PEER database is considered as a hypothetical bridge pier to be corroded over its service life. Nonlinear cyclic and pushover analyses are conducted to investigate the influence of material degradation due to corrosion on the component response.

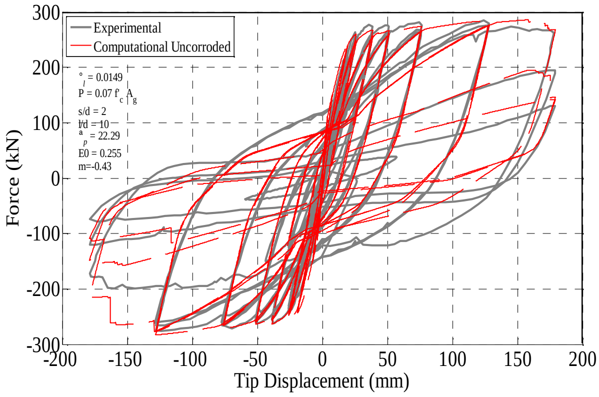
Figure 5 shows the results of nonlinear cyclic analysis of Lehman's column 415 (Lehman and Moehle 2000). Figure 5 (a) shows the uncorroded column and Figure 5(b) and (c) show Lehman's column considering corrosion damage at 10% and 20%.

It is clear from the Figure 5 that corrosion significantly influences the drift and energy dissipation capacity. The failure mode of the uncorroded column is fracture of the reinforcing steel in tension due to low-cycle fatigue. A 10% mass loss (Figure 5 (b)) reduced the low-cycle fatigue life of reinforcement and therefore, premature fracture of reinforcement is observed. However, once the mass loss ratio increased to 20% (Figure 5 (c)) the failure mode changes to combined buckling of vertical reinforcement and crushing of core concrete in compression. This is due to the significant effect of corrosion on buckling of reinforcement and confined concrete behaviour.

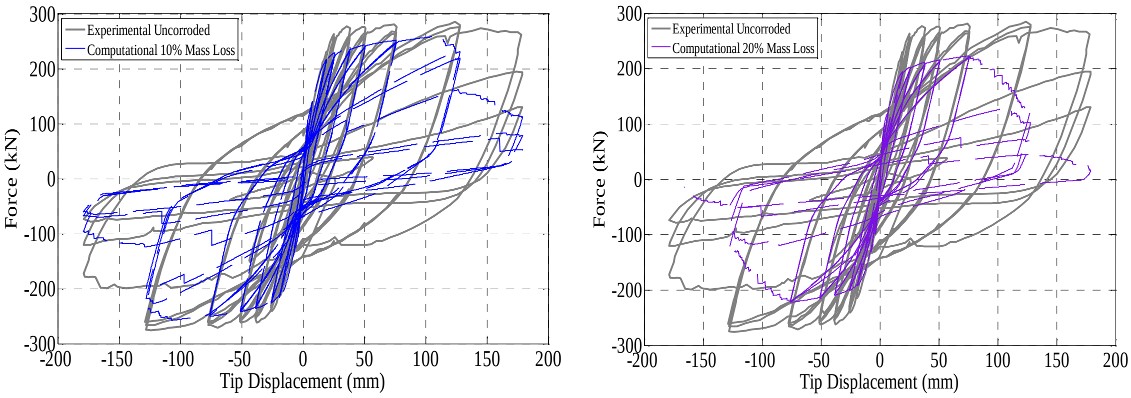
In order to demonstrate the influence of corrosion on capacity reduction of RC columns; a series of nonlinear pushover analyses on the same column were conducted and the results are shown in Figure 6.

As it is clear in Figure 6 corrosion has much more significant influence on drift capacity than strength. For example, in this column 40% mass loss results in about 39% reduction in strength but it reduces the drift capacity by 76%.

The results of this study show that material degradation has significant impact on component response which subsequently will impact the system response. Therefore, considering only a uniform area loss of steel in seismic vulnerability and fragility analysis of corrosion damaged bridges is not a sufficient assumption. Although the present numerical model provides a good indication on the extent of problems, there is still need for further experimental studies on at component level for validation and calibration of the current methodology.



(a)



(a) (b)

Figure 5. Nonlinear cyclic response of Lehman's column 415:
(a) uncorroded (b) 10% mass loss and (c) 20% mass loss

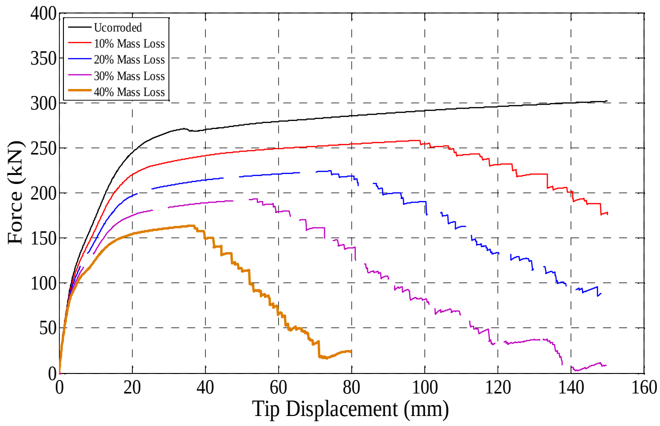


Figure 6. Nonlinear pushover analysis of Lehman's column 415

CONCLUSIONS

A series of pushover and cyclic analyses on a hypothetical corroded RC column are conducted. The impact of corrosion on reinforcing steel and concrete is modelled. The influence of cyclic degradation due to low-cycle fatigue is also modelled. The main outcome of this study can be summarised as follows:

(1) Corrosion has a more significant impact on ductility loss of RC columns than the strength loss (plastic moment capacity).

(2) It was found that the flexural failure is initiated by buckling of vertical bars and crushing of core concrete which then followed by fracture of bars in tension.

(3) The analyses results showed that for seismic performance and evaluation of existing corroded bridges monotonic pushover analysis is insufficient. The cyclic degradation due to low-cycle fatigue has a significant influence on the response of corroded RC columns.
(4) Further experimental study is required for validation and calibrate of the present numerical model. However, the modelling technique developed in this paper has significantly improved the earlier models and can be used by other researchers in the future research for seismic vulnerability and fragility analysis of corroded RC bridges.

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