Nonlinear FEM Simulation of Structural Performance of Corroded RCColumns subjected to Axial Compression

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ABSTRACT

This paper presents a numerical model for predicting the behaviour of reinforced concrete (RC) columns with corroded reinforcing steel subjected to axial compression. The influence of the steel corrosion on the mechanical properties of the rebars and the concrete (in the unconfined cover and the confined core) is taken into account in the numerical model. In addition, the premature buckling behaviour of the corroded longitudinal rebars under compression is also considered. To model the complex material behaviour of the concrete, the recently developed microplane model M4L is used. It is found that the predictions from the computational model are in very good agreement with the test observations.

Key words: Reinforced concrete (RC) column, axial compression, steel corrosion, finite element simulation, microplane model

1. INTRODUCTION

The corrosion of embedded reinforcing steel is the principal cause of deterioration of reinforced concrete (RC) structures in a chloride-laden environment. The corrosion of the reinforcing steel results in the loss of the steel cross section and of the mechanical properties of the material, the cracking, spalling and delamination of the cover concrete, as well as the decrease of the bond between concrete and steel. As a consequence, the serviceability, the load carrying capacity and the residual service life of the structures are reduced.

Nonlinear finite element method (FEM) provides an important option for studying the response and residual load carrying capacity of corroded RC structures. In the past years, significant efforts have been devoted in this field. Nonlinear FEM simulation of corroded RC structures is often conducted through incorporating the corrosion induced damage into the computational model for non-corroded structures through modifying various input parameters. Most previous efforts were focused on the numerical simulation of the flexural and shear performance of RC members. In these studies, the loss of the cross section and/or the strength and ductility of the reinforcing steel, as well as the reduction of the bond between concrete and steel were often considered [1]. In some studies [2-4], the decrease of the compressive strength of the cracked concrete caused by the steel corrosion was also taken into account to better simulate the structural response. Recently, Kioumarsi et al. [5-6] performed a detailed 3D non-linear finite element simulation of the residual flexural capacity of corroded RC beam. In their work, the damage induced by the steel corrosion was simulated by reducing the cross section, reducing the yield and ultimate strength of the rebars, decreasing the bond strength and modifying the bond-slip behaviour between concrete and steel, and reducing the strength of cracked concrete.

Until now, only very limited work on the numerical simulation of corroded RC columns under axial compression has been carried out, despite that the corrosion of the reinforcing steel can have a profound influence on the stiffness and the load carrying capacity of RC columns [7-8]. It is thus of crucial importance to accurately predict the real behaviour of axially loaded RC columns affected by steel corrosion. Finozzi and Saetta [9] reported such a numerical simulation using a two-dimensional (2D) numerical model based on damage mechanics. The predicted failure loads for the columns were in good agreement with the test data; however, the depicted stiffness and deformation behaviour of the columns are less satisfactory. This has motivated the authors of this paper to carry out the study in the present paper.

In this paper, a three dimensional (3D) numerical model incorporating a sophisticated material model for concrete is developed to simulate the structural performance of corroded RC columns.

2. ANALYTICAL OBJECTS

Based on the related experimental evidences [7-8], the following effects need to be taken into account in the analysis of axially compressed RC columns affected by steel corrosion:

- The loss of the steel cross section;
- The cracking and spalling of the cover concrete;
- The reduction of the confinement provided by the transverse steel to the core concrete;
- The premature buckling of the longitudinal rebars; and
- The increase of the load eccentricity.

Rodríguez et al. [8] tested a total of 24 RC columns to investigate the impact of the steel corrosion on the response of RC columns. In the present work, two columns tested by Rodríguez et al. [8] are simulated. They are column No. 28 with corroded steel rebars and column No. 22 without any corrosion as a reference column. The columns had a 200×200 mm^2 cross section and a height of 2000 mm. The longitudinal rebars were 4 Φ16 and the transverse rebars were Φ6 (spacing s = 150 mm).The compressive strength of the concrete were 34.0 MPa and 35.6 MPa in the non-corroded and corroded columns, respectively. The yield strengths of the longitudinal and transverse rebars were in the range of 550 – 590 MPa. The chloride attack penetration depth in the corroded longitudinal rebars was 0.63 mm while it was 0.50 mm in the transverse rebars (maximum value of 4.7 mm). The reference column failed at a load of 1702 kN while the failure load of the corroded column was 997 kN, which is about 51% lower than that of the reference column. As mentioned above, the two columns were also simulated by Finozzi and Saetta [9] using a 2D numerical model based on damage mechanics.

