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A multi-mechanical nonlinear fibre beam-column model for corroded columns

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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 sections using OpenSees. The nonlinear uniaxial material models used in the fibre sections 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 advance material model is used to simulate the nonlinear behaviour of the 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 columns.

1 Introduction

Over the past couple of decades researchers have made significant efforts to improve a general understanding of seismic design and analysis of structures in earthquake prone regions. As a result of these efforts the Performance-Based Earthquake Engineering (PBEE) framework has been developed. This is very well established among researchers and practising engineers around the world.

Many structures, in regions of high seismicity, are also exposed to corrosive environments. Among the different deterioration mechanisms, corrosion of reinforcing steel is the most

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common reason for the premature deterioration of RC structures in a chloride laden environment. This leads to loss of the steel, within the cross section, and a weakening of the bond and anchorage between concrete and reinforcement. This directly affects structural serviceability and strength. Therefore, this can significantly increase the seismic risk of deteriorating structures. Additionally, this increased vulnerability may be seen at all performance levels; and so it can increase the Whole Life Cycle Cost (WLCC) of the structure. 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.

This has led researchers around world to study the effect of corrosion on seismic vulnerability and fragility of existing aging bridges (Choe et al., 2008, Berto et al., 2009, Gosh and Padgett 2010, Alipour et al. 2011, Biondini et al., 2013).

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 the stress-strain behaviour of reinforcing steel. Moreover, in most cases the corrosion damage has only been limited to the reinforcing bars (only considering an average reduced area or reduced yield strength). The impact of corrosion on ductility loss and reduced low-cycle fatigue life of the reinforcing steel in tension and its buckling strength in compression is not considered. The impact of corrosion of horizontal tie reinforcement on confined concrete and cracking of cover concrete due to corrosion of vertical reinforcement are ignored in the previous models. Therefore, the seismic vulnerability of corroded bridges might be underestimated. Furthermore, recent experimental studies on the nonlinear stress-strain behaviour of corroded reinforcing bars under monotonic and cyclic loading showed that corrosion has a significant effect on hysteretic and inelastic buckling behaviour of corroded bars (Apostolopoulos and Michalopoulos 2006, Apostolopoulos et.al. 2008, Apostolopoulos and Michalopoulos 2007, Apostolopoulos 2007, Apostolopoulos et. al. 2008, Kashani et al. 2013a, b). To this end, there is a need for more detailed and accurate numerical model to represent the impact of corrosion on nonlinear seismic response of RC structures.

This paper presents an advanced numerical model for the response prediction of the corroded RC columns. The model accounts for the impact of corrosion on (i) reinforcing steel

(including pitting effect, buckling, ductility loss and reduced low-cycle fatigue life), (ii) cracked cover concrete due to corrosion of reinforcement and (iii) reduced capacity and ductility of confined concrete due to corrosion of confinement reinforcement.

2 Finite element model development

2.1 Proposed nonlinear fibre beam-column 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 The proposed finite element model utilising nonlinear fibre beam-column element

2.2 Modelling geometrical properties of corroded bars

The 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 .

$$A_{ave} = A_0(1 - 0.01\psi) \quad (1)$$

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).

$$A' = \gamma A_{ave} \quad (2)$$

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:

$$I'_{min} = K I_0 \quad (3)$$

where, K is the mean value of pitting coefficient of minimum second moment of area of corroded 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).

$$M_{(\gamma \text{ or } K)} = \exp\left(\mu + \frac{\sigma^2}{2}\right) \quad (4)$$

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

$$\mu = a\psi^b \quad (5)$$

$$\sigma = c\psi^d \quad (6)$$

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

2.3 Buckling length calculation using Dhakal-Maekawa method

Dhakal and Maekawa (2002a) studied the buckling behaviour of vertical reinforcement in rectangular columns. Using energy method, they derived the buckling mode shape accounting

for the influence of tie stiffness on buckling length. This model was used in a finite element analysis of a cantilever column that was subjected to lateral and axial loads. The results of this model agreed fairly well with experimental results. However, Dhakal-Maekawa model has not been validated for circular columns. In this research, the proposed Dhakal-Maekawa model has been used to calculate the buckling length of proposed RC column that is discussed in Section 3 of this paper.

The proposed Dhakal-Maekawa model is shown in Figure 2. The longitudinal reinforcing bar is considered as a beam fixed at both ends of the buckling length to emulate the restraining mechanism of horizontal ties. A cosine shape function satisfying the fixed boundary condition is then employed to define the deformed configuration of buckled bar.

Figure 2 Dhakal-Maekawa bar buckling model

Given the buckling of reinforcing bars is an inelastic buckling phenomenon the elastic flexural rigidity $E_s I$ cannot be used here (Timoshenko 1963). Dhakal-Maekawa suggested an average flexural rigidity EI defined in Equation (1) in which has been validated against an extensive set of experimental data.

$$EI = \frac{E_s I}{2} \sqrt{\frac{\sigma_y}{400}} \quad (7)$$

Where, E_s and σ_y are the elastic modules and yield strength of the vertical reinforcement in MPa respectively.

