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A 3D flexure–shear fiber element for modeling the seismic behavior of reinforced concrete columns

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ABSTRACT

In order to model the nonlinear seismic behavior of reinforced concrete (RC) columns under a combined loading of axial force, biaxial bending moment and shear force, a displacement-based 3D flexure–shear fiber element accounting for the effect of shear–bending interaction is developed and presented. The element is based on the Timoshenko beam theory and the section is discretized into two types of fibers: fiber representing the longitudinal reinforcement bar and fiber representing the concrete with smeared stirrups. The constitutive law of the steel material follows the Menegotto–Pinto model, in which strain hardening and Bauschinger effects are considered. The 3D constitutive model for reinforced concrete follows the basic assumptions of the enhanced Modified Compression Field Theory (MCFT), where plastic strains are introduced as offsets to account for cyclic loading. The axial, shear and bending effects are fully coupled at both the section and the element level, since normal–shear interaction has been taken into account in the enhanced MCFT. The developed fiber element is implemented as a user-defined element in a FEA program, and validated with experimental results for columns under in-plane (2D) and bilateral (3D) cyclic loading. It is found that the proposed 3D flexural–shear fiber element is able to capture the complex hysteretic behavior of shear-dominated RC columns under 2D as well as 3D cyclic loading reasonably well.

1. Introduction

Under earthquake ground motions, reinforced concrete (RC) columns and piers are typically subjected to a combined action of cyclic axial force, biaxial bending and biaxial shear force, and will inevitably enter the nonlinear stage and exhibit complex nonlinear behavior, such as strength deterioration, stiffness degradation, and sometimes pinching of the force–displacement loops when the shear effects dominate. Therefore, the axial–shear–flexure interaction is important for the hysteretic behavior of RC columns and piers [1]. In order to accurately capture such complex structural behavior, solid elements can be adopted in a structural analysis, which, however, will incur high computational costs due to the large number of degrees of freedom involved and therefore are not suitable for common engineering practice [2].

Based on the Euler–Bernouli beam theory in which the effects of shear deformation are neglected [3–5], fiber beam–column element has been developed and adopted in analyzing the dynamic responses of RC members [6], buildings [7] and bridges [8]. This model is capable of predicting the coupled axial and flexural effects on slender beam–column members [5], and offers a good balance between efficiency and accuracy when simulating flexure-dominated RC members. However, the simulation results will not be accurate enough if the shear deformation of the member is obvious, for example, when a column has a shear span ratio lower than 2.

As a result, several modified fiber beam–column elements based on the Timoshenko beam theory or even a generalized beam theory have been proposed to account for the shear deformation in the element. Marini and Spacone [9] developed a fiber-based beam element accounting for shear deformation, with a shear force–deformation relationship at the section level. The shear force and bending moment were coupled at the element level, since equilibrium was enforced along the element. However, the shear behavior was uncoupled from the axial and flexural behavior at the section level, and thus a multi-axial material constitutive model would be needed in order to account for the flexural–shear interaction at both the section and the element levels.

Smeared-crack models, including models based on Modified Compression Field Theory (MCFT) [10] and the softened membrane model (SMM) [11], are considered specifically suitable for the aforementioned purpose [12]. Vecchio and Collins [10] proposed

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the MCFT to predict the shear strength of cracked reinforced concrete members subjected to monotonic loads, and Vecchio [13] introduced the plastic offsets for the cyclic cases. Different fiber beam–column elements adopting the MCFT have been developed by several researchers including Vecchio and Collins [14], Guner [15], Ceresa et al. [16] and Guner and Vecchio [17]. Hsu and Zhu [11] used a different approach and developed the softened membrane model (SMM), which took into account the Poisson's effect after concrete cracked, characterized by two Hsu/Zhu ratios [18]. Mullapudi and Ayoub [19] proposed a flexibility-based fiber beam–column element to account for the flexural–shear interaction using the SMM.

With different concrete 2D constitutive laws, Mohr et al. [2,20] developed a flexibility-based frame element model, in which the shear and vertical strain distributions were assumed to be composed of a series of polynomial shape functions depending on the material state, and both the actual deformation and structural failure mode can be well-captured by this model. In order to perform life-time analysis of RC structures under high shear forces, Ferreira et al. [21] proposed a time-dependent fiber beam element model, which adopted a hybrid (kinematic/force) sectional formulation to simulate the response of RC sections.

The models mentioned above were developed for the 2D monotonic or cyclic loading case. In order to analyze the reinforced concrete members under more complex loading conditions, including axial force, biaxial bending moment and biaxial shear force, different 3D models were developed. Bairan and Mari [22,23] developed a 3D nonlinear fiber sectional model for concrete structures capable of simulating the total interaction between all six internal forces and deformations. The warping–distortion of the section was considered in the section kinematics. Based on the simple section kinematic assumptions in the Timoshenko beam theory, Gregori et al. [24] proposed a model that used a 3D reinforced concrete constitutive model based on the MCFT for the analysis of curved 3D frame elements under combined axial force, biaxial bending moment, torsion and biaxial shear force. Based on the concept of degenerated solid element, Long et al. [25] proposed a fiber beam element using a 3D plasticity-based concrete constitutive model to predict the shear failure of RC beam–column members. However, all these 3D models were used to simulate the behavior of RC beam–column members subjected to monotonic loading only, and did not consider the cyclic loading case, which limited their application in earthquake engineering. To consider the cyclic loading case, Saritas and Filippou [26] proposed a 3D model using a class of plastic-damage material model as the concrete constitutive model, which could simulate the extreme loading situations in the columns. However, the model was verified in a plane stress condition instead of under 3D loading, and it could not capture the pinching effects observed in previous experimental research. Mullapudi and Ayoub [27] proposed a force-based 3D frame element using a 3D concrete constitutive model based on the softened membrane model, in order to simulate the combined 3D loading effect on concrete members. The model was validated with experimental results for columns subjected to a combined action of axial force, torsion and cyclic uniaxial moment.

