



Experimental and Numerical Study on Mixed Crack Propagation Characteristics in Rock-Like Material Under Uniaxial Loading

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Received: 17 April 2019 / Accepted: 9 July 2019 / Published online: 15 July 2019
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Abstract The cracks of rock mass were in complicated geometric distribution, whose propagation characteristics and stress distribution change with the geometric distribution accordingly. In this research, propagation tests on mixed crack (horizontal edge cracks and inclined cracks) were conducted to analyze the propagation characteristics and stress distribution by lab tests and numerical modelling. The failure mode of specimens in Group 1 and Group 2 was the mixed crack (shear crack and tensile crack) and the coalescence of the pre-existing cracks propagation, respectively. The crack initiating from edge crack was the mixed crack–shear crack and tensile crack, and the

crack initiating from inclined crack was the wing crack–tensile crack. The peak of energy index appeared in the crack initiation, coalescence and specimen failure. The energy release of an inclined crack was less than that of an edge crack. The existence of pre-existing inclined crack resulted in the strength decrease of specimens. Stress concentration produced in the tips of the pre-existing cracks, and the concentration degree of edge cracks was much bigger than that of inclined cracks. The mechanism of buried structure water inrush was illustrated in this study. The working faces and buried structure could be simplified as the horizontal edge crack and inclined crack. The buried structure (inclined cracks) propagated and connected with the mining damage zone (horizontal edge cracks) and confined aquifer, so that water inrush paths were formed in the buried structure (similar to macroscopic cracks formed by the pre-existing crack propagation). This research provides a reference for the study on the water inrush in the buried structure.

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Keywords Mixed cracks · Propagation law · Acoustic emission characteristics · FRACOD^{2D} software · Stress distribution

1 Introduction

The propagation of original damages (cracks, joints, etc.) in the fractured rock mass is the main cause of

engineering geological hazards. The distribution of original damages greatly influences the disaster mechanism. Therefore, it is significant to investigate the propagation characteristics of original damages in rock mass.

Since the practical measure research on the distribution of original damages was complicated to be conducted, many lab tests and numerical modelling were performed to reveal the crack propagation characteristics under the influence of geometry distribution. Many experimental studies (Shen et al. 1995; Wong and Chau 1998; Bobet and Einstein 1998; Wong and Einstein 2009a, b; Park and Bobet 2009; Janeiro and Einstein 2010) and numerical modelling (Yoon et al. 2014; Shi and Shen 2018; Lu and Wu 2006; Zhang and Wong 2012; Zhao et al. 2015; Zhang et al. 2019) were conducted to analyze the process and mechanics of inclined crack propagation. However, horizontal edge crack is hardly considered in these studies. Under different conditions, such as the uniaxial loading (Huang et al. 2019), multi-field coupling (Zhang et al. 2015) and in the rock-like material (Zhang et al. 2018), edge crack propagation characteristics were analyzed. However, propagation characteristics of mixed cracks (horizontal edge crack and inclined crack) still need to be further investigated.

In this study, propagation tests of mixed cracks (horizontal edge crack and inclined crack) were conducted in rock-like material under uniaxial loading by lab tests and numerical modelling (discontinuous displacement method, FRACOD^{2D}). The crack propagation, strength characteristics, stress distribution and its application were mainly investigated.

2 Mixed Cracks Propagation Tests and Analysis

The mixed cracks propagation tests of rock-like material were conducted under the uniaxial loading, and propagation laws and AE characteristics were the main targets of the investigation.

2.1 Experimental Designs, Loading and Monitoring System

Specimen were classified into two groups for propagation tests of mixed cracks. Horizontal edge cracks

were only included in Group 1 (Fig. 1a); while horizontal edge crack and inclined crack were included in Group 2 (Fig. 1b). Manufacture process and mechanical parameters (Table 1) of the rock-like material were obtained by Sun and Shen (Sun et al. 2018). This rock-like material had a good brittleness to simulate the brittle fracture under the uniaxial loading.