3. MODELLING DETAILS

3.1 Material model for concrete

In numerical analysis of RC structures, the modelling of concrete has always been a challenging issue due to the complexity of its material behaviour. To simulate the complex behaviour of the concrete in RC columns under axial compression, a triaxial constitutive model is necessary. In this study, the microplane model M4L for concrete, which was developed in [10-11] recently, is employed to simulate both the column core concrete and the column cover concrete. The model M4L is a macroscopic material model for concrete, which represents a refinement of the previous model M4 [12-13]. In the model M4L for concrete, the constitutive properties of the material are characterized by a relation between the stress and strain components on the mesolevel. The stress-strain relations are defined not in terms of the macrolevel continuum tensors, but in terms of the stress and strain vectors on planes of all possible orientations within the material, which are called microplanes. Through comparing the model predictions with a broad range of test data in literature, the model M4L has been proven to be able to realistically simulate the uni-, bi- and triaxial material behaviour of concrete. More details about the performance of the model and the comparisons with the test data can be found in [11].

The model M4L uses a set of parameters to simulate the mechanical behaviour of concrete subjected to various stress states. These parameters include the modulus of elasticity E_c, the Poisson's ratio v and two groups of microplane parameters, namely k_1 - k_4 and c_1 - c_{27}. The k- and c- parameters are connected to the microplanes, thus they have generally no direct macroscopic physical meanings. The microplane parameters can be identified through numerical fitting of material test data. Numerical experiments [11, 14] indicated that the c- parameters can generally be fixed for all normal concretes. Their reference values are given in [11]. These values for the c- parameters are used in the present work. However, the k- parameters have to be calibrated according to the specified concrete.

However, due to the fact that the microplane constitutive laws on individual microplanes are generally simple one-to-one relations, the fitting of the microplane parameters is possible by using test data for simple stress states, such as unconfined uniaxial compression test, hydrostatic compression test and high confinement compression test. In most cases, only the unconfined uniaxial compression test data is adequate for determining the model parameters.

For the core and the cover concretes in the non-corroded column as well as the core concrete in the corroded column, the model parameters can be easily determined on the basis of the assumed unconfined compression behaviour. It should be noted that the same set of parameters are used for the core and the cover concretes in the non-corroded column, namely,

$E_c = 26165$ MPa, $v = 0.20$, $k_1 = 1.12 \times 10^{-4}$, $k_2 = 1000$, $k_3 = 16$, $k_4 = 15$.

For the core concrete in the corroded column, the used model parameters are:

$E_c = 26774$ MPa, $v = 0.20$, $k_1 = 1.14 \times 10^{-4}$, $k_2 = 1000$, $k_3 = 16$, $k_4 = 15$.

In the corroded RC column, the corrosion of the reinforcing rebars causes longitudinal cracking in the cover concrete. This cracking reduces the compressive strength of the concrete and needs to be taken into account in numerical simulation. In this paper, the proposal by Coronelli and Gambarova [2] is adopted. In this method, the compressive strength of the (cracked) cover concrete is computed as:

$$f_c^* = \frac{f_c}{1 + k\dfrac{\varepsilon_1}{\varepsilon_{c0}}} \tag{1}$$

in which k is a coefficient depending on the bar roughness and diameter, typically $k = 0.1$; ε_{c0} is the strain at the peak compressive stress (strength) f_c; ε_1 is the average tensile strain in the cracked concrete. More details about the determination of the compressive strength of the cracked concrete can be found in Coronelli and Gambarova [2].

Based on the estimated compressive strength of the cracked cover concrete according to Equation (1), the model parameters for the (cracked) cover concrete in the corroded column are determined as:

$E_c = 15032$ MPa, $v = 0.20$, $k_1 = 0.66 \times 10^{-4}$, $k_2 = 1000$, $k_3 = 16$, $k_4 = 15$.

