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Experimental and discrete element modeling on cracking behavior of sandstone containing a single oval flaw under uniaxial compression

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ABSTRACT

In the rock engineering, it is very significant to focus on the failure mechanical behavior of rocks containing all kinds of flaws. In this research, the strength, deformation and crack evolution behavior of sandstone containing a single oval flaw under uniaxial compression were evaluated by experiment and numerical simulation using a two-dimension particle flow code (PFC^{2D}). The experimental results show that the peak strength and elastic modulus first decrease and subsequently increase with increasing oval flaw angle (α); the lowest value appears when $\alpha = 15°$, but the oval flaw angle has little effect on peak strain. The oval flaw angle has a great effect on crack initiation and propagation, as observed from photographic monitoring and the AE technique. The AE counts of flawed specimens show several larger peak values prior to peak strength, which correspond to crack initiation and propagation in the specimen. And then, PFC^{2D} was used to simulate sandstone containing a single oval flaw under uniaxial compression, and the simulated results are in good agreement with the experimental results. By analyzing the stress surrounding the oval flaw periphery, we explain that the wing tensile crack initiation area transfers from the middle of the oval flaw periphery to the tip of the oval with increasing oval flaw angle, shear crack is easily initiated at the tip of the oval flaw, and the stress of the first wing crack increases with increasing oval flaw angle. Finally, the variance of the stress of the measurement circle along the crack propagation path with axial strain was analyzed and combined with the crack evolution process and stress–strain curve. As a result, the crack evolution mechanism and cracking type in sandstone containing a single oval flaw under uniaxial compression are revealed.

1. Introduction

Sandstone is a sedimentary rock composed of clastic and filler content and widely distributed throughout the earth. As an engineering rock, sandstone often appears in underground engineering related to geothermy, coal mine, petroleum and CO_2 sequestration, which has drawn the attention of many scholars [1,2]. As the geothermal repository, the fractographs characteristic [3],

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Nomenclature

a	length of the long axis of the oval
b	length of the short axis of the oval
α	oval flaw angle
W	width
H	height
T	thickness
σ_1	axial stress
σ_c	uniaxial compression strength (UCS)
ε_1	axial strain
E_S	elastic modulus
ε_{1c}	peak axial strain
E_c	Young's modulus of the particle
$\overline{E}_c$	Young's modulus of the parallel bond
k_n/k_s	ratio of normal to shear stiffness of the particle
$\overline{k}_n/\overline{k}_s$	ratio of normal to shear stiffness of the parallel bond
μ	particle friction coefficient
σ_n	parallel-bond normal strength, mean
τ_n	parallel-bond shear strength, mean
$\overline{\sigma}ij$	average stress
V	volume in PFC
η	angle between measurement circle and long axis of the oval
PFC^{2D}	two-dimension particle flow code
AE	acoustic emission
T	tensile crack
C	compression crack
S	shear crack
T/S	tension/shear crack
XRD	X-ray diffraction
ISRM	International Society for Rock Mechanics
AEs	AE counts
AAEs	accumulated AE counts
GPD	general particle dynamics

static and dynamic mechanical behavior [4], and fracture toughness [5] of sandstone may be affected by high temperature. As CO_2 sequestration repository, mechanical properties may be affected by salinity concentration [6]. As petroleum drilling surrounding rock, the deformation, peak strength and crack damage behavior may be affected by hollow radius [2].

However, natural rock masses generally contain a lot of ovals, such as faults, joints, holes or fissures. The failure mechanism of these materials strongly depends on crack initiation, propagation and coalescence [7–9]. Therefore, investigating the strength, deformation, fracture behavior and stress distribution is significant for the understanding of the fracture mechanism of the rock mass and the prediction the unstable failure of rock engineering. The cracking behavior was firstly investigated using rock-like material. Lajtai [10] examined crack initiation and propagation and the contributions to the failure of the rock-like material in compression and divided the failure process into six stages. Bobet [11,12] investigated the fracture coalescence of rock-like material containing two pre-existing fractures arranged in different geometries and that were either open or closed under uniaxial and biaxial loading. Wong and Chau [13], Wong et al. [14] and Tang et al. [15] investigated the pattern of crack coalescence and strength of a sandstone-like material containing two parallel inclined frictional fissures under uniaxial compression, and three main modes of cracks coalescence were observed. Prudencio [16] presented the results of biaxial tests performed on physical models of rock with a non-persistent joint and proposed three basic failure modes: failure through a planar surface, stepped failure, and failure by rotation of new blocks. Zhuang [17] studied and analyzed the crack propagation behavior of filled and unfilled fissures in rock-like specimens under uniaxial compression. Wong and Einstein [18,19] used molded gypsum and Carrara marble specimens containing parallel pre-existing open flaws to investigate the cracking and coalescence behavior at the macroscopic and microscopic scales. Zhou et al. [20] conducted the experimental investigation on rock-like materials containing multiple flaws under uniaxial compression, which analyzed the influence of the non-overlapping length and flaw angle on the deformation and strength, and also revealed five types of cracks, including wing cracks, quasi-coplanar secondary cracks, oblique secondary cracks, out-of-plane tensile cracks and out-of-plane shear cracks.

With the development of technology pre-existing the flaws in real rock material, rock material containing pre-existing flaws was adopted to investigate cracking behavior of flawed rock. Heekwang and Seokwon [21] studied the crack initiation, propagation and coalescence of a pre-existing unparallel fissure in rock specimens under uniaxial compression. Huang [22] investigated the deformation and strength behavior of sandstone specimens containing two pre-existing closed non-overlapping flaws under triaxial compression. Yang and Jing [23], Yang [24] and Yang et al. [25] investigated the crack initiation and propagation process of sandstone containing a single, two and three pre-existing fissures with different geometries under uniaxial compression. Lee and Rathnaweera [26] used petrographical approach to analyze the fracturing characteristics, the propagation of pre-existing cracks in real rock material is found to be more complicated than that in gypsum plaster, but crack coalescence of wing cracks of different isolated crack systems is the main source of disintegration of specimens. Afterwards, with the development of computer technology, the methods of numerical simulation were also used to analyze the cracking behavior of flawed rock material. Zhang and Wong [27–29] used PFC^{2D} to simulate the crack initiation and propagation process of flawed specimens with different geometries, loading rates, and sizes. Using general particle dynamics (GPD), Zhou et al. [30] carried out numerical simulation on rock-like specimens containing four pre-existing flaws under uniaxial compression, which observed four coalescence modes: tensile (T), compression (C), shear (S), and mixed tension/shear (TS). Camas et al. [31] used powerful 3D ultrafine finite element to analyze in terms of the crack tip plasticity for a range of different conditions.

In nature rock engineering, the flaw sometimes occurred in the form of oval [32], and the flaw was simplified as oval by Griffith [34] at the earliest. So, Wang [35] employed brittle rock-like material to investigate the new crack initiation, propagation and coalescence law of specimens containing pre-existing three-dimensional oval flaws. However, the experiments and numerical simulations on the strength and crack evolution behavior of the rock containing oval flaws have rarely been investigated [32,33]. Therefore, the main aims of this research are to analyze the strength and deformation behavior of sandstone specimens containing a