The AG-X250 loading system (Fig. 2a) was used in tests. The specimens were conducted in displacement-controlled mode at an average loading rate of 0.0005 mm/s. The PCI-2 AE System (Physical Acoustics Corporation, Princeton Jct, NJ, USA, Fig. 2b) was adopted to monitor AE characteristics of crack propagation. Figure 2c shows the configuration of the AE sensor, which can ensure the monitor effectiveness and minimize the artificial effect for test results. Table 2 shows the set parameters of AE test. The AE system was calibrated according to ASTM. The loading system, video camera and AE system were set at the same time stamp in the test process.

2.2 Propagation and AE Characteristics

A total of six tests in two groups (distinguished by geometry distribution) were conducted. Figures 3, 4 show typical results from each group.

Group 1: **Crack A1** was mixed crack (Fig. 3A): it was shear crack (45° with the edge crack) during the initiation; and then tensile crack during the propagation (along the max principal major stress). **Mixed crack A1** (The crack initiated from the tip of a pre-

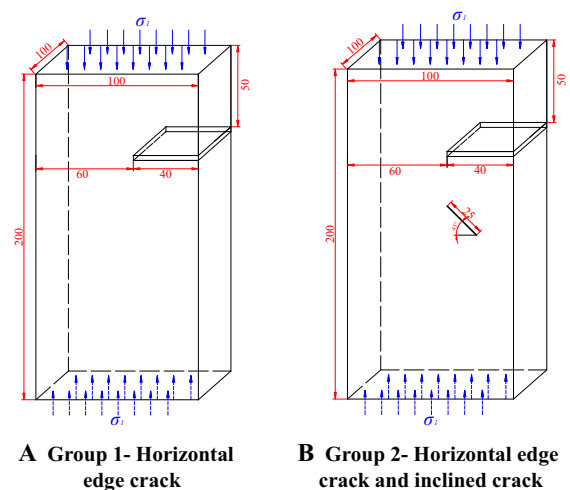


Fig. 1 Crack configuration

Table 1 Main parameters of the rock-like material (Sun et al. 2018)

Mass ratio	Model-gypsum:water:micro-silicon powder = 165:70:2
Specimen size	200 mm × 200 mm × 400 mm
Crack size	Edge crack: 40 mm (length) × 1.5 mm (aperture); inclined crack: 25 mm (length), 45° with horizontal direction
Unit weight	$\gamma_m = 13.5 \text{ kN/m}^3$
Uniaxial compression strength	$\sigma_c = 23.13 \text{ MPa}$
Uniaxial tensile strength	$\sigma_t = 2.76 \text{ MPa}$
Tangent elastic modulus	$E_m = 4.25 \text{ GPa}$
Cohesion	$c = 3.6 \text{ MPa}$
Internal friction angle	$\varphi = 31.2^\circ$