3.2 Material model for reinforcing steel

The stress-strain behaviour of the non-corroded reinforcing steels is simulated by a linear elastic-perfect plastic material model, which is described by the modulus of elasticity E_s and the yield strength f_y of the material.

For the corroded rebars, the loss of the cross section and/or the mechanical properties needs be taken into account in the numerical model. In addition, the premature buckling of the longitudinal rebar and the break of the transverse rebar, as observed in the test [8], should also be considered. In this paper, a bilinear constitutive model is adopted to describe the premature buckling of the corroded longitudinal rebar:

$$\sigma_s = \begin{cases} E_0 \varepsilon_s & (0 \le \varepsilon_s \le \varepsilon_{crit}) \\ E_n \varepsilon_s & (\varepsilon_s > \varepsilon_{crit}) \end{cases} \tag{2}$$

where, ε_{crit} is the steel strain corresponding to the critical stress σ_{crit}, which is calculated as [8]:

$$\sigma_{crit} = \frac{\pi^2 E_s (0.25D)^2}{(0.75L^2)} \tag{3}$$

where, D is the diameter of the corroded longitudinal rebars while L is the buckling length of the transverse rebars, which is assumed to be $L = 3s$ (transverse rebar spacing) since it was detected in the test [8] that 4 transverse rebars were broken. E_n is the slope of the softening branch, which is determined as in [9].

The corroded transverse reinforcing steel is simulated with a linear elastic – plastic material model with limited ductility. The reduced ultimate strain of the steel due to the corrosion is described according to Du et al. [15-16].

3.3 Modelling of reduced cross section of corroded reinforcements

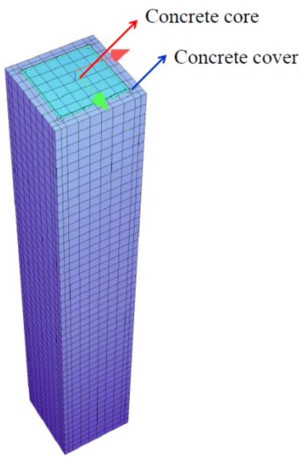
It was observed in the test [8] that the longitudinal rebars in the corroded columns mainly underwent uniform corrosion; while the transverse rebars exhibited both uniform and profound localised (pitting) corrosion with a higher damage level. Based on these observations, the residual cross section of the corroded longitudinal rebar is calculated as:

$$A_{sl} = \frac{\pi}{4}(D_0 - 2\chi)^2 \tag{4}$$

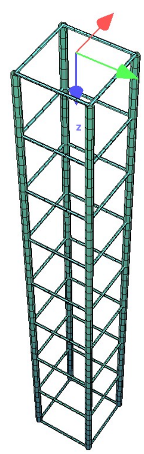
in which, D_0 is the initial diameter of the reinforcement; χ is the depth of corrosion (mm).

The residual cross section area of the corroded transverse reinforcement is computed as [9]:

$$A_{st} = \frac{\pi}{4}D_0^2 - \frac{\pi}{4}(2D_0\chi - \chi^2) \tag{5}$$



(a) *Cover and core concrete*



(b) *Longitudinal and transverse reinforcements*

Figure 1 – Finite element mesh of the columns

3.4 Finite element types and meshes

Both the column core and cover concretes are discretised into 8-node brick elements with 2 × 2 × 2 integration points. The reinforcing steels are simulated with 2-node truss elements. Since the columns were subjected to axial compression, no slip between the concrete and reinforcements is assumed. The 3D finite element mesh of the column is illustrated in Figure 1. To facilitate the comparison, the same mesh is used for both the non-corroded and corroded columns. The general crack band model is used to minimize the mesh sensitivity. A uniform displacement is applied on the column top to simulate the axial loading. The increased eccentricity due to the asymmetric damage of the cover concrete is ignored since the selected columns had minimal eccentricity.

