

Article

Characteristics of Crack Deflection and Mixed-Mode I-II Fracture Controlled by Bedding in Oil Shale Under Three-Point Bending

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Abstract

Oil shale often exhibits well-developed internal bedding planes, microcracks and organic-rich weak interfaces, while a mixed failure mode of tensile fracture and shear slip along weak bedding planes can be observed under bending loads. In this study, three-point bending tests were performed on the oil shale, and with the combination of acoustic emission (AE) monitoring to analyze the crack propagation paths, the crack path selection and mixed-mode I-II fracture behavior controlled by bedding were symmetrically investigated. The experimental results demonstrate that crack propagation does not always steadily proceed along the initial direction of pre-existing crack, and instead, the occurrence of pronounced deflection can be observed near the weak bedding planes, indicating a trend of transition from tensile crack to shear slip along bedding, while the obvious mixed-mode I-II fracture characteristics are presented. Meanwhile, this process is also accompanied by the enhanced AE activity and the occurrence of a localized high-energy event. Furthermore, based on theoretical fracture mechanics analysis, it is interpreted that the localized driving force conditions at the crack tip can be altered by the mechanical differences between the bedding weak planes and the matrix, which provides a theoretical explanation for why the crack deflection along the structural weak planes is promoted. These research findings correlate the crack propagation path evolution, AE response and mixed-mode fracture characteristics, which can provide the experimental evidence for understanding the controlling role of crack path selection in brittle shale under bending conditions.

Keywords: crack deflection; interfacial slip; acoustic emission; mixed-mode I-II fracture; damage evolution



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1. Introduction

Oil shale is a highly complex sedimentary rock that is primarily distinguished from typical sedimentary rocks by the abundant presence of solid hydrocarbons, mostly in the form of kerogen. Accompanied by this unique composition, oil shale features well-developed internal bedding planes, microcracks, and organic-rich weak interfaces, which collectively impart remarkable anisotropy and brittle fracture characteristics [1,2]. Compared with homogeneous brittle materials, the presence of weak bedding planes in oil shale not only alters the crack initiation location and propagation direction, but also further

affects the crack propagation path, failure mode and energy release mechanism [3–5]. Accordingly, it is essential to explore the crack evolution law of oil shale under bending loads for understanding the fracture instability behavior of brittle layered rocks.

Generally, the three-point bending test is a crucial approach for investigating the crack initiation, propagation and brittle instability of materials [6]. For homogeneous materials, the main crack often propagates from the notch tip along the direction of maximum principal tensile stress, which exhibits a classical mode-I tensile fracture [7]. Moreover, the direction of crack initiation can be predicted using classical fracture mechanics methods, including the maximum circumferential stress criterion and the strain energy density theory [8,9]. For the layered rocks such as oil shale, the fracture behavior is primarily controlled by the bedding orientation, the strength of the weak plane and the geometric characteristics of the interface, while the fracture toughness is dependent on the orientations of weak bedding planes and the geometric relationships between the cracks and the bedding planes [10]. Specifically, during the crack propagation process, the crack no longer propagates along a single path, and instead, the occurrence of deflection can be observed near the weak bedding planes, after which the crack penetrates into the interface and propagates along the weak plane via slip, ultimately leading to the formation of mixed tensile–shear fracture mode [11].

Owing to the high sensitivity to microcracking activity, acoustic emission (AE) technology can effectively identify the crack initiation, propagation and damage evolution within the rocks, which provides crucial evidence for distinguishing fracture mechanisms [12–14]. The fracture events can be classified into tensile and shear modes by the AF-RA method through collecting AE waveform parameters including amplitude, ring count, duration and rise time [15,16]. For instance, related studies have adopted this method to illustrate the temporal sequence, spatial distribution, and energy release characteristics of crack evolution [17], and thereby the advantages of AE technology in revealing the details of damage evolution in brittle rocks were comprehensively elucidated.

In recent years, substantial research achievements have been accumulated in terms of anisotropic fractures and AE responses in layered shale. In terms of mechanical properties, numerous studies have systematically uncovered the controlling effects of bedding inclination angle on the uniaxial and triaxial compressive strength, deformation mode and failure morphology of shale [1,4,18,19]. In terms of fracture toughness, the researchers have utilized configurations such as the semicircular bending (SCB) and the cracked straight-through Brazilian disk (CSTBD) to determine mode I, mode II, and mixed-mode I-II fracture toughness of shale under different bedding orientations, and thus the significant impact of weak plane orientation on the crack propagation resistance was validated [20,21]. In terms of AE monitoring, existing studies have applied the AF-RA classification method to layered shale under loading conditions such as uniaxial compression and Brazilian splitting, and thereby the temporal evolution of tensile and shear fracture events can be successfully identified, while the correlation between weak bedding plane activation and crack type transition was established [5,16]. Overall, the aforementioned research outcomes have advanced the understanding of anisotropic fracture behavior in layered shale from various perspectives.

Existing studies have primarily concentrated on the determination of fracture toughness and failure mode under compression or mixed-mode loading conditions. In particular, insufficient attention has been devoted to the role of weak bedding planes in interrupting and altering the continuous crack propagation paths under the three-point bending condition dominated by tensile stress. Specifically, under three-point bending conditions, the complete crack path transition sequence involving the crack initiation at the pre-existing notch tip, nearly vertical tensile propagation within the matrix, deflection after approach-

ing the weak bedding planes, and subsequent transition to interfacial slip propagation remains lacking in systematic experimental documentation and mechanical explanations. More importantly, although previous studies have successfully identified the conditions governing fracture occurrence and fracture modes, it is still challenging to provide a satisfactory explanation for the critical mechanical issues of why the crack deflection occurs at specific locations and how the failure mode evolves before and after deflection, particularly relying solely on the statistical characterizations of AE events such as event counts, mode proportions, and waveform parameters. This is mainly attributed to the occurrence of crack deflection along the weak bedding planes, where abrupt changes are presented in geometric characteristics and mechanical properties [22], while the crack path selection is essentially controlled by the combination of stress field at the crack tip and mechanical mismatch at the interface.

Accordingly, in this study, the oil shale was selected as the research object, and then the pre-existing notched three-point bending fracture tests were conducted. With the combination of AE monitoring, the crack temporal evolution and the energy release characteristics were systematically investigated. On this basis, the fracture mechanics theory was introduced to elucidate the mechanical mechanism governing the transition of crack propagation from the matrix tensile propagation to the propagation slip along bedding planes. By combining experimental observations with this interpretative approach, it aims to qualitatively explain the mechanical driving mechanisms behind crack deflection and mode transition. Specifically, the staged characteristics of crack path evolution in oil shale were identified, while the differences in both the number and energy of tensile- and shear-mode fracture events were explicitly clarified, and thereby the mechanical driving mechanisms governing the crack deflection and the interfacial slip induced by weak bedding planes were further revealed.