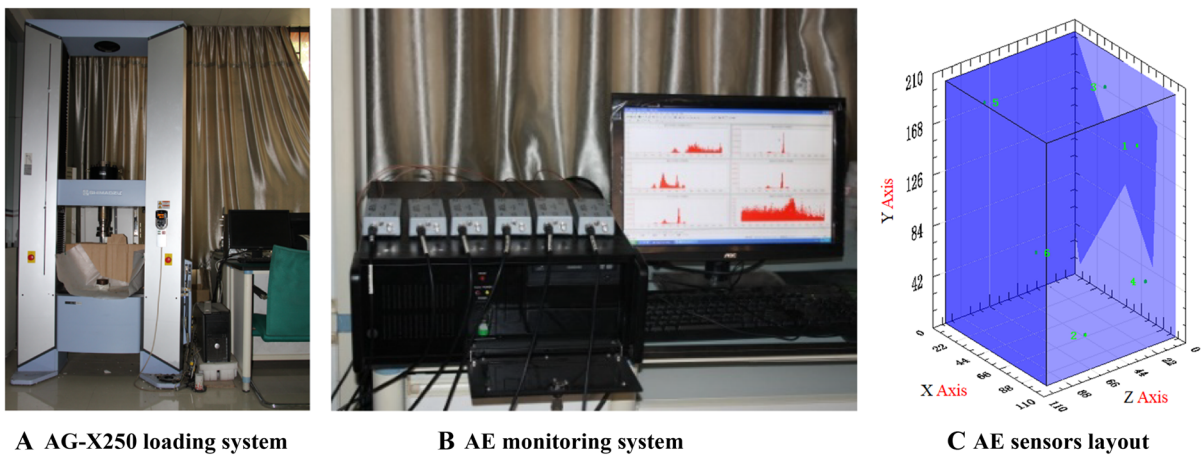


Fig. 2 The loading and monitoring system

Table 2 Parameters setting in the test

Sensor type	Nano 30
System threshold	40 dB
Floating threshold	6 dB
Resonant frequency	100–400 kHz,
Sampling frequency	$10^6/s$
AE sensor position (Unit: mm)	1# (100,170,30), 2# (100,30,70), 3# (30,170, 0), 4# (70, 30,0), 5# (0,170, 70), 6# (0, 30, 30)

existing crack, and exhibited two different crack modes—shear crack and tensile crack.) initiated (Fig. 3B) with the peak of energy index (The energy index is the integral relationship without unit, it is defined as the waveform envelope area of the AE waveform signal), and the bearing capacity of specimens decreased momentarily, as reflected in the stress–

strain curve as a small decrease. The specimen was damaged at the peak stress, and then the vertical tensile crack was formed.

Group 2: **Wing Crack B1** and **B2** initiated from the tip of inclined cracks, and propagated along the max major stress. The edge crack initiated and connected with the wing crack (Fig. 4A). Crack initiation,

