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Research Paper

Influence of single flaw on the failure process and energy mechanics of rock-like material

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A B S T R A C T

This paper investigates the influence of a flaw on crack initiation, the failure mode, deformation field and energy mechanism of the rock-like material under uniaxial compression. The results of laboratory test and numerical simulation demonstrate the flaw inclination effect can be classified into three groups: 0–30°, 30–60° and 75–90°. The characteristic stresses increase as the flaw angle increases. The tensile cracks initiate from gentle flaws ($\alpha \leqslant 30°$) and shear cracks appear at tips of steep flaws ($\alpha \geqslant 45°$). The input energy, strain energy and dissipation energy of a specimen show approximate increasing trends as the flaw angle increases.

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1. Introduction

Defects of different sizes in a rock mass, such as holes, flaws and fissures, significantly influence the mechanics of the rock mass and make the material irregular, discontinuous and heterogeneous. Research shows that the immediate cause of a collapse in a rock mass is the process of crack propagation and coherence. The structural geometry of the rock mass has a close relationship with its failure mode.

Many studies have been conducted on different aspects of the rock failure process and mechanism. A number of laboratory experiments have been performed to investigate the effect of discontinuities in specimens using rocks and different material with similar properties, such as plaster, cement and optical plastics [1–20]. These studies analyzed the failure pattern, crack initiation and propagation in pre-cracked rock-type specimens.

Due to the rapidness and convenience of numerical methods, they have become a widely used way to investigate the deformation failure mechanism of rock material. Researchers have developed and proposed many different numerical methods to simulate a rock specimen, such as the finite element method (FEM) [21–23], the boundary element method (BEM) [24,25], the displacement discontinuity method (DDM) [26,27] and the discrete element method (DEM) [28]. Some researchers have developed a method or combined two of them to obtain better simulation results [29–31].

The particle flow code (PFC), a type of DEM, has some advantages for large deformations and in relation to model establishment [32]. The bonded-particle model (BPM) is widely used to simulate various rock laboratory tests and engineering problems [33–43].

The failure process of a rock mass is a path from random micro damage to local failure and eventually to wholesale destruction. This process can be analyzed in terms of mechanics. The energy mechanism is an irreversible process of energy dissipation [44]. During the loading process, energy dissipation causes damage accumulation and the energy release causes a collapse [45]. Many researchers have studied the failure process of rock masses with energy mechanics and helped to improve the understanding of the deformation failure mechanism of rock materials [44–50].

In this paper, uniaxial compression experiments were conducted on a series of specimens containing flaws, both in the laboratory and using PFC. The failure pattern of pre-cracked specimens was analyzed in different ways based on the results of the laboratory tests and PFC. The particle displacement field and energy dissipation were investigated in the pre-peak duration.

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2. Laboratory tests

To study the influence of a flaw on the rock failure process, a series of cement specimens have been used for uniaxial compression tests with an electronic-hydraulic servo controlled testing machine.

2.1. Specimen manufacture

The specimens were made of cement, sand and water with a volume mixture ratio of 1:0.5:0.5. The prefabrication of concrete specimens used white cement instead of Portland cement for propitious observation in the test.

Each mold is composed of four steel plates and each pair of plates are joined with screws. Each vertex of the rectangular box has two screws to guarantee the perpendicularity of neighboring edges. These steel plates are stainless and have a thickness of 8 mm to lessen the swelling deformation due to the hydration of cement. The other two faces are covered with plastic rigid boards. To protect specimens from the damage caused by mold removal, the steel plates and plastic boards are greased before pouring the cement mortar into them.

The dimension of the specimen is 50 mm (length) × 100 mm (height) × 30 mm (width) as illustrated in Fig. 1. The position and orientation of the flaw and the loading direction are shown in the Fig. 1. The single flaw in the specimen has a different inclination angle changing from 0° to 90° with an interval of 15°.

The flaw in the block was created by inserting a greased thin steel shim. The steel strips were 20 mm in length and 0.4 mm in thickness. To ensure the accuracy of the position and inclination of flaws, each pair of plastic boards had a slot cut for inserting the steel shim, and the cover boards were fixed by screws. After 24 h for the initial setting of the concrete, the shim was pulled out, and the molds were released. The curing time was 28 days for each sample.