2. Materials and Methods

2.1. Specimen Preparation and Physicochemical Parameters

2.1.1. Sampling and Processing

In this study, the oil shale specimens were collected from the Wayaobao Formation of Hecaogou Coal Mine in Shaanxi Province, China (Figure 1), and this stratigraphic region can be assigned to the Ordos Basin. The thickness of the oil shale layer reaches 11.92 m. The rock specimens exhibit dark gray to grayish-black in color, while a clear bedding structure can be observed with smooth bedding planes and joint surfaces. During the specimen processing, this oil shale is highly susceptible to delamination failure along the weak bedding planes, indicating that the vibration of the cutting machine can induce the occurrence of delamination between layers. Six rough blocks were initially processed. However, due to the severe mechanical mismatch between the hard matrix and the weak bedding planes, three specimens underwent premature splitting or localized delamination during the cutting process during sample preparation. Only the specimens that strictly maintained their structural integrity without visual pre-existing separation were retained for the subsequent three-point bending tests. This pronounced rejection rate provides valuable quantitative evidence for the significant macroscopic heterogeneity and the extreme mechanical vulnerability of the layered structures within the tested oil shale. All three successfully tested specimens are reported in this study; no specimen was excluded based on the experimental outcomes.

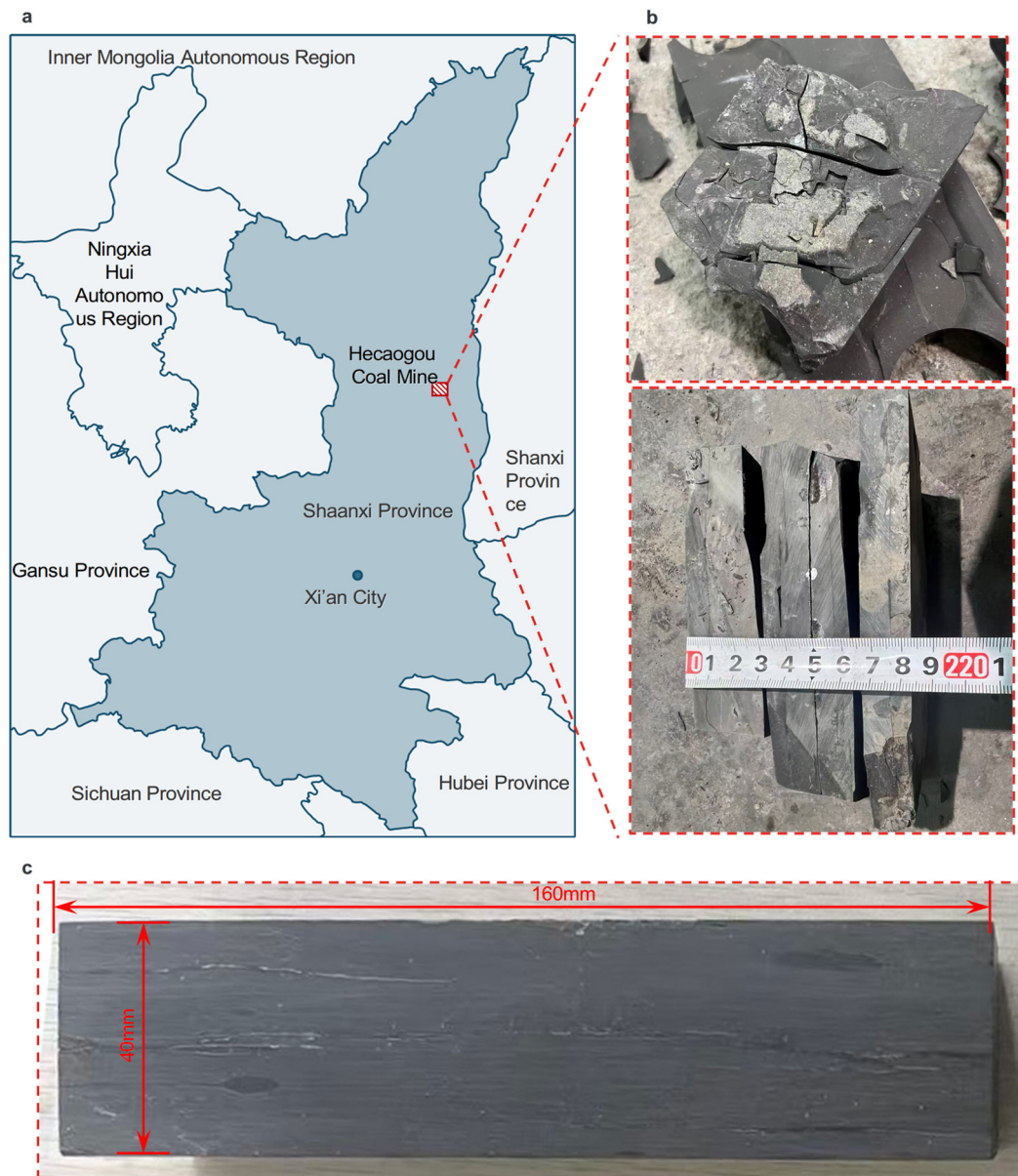


Figure 1. Shale sampling location and specimens: (a) shale sampling location; (b) sampling and fragmented specimens; (c) specimen processed for three-point bending.

As illustrated in Figure 1b, the specimens are broken into the laminated fragments with a thickness of ~2–3 cm. Eventually, the specimens for three-point bending were processed with dimensions of 40 mm × 40 mm × 160 mm. During the specimen processing, the weak bedding planes were horizontally placed, and the pre-existing notch direction was perpendicular to the weak bedding planes.

2.1.2. X-Ray Diffraction (XRD) Analysis

To examine the mineral composition and micromechanical performance of oil shale, X-ray diffraction (XRD) analysis was carried out. The mineral composition of oil shale was detected using a D8 Advance XRD system manufactured by Bruker GmbH, Bremen, Germany. Before the XRD analysis, the oil shale specimens were thoroughly ground using an agate mortar and then sieved through a 200-mesh sieve. The resulting XRD patterns were processed using MDI Jade software version 6.5, and based on the standard diffraction patterns from the International Centre for Diffraction Data (ICDD), the minerals in oil

shale were identified and quantitatively analyzed (Figure 2a,b). It should be noted that XRD-based quantification of multi-component samples carries inherent uncertainties, and the reported values should be interpreted as approximate estimates rather than exact measurements. The oil shale specimen is mainly composed of muscovite, quartz, kaolinite, feldspar, pyrite, and kerogen. Specifically, muscovite shows the highest content of 33 wt.%, while the content of kaolinite and pyrite each accounts for 15 wt.%, and the content of feldspar reaches 14 wt.%. Further, the contents of kerogen and quartz account for 10.9% and 6 wt.%, respectively, while the content of other components is 5 wt.%. Notably, the oil shale specimen exhibits a high proportion of clay minerals, with the total content of muscovite and kaolinite reaching 48 wt.%.