In this study the stiffness of horizontal ties (spiral reinforcement) is computed using the empirical Equation (2) suggested by Pantazopoulou (1998).

$$K_t = \frac{4E_{sp}A_{sp}}{\sqrt{(s^2 + d_c^2)}} \quad (8)$$

Where, E_{sp} is the elastic modules of spiral reinforcement, A_{sp} is the cross section area of spiral reinforcement, s is the spiral pitch and d_c is the core diameter.

The impact of corrosion on buckling length of corroded columns can be considered by modifying the geometrical properties and yield strength of corroded bars. Further details are available in Kashani (2014).

2.4 Phenomenological hysteretic model for reinforcing steel

In the previous section the geometrical properties of the vertical reinforcement in column have been modified using the experimental data and the mathematical models available in the literature (Kashani et al. 2013a, b). The impact of the corrosion pattern on nonlinear cyclic response of corroded reinforcing bars has been investigated by Kashani et al. (2014) through a comprehensive nonlinear finite element analysis. Using the data generated from the nonlinear finite element analysis and experimental data (Kashani et al. 2013a, b) they have developed a new phenomenological hysteretic model for corroded reinforcing bars. The features included in the new model are including the inelastic buckling and post-buckling, reduced yield strength and ductility and low-cycle fatigue degradation due to corrosion. Once the model is validated against the experimental data of isolated corroded bars, it has been implemented in OpenSees (Figure 3). To account for the influence of ties stiffness on cyclic behaviour of vertical reinforcement a parametric study conducted on 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

2.5 Confined and unconfined concrete model accounting for corrosion damage

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 the 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 confined concrete as a function of reduced ductility of hoop reinforcement (further detail is available in Kashani (2014)). The *Concrete04* (material model) available in the OpenSees is used to model both confined and unconfined concrete. The 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. It should be noted that the unconfined concrete model is used for cover concrete and a confined concrete model is used for the core concrete. The unconfined and confined concrete models used in the analysis are shown in Figure 4.

(a)

(b)

Figure 4 Material model of concrete (tension positive and compression negative): (a) unconfined cover concrete (b) confined core concrete

2.6 Modelling strain penetration at base of the column using zero length element

Corrosion affects the reinforcing bars that lie 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 in uncorroded columns. This has been observed experimentally (Ou et al. 2011, Ma et al. 2012).

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 here to model the bond-slip behaviour of RC columns due to strain penetration at the column foundation interface.

3 Proposed case study column

UW-PEER experimental RC column database (Berry et al. 2004) is used to validate the basic uncorroded model. The details of the model validation and calibration process are available in Kashani (2014). The impact of corrosion on material properties including inelastic buckling and low-cycle fatigue life of the reinforcing bars are validated against material dataset explained in previous sections. Here, one of the columns in UW-PEER database is considered as a case study column 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 details of case study column analysed in this paper.

Figure 5 Details of the case study column: (a) cross section (b) elevation

4 Nonlinear analysis of the case study column

The impact of different corrosion models on the nonlinear response of this RC columns is explored in this section. This exploration study uses a series of nonlinear pushover and cyclic finite element analyses. The experimental data of the actual uncorroded column is used to validate and calibrate the basic numerical model for the uncorroded columns. Figure 6 shows a comparison of the numerical model and experimental response of this column.

Figure 6 Comparison of the experimental and numerical result of the original uncorroded column

Nonlinear pushover analysis is conducted to explore the impact of corrosion on drift capacity and strength loss of the RC column with varied corrosion levels. Nonlinear cyclic analysis using the load history that was used in the experiment is conducted to explore the impact of cyclic degradation. For each analysis type three cases are considered:

- i. Reinforcing steel is corroded; cover and core concrete are not affected by corrosion.
- ii. Reinforcing steel is corroded, cover concrete is cracked due to corrosion and core concrete is not affected by corrosion.
- iii. Reinforcing steel is corroded, cover concrete is cracked and core concrete is affected due to corrosion of confining reinforcement.

4.1 Case i: Corrosion induced damage to vertical reinforcement only

The steel model described in Section 2.4 is used which includes the impact of corrosion on the buckling and post-buckling behaviour in compression and strength and ductility loss in tension. It is assumed that the corrosion damage is only limited to the steel reinforcement (both vertical and horizontal tie reinforcement), cover concrete is uncracked and corrosion of confining reinforcement doesn't affect the confined concrete behaviour.

The results of monotonic pushover analyses are shown in Figure 7. The results show that the failure mode of the column is bar buckling and concrete crushing up to 10% mass loss. However, once the corrosion level exceeds 10% mass loss the failure mode changes from bar buckling and concrete crushing in compression to fracture of vertical bars in tension.

