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Comparative investigation on influences of concrete material constitutive models on structural behavior

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HIGHLIGHTS

- The two commonly used concrete constitutive models were comprehensively compared.
- The concrete cyclic behavior and crack opening-closing characteristic were investigated.
- The non-linear behavior of composite members was comparatively analyzed.

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ABSTRACT

This analysis was carried out based on the smeared crack model and plasticity damage model in general finite element program ABAQUS. Comparison and analysis were made on the key factors of concrete constitutive models that have effect on the static mechanical behavior of structural members. Then the mechanical behavior of reinforced concrete members and steel-concrete composite members under monotonic loading and cyclic loading were simulated using various concrete constitutive models. Both the smeared cracking model and the plasticity damage model could accurately simulate the macroscopic response of flexural concrete members or flexural composite members subjected to monotonic load, and the smeared cracking model was more accurate in simulating the cracking behavior of concrete, applicable for analyzing the stress situation of concrete during stress-strain space constantly changing after cracking. Besides, the plasticity damage model could be adopted to simulate the stress behavior of concrete structures or composite structures under the action of cyclic load. The two models could not accurately simulate the whole process of stress behavior of concrete in two-dimensional or three-dimensional stress state.
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1. Introduction

Experimental methods such as quasi-static, pseudo-dynamic and shaking table were commonly adopted to study the scale model of structural components or system in traditional method of seismic analysis for structural system. The experimental research on structural members had been relatively mature at present, but there were some shortcomings such as the small reduced-scale of scale model and the insufficient measurement range of the experimental study of structural system, which made it difficult to fully and truthfully reflected the mechanical behavior of the practical structural members under earthquake cyclic load, such as bond slip between reinforcement and concrete, cracking behavior on the surface of the concrete and other key characteristics under load. In addition, the costs of economy and time that the traditional experimental means took were relatively high.

Recently, with the development of structural finite element theory and modern computer technology, the finite element method was used to analyze the elastic-plastic time-history of the structural system under the action of seismic cyclic load in order to obtain the response of the structural system under the earthquake load, which was an effective method. When the finite element program was applied to the elastic-plastic analysis of reinforced concrete structure and steel-concrete composite structural system, the constitutive relationship of material was the key to determining whether the results of finite element simulation for structural system could reflect the true seismic response of structural system. Steel was a kind of isotropic metal material, and scholars in the world had put forward a variety of mature constitutive relations which took the elasticity, elastic-plasticity, reinforcement, fracture and Bauschinger effect of steel into account and had been fully tested. As a result the current constitutive model of steel had been mature. The exact constitutive model was not easy to be established because concrete was essentially a mixed material with different mechanical properties in the direction of tension and

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compression, and there existed complex mechanical behaviors such as strengthening, softening, cracking and damage. Therefore, the methods of accurately simulating the constitutive relationship of concrete material in general finite element program was the key to make sure the finite element analysis can reflect the behavior of concrete structure and composite structure system under the action of the earthquake. Scholars all over the world had proposed a variety of analytical theories for the constitutive relationship of concrete materials which have been widely applied in the finite element program.

Relevant studies of constitutive model of concrete material simulated in ABAQUS had been carried out in the existing literatures [1–3], but they commonly concentrated on the reaction of structural components under static monotonic load, lacking in discussion of the reaction of concrete materials subjected to the cyclic load which was an important force characteristic of structure under the earthquake load. Besides, few researches had been conducted on the key factors like the cracking model of the concrete constitutive model and behaviors of cracking surface.

Three constitutive models of concrete were provided in ABAQUS [4]: (1) Brittle cracking, (2) Smeared crack, (3) Plasticity damage. The brittle cracking model which only considered nonlinear behavior of concrete under tension was suitable for the simulation of the constitutive relation of concrete materials in structural members of plain concrete or concrete structural members with a small quantity of reinforcements, not applicable to the simulation of concrete in normal reinforced concrete structures and composite structures. And it was mainly used to simulate the structures of hydraulic dams. So, this paper mainly focused on the comparative study of smeared cracking model and plasticity damage model. The smeared cracking model was applied to homogenize the discrete cracks of concrete in actual structural members. To simulate the behavior of the concrete after cracking, soften stage in the stress-strain curve of the concrete under tension is modified. The plasticity damage model could be used to simulate the constitutive relationship of concrete materials under cyclic load and to consider the damage, cracking development, cracking closure and stiffness recovery of material under cyclic load.

