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Effects of crack inclination and aperture on mechanical properties and fracture behavior of sandstone: an experimental study based on acoustic emission monitoring



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Abstract: The inclination and aperture of rock fractures significantly influence the mechanical properties and crack propagation behavior of rock masses. To investigate the deformation characteristics and crack evolution in sandstone, uniaxial compression tests were conducted on specimens containing pre-existing cracks with different apertures (1 mm, 3 mm, and 6 mm) and inclination angles (0°, 30°, 45°, 75°, and 90°). Acoustic emission (AE) monitoring was employed to capture the mechanical response and crack development in real time. The experimental results indicate that the peak strength decreases significantly with increasing crack aperture, while it increases with larger inclination angles. The stress-strain curves can be divided into four distinct stages: initial compaction of pores and micro-cracks, linear elastic deformation, stable crack propagation, and post-peak failure. The failure mode transitions from shear-dominated to tensile-dominated fracture as the inclination angle increases. Based on the crack initiation stress criterion, the crack initiation stress increases with higher inclination angles due to the enhanced restraining effect of the maximum horizontal principal stress on crack opening. In contrast, the crack initiation stress decreases with larger apertures, which is attributed to the greater proportion of initial defects and their significant influence on stress distribution and crack propagation patterns. These findings provide valuable insight into the mechanical behavior and failure mechanisms of fractured sandstone.

Keywords: fractured rock; acoustic emission; crack initiation stress; failure mode

1. Introduction

Rock, serving as the elementary constituent of rock masses, is a complex geological material comprising an assemblage of distinct minerals. Throughout its geological history, subsequent to initial formation, rock materials are subjected to prolonged weathering and tectonic activities, which introduce multiscale initial defects including pores, fissures, and fractures. The morphological attributes, dimensional characteristics, and spatial arrangement of these inherent defects govern the heterogeneous mechanical



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response and deformation behavior of rocks, thereby exerting a profound influence on the nucleation and evolution of microcracks [1,2]. It is widely recognized that the initiation and progressive propagation of microcracks represent key mechanisms driving rock instability and ultimate structural failure. Consequently, comprehensive research into the crack propagation trajectories and coalescence mechanisms in rocks containing pre-existing flaws is of substantial scientific and practical relevance. As a dynamic non-destructive monitoring technique, Acoustic Emission (AE) testing has been increasingly and effectively utilized across various disciplines, including geotechnical engineering, seismic activity prediction, and early warning systems for rock mass failure.

Numerous studies have been conducted by researchers worldwide on the acoustic emission characteristics of rocks. Regarding AE and damage in rocks: Otto [3] and Ohtsu [4] applied rate process theory to utilize AE for damage assessment in concrete, concluding that AE activity is positively correlated with the number of cracks in the material. Yang *et al.* [5], through acoustic testing during uniaxial compression experiments, discovered that macroscopic deformation, crack development, and stress evolution in rocks exhibit clear staging and synchrony with AE events. Liu Baoxian *et al.* [6] investigated the damage evolution laws and AE characteristics of coal rock under uniaxial stress, establishing a damage model based on AE features and deriving the damage evolution curve and equation for coal rock. Dong Longjun *et al.* [7] utilized AE information obtained from uniaxial compression tests and machine learning models to develop a method for identifying the compaction, elastic, stable crack propagation, and unstable crack propagation stages during granite failure. Zhou Zhiwei *et al.* [8] studied damage and AE in salt rock under uniaxial stress, suggesting that ring-down counts reflect the damage evolution process more effectively than energy parameters. Li Xiulei *et al.* [9] performed uniaxial compression tests on intact granite specimens with pre-existing cracks at different inclination angles, demonstrating that rock behavior varies significantly with changes in crack inclination. These studies illustrate the widespread application of AE technology in researching rock damage, crack development, and fracture behavior.

In summary, researchers have extensively used AE technology to study the mechanical properties of fractured rocks, leading to a profound understanding that plays a crucial role in assessing the stability of rock engineering. Currently, most studies focus on the influence of crack inclination angles on rock damage degree and crack initiation failure modes under a specific crack aperture. However, there is relatively little research on how combined variations in both crack aperture and inclination angle affect rock damage and failure patterns. This paper aims to address this gap by conducting uniaxial compression tests on sandstone specimens. The study will investigate the correlations between AE characteristics, crack propagation, and stress evolution throughout the entire failure process of rocks with different pre-existing crack inclination angles and apertures, and analyze the impact of crack morphology.