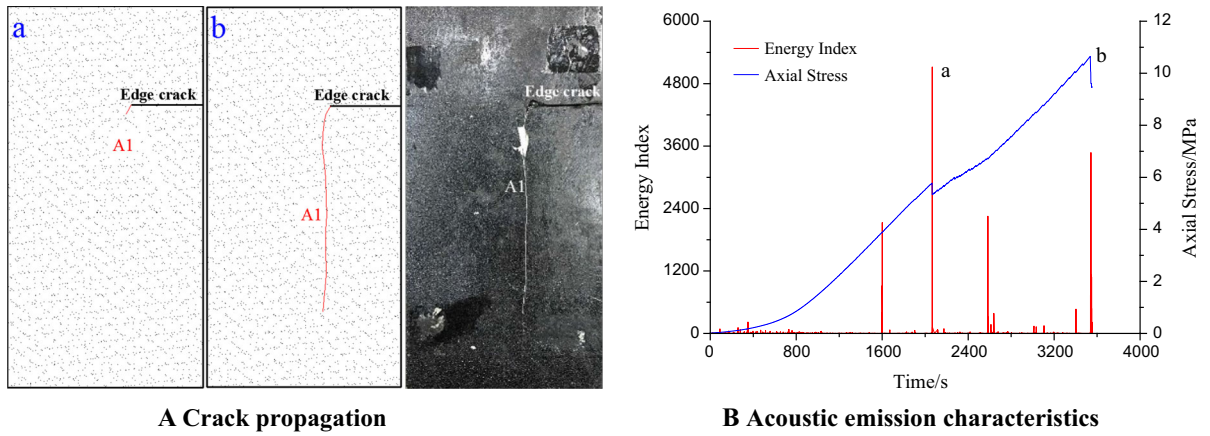


Fig. 3 Edge crack propagation of specimens in Group 1 under the uniaxial loading

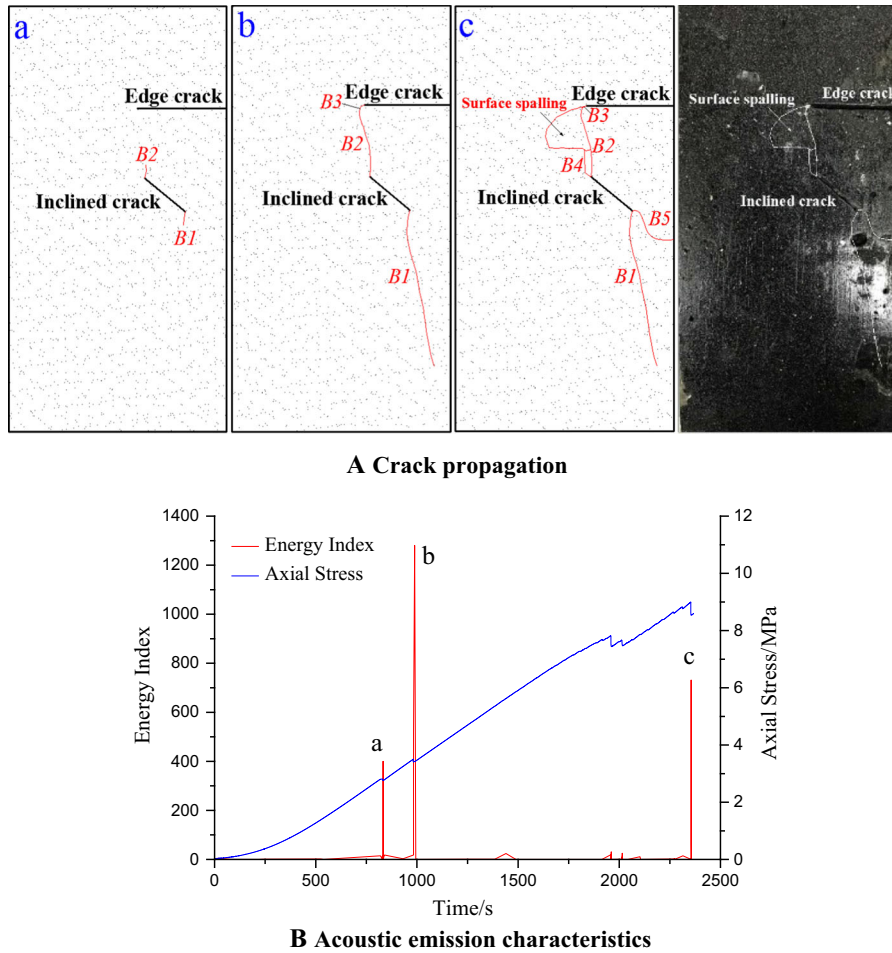


Fig. 4 Edge crack and inclined crack propagation of specimens in Group 2 under the uniaxial loading

coalescence and specimen failure led to the peak of energy index (Fig. 4B). The energy index of edge crack initiation and crack coalescence was bigger than that of an inclined crack initiation.

Table 3 shows the exact crack types. The crack mode was tensile crack which initiated from the inclined crack. However, the shear crack initiated from the edge crack firstly. The initiation energy of tensile crack was less than that of shear crack, and the initiation of the inclined crack was easier than that of the edge crack. The failure mode of Group 2 (inclined crack and edge crack) was more complicated than that in Group 1 (edge crack).

3 Numerical Modelling Tests and Analysis

The FRACOD^{2D} (Shen et al. 2014) can effectively study the coupling fracture propagation in liquefied natural gas (LNG) underground storage (Shen et al. 2013), CO₂ sequestration (Shen and Shi 2016), etc. Hence, FRACOD^{2D} (Shen et al. 2014) was used to simulate the mixed cracks propagation characteristics. The simulation parameters were shown in Table 1, where K_{IC} is 0.03 MPa m^{1/2}, and K_{IIC} is 0.18 MPa m^{1/2}. The loading control method was used in the numerical tests.

Figure 5 shows the stress concentration, crack propagation, principal major stress distribution, and X-direction displacement of specimens in Group 1. Stress concentration (about 45 MPa, Fig. 5a) and energy accumulation occurred at crack tips under the uniaxial loading. The propagation firstly initiated from the edge crack tip, and then the crack propagated along the max principal major stress, resulting in the mode failure (Fig. 5b). The maximum stress was 35 MPa at the edge crack tip (Fig. 5c) when the numerical modelling was finished.