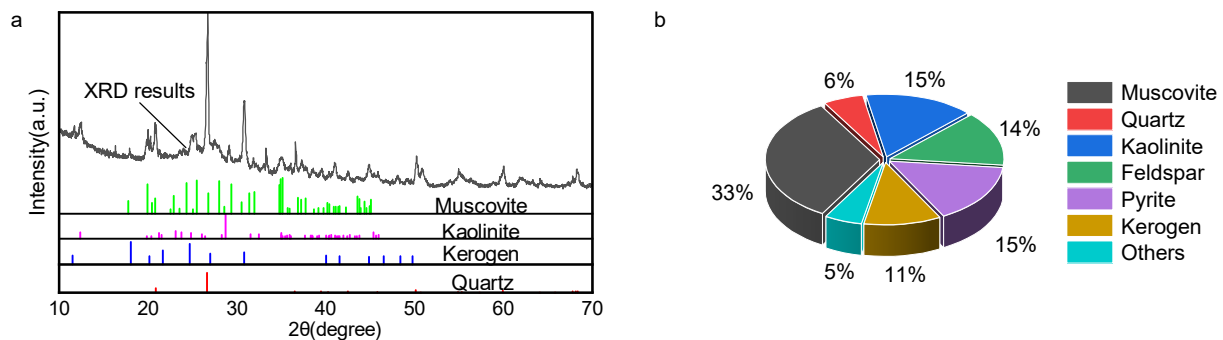


Figure 2. Composition characterization of oil shale: (a) XRD pattern; (b) Composition analysis.

2.2. Experimental Apparatus and Loading Scheme

In this study, to reveal the mechanical response and crack activity characteristics during the process of crack initiation, propagation, deflection and unstable penetration in the oil shale specimen under three-point bending, an experimental platform was established, which contained a three-point bending loading system and an AE monitoring system. During the testing process, these two systems were adopted to record the macroscopic load response and microscopic fracture events of the oil shale specimen, respectively. Figure 3 presents the overall experimental apparatus and the as-prepared oil shale specimen for the three-point bending test.

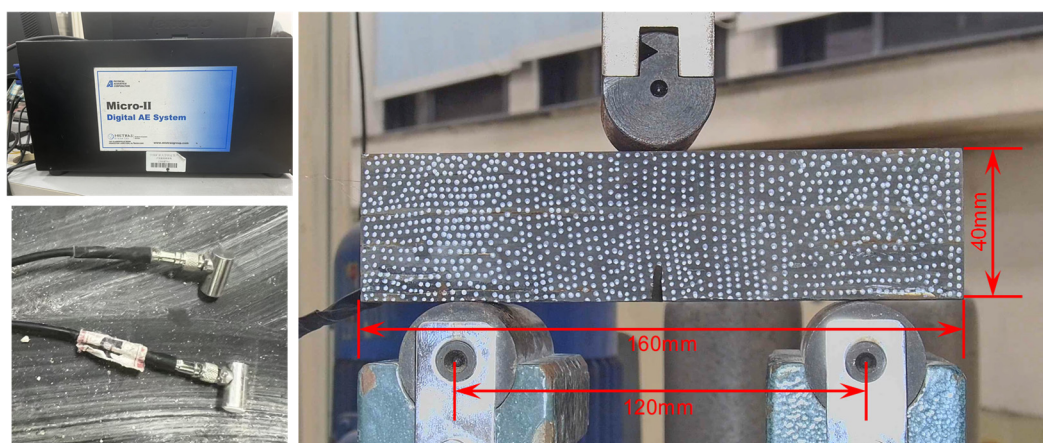


Figure 3. Experimental apparatus and as-prepared oil shale specimens.

All mechanical tests were conducted on a WDW-300 electronic universal testing machine (Jinan Victory Instrument Co., Ltd., Jinan, China). To ensure that crack initiation and stable crack propagation occurred under quasi-static conditions, the displacement control mode was adopted with the loading rate of 0.003 mm/s, consistent with the ISRM suggested

method for quasi-brittle fracture toughness testing [23], and the interference of loading rate fluctuations on the AE signal acquisition was minimized. During the testing process, the specimen was placed on a three-point bending fixture, while the two lower supports were symmetrically arranged, and the upper loading nose was located at the mid-span position of the specimen. The dimensions of the specimen were 40 mm × 40 mm × 160 mm, and the support span S was 120 mm, while the pre-existing notch depth a was 10 mm. To ensure that crack initiation preferentially occurred at the pre-existing notch tip, the loading nose was maintained at the mid-span position throughout the loading process, while the loading was continuously imposed until the specimen exhibited obvious macroscopic fracture and essentially lost its load-bearing capacity.

2.3. AE System and Parameter Monitoring

2.3.1. AE Monitoring System

In this study, to accurately capture in real-time fracture activities of microcrack initiation, propagation, penetration, and interfacial slip during the three-point bending process of oil shale, the PCI-2 type AE monitoring system manufactured by Physical Acoustics Corporation, West Windsor Township, NJ, USA, was utilized to monitor the fracture process of the specimen. The AE sensor was placed on the non-loaded side surface of the specimen, and the direct contact area between the loading nose and the support was avoided to minimize the interference of mechanical contact noise on the AE signal acquisition. To enhance the acoustic coupling quality between the sensor and the specimen surface, Vaseline was evenly coated as a coupling agent at the sensor–specimen contact interface, and subsequently, the signal verification was conducted after installation to ensure the stability and reliability of AE monitoring signals.

Due to the natural heterogeneity of the prepared oil shale specimens and the localized surface roughness caused by minor flaking of weak bedding planes, strict adherence to precisely identical geometric coordinates for sensor placement was practically challenging. To ensure optimal acoustic coupling quality between the sensor and the specimen surface, slight positional adjustments (within a deviation range of ± 5 mm) were intentionally made on different specimens to avoid surface defects and rough laminae. Prior to the formal testing, signal verifications (e.g., lead break tests) were conducted for each specimen. Given the relatively small dimensions of the specimens (40 mm × 40 mm × 160 mm) and the high propagation velocity of acoustic waves in brittle rock, such minor localized adjustments in sensor position exert negligible influences on the spatial wave attenuation, the AF-RA classification, and the overall statistical characteristics of AE energy.