2. Experimental Program

2.1. Specimen Preparation

In this experimental investigation, argillaceous siltstone specimens were sourced from the Dahao No. 1 Tunnel, located within the mileage section K2 + 214 to K2 + 242, as part of the Laoying–Banqiao reconstruction project along the Daba Expressway. The selected rock material is representative of the geological conditions encountered in the tunnel, providing relevant insight into the mechanical behavior

of such sedimentary formations. In accordance with the testing standards recommended by the International Society for Rock Mechanics (ISRM), the collected samples were precision-machined into rectangular prismatic specimens with dimensions of 50 mm × 50 mm × 100 mm, ensuring a consistent height-to-width ratio of 2:1. To meet strict geometric tolerances, the end surfaces of each specimen were ground to a high degree of flatness, with deviations controlled within 0.01 mm using a specialized rock cutting machine.

Artificial flaws were introduced at the geometric center of each specimen by means of high-pressure water jet cutting, a technique that allows for accurate and consistent flaw generation. These pre-existing flaws were fabricated with a constant length of 20 mm, while varying in width to simulate different fissure types: 1 mm (representing a closed fissure), 3 mm (an open fissure), and 6 mm (a wide-open fissure). The inclination of these flaws, defined by the dip angle (β) relative to the horizontal plane, was systematically set at 0°, 30°, 45°, 75°, and 90°. This experimental design resulted in a total of 15 distinct flaw configurations, as illustrated in Figure 1, enabling a comprehensive analysis of flaw geometry influence on mechanical performance. Prior to mechanical testing, all specimens were thoroughly oven-dried to eliminate moisture content. The average physical properties of the sandstone, including density and longitudinal wave velocity, were measured as 2.21 g/cm³ and 2954.3 m/s, respectively, providing essential reference data for subsequent analysis.



Figure 1. Test specimens.

2.2. Experimental Setup

The loading system employed in this study was a CSS-WAW-600 electro-hydraulic servo-controlled universal testing machine with a measurement accuracy of $\pm 1\%$. This system is capable of automatic load control and displacement control. All tests were conducted under displacement control at a constant rate of 0.2 mm/min.

AE monitoring was performed using a DS5 series eight-channel full-information AE signal analysis system (Beijing Ruandao Shidai Technology Co., Ltd.). For strain measurement, a non-contact XTDIC digital image correlation (DIC) system was utilized. The front surface of each specimen was prepared with a speckle pattern by applying matte white and black spray paints. On the rear surface, four RS-2A AE sensors were symmetrically attached using adhesive to form a planar AE monitoring network, ensuring firm bonding to prevent detachment during testing, as illustrated in Figure 1.

The AE system parameters were set as follows: the preamplifier gain was 40 dB, the threshold was 100 mV, and the sampling rate was 6 MHz. A hardware analog filter with a passband from 100 kHz to 500 kHz was applied to reduce noise. The performance and coupling of each sensor were verified through repeated pencil-lead break tests prior to the formal experiments.

3. Mechanical Properties

3.1. Influence of Fissure Inclination on Deformation Characteristics at a Constant Aperture

Figure 2 illustrates the stress-strain curves of specimens containing fissures with an aperture of 1 mm at various inclination angles. As observed, the curves for different angles under the same aperture are broadly similar and can be divided into four distinct stages: (1) the initial pore and fissure compression stage, (2) the linear elastic deformation stage, (3) the crack propagation stage, and (4) the post-peak failure stage.

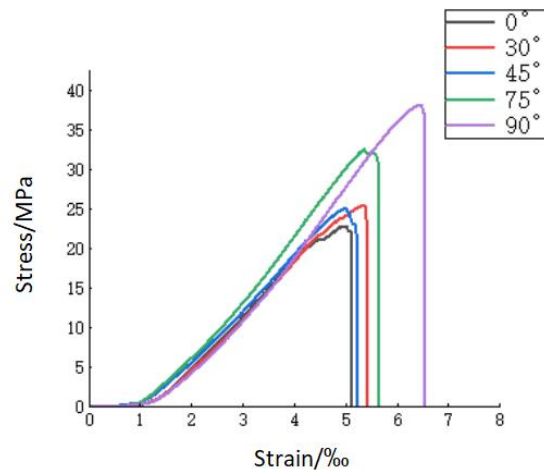


Figure 2. Stress-strain curves under different fissure inclination angles.

(1) Initial Pore and Fissure Compression Stage: Upon application of axial load, the pre-existing micro-pores and micro-fissures within the sandstone specimen are gradually compressed. This stage is characterized by a concave upward curve shape, indicating a relatively slow, non-linear increase in strain with stress.

