Engineering Structures 166 (2018) 363–375

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Cyclic behavior modeling of reinforced concrete shear walls based on softened damage-plasticity model

De-Cheng Feng[a], Xiao-Dan Ren[b], Jie Li[b,*]

[a] Key Laboratory of Concrete and Prestressed Concrete Structures of the Ministry of Education, Southeast University, Nanjing 210096, China
[b] School of Civil Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Keywords:
Cyclic behavior
Shear wall
Softened damage-plasticity model
Multi-layer shell element
Quasi-Newton method
Plasticity offset

ABSTRACT

In this paper, a rational analysis procedure is presented to model the typical cyclic behavior of reinforced concrete (RC) shear wall structures. A recently developed multi-dimensional softened damage-plasticity damage model, where the compression-softening effect of reinforced concrete is considered, is adopted to describe the concrete material behaviors. The steel material behaviors follow a modified Menegotto-Pinto model that including strain hardening, Bauschinger effect and tension stiffening. The multi-layer shell element, which is capable of simulating the coupled in-plane/out-of-plane bending as well as in-plane direct shear and the coupled bending-shear behavior of RC shear walls, is used for the finite element modeling of the structures. To overcome the convergence issues in the analysis procedure, the quasi-Newton method is adopted to solve the nonlinear finite equations and the iterative secant stiffness with plasticity offset for cyclic loading is introduced. Finally, several numerical simulations of RC shear walls with different failure modes are given, illustrating that the developed numerical model can accurately predict the cyclic behavior of RC shear wall structures.

1. Introduction

Nonlinear analysis of reinforced concrete (RC) structures subjected to shear is of great importance for the assessment of the safety performance and development of new design methodology in structural engineering. In the past four decades, several remarkable works [1–7] have been done to establish the analysis method for RC structures in shear. However, there is still an increasing need for rational and robust numerical models in this field.

Traditionally, the related studies can be mainly subdivided into two parts: the constitutive modeling of reinforced concrete, and the finite element formulation for basic structural members. On the first part, various approaches can be used for the material modeling of concrete, e.g., smeared-crack models [1–4] and damage-plasticity models [8–12] among others. The smeared-crack models treat concrete as an orthotropic material, and the cracks are set as the fundamental aspect of the material behavior. In these models, cracks are smeared over the whole material and the strength and stiffness degradation of concrete are represented by the propagation of the cracks. Furthermore, according to the assumption of the cracking direction and the principal stress direction, the models can be grouped into rotating angle models [1,3] and fixed angle models [4]. However, early smeared-crack models are for plain concrete only, the interaction effects between concrete and reinforcement bars in reinforced concrete subjected to shear are neglected. In fact, when subjected to shear, reinforced concrete behaviors can be resolved in the coordinate system of the principal stress direction. The principal tensile stress of concrete will not decay to zero quickly like plain concrete due to the presence of reinforcement bars, which is defined as *tension-stiffening*, while the principal compressive stress will be softened by the transverse stresses and cracks, which is defined as *compression-softening*. The shear behavior of RC structures strongly depends on these two effects. Actually, compression-softening effect was first observed by Robinson and Demorieux [13] in 1968, and then quantified by Vecchio and Collins [1] and Hsu [3], respectively. They have conducted a series of RC shear panel tests, and proposed the uniaxial stress-strain relationships, where a softening coefficient is introduced to account for compression-softening, for reinforced concrete in terms of average stress and average strain through fitting the test data. Then combing equilibrium, compatibility and constitutive laws, they derived two kinds of smeared-crack models for shear behavior modeling of RC structures, which have gradually developed into two families of theories: the modified compressive filed theory (MCFT) family, including MCFT [1] and distributed stress field model (DSFM) [2], and the softened truss model (STM) family, including rotating-angle softened truss model (RA-STM) [3], fixed-angle softened truss model (FA-STM) [4]. These two families are the pioneer work in determining

* Corresponding author.
E-mail address: lijie@tongji.edu.cn (J. Li).

https://doi.org/10.1016/j.engstruct.2018.03.085
Received 24 August 2017; Received in revised form 26 March 2018; Accepted 28 March 2018
0141-0296/ © 2018 Elsevier Ltd. All rights reserved.

the realistic shear behavior of RC structures, and their main contribution is the softening coefficient that considers compression-softening. Now they have been implemented into finite element codes and applied to several numerical investigations of RC structures already.