During the testing process, the preamplifier gain of the AE system was set to 40 dB, and the sampling frequency was set to 1 MHz to meet the collection demands for high-frequency transient signals during the brittle fracture of the oil shale specimen. To reduce the interference of environmental noise and vibration from the loading system on the identification of effective AE events, the trigger threshold was set to 45 dB in this system.

2.3.2. Definition of Damage Variables

In this study, to evaluate the damage degree of the specimen during the loading process, the cumulative AE count was adopted to calculate the damage variable D , and the corresponding calculation can be expressed by Equation (1):

$$D = \frac{C_t}{C_0} \quad (1)$$

where C_t is the cumulative AE count at time t , C_0 is the total cumulative AE count at the time of complete failure. The damage variable D is within the range of 0~1. When D is relatively small, it indicates that only a small amount of dispersed microcrack activity

occurs within the specimen. In contrast, when D is close to 1, it indicates that the specimen approaches or reaches a macroscopic unstable state.

Since each AE event is assigned equal weight regardless of its magnitude, the cumulative count does not distinguish between high-energy events associated with large-scale crack propagation and low-energy events corresponding to minor microcracking activity. Consequently, the AE count does not always reflect the actual degree of material degradation as reliably as alternative metrics such as cumulative AE energy or source localization analysis. Nevertheless, the count-based damage variable was adopted in this study as a simplified indicator for characterizing the overall trend of damage accumulation during the loading process, given its widespread use in the rock mechanics literature and its straightforward physical interpretation.

2.3.3. Classification of Tensile/Shear Cracks Based on AF-RA

It is essential to distinguish the tensile and shear fracture events in terms of their temporal and frequency-domain characteristics for understanding the fracture process of oil shale. Because the tensile and shear cracks differ in their relative motion and waveform characteristics on the crack surface, the classification of cracks can be determined by the combination of average frequency (AF) and RA value [19,20]. Specifically, AF can be defined by Equation (2):

$$AF = \frac{Counts}{Duration} \quad (2)$$

where *Counts* represent the ring count of the AE event, and *Duration* is the AE signal duration. Meanwhile, the RA value can be defined by Equation (3):

$$RA = \frac{Rise\ Time}{Amplitude} \quad (3)$$

where *Rise Time* is the rise time, and *Amplitude* is the amplitude of the AE signal.

Generally, it is recognized that during the formation of tensile cracks, the rapid crack opening can be observed on the surface, while the corresponding AE signals exhibit a short rise time and high frequency, i.e., high AF and low RA . In contrast, the shear cracks are usually accompanied by the frictional slip and relative displacement of the crack surface, while the corresponding AE signals exhibit a longer rise time and lower frequency, i.e., low AF and high RA . In this study, the commonly used empirical slope of rocks/quasi-brittle materials in the literature was adopted as a qualitative classification criterion, and the empirical segmentation slope $K = 11$ was used as the discrimination threshold between tensile cracks and shear cracks [24]. As presented in Figure 4, when the AE event is located on one side of the boundary line in the AF - RA diagram, it can be determined as a tensile crack event. Conversely, the AE event is located on the other side of the boundary line in the AF - RA diagram; it can be identified as a shear crack event. It should be emphasized that the primary objective of relying on the AF - RA classification in this study is to qualitatively track the temporal transition boundary of fracture mechanisms as the crack approaches the weak bedding planes, rather than to pursue the strict absolute proportion of each crack type. While the exact empirical cutoff of K might shift the absolute numbers of categorized events slightly due to specific rock types and testing conditions, it does not fundamentally alter the chronological evolutionary sequence and the relative transition trend between tensile and shear events.

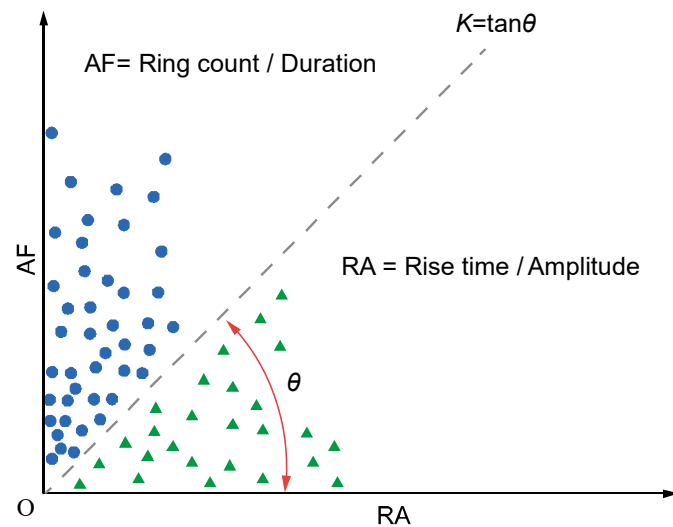


Figure 4. Schematic diagram of AF-RA scatter point distribution for the identification of crack types.

3. Results

3.1. Mechanical Response and Damage Evolution of Oil Shale Under Three-Point Bending

The damage evolution and failure process of oil shale under three-point bending display remarkable staged brittle characteristics. Figure 5 shows the monitoring results of load, AE ring count, and damage variable D for three oil shale specimens. During the loading process, all specimens universally exhibit multiple dense fracture events, whereas relatively quiescent intervals are also observed between adjacent fracture events. Notably, when the load reaches the peak strength of the specimen, instantaneous failure occurs. This common mechanical behavior demonstrates that the damage accumulation process of oil shale is not continuously stable, but rather gradually evolves through an intermittent fracture mode, ultimately resulting in the occurrence of sudden instability.

The specimen 1 was taken as an example (Figure 5a). In the early stage of loading, the number of AE events is relatively small and discretely distributed across multiple loading levels. As damage is continuously accumulated, the intensity of isolated AE events is significantly enhanced, leading to a pronounced stepwise increase in the damage variable D . Particularly, two extremely dense AE events occur around the 287–288 s and 317 s of loading, respectively, which are immediately followed by abrupt drops observed in the loading curve. From a mechanical perspective, the sparse AE signals in the early stage correspond to the gradual initiation of microcracks within the material. In the middle and later stages, the increased intensity of dense AE events and the stepwise abrupt change in the damage variable D can directly reflect the rapid penetration of microcracks and the formation of macroscopic cracks. Eventually, the sudden drop in the load and the instantaneous loss of bearing capacity can sufficiently demonstrate the extremely brittle fracture nature of oil shale.