(2) Linear Elastic Deformation Stage: With a continuous increase in external load, the specimen enters the linear elastic stage. During this phase, the stress-strain relationship becomes predominantly linear. The pre-existing micro-pores and fissures within the specimen undergo further compaction.

(3) Crack Propagation Stage: This stage marks the transition from elastic to plastic deformation. The internal micro-cracks and micro-pores initiate, nucleate, and progressively coalesce, eventually forming macroscopic cracks.

(4) Post-Peak Failure Stage: After the axial load reaches the peak strength (ultimate bearing capacity), the specimen enters the post-peak stage. The fissures and pores develop and propagate rapidly, leading to the formation of a major macroscopic fracture surface and resulting in the complete failure of the rock specimen.

3.2. Strength Characteristics under Various Fissure Apertures and Inclination Angles

Peak strength represents a crucial mechanical parameter in rock engineering, providing significant insights into the failure mechanisms of rock materials. This study systematically examines the peak strength of sandstone specimens containing pre-existing flaws with varying apertures and inclination angles. The observed relationships are graphically summarized in Figure 3.

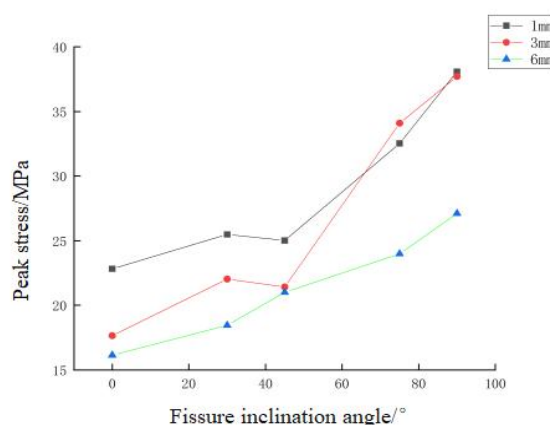


Figure 3. Stress-strain curves under different fissure inclination angles.

As demonstrated in the results, the peak strength shows a consistent increasing trend with greater flaw inclination angles across all aperture conditions. Specifically, for specimens with 1 mm flaw apertures, the peak strength increases from 22.83 MPa to 38.09 MPa; for those with 3 mm apertures, it rises from 17.65 MPa to 37.71 MPa; and for specimens with 6 mm apertures, it grows from 16.15 MPa to 27.17 MPa. This pattern can be explained by the enhanced constraining effect of the maximum principal stress in the horizontal direction on crack opening as the flaw inclination angle increases.

Conversely, a clear reduction in peak strength is observed with increasing flaw aperture. This phenomenon is attributable to the larger volume of internal defects within the specimen, which effectively diminishes its capacity to withstand external loads and accelerates the failure process. The experimental data clearly demonstrate that both flaw geometry parameters exert considerable influence on the mechanical behavior of fissured rock masses.

4. Acoustic Emission Characteristics

4.1. Evolution of AE in Fractured Sandstone

Based on the analysis of the AE evolution characteristics of fissured sandstone, the entire failure process from initial loading to complete rupture can be divided into three distinct stages:

AE Quiescent Stage: During this initial phase, as external load is applied, the closure and slip of pre-existing micro-fissures within the rock result in the release of a limited amount of elastic stress

waves. Acoustic emission activity remains scarce, with no significant AE signals detected. The cumulative ring-down count remains close to zero, indicating minimal micro-fracturing activity.

AE Development Stage: In this intermediate phase, a gradual increase in AE signals is observed, signifying the initiation and stable propagation of micro-cracks, predominantly near the tips of pre-existing flaws. The steady rise in acoustic emission reflects the progressive accumulation of damage within the rock material.

AE Rapid Growth Stage: The final stage is characterized by a sharp surge in AE signals, accompanied by a rapid increase in the cumulative ring-down count. This accelerated acoustic emission response indicates the swift propagation, coalescence, and interconnection of micro-cracks, ultimately leading to macroscopic failure and the complete loss of the specimen's structural integrity.

4.2. Propagation Modes Based on AE Parameters

Average frequency (AF) and rise angle (RA) serve as two characteristic parameters that effectively characterize AE events and are widely used for identifying crack types. The relevant AE signal parameters are illustrated in Figure 5. Specifically, AF represents the frequency content of a complete AE waveform, while RA is defined as the ratio of the rise time (the duration from the first threshold crossing to the peak amplitude) to the amplitude of the signal. The RA-AF correlation method for crack classification is schematically presented in Figure 4.