In this paper, using the constitutive model of smeared cracking model and plasticity damage model provided by ABAQUS, the comparative calculating analysis was carried out combining with the testing results of existing structural members, mainly focusing on the influence of the key parameters in concrete constitutive model on the hysteretic characteristics of members in the concrete structures and the composite structures, analyzing and showing the applicable range of different material models of concrete in analysis of the actual structural members at the same time. In this analysis, the different loading condition and complex loading path were chosen for the cyclic analysis, which is a more detailed investigation about the influences of concrete models on structural cyclic behavior. As we know, the behavior of structures under actual earthquake is very complex, which is much different from that under quasi-static load in the test, so it is necessary to conduct the comparative study in order to choose the more suitable concrete model in finite element analysis for structures under earthquake. The unique contribution of this study is the first comprehensive research and comparative calculation results on the smeared cracking concrete model and plasticity damage concrete model, which is helpful for researchers and designers to analyze the non-linear behavior of structures under complex earthquake load.

2. Comparison of constitutive model

2.1. Behavior of cracked surface

Structural components in the actual situation was often subjected to a variety of complex loading conditions, and before cracking, concrete material was basically an isotropic linear elastic material whose principal strain space was consistent with the principal stress space, but the cracked concrete was an orthotropic material with different stress-strain relationships in the direction of tension and compression, and with the rotation of the strain space, the stress space was no longer consistent with the strain space. The behavior of cracking surface of concrete was the key factor to influence the spatial relationship between principal strain and principal stress. A plain concrete element given various constitutive relations of concrete was established to investigate the simulating effect of smeared cracking model and plasticity damage model on the behavior of cracking surfaces in ABAQUS. Constant value of the tensile strain was firstly applied to make concrete element produce "cracked surface", and then the shear strain was gradually increased to investigate the shear behavior of the cracking surface. In order to conduct the comparative study conveniently, the RA-STM coaxial rotation crack model [5] proposed by Hsu was adopted at the same time. The relationship between shear stress and shear strain of different constitutive models of concrete material under different constant tensile strain was shown in Fig. 1.

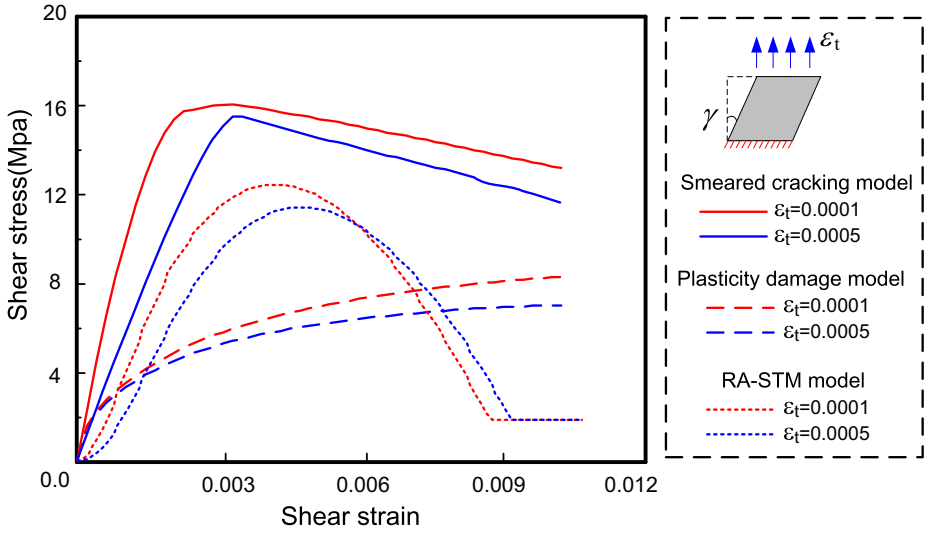

Fig. 1. Comparison of behavior of concrete cracked surface using different models.

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