Meanwhile, for specimen 2 and specimen 3, the load, AE and damage evolution process are generally consistent with those of specimen 1. The primary differences among the three specimens can be described as follows. As shown in Figure 5b, specimen 2 exhibits relatively concentrated burst AE events with only two relatively obvious AE activities before the peak, followed by instability and failure. In contrast, as shown in Figure 5c, specimen 3 undergoes multiple intermittent increases in AE activity before the peak, and thereby the damage accumulation process is relatively scattered. These individual differences are likely attributable to the natural variations in the internal bedding spacing, organic matter distribution and microdefect development degree of each specimen, which are commonly observed in layered sedimentary rocks. However, this attribution represents an interpretive

inference rather than a direct experimental measurement, as the exact bedding spacing and organic-matter distribution of each specimen were not independently characterized in this study. Despite these specimen-to-specimen variations, the fundamental failure characteristics of brittle instability in oil shale remain consistent across all tested specimens, confirming the robustness of the observed fracture mechanism.

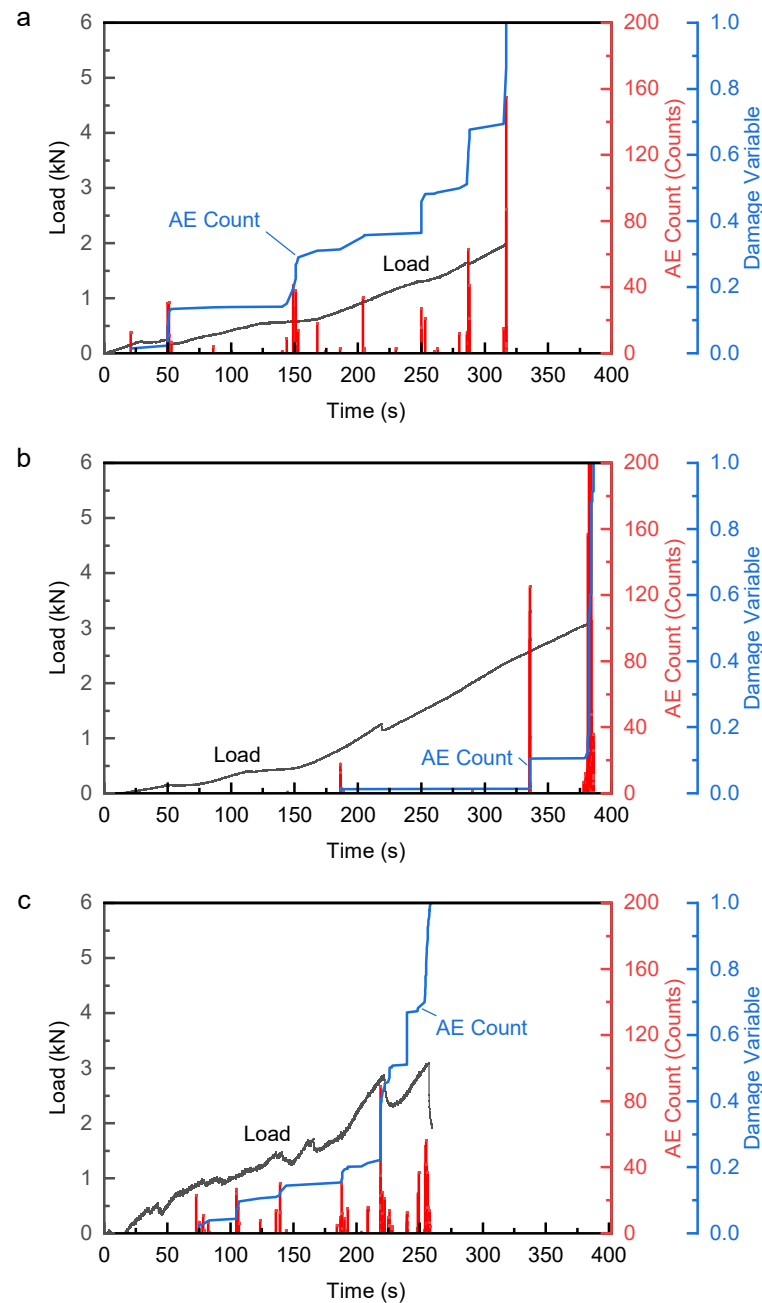


Figure 5. Monitoring results of load, AE ring count, and damage variable D for three oil shale specimens: (a) specimen 1; (b) specimen 2; (c) specimen 3.

3.2. Crack Initiation, Propagation and Failure Modes in Oil Shale

3.2.1. Crack Initiation and Propagation Process

Under three-point bending conditions, the cracks within oil shale exhibit a complex transition process from a tensile-dominated to a mixed tensile–shear failure mode. The direct evidence for this process is derived from the temporal observation of crack propagation. As illustrated in Figure 6a, in the early stage of loading, the crack initiation occurs near

the pre-existing notch tip at the bottom of the specimen, and thereby two cracks, T1 and T2, are generated. With continued loading, when the vertical cracks T1 and T2 approach the weak bedding planes with organic matter, the deflection of crack propagation occurs, and thereby the first horizontal crack S1 is generated and propagated along the bedding planes. Meanwhile, new tensile cracks T3 and T4 are successively generated within the upper region of the specimen (Figure 6b). As presented in Figure 6c, when approaching the peak load and failure stage, the cracks T1, T2, T3 and T4 exhibit various degrees of propagation, whereas the horizontal crack S1 continues to propagate along the bedding planes. The complete crack evolution process from the crack initiation at the pre-existing notch tip, vertical tensile propagation, deflection after approaching the weak bedding planes, to horizontal shear slip propagation reveals the controlling role of weak bedding planes in the crack propagation path.

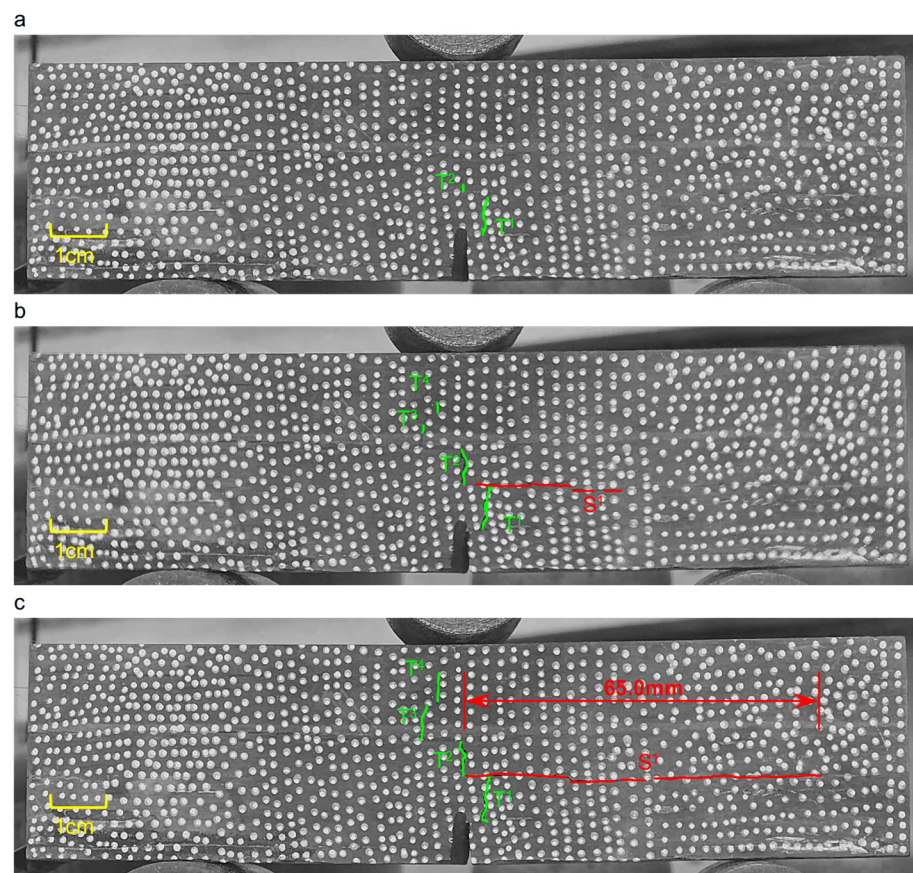


Figure 6. Crack development process in oil shale specimen: (a) 150 s; (b) 250 s; (c) 317 s.

3.2.2. Final Failure Mode

The controlling role of weak bedding planes revealed by the above crack evolution process is more comprehensively manifested in the final macroscopic failure mode of specimens, which exhibit a mixed-mode I-II failure rather than a simple mode I tensile fracture. Figure 7 shows the crack morphologies of three specimens after failure. After a bending fracture, there is no single strictly vertical crack penetration along the maximum principal tensile stress direction in the oil shale specimen, whereas a mixed failure mode containing the interleaved mode I vertical tensile cracks and mode II horizontal shear cracks is presented. In addition, from the perspective of the geometric characteristics of cracks, the total length of horizontal cracks is remarkably larger than that of the vertical cracks. For instance, as shown in Figure 7a, the total length of the horizontal crack reaches 64.3 mm. As presented in Figure 7b, the horizontal crack propagation extends to the specimen boundary.

In contrast, the vertical tensile cracks are characterized by segmented, discontinuous, and deflected propagation path morphology with the absence of continuous connectivity. This failure mode demonstrates that the tensile crack initiation is first induced near the notch tip under three-point bending, but when the crack front propagates into the weak bedding planes, the weak interface with relatively low strength becomes the preferred path for crack propagation. The crack propagation mechanism progressively evolves from the tensile-dominated process in the early stage to a mixed process controlled by tensile cracks and interfacial slip.

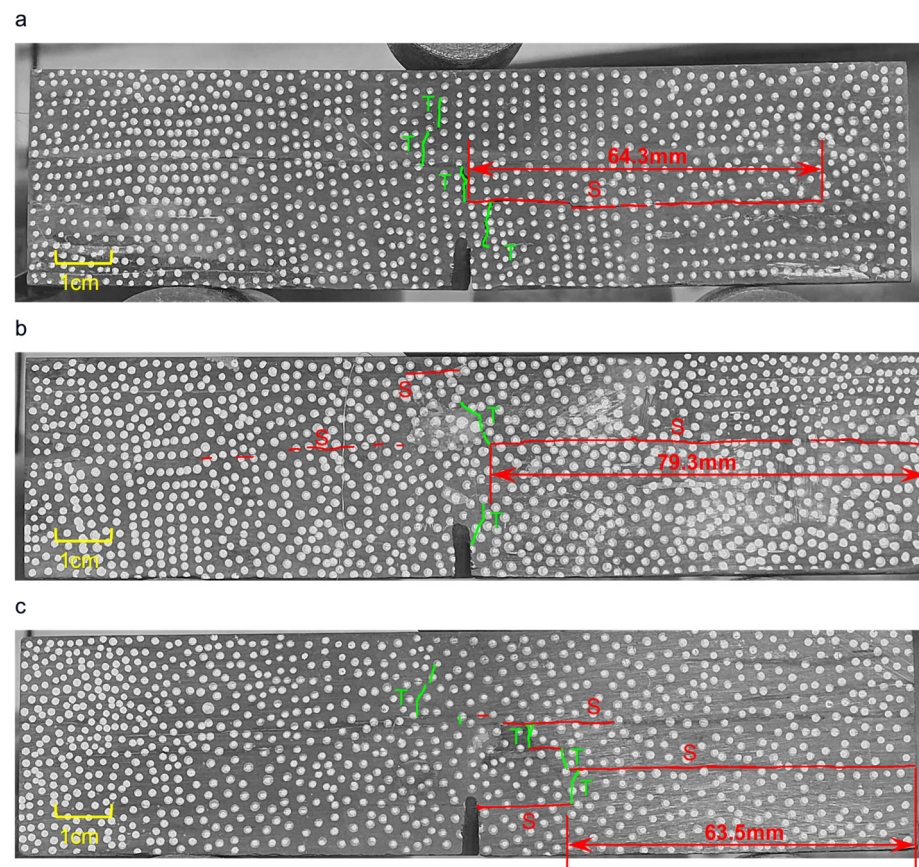


Figure 7. Crack morphologies of oil shale specimens: (a) specimen A; (b) specimen B; (c) specimen C.

3.3. Temporal Sequence and Frequency-Domain Evolution Characteristics of Tensile and Shear Cracks

To reveal the mixed-mode I-II fracture mechanism of oil shale, the effective AE events during the loading process of three specimens were classified and statistically analyzed, and the corresponding results are shown in Figure 8. Overall, the oil shale specimens exhibit obvious tensile–shear mixed failure characteristics under three-point bending conditions, whereas the entire loading process is still dominated by tensile fracture events.