This dual-parameter approach offers enhanced discrimination capability compared to single-parameter analyses. High AF values typically correspond to tensile-dominated cracks, which generate signals with higher frequency components, whereas high RA values are generally indicative of shear-induced cracks characterized by longer rise times relative to their amplitudes. The quantitative relationship between these parameters provides a robust framework for interpreting fracture mechanisms in rock under various loading conditions.

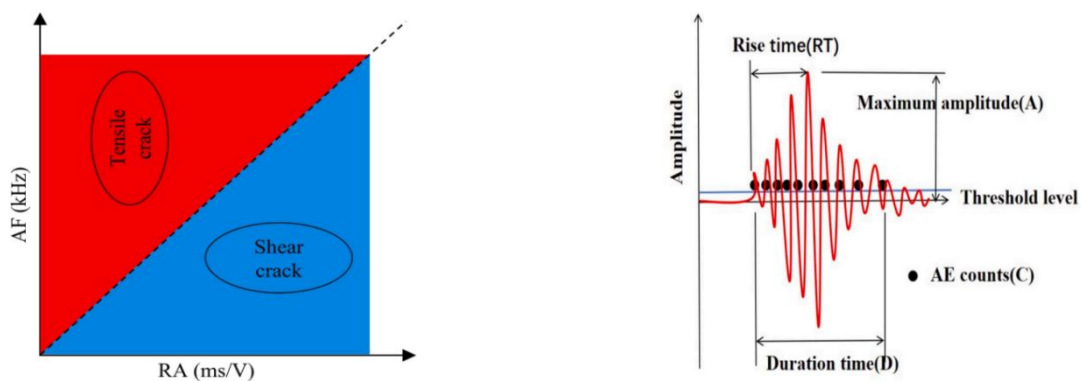


Figure 4. Schematic diagram of acoustic emission waveform and characteristic parameters.

The computational expressions for AF and RA are given as follows:

$$AF = \text{Ring-down Count/Duration}$$

$$RA = \text{Rise Time/Peak Amplitude}$$

Existing research findings [10] indicate that when an AE signal exhibits a high RA value and a low AF value, the associated crack mechanism is predominantly shear. Conversely, a low RA value coupled

with a high AF value suggests a tensile cracking mechanism. Consequently, the cracking mode can be classified based on the AF/RA ratio: a ratio of $AF/RA < 1.0$ signifies a primarily tensile fracture, while a ratio of $AF/RA > 1.0$ indicates a shear-dominated fracture. Given that the distribution patterns in the AF-RA plots were similar across different fissure apertures, the representative plot for specimens with a 3 mm aperture is presented in Figure 6 to analyze the underlying trends.

Figure 5 presents a systematic statistical classification of AE events generated during the uniaxial compression testing of sandstone specimens containing pre-existing flaws, with particular emphasis on the distribution patterns of tensile and shear cracks under varying flaw inclination angles (β). By employing the RA-AF correlation analysis method, this study enables quantitative identification of the dominant fracture mechanisms at different loading stages, thereby providing critical insights into the failure evolution process of fissured rock masses.