On the other hand, damage-plasticity model is another one of the most used models for analysis of RC structures. The material degradation is generalized as an internal variable, i.e., damage variable, and the residual strains are described as plastic strains in the framework. By introducing the thermodynamics and the energy based representations, damage and plasticity could be well organized in a class of unified theories. Moreover, several numerical integration algorithms for damage models have also been developed for the material state updating, making the damage-plasticity models a standard tool for the nonlinear numerical simulations of concrete structures [14]. Recently, a kind of phase field models [15,16] are also developed for damage and failure analysis of concrete structures. However, currently most damage models are for plain concrete, which means the compression-softening effect of reinforced concrete in shear cannot be reflected by this kind of models, leading to an over-estimation of the responses.

On the second part, finite element formulation is the other important factor in nonlinear analysis of RC structures. Generally, two kinds of modeling strategies can be followed: macroscopic modeling and microscopic modeling. The macroscopic models, such as fiber beam element [17], multiple vertical line element model (MVLEM) [18], enhanced beam model with shear [19], etc., usually define several simplifications and assumptions on both the element kinematics and material properties. The advantages of this kind of models is simplicity and computational efficiency, thus they can be used for analysis of large scale structures. However, only the global responses can be attained and the numerical accuracy of these models cannot always be guaranteed due to the remarkable multi-dimensional stress state. By contrast, microscopic modeling use 2-D plane strain/stress elements, 2-D shell elements or even 3-D solid elements, along with multi-dimensional constitutive laws, to describe the behavior of structures. Obviously, this approach is more elaborate and provides detailed responses of the local region. Although some numerical issues may arise and the computational cost may be high compared with the macro-models, micro-modeling is still the trend that seems to meet the challenges of engineering practice with the development of numerical methods and computer science.

Based on the above-mentioned background, this paper aims at constructing a rational procedure for the analysis of cyclic shear behaviors of RC structures. The damage-plasticity model is adopted as the framework for the concrete constitutive relation due to its ability and numerical efficiency, and a softened coefficient is introduced to the model to reflect compression softening. The Menegotto-Pinto model with Bauschinger effect is used to model reinforcement bars embedded in concrete while its skeleton curve is modified considering tension-stiffening effect. Multi-layer shell element is employed as the basic finite element for the modeling of typical RC structures subjected to shear, i.e., shear walls. Meanwhile, to improve the numerical performance of the proposed models and avoid convergence problems, the quasi-Newton method is applied to solve the nonlinear equations, and the iterative secant stiffness with plasticity offset corresponding to the developed damage model is also derived for cyclic loading. Several numerical examples are demonstrated finally, verifying the performance of the whole procedure.

2. Softened damage-plasticity model for concrete

2.1. Damage-plasticity model

The bi-scalar damage-plasticity model developed by Wu et al. [12] is adopted as the framework in the paper. According to the thermodynamics, the constitutive relation of concrete can be derived as

$$\boldsymbol{\sigma} = (\mathbb{I}-\mathbb{D}):\mathbb{E}_0:(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{\mathbf{p}}) \tag{1}$$

where $\boldsymbol{\sigma}$ is the stress tensor; $\mathbb{E}_0$ is the fourth-order elastic stiffness tensor; $\mathbb{D}$ is the fourth-order damage tensor; $\mathbb{I}$ is the identity tensor; $\boldsymbol{\varepsilon}$ is the strain tensor and be split into an elastic part $\boldsymbol{\varepsilon}^{\mathbf{e}}$ and a plastic part $\boldsymbol{\varepsilon}^{\mathbf{p}}$ as

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\mathbf{e}} + \boldsymbol{\varepsilon}^{\mathbf{p}} \tag{2}$$

Call for the strain equivalence hypothesis [12], the stress of the undamaged part of material can defined as the effective stress $\bar{\boldsymbol{\sigma}}$, which has the following form

$$\bar{\boldsymbol{\sigma}} = \mathbb{E}_0:(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{\mathbf{p}}) \tag{3}$$