From the perspective of the temporal sequence of events, the tensile fracture event first occurs in all cases. As illustrated in Figure 8a,c,e, all specimens exhibit the first occurrence of dense tensile fracture events in the early stage of loading. For example, as shown in Figure 8a, three dense tensile fracture events occur first, followed by the appearance of shear crack events. This phenomenon demonstrates that the crack initiation and propagation in the early stage are mainly controlled by the tensile fracture. As the main crack gradually approaches the weak bedding planes with organic matter, the deflection of crack propagation occurs, and thereby the localized frictional slip and relative displacement of weak bedding planes are enhanced, leading to a progressive increase in shear fracture

events. Accordingly, the shear fracture event does not play a dominant role in the crack initiation, but it is mainly involved in the crack deflection, slip along the weak bedding planes, and the later instability evolution process.

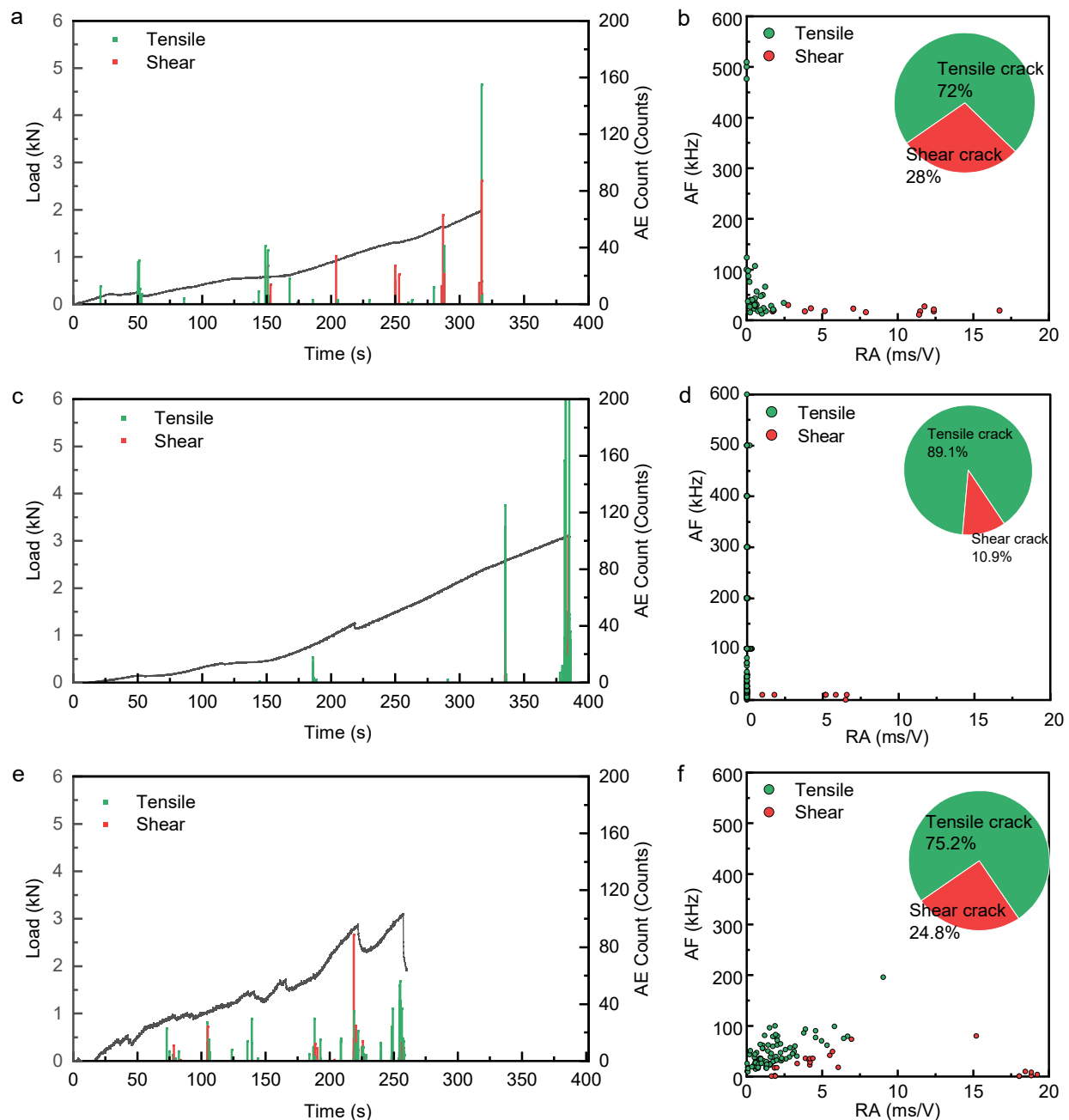


Figure 8. AF-RA data and statistical results of crack types for different oil shale specimens: (a) stress and tensile-shear crack events versus time for specimen 1; (b) statistical data of tensile-shear cracks for specimen 1; (c) stress and tensile-shear crack events versus time for specimen 2; (d) statistical data of tensile-shear cracks for specimen 2; (e) stress and tensile-shear crack events versus time for specimen 3; (f) Statistical data of tensile-shear cracks for specimen 3.

From the perspective of the overall frequency of crack events, the tensile fracture event exhibits an absolute dominance in terms of quantity. As illustrated in Figure 8b,d,f, the total numbers of effective AE events recorded for specimens 1, 2, and 3 are 108, 249, and 218, respectively, among which 78, 222, and 164 are classified as tensile fracture events, corresponding to proportions of 72.00%, 89.10%, and 75.20%, respectively. These results

demonstrate that under three-point bending conditions, the damage and fracture events of oil shale are generally dominated by tensile failure. Notably, there are some fluctuations among different specimens, but the tensile fracture events consistently play a dominant role. With the combination of crack morphologies in Figures 6 and 7, it is evident that the lower edges of specimens are located within the region of maximum tensile stress, where the microcracks preferentially initiate and vertically propagate, and thereby numerous tensile fracture events occur. When the crack propagation proceeds near the weak bedding planes, the localized stress state is gradually changed from being controlled by a single tensile force to a mixed tensile–shear effect, and thereby the occurrence and accumulation of shear fracture events are promoted.

3.4. AE Energy Release Characteristics of Different Crack Types

Although the temporal sequence and quantitative characteristics of fracture events can mainly reflect the activity level of different crack types during the loading process, the controlling role of the oil shale fracture cannot be characterized. Accordingly, the fracture process was further analyzed through the combination of AE energy characteristics. As presented in Figure 9, these three specimens generally exhibit the consistent energy release characteristics of different crack types. Overall, the number of tension fracture events is relatively high, while the energy distribution of individual events is relatively discrete. The occurrence of shear fracture events is enhanced in the later stage, but the overall energy of individual shear fracture events is lower than that of individual tensile fracture events.