The objective of the research presented in this paper is to develop a 3D fiber beam–column model for simulating the nonlinear behavior of shear-dominated RC columns under cyclic 3D loading, which can also capture the pinching effects. The model is a 3-node fiber beam–column element based on the Timoshenko beam theory. Each section of the fiber element is discretized into two types of fibers: fiber representing the longitudinal reinforcement bar and fiber representing the concrete with smeared stirrups. The reinforced concrete constitutive behavior used is based on the enhanced Modified Compression Field Theory, where the plastic strains are introduced as offsets to account for cyclic loading. Normal–shear interaction is inherently considered, since normal and shear behavior are based on 3D stress–strain states. Thus, the axial, biaxial bending and biaxial shear effects are fully coupled at both the section level and the element level. The proposed element is implemented in the explicit finite element code ABAQUS [28] via the user subroutine VUEL.

2. Constitutive models

2.1. 3D constitutive model for concrete

The Modified Compression Field Theory (MCFT) is capable of accurately predicting the shear strength of reinforced concrete members under 2D stress conditions, and plastic offsets was introduced by Vecchio [13] in order to model cyclic responses. MCFT was extended to the 3D monotonic case by Vecchio and Selby [29]. Therefore, plastic strains are introduced as offsets to the 3D MCFT-based model proposed in this paper, in order to model cyclic responses.

The pseudo-force approach is used to account for the plastic offsets. Hence,

$$\{\sigma\} = [D]\cdot\{\varepsilon\} - \{\sigma^0\} \tag{1}$$

where $[D]$ is the stiffness matrix. $\{\sigma^0\}$ is the pseudo-stress vector due to the plastic offsets considering contributions from concrete and reinforcement bars:

$$\{\sigma^0\} = [D_c]\{\varepsilon_c^p\} + [D_{sx}]\{\varepsilon_{sx}^p\} + [D_{sy}]\left\{\varepsilon_{sy}^p\right\} + [D_{sz}]\{\varepsilon_{sz}^p\} \tag{2}$$

where $[D_c]$ is the stiffness matrix for the concrete; $[D_{sx}]$, $[D_{sy}]$ and $[D_{sz}]$ are the stiffness matrices for the reinforcement in the x-, y- and z-directions, respectively.

Cracked concrete is treated as an orthotropic material in the principal directions (1, 2, 3) and Poisson's effect is generally negligible after cracking [29]. Thus, the concrete material stiffness matrix $[D_c]'$, evaluated with respect to the principal axes, is

$$[D_c]' = \begin{bmatrix} \overline{E}_{c1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \overline{E}_{c2} & 0 & 0 & 0 & 0 \\ 0 & 0 & \overline{E}_{c3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \overline{G}_{c12} & 0 & 0 \\ 0 & 0 & 0 & 0 & \overline{G}_{c23} & 0 \\ 0 & 0 & 0 & 0 & 0 & \overline{G}_{c13} \end{bmatrix} \tag{3}$$

where $\overline{E}_{c1}$, $\overline{E}_{c2}$, $\overline{E}_{c3}$, $\overline{G}_{c12}$, $\overline{G}_{c23}$ and $\overline{G}_{c13}$ are the secant moduli, which are defined as follows [29]:

$$\overline{E}_{c1} = \frac{\sigma_{c1}}{\varepsilon_{c1}^e},\quad \overline{E}_{c2} = \frac{\sigma_{c2}}{\varepsilon_{c2}^e},\quad \overline{E}_{c3} = \frac{\sigma_{c3}}{\varepsilon_{c3}^e},\quad \overline{G}_{c12} = \frac{\overline{E}_{c1}\cdot\overline{E}_{c2}}{\overline{E}_{c1}+\overline{E}_{c2}},$$
$$\overline{G}_{c23} = \frac{\overline{E}_{c2}\cdot\overline{E}_{c3}}{\overline{E}_{c2}+\overline{E}_{c3}},\quad \overline{G}_{c13} = \frac{\overline{E}_{c1}\cdot\overline{E}_{c3}}{\overline{E}_{c1}+\overline{E}_{c3}} \tag{4}$$

where ε_{c1}^e, ε_{c2}^e and ε_{c3}^e are the principal elastic strains in the concrete; σ_{c1}, σ_{c2} and σ_{c3} are the corresponding principal stresses.

In MCFT, the principal strain–stress directions are those corresponding to the average elastic compressive and tensile strains (crack directions) [10,29]. The concrete material stiffness matrix needs to be transformed from the principal axes system to the global axes system.

$$[D_c] = [T_c]^T[D_c]'[T_c] \tag{5}$$

where the transformation matrix $[T_c]$ is given as follows [29]: