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A damage constitutive model for intermittent jointed rocks under cyclic uniaxial compression

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ABSTRACT

A damage constitutive model is proposed to describe the deformation and strength characteristics of intermittent jointed rocks under cyclic uniaxial compression. First, a coupled damage tensor for intermittent jointed rocks is derived based on the Lemaitre strain equivalence hypothesis, which combines the Weibull statistical damage model for micro-flaws and the fracture mechanics model for macro-joints. Second, a fatigue constitutive model with an internal variable (i.e., irreversible plastic strain) is proposed to reproduce the degradation behaviors in fatigue deformation and strength of rocks under cyclic loading. Finally, a damage constitutive model with a definite physical significance is constructed for the intermittent jointed rocks under cyclic uniaxial compression. Our new model comprehensively reflects the coupled damage induced by micro-flaws and macro-joints, in which the geometric parameters and the mechanical properties of intermittent joints are considered simultaneously. Moreover, this model is able to reproduce the hysteretic stress-strain curves and the cumulative fatigue plastic deformation of rock materials under cyclic loading. In addition, a compaction coefficient, which is defined as the ratio of the secant modulus to the Young's modulus, is proposed to reflect the compaction stage of rock materials during the first loading process. To validate this new model, nine cyclic uniaxial compression tests are conducted on both intact and jointed rock samples prepared with synthetic rock-like materials. A reasonable consistency is observed between the theoretical and experimental results for the cyclic stress-strain curves and the fatigue deformation modulus.

1. Introduction

Cyclic loading is likely to occur in myriads of geophysical processes and engineering applications involving rock structures, such as earthquakes, rock blasting, underground excavation and explosive fracturing.[1] Widely existing in these engineering structures, intermittent jointed rocks are extraordinarily susceptible to cyclic loading conditions.[2] Since the constitutive relationship of rocks lays the foundation for the rational design and the stability assessment of engineering structures,[3] it is crucial to develop a reasonable constitutive model for intermittent jointed rocks under cyclic loading conditions.

Existing studies on the constitutive model of jointed rocks mainly focused on quasi-static loading. This research realm has been established in the framework of continuous damage mechanics, which is essentially an extension of the damage model of jointed rock masses proposed by Kawamoto et al.[4] that characterized the distributed joints using a second-order damage tensor. Thereafter, based on the geometrical damage theory, researchers further investigated the damage tensor and the constitutive model of jointed rocks to describe the anisotropic damage, the strength and deformation behaviors of rocks induced by existing joints.[5–8] Although the damage tensor defined in these studies reflect the effects of joint geometric configurations, including dip angle, spacing and length, the mechanical behaviors of joints, such as internal friction angle and cohesion, are not taken into account. Swoboda and Yang[9] introduced a stress transferring constant of joints to improve the above models, but this constant was determined empirically.

The above investigations mainly concentrate on the influences of macro-joints, while ignoring the effects of micro-flaws that exist in rock materials. By virtue of statistical damage mechanics, Krajcinovic and Silva[10] considered randomly distributed micro-flaws and established a constitutive model for rocks with a Weibull distribution[11] of the rupture strength. This statistical damage model has been widely accepted. Researchers also reported that the stochastic micro-flaws would induce isotropic damage in rock masses, which would lead to a degradation of the strength and stiffness properties.[12–15] In fact, it is inappropriate to consider the effect of macro-joints and micro-flaws separately because a sophisticated interaction exists between the two types of flaws[16]; thus

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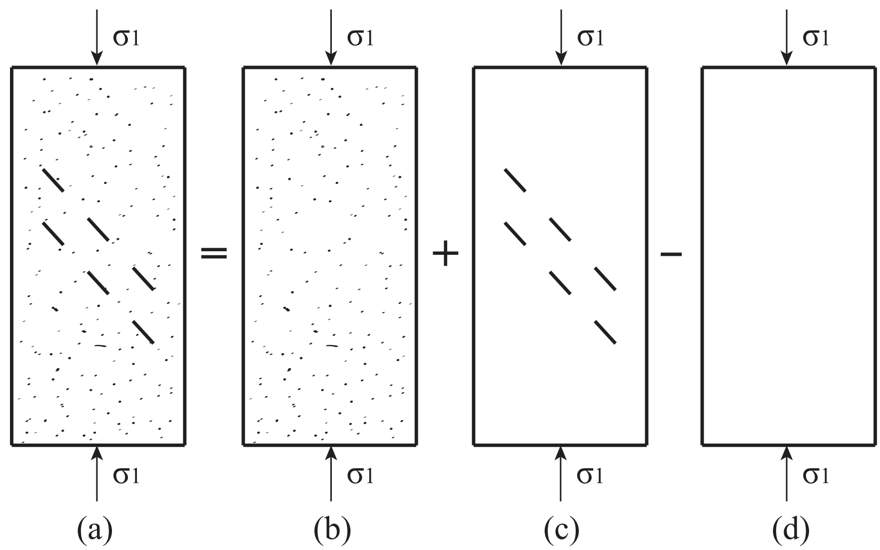

Fig. 1. Calculation of the coupled damage variable of intermittent jointed rocks: (a) intermittent jointed rock, (b) rock containing only micro-flaws, (c) rock containing only macro-joints and (d) virgin rock without any flaws.

