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A computationally efficient model for the cyclic behavior of reinforced concrete structural members

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ABSTRACT

During the last decades, many researchers have proposed a number of constitutive models for simulating the behavior of reinforced concrete structures under cyclic loading. The finite element analysis, has been used in the past, to produce solutions for specific structural members that undergo different loading conditions. The purpose of this paper is to propose a computationally efficient finite element based numerical method in order to simulate accurately and efficiently the mechanical behavior of a wide range of reinforced concrete structural members under cyclic loading. The proposed method is based on the experimental results and the concrete modeling of Kotsovos and Pavlovic (1995) as modified by Markou and Papadrakakis (2013). A new algorithmic formulation that describes the development of microcracking, macrocracking and the brittle behavior of the concrete under cyclic behavior, is presented. The concrete domain is simulated by 8- and 20-noded hexahedral elements, which treat cracking with the smeared crack approach. Steel reinforcement is modeled with truss and beam elements which are considered embedded inside the hexahedral concrete mesh. The numerical accuracy of the proposed method is demonstrated by comparing the numerically force-deflection curves with the corresponding experimental results found in the literature.

1. Introduction

The complex behavior of reinforced concrete under biaxial or triaxial cyclically varying stresses necessitates the use of advanced theoretical tools for investigation of the behavior of such structures. In addition, analytical or numerical models have been implemented to allow the extrapolation of experimental results to cover the many parameter variations which cannot be experimentally investigated because of cost limitations. Most numerical applications which are presented in the literature, produce realistic solutions to restricted types of structural members. A brief literature review of the developed numerical models in order to analyze RC structures under cyclic loading conditions are presented below.

Most researchers use elastoplastic uniaxial constitutive laws in order to describe the mechanical behavior of concrete. The uncracked concrete behaves as an isotropic material while after cracking an orthotropic constitutive law normal to crack direction is used. Cervenka et al. [3] proposed an inelastic behavior of reinforced concrete planar triangular elements which are subjected to in plane forces. The model used a uniaxial constitutive law of concrete which behaves as elastic perfectly plastic in compression and elastically in tension. This study indicates the necessity of accurate simulation of bond-slip and multiple cracking during cyclic loading. Agrawal et al. [4] proposed an elastoplastic behavior for both concrete and steel reinforcement in order to simulate planar reinforced concrete members under cyclic loads. This study predicts the setting of two open cracks in a concrete element and its major role for the cyclic behavior of concrete. Rule and Rowlands [5], developed a nonlinear model with the use of constant-strain triangular elements in order to predict the ultimate capacity of RC structures under cyclic plane stress conditions. The study suggests that reinforced concrete behaves like a strain-induced orthotropic material and steel reinforcement would provide some shear stiffness to the reinforced concrete structure by introducing a non-zero shear modulus. The model is validated by simulating the biaxial response of a cyclically loaded deep beam structural member. Kwan and Billington [6], implemented 8-noded plane-stress finite elements for investigating the influence of the material model and the method of simulating some postcracking characteristics on hysteretic behavior of reinforced concrete structures. The authors reported that the proposed model was able to describe efficiently the flexure-dominated behavior of the structures. Kwak

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and Kim [7], proposed a numerical orthotropic strain induced constitutive model for 2D analysis of reinforced concrete shear walls subjected to cyclic loading conditions. The concrete domain is discretized by 4-noded quadrilateral elements. Their numerical model proposed a modification of the stress-strain law of steel reinforcement in order to simulate the pinching effects on the response of shear walls under cyclic loading.

Many researchers used the "equivalent uniaxial strain" concept introduced by Darwin and Pecknold [8] in order to associate biaxial or triaxial response of RC structures through the use of orthotropic uniaxial constitutive laws. Darwin and Pecknold [8] developed a nonlinear stress-strain law for plain concrete under biaxial stresses and incorporated into four-noded isoparametric quadrilateral finite elements. The analysis showed reasonable agreement with experimental results as stated by the authors. Balan et al. [9] proposed a 3D constitutive hypoplastic orthotropic model by using the equivalent uniaxial concept advanced by Darwin and Pecnold [8]. The model was implemented in a single 8-noded 3D concrete element in order to capture the triaxial cyclic response of a concrete specimen. Later, Balan et al. [10] improve this model by considering the effect of the post peak behavior of concrete due to lateral confinement. The model is also used efficiently by Kwon et Spacone [11] adding the coupling between the deviatoric and the volumetric stresses. The model is used for the analysis of the three dimensional response of concrete specimens under cyclic loading and RC column under monotonic loading conditions. Girard and Bastien [12], developed a 3D hypoelastic constitutive numerical model, based in the equivalent strains proposed by Darwin and Pecknold [8], in order to investigate the cyclic response of columns taking into account the bond-slip effect. This study used 20-noded hexahedral finite elements in order to analyze a RC column. The study indicates the essence of a realistic modeling of bond-slip effects on structural behavior. Finally, Au and Bai [13] presented an orthotropic strain induced constitutive model based on secant modulus approach using the uniaxial strain concept with 4-node rectangular linear displacement finite elements for 2D analysis of reinforced concrete beams under monotonic and non-reversed cyclic loading. In addition to that, the bond-slip effect was modeled by adopting contact elements. They stated that the numerical results showed good agreement with the experimental data.

Other researchers try to construct constitutive models based on the principles of plasticity using biaxial or triaxial failure surfaces. Sfakianakis and Fardis [14] proposed a finite element formulation which is based on the distributed inelasticity discrete models for the flexural response of slender reinforced concrete columns under cyclic loading. The tangent flexibility matrix is constructed according to the bounding surface of each cross section along the member length. According to this approach, the model takes into account the distributed nonlinearity across the member and the effect of a non-zero and varying axial load, on the flexural response. Pagnoni et al. [15], suggested a 3D RC bounding surface model combined with the smeared crack approach with the use of isoparametric 8-noded finite elements. This study indicates the necessity of the accurate prediction of concrete under triaxial state of stress. Cela [16], described an elastic-viscoplastic law based on the Drucker-Prager model for simulating the reinforced concrete behavior subjected to dynamic plain-stress loading conditions. Ozbolt et al. [17] proposed a three-dimensional microplane model by introducing many material parameters which are defined for every microplane. The model is implemented within a 4-noded isoparametric plane-stress finite element in order to describe the biaxial response and examine the rate effect of concrete specimens under cyclic loading conditions. Eligehausen et al. [18], studied a numerical simulation of beam-column RC joints for 3D nonlinear analyses under cyclic loading, based on Ozbolt's [17] microplane model. The bond-slip effect was taken into account by assuming a 1D nonlinear spring with a bond-slip relationship. The simulation was capable to model the general behavior of the specimens, as stated by the authors.

In addition to the above, many researchers used the compression field theory to treat the behavior of cracked RC elements subjected to shear. Inoue et al. [19], presented a nonlinear finite element method for dynamic analysis of shear walls, in which hysteretic characteristics of concrete and reinforcement were proposed using uniaxial constitutive models. The FEM analysis is implemented by assembling isoparametric plane-stress elements with four nodes for reinforced concrete wall panels and 8-noded solid elements for slabs that were supported on wall panels. Vecchio [20], modeled the RC members through the use of a 4-noded plane-stress finite elements. A secant stiffness-based finite element algorithm was presented for the analysis of concrete structures under general loading conditions, including reversed cyclic loads. Palermo and Vecchio [21], predicted the load-deformation of shear walls based on a modified compression field theory using 4-noded plane and hexahedral elements in order to evaluate 2D and 3D analysis, respectively, under cyclic loading conditions. They stated that their proposed model provides satisfactory results although improvements to the hysteretic behavior are required.

Other models found in the international literature, combine the elastoplastic isotropic uncracked behavior of concrete with fracture energy based smeared crack approaches for the cracked concrete. Ile and Reynouard [22], proposed a constitutive model for predicting the cyclic biaxial response of RC shear walls assuming that concrete is dominated by a plane state of stress through the use of 4-noded isoparametric finite elements. The authors reported that the numerical results showed a good correlation with the experimental data. Furthermore, He et al. [23], proposed an energy based model incorporated in a 4-noded plane-stress quadrilateral finite element for 2D analysis under cyclic loading conditions.

Another group of models proposes the use of different uniaxial constitutive laws in different regions inside the concrete members. To et al. [24], proposed a strut and tie nonlinear model of RC frames using five different element types for cyclic loading conditions. Melo et al. [25], used fiber beam elements in order to model the nonlinear analysis of a two-span RC beam during cyclic loading. Each element was divided into three partitions: two hinges at the ends and a linear-elastic region in the middle. The model notes the importance of including the bond-slip effect on the global response of the beam.

Some models based on damage mechanics are suggested for concrete behavior under cyclic loading. Richard et al. [26], presented a set of constitutive equations which describe microcracking, sliding influence and partial stiffness recovery in order to compose a 3D constitutive model for concrete structures based on isotropic damage mechanics. The authors claimed that the proposed model could be used for large scale structures. Yuchuan et al. [27], developed an energy based anisotropic damage model for analyzing the cyclic behavior of concrete structures. The model proposed nonlinear unloading branches in order to model the hysteretic behavior in tension and compression. An 8-noded hexahedral element was used to model the behavior of a concrete specimen. The authors stated that the numerical results showed reasonable agreement with the experimental ones.

Furthermore, recent studies try to describe the fracture mechanisms of concrete introducing discontinuities within the finite elements. Feist et al. [28] proposed a numerical model based on the strong discontinuity approach (SDA) where elements with embedded discontinuities were used to simulate the fracture processes in plain concrete. Roth et al. [29] combine a damage mechanic model with the extended finite element method (XFEM). In this method the kinematic enrichment is done by introducing additional