Figure 6 shows the crack propagation characteristics of specimens in Group 2. The edge crack and inclined crack initiated under the influence of stress concentration (Fig. 6a), with the corresponding stress of 45 MPa and 30 MPa. With the initiation angle of 45°, edge crack propagated along the maximum major stress direction gradually. The wing cracks were the main propagation mode of the inclined crack. The edge crack and inclined crack propagated independently at the preliminary stage. The coalescence of crack propagation led to the mode failure.

The results of numerical modelling were basically consistent with lab tests results. However, there are some differences between lab tests and numerical simulation in material properties and action mechanism, resulting in some differences between the two results.

4 Discussion and Application

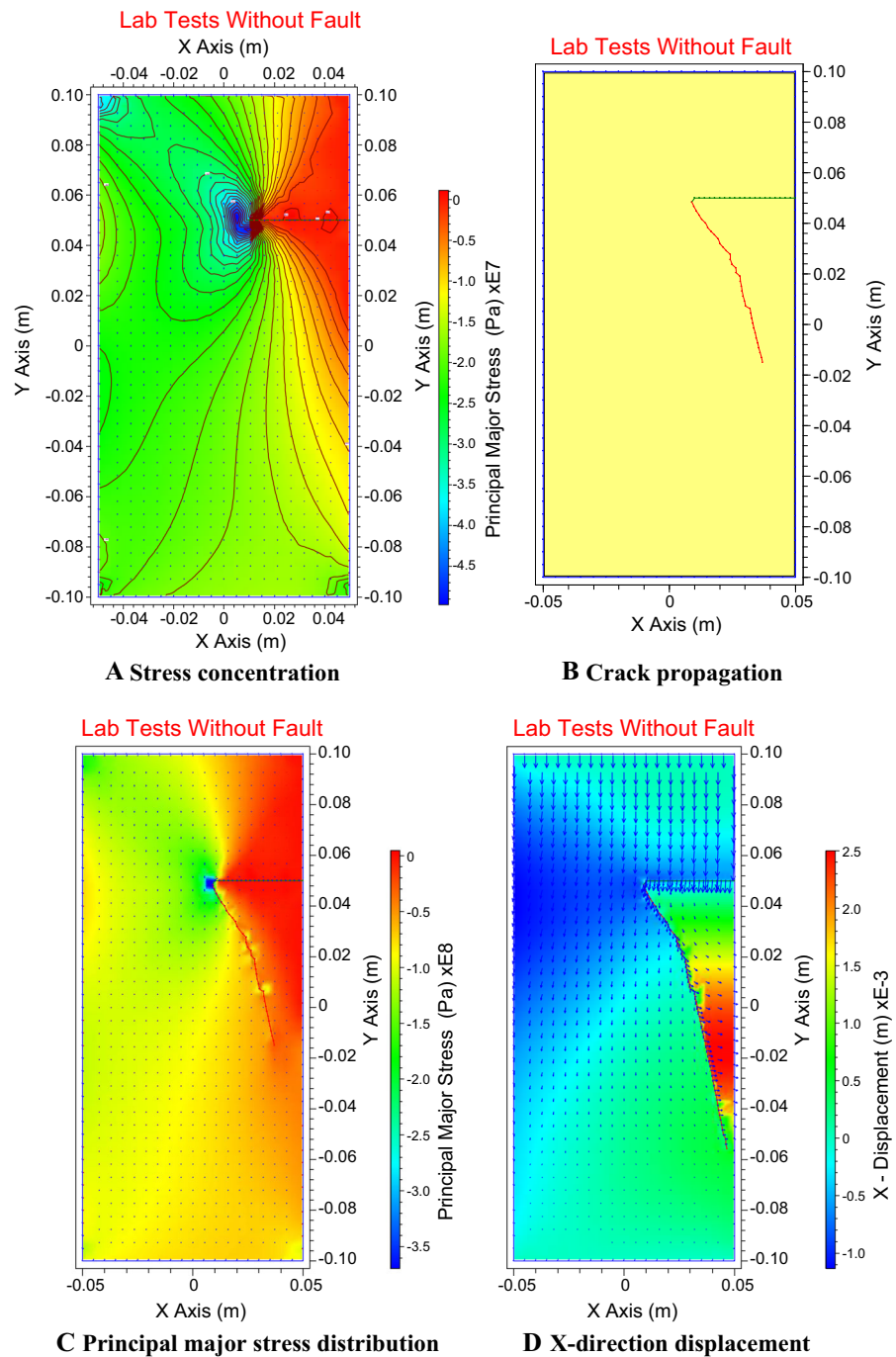
Lab tests and numerical modelling tests can effectively reveal AE characteristics, crack propagation and stress distribution of rock mass. The stress concentration firstly occurred at the tips of edge crack and inclined crack. Stress concentration degree of edge crack was 50% bigger than that of inclined crack. The crack initiating from edge crack was shear crack (Fig. 7), and propagated rapidly. The crack initiating from inclined crack was tensile crack (Fig. 7), and propagated steadily. The strength of specimens in Group 1 (10.6 MPa) was 10.5% bigger than that in Group 2 (9.5 MPa), and the existence of inclined crack weakened the strength of specimen.