Eq. (3) enables us to decouple the damage and plasticity in the constitutive relation, and thus the plastic strain can be handled in the effective stress space, which may avoid several numerical problems in application. Furthermore, considering the different behaviors of concrete under tension and compression, the effective stress can be decomposed to a positive part $\bar{\boldsymbol{\sigma}}^+$, which denotes the tensile behavior of concrete, and a negative part $\bar{\boldsymbol{\sigma}}^-$, which denotes the compressive behavior of concrete

$$\bar{\boldsymbol{\sigma}} = \bar{\boldsymbol{\sigma}}^+ + \bar{\boldsymbol{\sigma}}^- \tag{4}$$

The spectral decomposition can be followed to achieve Eq. (4), and the expressions of different parts are

$$\bar{\boldsymbol{\sigma}}^+ = \mathbb{P}^+:\bar{\boldsymbol{\sigma}}^+, \quad \bar{\boldsymbol{\sigma}}^- = \mathbb{P}^-:\bar{\boldsymbol{\sigma}}^- \tag{5}$$

$$\mathbb{P}^+ = \sum_i H(\hat{\bar{\sigma}}_i)p_i \otimes p_i, \quad \mathbb{P}^- = \mathbb{I}-\mathbb{P}^+ \tag{6}$$

where $\mathbb{P}^+$ and $\mathbb{P}^-$ are the projection tensors; $\hat{\bar{\sigma}}_i$ is the *i-th* principal stress of the effective stress and p_i is the corresponding principal direction; $H(\cdot)$ is the Heaviside function.

Introducing two damage variables to represent the damage in tensile part and compressive part respectively, the relationship between Cauchy stress and effective stress can be expressed as

$$\boldsymbol{\sigma} = (1-d^+)\bar{\boldsymbol{\sigma}}^+ + (1-d^-)\bar{\boldsymbol{\sigma}}^- \tag{7}$$

Consequently, the fourth-order damage tensor in Eq. (1) can be obtained

$$\mathbb{D} = d^+\mathbb{P}^+ + d^-\mathbb{P}^- \tag{8}$$

The evolution of damage variables can be given in the framework of thermodynamics by proposing Helmholtz free energy potential $\psi^\pm$ and the associated damage release rates $Y^\pm$, which are the driven forces of damages. Moreover, to simplify the construction of damage evolution, Li and Ren [20] proposed the damage consistent condition and the energy equivalent strains enabling that the multi-dimensional damage can be calculated by a uniaxial damage function. The expressions of the energy equivalent strains is given as follows

$$\bar{\varepsilon}^{eq+} = \sqrt{\frac{2Y^+}{E_0}}, \quad \bar{\varepsilon}^{eq-} = \frac{1}{E_0(1-\alpha)}\sqrt{\frac{Y^-}{b_0}} \tag{9}$$

where $\bar{\varepsilon}^{eq+}$ and $\bar{\varepsilon}^{eq-}$ are the tensile and compressive energy equivalent strains, respectively; E_0 is the elastic modulus of concrete; α and b_0 are material parameters; Y^+ and Y^- are the damage release rates as

$$Y^+ = \frac{1}{2}(\bar{\boldsymbol{\sigma}}^+:\mathbb{E}_0^{-1}:\bar{\boldsymbol{\sigma}}), \quad Y^- = b_0(\alpha\bar{I}_1^- + \sqrt{3\bar{J}_2^-})^2 \tag{10}$$

where $\bar{I}_1^-$ is the first invariant of the compressive effective stress $\bar{\boldsymbol{\sigma}}^-$; $\bar{J}_2^-$ is the second invariant of the deviator $\bar{\mathbf{s}}^-$ of the compressive effective stress $\bar{\boldsymbol{\sigma}}^-$.

Therefore, the damage evolution can be obtained by the following uniaxial experimental functions [21,23]

$$d^\pm = \begin{cases} 1-\dfrac{\rho^\pm n^\pm}{n^\pm-1+(x^\pm)^{n^\pm}} & x^\pm < 1 \\ 1-\dfrac{\rho^\pm}{\alpha^\pm(x^\pm-1)^2+x^\pm} & x^\pm > 1 \end{cases} \tag{11}$$

Download English Version:

https://daneshyari.com/en/article/6737497

Download Persian Version:

https://daneshyari.com/article/6737497

Daneshyari.com