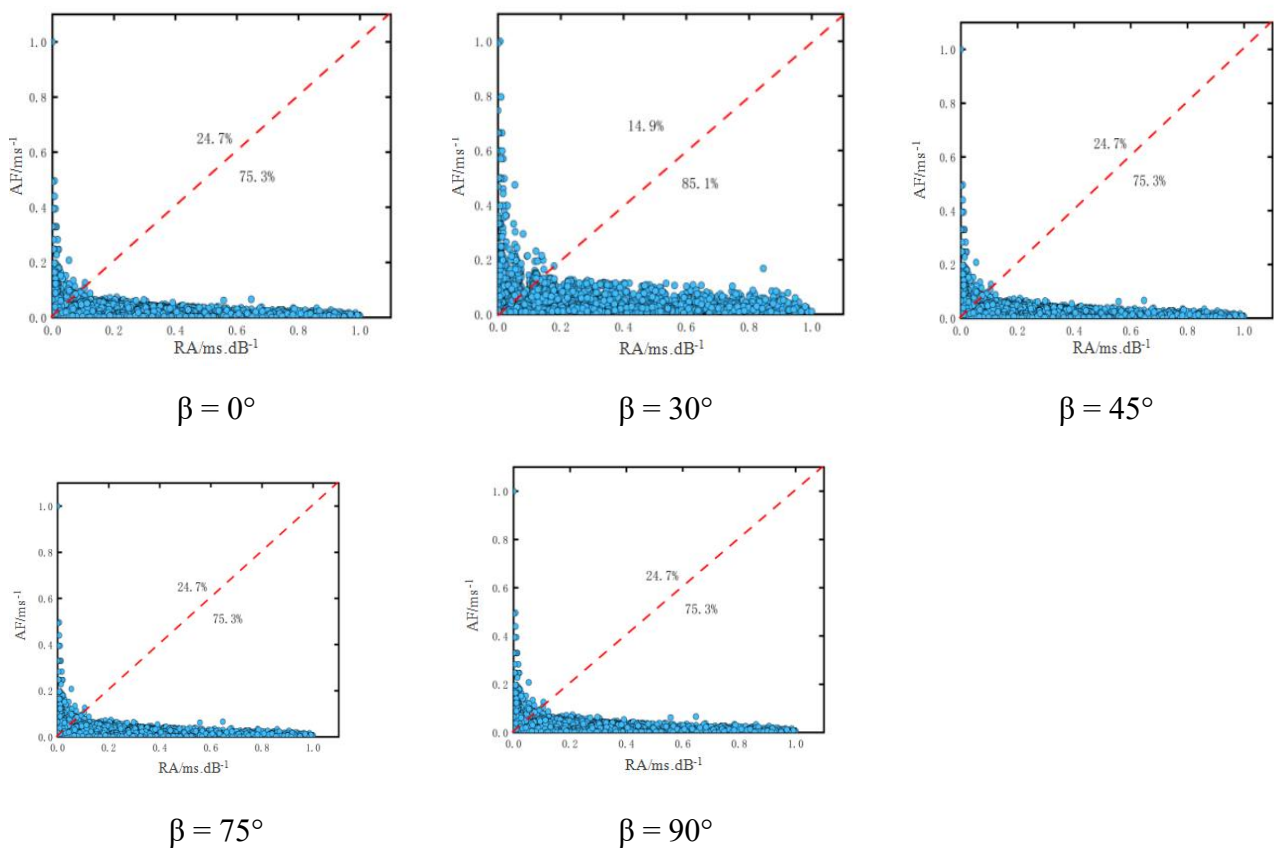


Figure 5. Relationship between normalized RA value and AF value.

Detailed experimental results indicate that when the flaw inclination angle β is 0° and 30° , the crack distribution points are predominantly concentrated in the RA-dominant region ($RA/AF > 1$), with corresponding proportions reaching 85.1% and 75.3%, respectively. This statistical characteristic strongly suggests that under low inclination angles, rock failure is primarily governed by shear slip, reflecting mechanical behavior controlled by shear stress along structural planes. As β increases to 45° , the crack distribution demonstrates a distinct transitional characteristic, with proportions in the RA and AF zones being 54.9% and 45.1%, respectively. This indicates the simultaneous development of both tensile and shear cracks in the vicinity of this critical inclination angle, resulting in a typical tensile-

shear composite failure mode. Notably, when β further increases to 75° and 90° , the crack distribution shows a significant shift toward the AF-dominant region ($AF/RA > 1$), with proportions reaching 75.4% and 81.0%, respectively. This pattern clearly reveals that under high flaw inclination conditions, the rock failure mechanism is dominated by tensile fracture.

From the perspective of mechanical mechanisms, the observed phenomena can be attributed to the varying relationship between the flaw plane orientation and the direction of the maximum principal stress. At low inclination angles, the flaw planes are more susceptible to shear slip due to their favorable orientation relative to the applied stress field. At medium inclination angles, both tensile and shear stresses interact significantly, leading to the development of composite fracture patterns. At high inclination angles, the stress concentration at the flaw tips enhances tensile stress components, promoting tensile-dominated failure. This finding not only verifies the controlling influence of flaw geometric parameters on rock failure modes but also elucidates the progressive evolution of fracture mechanisms with increasing flaw inclination angle, following a distinct "shear failure $\rightarrow$ tensile-shear composite failure $\rightarrow$ tensile failure" transition sequence.

5. Crack Initiation Stress in Sandstone

Crack initiation stress, as one of the key stress thresholds indicating damage evolution in rock under compressive loading, plays a critical role in understanding the mechanistic transition from micro-crack nucleation, propagation, and coalescence to macroscopic failure. Accurate determination of this parameter is of considerable theoretical and practical importance for predicting rock failure processes and ensuring the stability of rock engineering structures.