Floor failure and mining damage zone can be caused by coal mining. Due to the existence of buried structures, excavation unloading can induce the initiation and propagation of buried structures. When the propagation of buried structure was connected with

Table 3 Crack types in lab tests

Experimental group	Crack number	Crack type
Group 1	A-1	Mixed crack–shear crack and tensile crack
Group 2	B-1	Tensile crack
	B-2	Tensile crack
	B-3	Mixed crack–shear crack and tensile crack
	B-4	Mixed crack–shear crack and tensile crack
	B-5	Mixed crack–shear crack and tensile crack

Fig. 5 Edge crack propagation characteristics of specimens in Group 1 under the uniaxial loading



the mining damage zone and confined aquifer, mining floor water inrush was caused. In this research, edge cracks and inclined cracks were regarded as working faces and buried structure. The initiation and propagation of edge cracks and inclined cracks formed macroscopic cracks in the loading process, and the

macroscopic cracks also were seen as underground watercourse. Lab tests and numerical modelling played an important role in defining the mechanism of buried structure water inrush (Fig. 8).

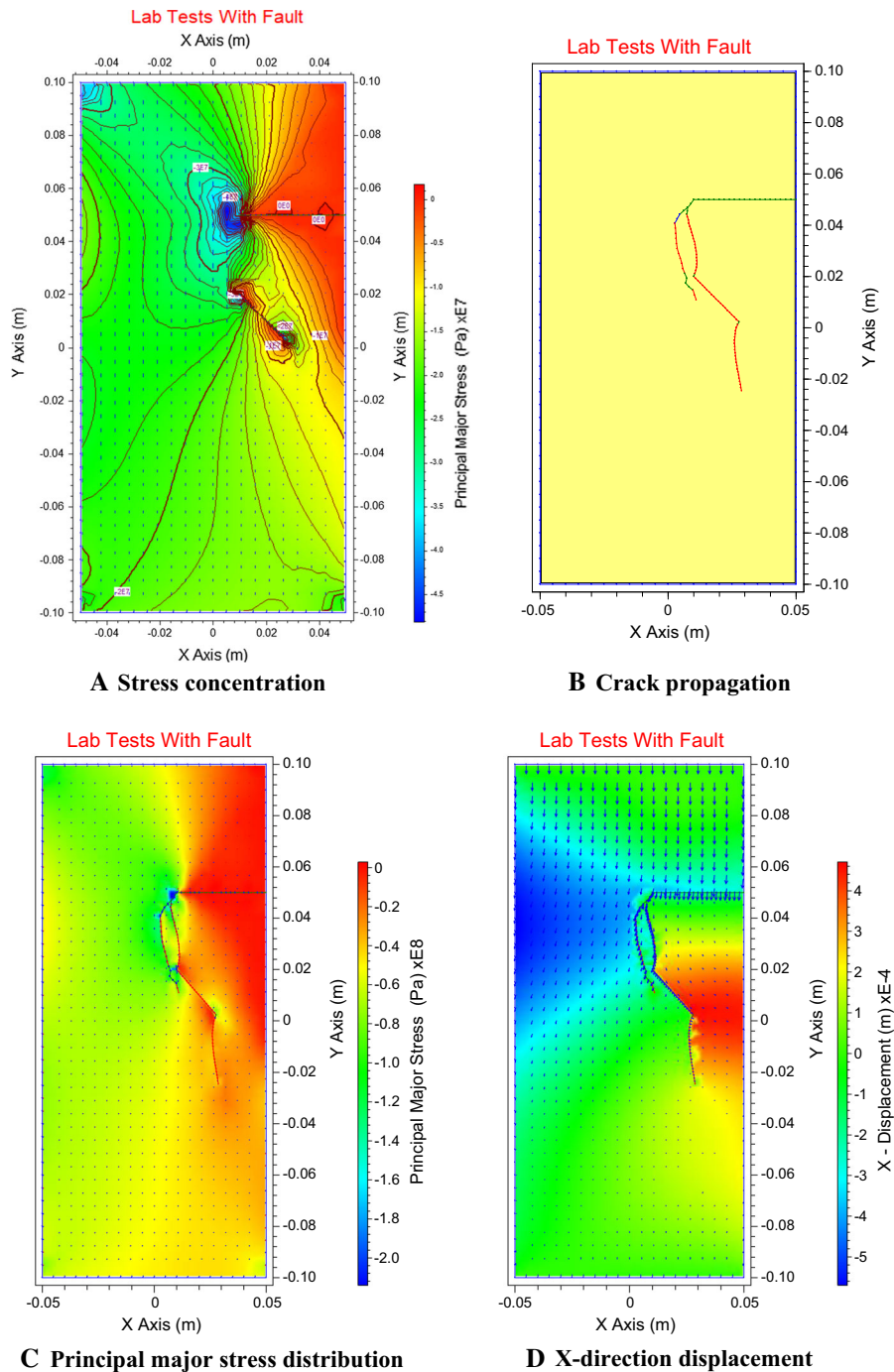


Fig. 6 Edge crack and inclined crack propagation characteristics of specimens in Group 2 under the uniaxial loading

5 Conclusions

The mixed crack propagation under uniaxial loading was conducted by lab tests and numerical modelling.

Crack propagation, AE characteristics and stress distribution were analyzed in this study. The main conclusions were drawn as follows:

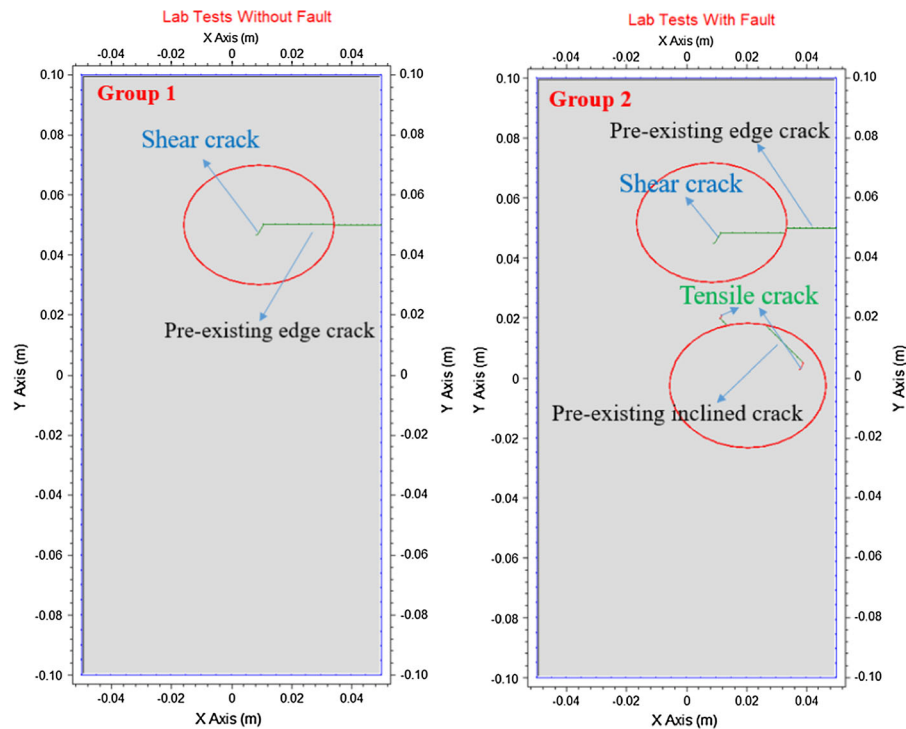


Fig. 7 Initiation crack properties of edge crack and inclined crack

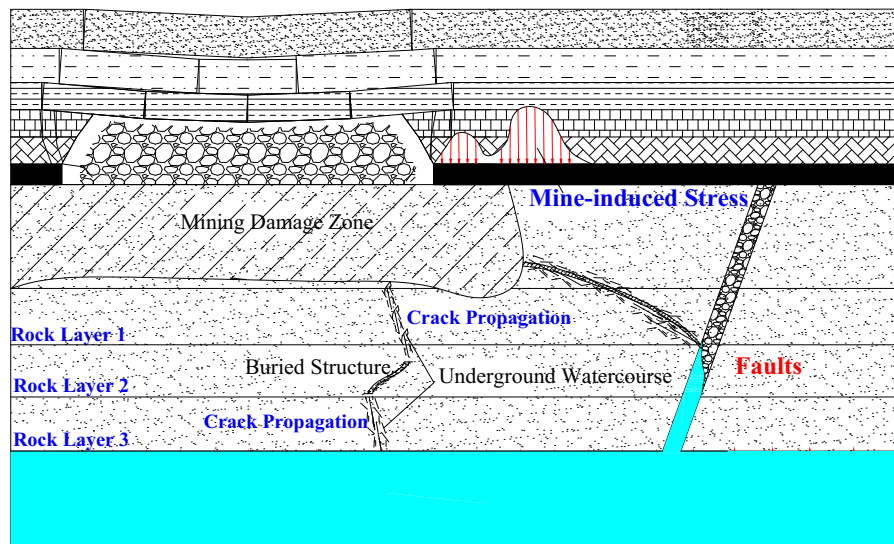


Fig. 8 The model of buried structure water inrush

- (1) The mixed crack (shear crack and tensile crack) initiating from pre-existing edge crack was the main mode of specimens in Group 1. The wing crack (90° with the edge crack with the inclined crack, propagated along the max major stress)

initiating from pre-existing inclined crack propagated and connected with the mixed crack initiating from pre-existing edge crack in Group 2, and the coalescence led to the specimen failure. The mixed crack was shear crack during

the initiation (45° with the edge crack), while it was changed to tensile crack during the propagation (along the max principal major stress).

- (2) Crack initiation, coalescence and specimen failure led to the peak of energy index. The energy index of edge crack initiation (shear crack) was much bigger than that of inclined crack (tensile crack). The uniaxial strength of specimens with pre-existing inclined cracks in Group 2 was about 10.5% lower than that of specimens in Group 1. The stress concentration obviously occurred at the tips of pre-existing cracks, and the degree of edge cracks was much bigger than that of inclined cracks.
- (3) The edge cracks and inclined cracks can be seen as working faces and buried structure, and macroscopic cracks (formed by the pre-existing crack propagation) could be seen as underground watercourse. When the buried structure propagated and connected with the mining damage zone and confined aquifer, water inrush of buried structure can be caused. Lab tests and numerical modelling illustrated the evolution characteristics of buried structure water inrush in some degree.

Acknowledgements This study were supported by the Shandong Provincial Natural Science Foundation, China (ZR2019BEE013, 2017BEE001), National Natural Science Foundation of China (No. 51704152), Taishan Scholar Talent Team Support Plan for Advantaged & Unique Discipline Areas, Key Laboratory Open Foundation of Deep Coal Mine Excavation Response & Disaster Prevention and Control (No. KLDCMERDPC17108).

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