2.2. Laboratory tests and tests results

There were eight types of specimens, including a group of intact specimens and seven groups of the so-called flaw specimens. The loading, which was controlled by displacement of a pressure plate, had a speed of 0.05 mm/s. Before each test, some grease was daubed on the load platens to reduce the end effect between the plates and the specimen. In each test, the stress-strain curve and the failure process of the sample were monitored. Representative peak uniaxial compression strengths (UCS) of each group are shown in Fig. 2.

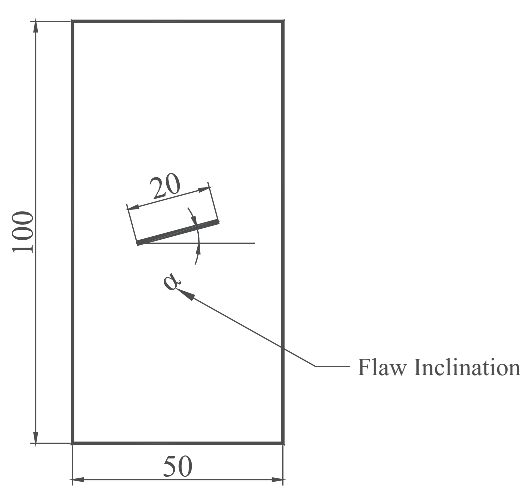

Fig. 1. Illustration of specimen geometry.

The representative UCSs of each group were selected with the following procedures: first, removing the maximum and minimum uniaxial compression strength (UCS) of the intact cement blocks; secondly, averaging the strengths of other specimens; and finally, choosing the specimens that have the UCS closest to the mean compression strength. In Fig. 2, it can be observed that the strength of flaw specimen increases as the flaw angle increases basically. There are two reasons that might explain the UCS trend of flaw specimens: according to the researches of Lajtai [7] and Pu [51], the compression stress concentration exists near the inclined open flaw tips under compression loads and decreases as the flaw angel increases. Meanwhile, the effective bearing area of the flaw specimen decreases as the flaw angel increases.

3. Numerical simulation

3.1. PFC fundamental

Particle Flow Code (PFC), a type of discrete element method, can fundamentally be described as follows: macro properties of a material are reflected by defining micro bond parameters among rigid elements. The constitutive relation is the relation of the force and displacement, and the motion equation is Newton's Second Law.

In PFC2D, a rock-like material is presented as a bonded assemblage of particles with certain thickness, i.e., a bonded particle model (BPM). PFC provides two types of bonds, the contact bond (CB) and the parallel bond (PB). In this paper, the contact bond was used to generate models. CB provides each contact point with a tensile normal and shear contact-force strength that can bear a tensile force but cannot resist the moment.

It is known that the parallel-bonded model is a more realistic model for rock-like materials. The resistance of the moment in parallel bond would lead to a model with more volume expansion and more particle rotation gradient at the edges of shear bands. However, the emphasis of this paper is on the strength, the displacement field and dissipation energy of the flawed specimens at the pre-peak stage. From the material structure, some researches show that the interface between the sand and the set cement is not dense and has holes existing in the hydration products. The cement among sands would have lower bending resistance.

3.2. Model generation and calibration

A bonded-particle model (BPM) was established at 100 mm in height and 50 mm in length, based on the size of the specimen in the laboratory test. To build a reasonable numerical model,

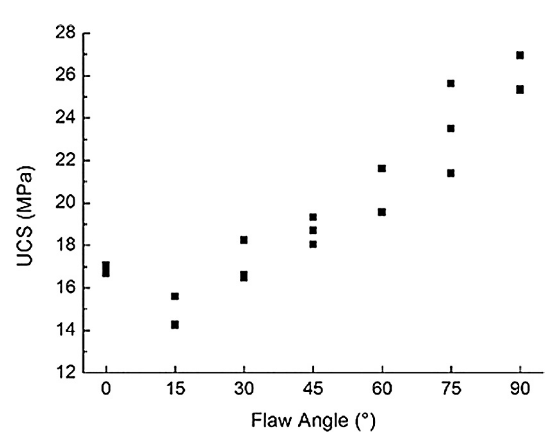

Fig. 2. UCS of specimens with a flaw in the laboratory tests.

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