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Phenomenological hysteretic model for corroded reinforcing bars including inelastic buckling and low-cycle fatigue degradation

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ABSTRACT

A new phenomenological hysteretic model for reinforcing bars with and without corrosion damage is presented. The model simulates buckling of reinforcement, deterioration in post-buckling compressive strength due to strain history and the impact of low-cycle fatigue on tension response. The model, for uncorroded reinforcing bars, is calibrated using data from numerical simulations and corrosion damage parameters are calibrated using experimental data. The model is evaluated using a comprehensive experimental data set, and the results show that the model is in a good agreement with the data.

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1. Introduction

Nonlinear analysis of reinforced concrete (RC) structures subject to seismic loading often employs fibre-type section models to simulate the flexural response of beams, columns and walls. These fibre-type section models are typically used within a plastic hinge or a lumped-or distributed-plasticity beam–column elements [1,2]. Examples include implementations in OpenSees, SeismoStruct and SAP2000 [3–5]. Using a fibre-type section model, the member cross section is decomposed into a number of steel and concrete fibres. The material nonlinearity is represented through uniaxial constitutive models for steel and confined and unconfined concrete. Therefore, the accuracy of the model is highly dependent on the accuracy of the uniaxial constitutive models.

Previous research shows that fibre-type section models and lumped or distribution plasticity element can provide highly accurate simulation of the stiffness, strength and cyclic response of RC members through moderate deformation demands [6,7]. However, few studies have addressed simulation of response to loss of lateral and, ultimately, axial load carrying capacity; and few studies have demonstrate accurate simulation of drift capacity (i.e. the drift at onset of significant lateral strength loss) [8]. For RC members responding in flexure, strength loss typically results from buckling of longitudinal reinforcement, fracture of longitudinal reinforcing due to low-cycle high-amplitude fatigue and/or crushing of core confined concrete. The research presented here focusses on simulating the behaviour of reinforcing steel with the objective of enabling accurate simulation of component failure.

In previous decades, a number of researchers have studied the cyclic behaviour of reinforcing steel with and without buckling [9–23]. They have tried to address simulation of uncorroded reinforcement; however, there are many critical structures that are located in regions of high seismicity and that are exposed to corrosive environments. Recent experimental studies of the cyclic behaviour of RC elements with corroded reinforcement show that corrosion has a significant impact on the response of these structures [24,25]. The experimental results showed that corrosion will change the failure mode of flexural RC components.

In some cases severe buckling were observed due to the combined effects of non-uniform pitting corrosion along the longitudinal reinforcement and corrosion of horizontal ties. Corrosion reduces the stiffness of horizontal ties that are very important elements to prevent the buckling of longitudinal bars. Once corroded bars buckle under cyclic loading, they fracture much faster at lower drift demands. This is due to the combined effect of buckling and non-uniform pitting corrosion that results in a significant reduction in low-cycle fatigue life of corroded RC elements. Accordingly, Kashani et al. [23,26–28] conducted a comprehensive experimental and computational study on the inelastic behaviour of corroded reinforcing bars, including the impact of corrosion pattern on inelastic buckling and degradation due to low-cycle fatigue.

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Moreover, Kashani et al. [23,28] explored that the inelastic buckling of reinforcing bars results in a severe pinching effect on the cyclic stress–strain response of reinforcing bars. This phenomenon is due to the effect of geometrical nonlinearity. This behaviour is not included in any of the previous models [9–11,13,19]. Therefore, one of the objectives of the current paper is to address this important issue.

Here a new phenomenological hysteretic model is developed that significantly improves the inelastic buckling simulation of reinforcing steel with and without corrosion damage. The aims of this paper are:

- To describe this new model that accounts for the combined effect of inelastic buckling and low-cycle fatigue.
- To demonstrate that this new model accounts for the influence of corrosion damage on inelastic buckling and low-cycle high-amplitude fatigue degradation of reinforcing bars.
- To calibrate and validate this model against an extensive experimental and computational data set.

The proposed model combines the material nonlinearity and geometrical nonlinearity due to buckling with low-cycle fatigue degradation into a single material model. This model is currently the most advanced uniaxial material model which is purposely developed for reinforcing bars with and without corrosion damage. Finally, this advanced uniaxial material model has been implemented to the OpenSees [3] to enable the earthquake engineering community to use it in the nonlinear seismic analysis of uncorroded and corroded RC structures.