Figure 7 Nonlinear pushover analyses considering corrosion of vertical reinforcement only

Figure 8a,b shows the results of nonlinear cyclic analyses of the case study column with 10% and 20% mass losses respectively. Comparing the monotonic and cyclic responses (the same

cyclic load protocol as the experiment) show that low-cycle fatigue has a significant impact on corroded columns. The monotonic analysis showed that 10% mass loss didn't result in bar fracture in tension and the failure governed by bar buckling and concrete crushing. However, in cyclic analysis the failure mode is combined bar buckling and concrete crushing in compression followed by bar fracture in tension due to low-cycle fatigue. It was found that mass loss ratio greater than 10% has a significant impact on nonlinear response of corroded columns due to reduced low-cycle fatigue life. Figure 8b shows that 20% mass loss resulted in bar fracture at 0.05 drift ratio in pushover analysis but it results in bar fracture at 0.03 drift ratio under cyclic loading due to low-cycle fatigue failure

Figure 8 Nonlinear cyclic analyses considering corrosion of vertical reinforcement only: (a) 10% mass loss (b) 20% mass loss

4.2 Case ii: Corrosion induced damage to vertical reinforcement and cover concrete

The assumption in this case is that corrosion damaged is affecting the reinforcing steel as well as the cover concrete through cracking and spalling. The results of the nonlinear

pushover analyses are shown in Figure 9. The results in this case are almost identical to the previous case (section 4.1) where the damage in cover concrete was not considered. Therefore, it is concluded that, considering the corrosion induced cracking of cover concrete doesn't have a significant impact on the nonlinear response of corroded columns.

Figure 9 Nonlinear pushover analyses considering corrosion of vertical reinforcement and corrosion induced crack in cover concrete

4.3 Case iii: Corrosion induced damage to vertical reinforcement, cover concrete and confined concrete

The assumption in this case is that corrosion affects the reinforcing steel, cracked cover concrete through corrosion of vertical reinforcement and damaged confined concrete through corrosion of horizontal tie reinforcement. The results of nonlinear pushover analyses are shown in Figure 10.

The results show that the failure mechanism of column, up to 10% mass loss, is bar buckling and concrete crushing in compression. However, once the corrosion level exceeds 10% it results in changing of the failure mode. It was found that generally in this case the drift capacity loss starts with bar buckling and concrete crushing in compression and then followed by bar fracture in tension. The analyses results show that considering the impact of corrosion damage on confined concrete results in a rapid reduction in strength and ductility of the corroded columns. It indicates a much more severe impact on the corroded columns compare to the previous cases where the confined concrete was considered to be undamaged.

Figure 10 Nonlinear pushover analyses considering corrosion of vertical reinforcement, cracked cover concrete and damaged core confined concrete

The results of nonlinear cyclic analyses are shown in Figure 11. It shows that the extent of corrosion damage under cyclic loading is more severe than monotonic loading. The results of monotonic analyses showed that considering ductility loss of corroded bars in tension and confinement reinforcement in compression has a big impact in bar buckling and fracture of reinforcement. However, cyclic analyses results show that considering cyclic degradation due to low-cycle fatigue is crucial to have a realistic evaluation of the seismic performance of existing corroded bridges. For example in Figure 11a,b the failure of the column was govern by bar buckling and concrete crushing for corrosion level up to 10% under monotonic loading. However, the same corrosion level results in more severe ductility loss under cyclic loading due to reduced low-cycle fatigue life.

(a)

(b)

Figure 11 Nonlinear pushover analyses considering corrosion of vertical reinforcement only

5 Conclusions

A numerical model is presented that enables simulation of the nonlinear flexural response of RC components with corroded reinforcement. This model simulates the inelastic buckling and low-cycle fatigue degradation of longitudinal reinforcement under cyclic loading. Typical concrete constitutive model functions are employed to simulate the response of components with corroded reinforcement. However, the cover concrete strength is adjusted to account for corrosion induced damage and the core concrete strength and ductility adjusted to account for corrosion induced damage to transverse reinforcement. Finally, nonlinear pushover and cyclic analyses on a hypothetical corroded RC column are conducted. The main outcome of this study can be summarised as follows:

- (1) The results of analyses showed that corrosion has a more significant impact on ductility loss of RC columns than the strength loss (plastic moment capacity). It was found that 10% mass loss results in about 10% reduction in the plastic moment capacity of the column but reduces the drift capacity by about 19%.
- (2) The simulation results showed that the cyclic degradation due to low-cycle fatigue has a significant influence on the response of corroded RC columns. Therefore, for seismic performance assessment and evaluation of existing corroded bridges monotonic pushover analysis is insufficient.
- (3) It was found that in some cases the flexural failure is initiated by the buckling of vertical bars and crushing of core concrete which then followed by fracture of bars in tension. This behaviour depends on the level of axial force, ratio of vertical reinforcement in

column, mass loss ratio and loading protocol (monotonic or cyclic). This is an area for future research.

- (4) The results of this study suggest that further experimental studies are required for validation and calibration of the proposed 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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