4. NUMERICAL RESULTS AND DISCUSSIONS

Figure 2 shows the simulated load – average strain curve of the column No. 22. It can be seen from the figure that the simulations are very close to the test data, both for the stiffness and the ultimate load. This implies that the model M4L is able to realistically capture the complex behaviour of the concrete in the column.

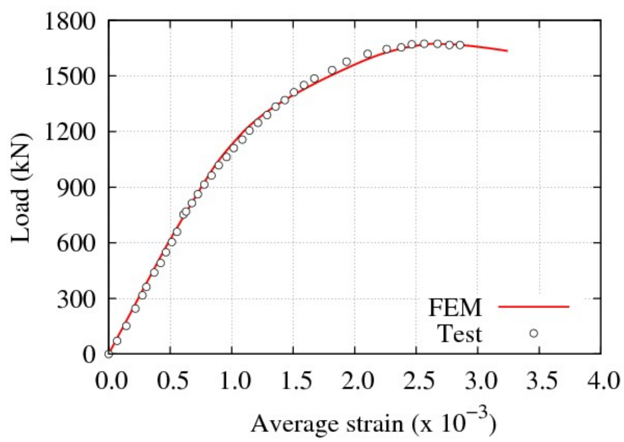


Figure 2 – Load –average strain curve of non-corroded column No.22

A comparison of the predicted load – average curves with the test data for the corroded column No.28 is shown in Figure 3. Two simulation results are shown in the figure: one considers the premature buckling of the longitudinal reinforcement while the other ignores the buckling of the longitudinal rebar (the rebar is modelled as a linear elastic-perfect plastic material). It can be seen that when the premature buckling behaviour of the longitudinal rebar is considered, the numerical predictions are fairly consistent with the test data; while the ignorance of this behaviour results in an overestimation of the maximum load and the post-peak ductility of the column. This indicates that it is necessary to take into account the premature buckling of the longitudinal rebar in numerical simulation of corroded RC columns under axial compression.

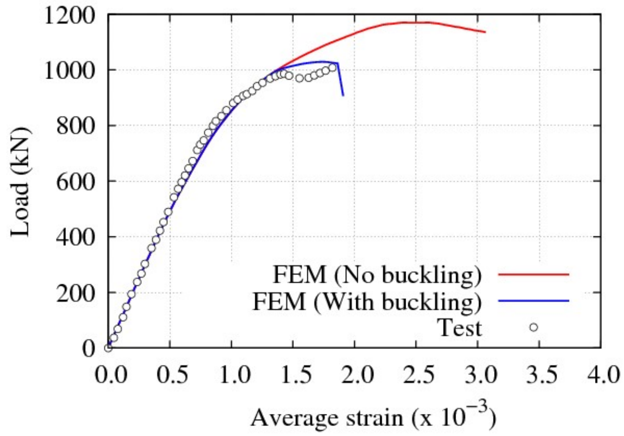


Figure 3 – Load –average strain curve of corroded column No.28

5. CONCLUSIONS AND REMARKS

This paper presents a numerical simulation of non-corroded and corroded RC columns under axial compression by virtue of nonlinear FEM. This work leads to the following conclusions:

- The adopted microplane model M4L is able to realistically capture the behaviour of the concrete in RC columns subjected to axial compression;
- The behaviour of the axially compressed RC column with corroded reinforcing steel can be simulated with adequate accuracy through properly taking into account the cracking and spalling in the concrete cover, the loss of cross section and the reduction of mechanical properties of the transverse rebar, as well as the premature buckling behaviour of the longitudinal rebar;
- An ignorance of the premature buckling of the longitudinal rebar overestimates the ultimate load and the post-peak ductility of the corroded RC column;
- Although the numerical model developed in this paper yields satisfactory simulations of the global load-strain (deformation) response of the corroded column, it should be noted that this model is not adequate for a realistic simulation of the occurrence of the spalling and the delamination of the cover concrete;
- The numerical model for corroded RC columns developed in this paper can be used to quantitatively assess the effect of each individual damage due to the corrosion, such as the corrosion in the reinforcing steel rebars, the premature buckling of the longitudinal rebars, the cracking and spalling of the cover concrete on the structural behaviour of RC columns, which helps to better understand the effect of the corrosion damage on the response of this kind of elements.

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