2. Modelling the nonlinear response of reinforcing bars with the effect of buckling and low-cycle high amplitude fatigue without corrosion damage

Kashani et al. [28] conducted a parametric study of the nonlinear cyclic behaviour of reinforcing bars with and without corrosion damage. The results of computational modelling showed that increasing the L/D ratio beyond 8 (L is the length and D is the diameter of reinforcing bars used in either experiment or finite element model) in reinforcing bars with yield strength between 400 MPa and 500 MPa results in a complex pinching effect in the hysteretic cycles. This is the influence of geometrical nonlinearity on the cyclic response. Other researchers have also come up with the same conclusion based on the experimental results [21–23]. This shows a stable pattern in cyclic behaviour of reinforcing bars with the effect of buckling.

Kashani et al. [28] have made a comparison between the existing analytical models and the computational results. They have demonstrated that the pinching effect due to the geometrical nonlinearity is not included in the existing analytical models (e.g. *ReinforcingSteel* model in OpenSees). The pinching effect in hysteretic cycles of longitudinal reinforcement has a significant influence on the cyclic degradation of RC components subject to seismic loading. Therefore, it needs to be considered in the material model of reinforcement in nonlinear analysis of RC structures under cyclic loading. Accordingly, a set of cyclic rules have been developed in this paper to capture this complex phenomenon.

2.1. Overview of the proposed model

The proposed model consists of seven main states. (1) Tension envelope (TE), (2) compression envelope (CE), (3) unload–reload response for compression to tension (URCT), (4) unload–reload response for tension to compression (URTC), (5) incomplete unload–reload cycles (IURC), (6) degradation in buckling strength due to cyclic loading (BUCKDEG), (7) degradation in tension strength due to low-cycle fatigue/cyclic loading (FATDEG). A diagram of the four main states of the proposed model is shown in Fig. 1. The incomplete unload–reload state and degradation states are not included as they are essentially just modifications of the four basic states and full details of these states are provided later in the paper.

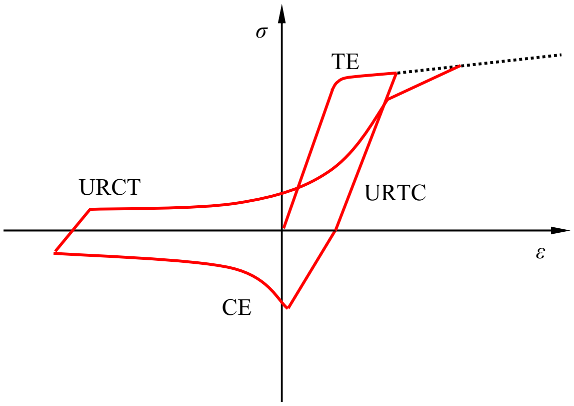

Fig. 1. Proposed phenomenological hysteretic model.

Table 1
Summary of model states and calibration methods.

State	Type of data used in calibration	Equation number in this paper
TE	Experimental	Eq. (1)
CE	Experimental and numerical	Eqs. 2–6
URCT	Experimental	Eqs. 10–16
URTC	Experimental and numerical	Eqs. 7–9
IURC	Experimental	Eq. (17)
BUCKDEG	Numerical	Eq. (7)
FATDEG	Experimental	Eq. (24)

Table 1 summarises the analytical equations and calibration methods used for each state. A mixture of experimental and numerical data have been used to calibrate the model parameters.

To calibrate the model parameters in the proposed model a comprehensive set of experimental and numerical dataset reported by Kashani et al. [23,26,28] is used. The material data for both monotonic bucking and cyclic loading are available in [23,26]. The numerical data used to calibrate the post-buckling behaviour is available in [28].

2.2. Modelling tension response (state TE)

Several models available in the literature define the tension envelope for reinforcing steel [13–16,29]. The model proposed by Balan et al. [15] employs a continuous function that provides a smooth transition from linear elastic to strain hardening region (Fig. 2). This will improve the numerical stability of nonlinear finite element analyses. Therefore, this model is use to define the tension envelope (Eq. (1)).

$$\sigma = \sigma_y \frac{(1-\mu)}{2}\left[1 + \frac{(1+\mu)}{(1-\mu)}\frac{\varepsilon}{\varepsilon_y} - \sqrt{\left(\frac{\varepsilon}{\varepsilon_y}\right)^2 + \delta}\right] \tag{1}$$

where $\mu = E_h/E_s$ is the hardening ratio with E_s and E_h equal to the elastic modulus and hardening modulus for the steel, σ_y is the yield stress, ε is the current strain, ε_y is the yield strain and δ is a shape parameter. Eq. (1) represents a hyperbola with two asymptotes, one with slope E_s and one with slope E_h. The shape parameter, δ, defines the curvature radius of the transition between linear elastic

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