Various methodologies have been proposed by researchers worldwide to identify the crack initiation stress; however, these approaches differ significantly in terms of theoretical basis, applicability, and operational feasibility, leading to the absence of a universally accepted standard. After a systematic evaluation of existing techniques, this study adopts the method developed by Li Pengfei *et al.* [11], which integrates stress–strain behavior with cumulative AE hit counts. This technique identifies the crack initiation stress by correlating mechanical response with AE activity, offering robust physical justification and practical reliability.

An AE hit refers to an individual acoustic emission event that exceeds a predefined threshold and is recorded by the acquisition system. The cumulative AE hit count serves as a reliable indicator of the intensity of micro-cracking activity within the rock. Figure 7 illustrates the typical stress–strain curve of a sandstone specimen under uniaxial compression, along with the corresponding cumulative AE hit count plotted against time or strain. It can be clearly observed that as the external load increases, the cumulative AE hit count exhibits an overall rising trend. However, the rate of increase varies notably across different loading stages, reflecting the progressive and phase-specific nature of internal damage evolution.

As clearly observed from the evolutionary curve of cumulative AE hits shown in Figure 6, the cumulative AE hits exhibit a characteristic inverted "S"-shaped growth trend when the rock undergoes three typical stages under uniaxial compression: crack closure, elastic deformation, and stable crack propagation. In the first stage, the curve demonstrates an upward convex morphology, where the cumulative AE hits increase rapidly with the rise in axial load. This phenomenon primarily originates from the concentrated release of AE signals generated by the closure of initial microcracks and pores

within the rock under compression. During the second stage, the curve gradually transitions into a phase of approximately linear growth, where the cumulative AE hits increase slowly with stress, corresponding to the linear elastic deformation behavior of the rock. Upon entering the third stage, the curve displays a distinct non-linear accelerated growth characteristic, with the growth rate of cumulative AE hits increasing significantly. This reflects the entry of internal cracks into a stage of unstable propagation, ultimately leading to macroscopic coalescence and complete failure.