Liu et al.[17] proposed a coupled damage tensor for persistent jointed rock masses under uniaxial compression.

Compared with studies on the quasi-static constitutive model ground on continuous damage mechanics, studies on a fatigue constitutive model under cyclic uniaxial compression have been performed using two approaches. One approach is to use plasticity mechanical models, aiming to construct a constitutive framework with classical plasticity theory to reproduce the fatigue behavior of plastic materials under cyclic loadings.[18–21] Because the basic premise of classical plasticity theory is the existence of a yield surface, this theory is thus challenged for applications on rocks, of which the yield surface would shrink into a point immediately once loading begins.[22,23] The other approach is to use the endochronic theory with an internal state variable, describing the fatigue plastic behavior in the framework of irreversible thermodynamics without complicated yield surface and loading functions.[22] Some efforts have been made to investigate the constitutive relationship of intact rocks under cyclic loadings utilizing the internal variable theory; this theory was demonstrated to be reasonable for situations involving cyclic loading-unloading and fatigue behavior.[23–26]

These studies on fatigue constitutive model focus only on intact rocks, which results in a rather limited understanding of the constitutive relation of jointed rocks under cyclic uniaxial compression. Li et al.[27] proposed a fatigue damage model for jointed medium based on energy principle and fracture mechanics, which gives a new insight to simultaneously consider the geometrical and mechanical properties of macro-joints. Nevertheless, the effects of micro-flaws were not considered in their model, and its ability to describe the degradation behaviors in fatigue deformation and strength of jointed rocks remains unverified. Recently, a microscopic reduction model in stiffness and strength parameters of DEM models (i.e., discrete element method) was developed by Liu et al.[28] to effectively simulate the hysteretic stress-strain curves and the cumulative plastic deformation of intermittent jointed rocks in numerical cyclic loading tests.

Note that for a reasonable constitutive model of jointed rocks under cyclic loadings, the following requirements should be satisfied: (i) the model reflects the coupled effects of micro-flaws and macro-joints, in which the geometrical and mechanical parameters of macro-joints are simultaneously considered; (ii) the model describes the fatigue deformation and strength characteristics, including the hysteretic stress-strain curves and the cumulative plastic deformation. Thus, our intension in this study is to develop such a model for intermittent jointed rocks under cyclic uniaxial compression. The remainder of this text is organized as follows. Section 2 derives the coupled damage tensor for intermittent jointed rocks based on Lemaitre strain equivalence hypothesis, followed by the establishment of an internal variable model for intact rocks and a damage constitutive model for intermittent jointed rocks in Section 3. Section 4 describes the test equipment and sample preparation, along with a comprehensive verification and discussion of our established model. Section 5 summarizes the whole study.

2. Coupled damage analysis of intermittent jointed rocks

2.1. Coupled damage tensor of intermittent jointed rocks

According to continuous damage mechanics,[29] the constitutive relation of damaged materials can be expressed as Eq. (1):

$$[\sigma] = [E][\varepsilon](1 - D) \tag{1}$$

where $[\sigma]$, $[\varepsilon]$, $[E]$ and D are the stress matrix, strain matrix, modulus matrix and damage variable, respectively. Thus, the key point to establish the constitutive model of damaged materials lies in determining the damage variable.

For intermittent jointed rocks containing both micro-flaws and macro-joints, the damage variable can be calculated by coupling the damages induced by these two types of flaws, as shown in Fig. 1. Based on the Lemaitre strain equivalence hypothesis, the equivalent strain of jointed rocks can be calculated as follows:

$$\varepsilon_J = \varepsilon_f + \varepsilon_j - \varepsilon_v \tag{2}$$

where ε is the uniaxial strain of rock materials, the footnotes J, f, j and v represent the jointed rock, the rock containing only micro-flaws, the rock containing only macro-joints and the virgin rock without any damage, respectively.

Under the uniaxial stress σ_1, the following equation is valid:

$$\frac{\sigma_1}{E_J} = \frac{\sigma_1}{E_f} + \frac{\sigma_1}{E_j} - \frac{\sigma_1}{E_v} \tag{3}$$

where E is the deformation modulus of rock materials.

Denoting the damage variables induced by micro-flaws and macro-joints as D_f and D_j, respectively, and their coupled damage variable as D_J, the following formulas can be obtained based on continuous damage mechanics: