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Progressive failure of new modelling material with a single internal crack under biaxial compression and the 3-D numerical simulation

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ABSTRACT

A new rock-like resin has been developed after extensive formula research. This resin is completely transparent and low temperature brittle. Its tension-compression ratio can reach 1/6.6 in the −10 to −15 °C temperature range. It can simulate many kinds of engineering rocks. Specimens are made with a single internal crack. The progressive failure processes of specimens under uniaxial and biaxial compressions are investigated. The uniaxial failure process of specimens is divided into four stages. Some forms of secondary cracks, like anti-wing cracks in biaxial test, have never been reported in previous studies. 3-D numerical simulation is carried out using FLAC3D. A new elastic-brittle constitutive model is developed in the simulation. Superfine element division is also required. The uniaxial and biaxial numerical results of the new method possess an excellent consistency with experiment results in this paper.

1. Introduction

Rock masses usually contain a great number of intrinsic joints, fractures and quite a few faults. Due to stress relief during excavation, the stress in rock masses is redistributed. As a result, the intrinsic defects propagate, which will change or affect the mechanical properties of jointed rock masses, such as deformation and strength. When the local stress subjected to interaction and superposition reaches the local failure strength of rock, the crack surface will slide or open, leading to initiation and propagation of secondary cracks. In previous studies [1–10] multiple methods were adopted to investigate the fracture propagation and failure modes for rock masses under loading, including model testing, rock sampling, geophysical methods, such as the electric resistance method, CT scanning and the acoustic emission method, and a multitude of numerical methods, such as FLAC, RFPA, ABAQUS, PFC, UDEC and DDA. However, the effect of rock heterogeneity cannot be ignored. The above methods have also been adopted by some researchers [2–5] to explore the causes of seismic activities or engineering stability. However, it is difficult to conduct experiments to investigate the interactions of 3D pre-cracks in samples under uniaxial and biaxial compression. For 3-D specimens, tensile cracks or shear cracks occurring in 3-D space make the evolution mechanism considerably more complicated and the observation of crack paths substantially more difficult accordingly,

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Nomenclature

$D_1, D_2, \ldots, D_5$	damage factors
K	bulk modulus
G	shear modulus
σ_t	tensile strength
c	cohesion
φ	internal friction angle
K'	bulk modulus of post-failure elements
G'	shear modulus of post-failure elements
$\sigma_t{}'$	tensile strength of post-failure elements
c'	cohesion of post-failure elements
φ'	internal friction angle of post-failure elements

the test results on propagation and coalescence of 3-D crack set have seldom been reported. In previous studies, penetrated cracks or surface cracks were usually created on a plane rock sample. The propagation process of single or multiple cracks under uniaxial or biaxial loading and the accompanying physical phenomena were observed and meaningful results were achieved [11–18]. A host of preliminary test results were also achieved on 3-D crack propagation. The fundamental characteristics of failure of a single 3-D crack were described [19–24]. In recent years, researchers [19,20,23,24] have conducted experiments and preliminary numerical simulations on 3-D crack propagation. Various materials, such as rock, ceramics, PMMA, resin and gypsum, were used to prepare specimens with pre-made 3-D cracks. Some fundamental understandings have been achieved by studies on the effects of crack direction and crack depth on crack propagation. Among transparent materials, the material brittleness reported in previous studies cannot satisfy the characteristics of rock-like materials. For instance, the CR-39 resin used by Dyskin et al. [19] and Sahouryeh et al. [20] merely had a tensile to compressive strength ratio of 1/3 at $-17\,°\mathrm{C}$; the PMMA selected by Wong et al. [21] also had a tensile to compressive strength ratio of 1/3 at $-50\,°\mathrm{C}$. Guo et al. [23] found a type of unsaturated polyester resin which had a tensile to compressive strength ratio of 1/5 at $-20\,°\mathrm{C}$, possessing higher brittleness, but much less transparency.

In the present study, after numerous trials on the mixture ratio, a type of mixed resin with a tensile to compressive strength ratio of 1/6.6 at -10 to $-15\,°\mathrm{C}$ was obtained for the first time. Its brittleness is closer to the brittleness of real rocks, such as marble and sandstone. This provides a promising opportunity to study crack propagation for real rock materials.

For numerical simulation, most of the above methods can successfully simulate simple and arbitrary crack initiation and propagation in 2-D cases. But, for 3-D cracking problems, it can be very complicated and difficult. Numerical simulation methods [24,25–30] for 3-D crack propagation are still a challenge. FLAC3D has been used by merely a handful of researchers [27,28] to simulate the 3-D crack propagation process. However, due to deficient reform of the software's function, the simulated pre-crack was invariably surrounded by a group of irregular plastic zones, which is inconsistent with the threadlike crack propagation observed during experiments.

The study on 3-D crack propagation, by either test or numerical simulation, is still in the preliminary stage. To date, consistent or verifiable tests and numerical results have seldom been reported, and further in-depth study is necessary. In this paper, a newly developed transparent resin material is used for preparation of samples with a single 3-D internal crack. The progressive failure processes of the specimen under uniaxial and biaxial compression are investigated. For numerical analysis, the original elastic-plastic constitutive model of FLAC3D is modified as a new elastic-brittle model. Also, superfine element division and proper mesh shape are required. The uniaxial and biaxial simulation results are all highly consistent with the experiment results of this paper.

2. Specimen preparation and test procedures

In this section, making technologies and test procedures of the new pre-cracked resin specimen are illustrated.

2.1. The brittle and transparent resin material

After many years of formula research, a new rock-like resin material, which is far more brittle than before, has been developed. This material requires high precision in the specimen-making process and is extremely strict with the temperature control at every stage. During the specimen-making, a set amount of hardener is added to the epoxy and they must be fully mixed. The mould is made of organic glass and must be prepared in advance for specimen shaping. After solidification, a repeated series of oven drying, cooling and vacuum treatments are required. The ready-made resin specimen is completely transparent and low temperature brittle. Its tension-compression ratio can reach 1/6.6 in the -10 to $-15\,°\mathrm{C}$ temperature