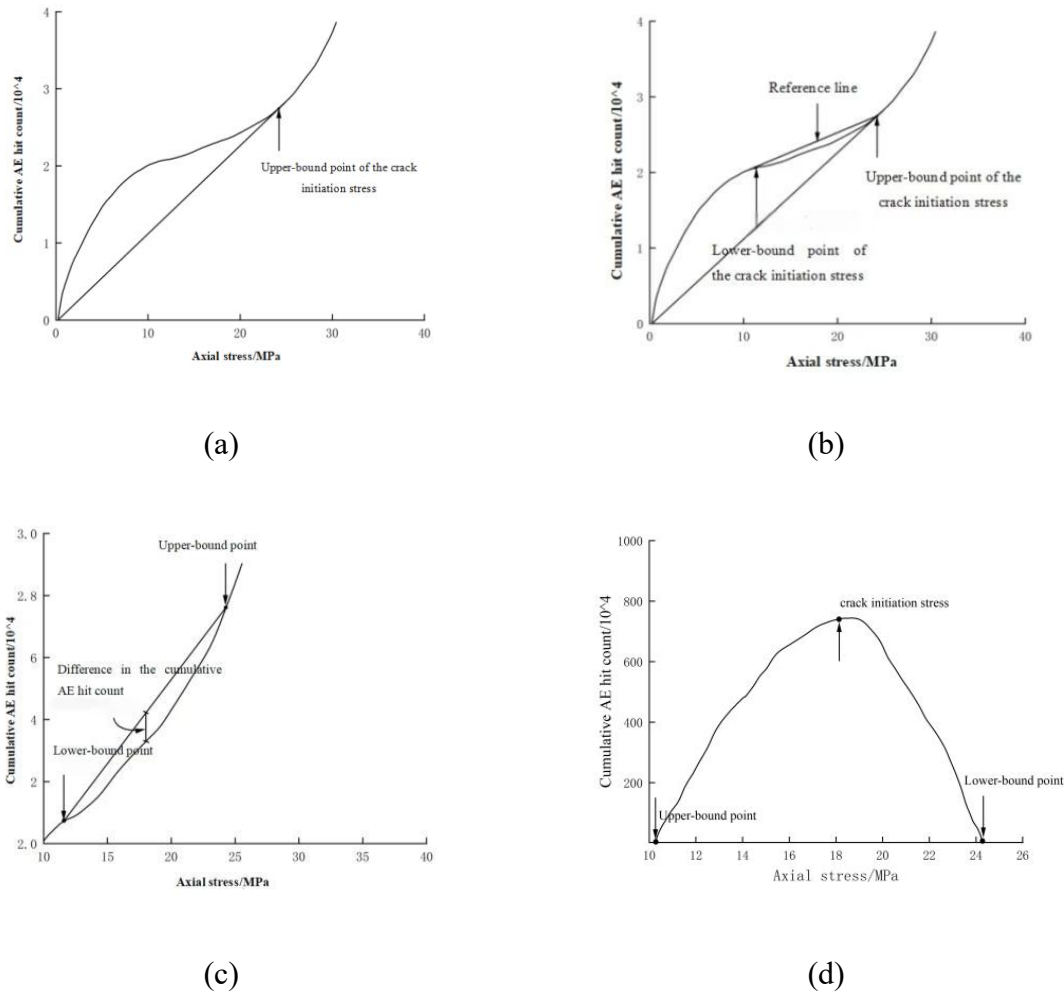


Figure 6. Procedure for determining the crack initiation stress. **(a)** Determine the upper-bound point of the crack initiation stress; **(b)** Determine the lower-bound point of the crack initiation stress; **(c)** Calculate the difference in the cumulative hit count; **(d)** Determine the crack initiation stress

Li Pengfei *et al.* proposed that when objectively determining the crack initiation stress using the cumulative AE hit count method, the stress range in which the crack initiation stress lies should first be clarified. The numerical value of the crack initiation stress cannot be higher than the stress level corresponding to the turning point (upward inflection point) of the third-stage curve, nor should it be lower than the stress value corresponding to the end of the upward convex segment of the first stage. Therefore, precise identification can be achieved by determining the upper and lower limits of the crack initiation stress and employing a successive approximation method. This paper takes a rock specimen

with an aperture of 1 mm and a flaw inclination angle of 75° as an example to elaborate the determination steps in detail:

(1) Determination of the Upper Limit Point of Crack Initiation Stress: Starting from the origin in Figure 6(a), a straight line is drawn with its slope gradually increasing from zero. The stress value corresponding to the point where this line is first tangent to the cumulative AE hit curve is identified as the upper limit point of the crack initiation stress. This point marks the critical state of the rock's transition from the compaction stage to the elastic deformation stage.

(2) Determination of the Lower Limit Point of Crack Initiation Stress: Based on the established upper limit point, another straight line is drawn from this point, again with a gradually increasing slope. The point of tangency between this line and the cumulative AE hit curve yields the lower limit point, as shown in Figure 6(b). This point corresponds to the initial stress at which microcracks begin to develop stably during the elastic stage.

(3) Calculation of the Cumulative AE Hit Difference: As illustrated in Figure 6(c), a reference line is constructed by connecting the upper and lower limit points. The difference between the actual cumulative AE hit count and the value on the reference line at the same stress level is then calculated for various stress levels. This difference reflects the intensity of the rock's damage evolution.

(4) Determination of the Crack Initiation Stress Value: By plotting the relationship curve between the cumulative AE hit difference and the axial stress, the stress value corresponding to the peak of this curve is identified as the crack initiation stress, shown in Figure 6(d). This peak point signifies the key stress threshold marking the transition of the rock from stable microcrack propagation to unstable propagation.

Based on the experimental program described above, the crack initiation stresses of rock specimens containing pre-existing fractures with various apertures and dip angles were systematically measured, and the corresponding results are presented in Figure 7. The data indicate a clear increasing trend in the crack initiation pressure as the dip angle of the pre-existing fracture increases. This trend is attributed to the enhanced constraining effect exerted by the maximum horizontal principal stress on fracture opening as the fracture plane becomes more aligned perpendicular to the stress direction. Consequently, a higher internal pressure is required to overcome the surrounding rock pressure and initiate cracking. Furthermore, the results demonstrate that, for a given fracture dip angle, the crack initiation stress decreases with increasing fracture aperture. This reduction is due to the fact that a larger aperture increases the mechanical influence of the fracture within the rock mass, thereby reducing its overall load-bearing capacity and facilitating crack initiation at a lower stress level. These findings highlight the significant influence of fracture geometry on the rock's fracture behavior, where the dip angle primarily governs the stress conditions required for crack initiation, while the aperture serves as an indicator of the degree of damage within the rock mass.

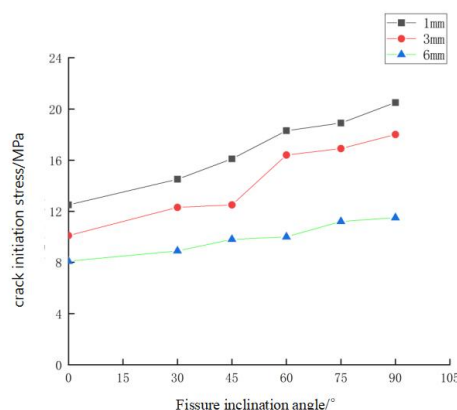


Figure 7. Crack initiation stress for different fissure apertures and inclination angles.

6. Conclusions

Through a series of experimental investigations, this study systematically examined the synergistic effects of fracture aperture and dip angle on the mechanical behavior, AE characteristics, and failure modes of sandstone. The principal conclusions derived from this research are summarized as follows:

(1) The geometric parameters of pre-existing fractures exert a decisive influence on the peak strength of sandstone. Test results indicate that under a constant dip angle, the peak strength of specimens decreases significantly with increasing fracture aperture. This reduction is primarily attributed to the diminished effective contact area at the fracture interface, which considerably weakens the load-bearing capacity of the rock bridges, thereby facilitating macroscopic failure at lower stress levels. Conversely, the peak strength demonstrates a consistent increasing trend with greater fracture dip angles. This trend results from the alteration in the relative orientation between the fracture plane and the direction of the maximum principal stress, which governs the susceptibility of the fracture to slip or opening.

(2) Real-time AE monitoring allowed for a clear division of the stress-strain response of fractured sandstone specimens into four distinct stages: the initial pore and crack compaction stage, the linear elastic deformation stage, the stages of stable and unstable crack propagation, and the post-peak failure stage. AE hit counts exhibited a strong correlation with the damage progression throughout these stages. Activity remained low during the elastic phase but increased sharply upon entering the crack propagation stage, particularly near the peak stress. This surge effectively reveals the dynamic processes of micro-crack initiation, growth, and coalescence within the material.

(3) The analysis of AE parameters, specifically the relationship between average frequency (AF) and the RA value (ratio of rise time to amplitude), served as an effective indicator for distinguishing fracture mechanisms. The analysis revealed that specimens with fracture angles (β) of 0° and 30° failed predominantly in shear. A mixed tensile-shear failure mode was observed at $\beta = 45^\circ$, while failure transitioned to a predominantly tensile mode at $\beta = 75^\circ$ and 90° . This pattern clearly illustrates a systematic transition in the dominant failure mechanism from shear to tensile as the fracture dip angle increases.

(4) The crack initiation stress under various fracture geometries was determined by correlating the stress-strain curves with the cumulative AE hit counts. The crack initiation stress was found to increase monotonically with the fracture dip angle. This is mechanistically explained by the enhanced confinement effect on tensile crack initiation as the fracture plane aligns more perpendicularly to the maximum horizontal principal stress, necessitating a higher internal pressure to initiate cracking. In contrast, the crack initiation stress decreased markedly with larger fracture apertures. This decrease is ascribed to the fact that a larger aperture not only reduces the effective load-bearing cross-section of the rock but also fundamentally alters the stress state and energy concentration at the crack tip, significantly influencing the subsequent crack propagation path and mode

Data availability statement

No supplementary or additional data were generated in this study.

Declaration of Generative AI and AI-assisted Technologies

During the preparation of this manuscript, the authors used generative AI-assisted tools solely to improve language and readability. The authors reviewed and edited all AI-assisted output and take full responsibility for the integrity, originality, and accuracy of the manuscript.

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Authors' contribution

Conceptualization, Dong Zhu and Zhenjie Zhang; methodology, Dong Zhu; validation, Dong Zhu and Zhenjie Zhang; formal analysis, Dong Zhu; investigation, Dong Zhu; resources, Zhenjie Zhang; data curation, Dong Zhu; writing—original draft preparation, Dong Zhu; writing—review and editing, Dong Zhu and Zhenjie Zhang; visualization, Dong Zhu; supervision, Dong Zhu; project administration, Dong Zhu; funding acquisition, Zhenjie Zhang. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

Zhenjie Zhang is employed by Baoshan Longying Expressway Co., Ltd., which provided funding and in-situ rock materials for this study. Dong Zhu declares no competing interests. The authors declare no other conflicts of interest.

Ethical statement

This study involved only laboratory testing and acoustic emission monitoring of sandstone specimens and did not involve human participants, human data, or animals. Therefore, institutional ethics committee or institutional review board approval was not required.

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