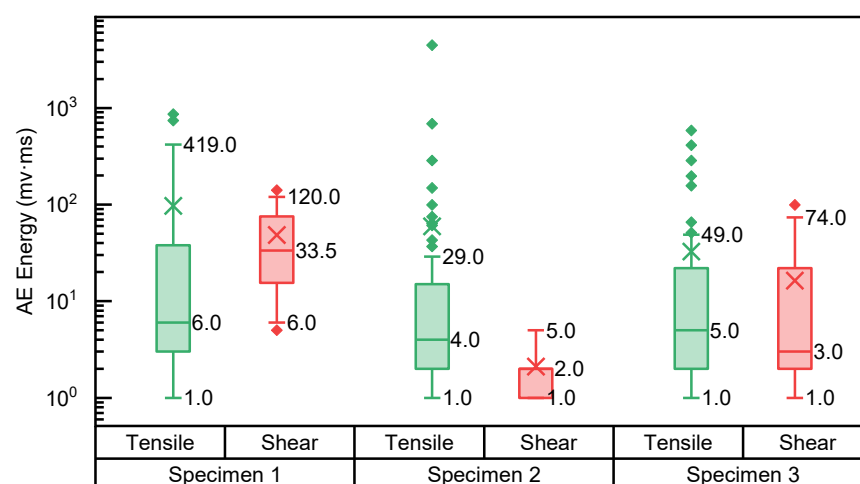


Figure 9. Statistical results of tensile and shear fracture events for different specimens. The median AE energy (50th percentile) is indicated in the plot, while the whiskers denote the interquartile range (25th–75th percentiles), providing a distribution-based comparison between tensile- and shear-mode events rather than relying solely on individual extreme values.

The specimen 1 exhibits multiple high-energy tensile fracture events with 237, 419, 739 and 861 mV·ms, respectively, whereas the shear fracture events in the specimen 1 exhibit relatively low energy levels with the maximum values of only 80, 120, and 141 mV·ms, respectively. The specimen 2 shows high-energy tensile fracture events with 287, 688 and 4462 mV·ms, respectively. In contrast, the energy levels of shear fracture events in specimen 2 are relatively low and are mainly located within the low value range. Furthermore, multiple high-energy tensile fracture events with 99, 197, 413 and 585 mV·ms simultaneously occur in specimen 3, whereas the overall energy levels of shear fracture events are relatively low, with the maximum value of only 157 mV·ms. Among the aforementioned results, the single high-energy events of three specimens can be determined as tensile fracture events. The occurrence of shear fracture events is continuously enhanced in

the vicinity of peak and in the post-peak stages, demonstrating that the slip of weak bedding planes cannot control the single highest energy release, but it is persistently involved in a crucial role in the crack deflection, interfacial slip, and the later complex instability evolution process.

4. Discussion

4.1. Mechanical Driving Mechanism of Crack Deflection in Oil Shale

In this study, the primary findings can be described as follows. Under three-point bending, the crack propagation in oil shale is not solely controlled by the initial direction of the pre-existing notch, but it is continuously affected by the bedding structure during the unstable crack propagation process. As the cracks gradually approach the mechanical weak bedding planes, the corresponding propagation path is transited from the tensile-dominated to deflection and slip propagation along the bedding orientation, while the significant mixed-mode I-II fracture characteristics are observed. Therefore, this transition is reflected not only in the final crack geometry but also in the enhanced AE activity and the simultaneous occurrence of localized high-energy events during the failure process. This phenomenon suggests that for the layered oil shale, the unstable crack propagation is essentially regarded as a crack path selection process impacted by the combined influences of stress field evolution at the crack tip and the constraint of weak bedding planes.

In this study, to explain this phenomenon, the analysis was conducted from the perspective of fracture mechanics. For the convenience of discussion, the fundamental assumptions were made as follows. Specifically, the oil shale matrix and the region adjacent to bedding planes in the pre-peak stage can be approximately regarded as linear elastomers. The cracks mainly exhibit the mode I tensile fracture before approaching the bedding planes, while compared with the oil shale matrix, the weak bedding planes can be treated as weak interfaces with lower strength and fracture energy. Meanwhile, the bedding thickness is negligible relative to the specimen size, and the crack propagation along the weak bedding planes after deflection can be simplified to the mixed-mode I-II fracture. For the mixed-mode I-II fracture, according to the K-field additivity, the stress intensity factor can be expressed by Equation (4):

$$\left. \begin{aligned} K'_I(\theta) &= K_I f_{\theta\theta}^I + K_{II} f_{\theta\theta}^{II} \\ K'_{II}(\theta) &= K_I f_{r\theta}^I + K_{II} f_{r\theta}^{II} \end{aligned} \right\} \quad (4)$$

where K_I and K_{II} are the mode I and mode II stress intensity factors at the original crack tip, respectively; $K'_I(\theta)$ and $K'_{II}(\theta)$ are the equivalent stress intensity factors when the crack propagates along the deflection direction θ .

Based on the mixed-mode crack theory established by Erdogan and Sih [8,9], the crack initiation along the direction that maximizes the circumferential stress $\sigma_{\theta\theta}$ at the crack tip with the shear stress of 0. Accordingly, the crack deflection angle θ_0 satisfies Equation (5):

$$\sin \theta_0 + \frac{K_{II}}{K_I} (3 \cos \theta_0 - 1) = 0 \quad (5)$$

Moreover, the corresponding θ_0 can be expressed by Equation (6):

$$\theta_0 = 2 \arctan \left[\frac{1}{4} \left(\frac{K_I}{K_{II}} - \sqrt{\left(\frac{K_I}{K_{II}} \right)^2 + 8} \right) \right] \quad (6)$$

From the mechanistic perspective of Equation (6), the occurrence probability of crack tip deflection is primarily determined by K_I/K_{II} . When the main crack is far from the weak bedding planes, the stress field at the crack tip is approximately symmetrical, and the

crack propagation is primarily controlled by K_I . As the crack approaches the weak bedding planes, the stress field at the crack tip is disturbed by the mechanical mismatch between the bedding and the matrix, and thereby a transition from mode I-dominated propagation to mixed-mode I–II propagation is induced. Similar results have been validated in previous studies of heterogeneous materials and interfacial fracture [21–23]. Hence, the presence of weak bedding planes leads to an increase in localized K_{II} , and thereby the likelihood of crack propagation along the weak interface is enhanced.

Figure 10 presents the crack deflection angles corresponding to various K_I/K_{II} ratios calculated by Equation (6). Specifically, when the crack is far from the weak bedding planes, the stress field at the crack tip is still dominated by K_I , whereas K_{II} is relatively small. Meanwhile, K_I/K_{II} is relatively high, and the crack propagates along the original direction without significant deflection. As the crack approaches the weak interface, K_{II} is further enhanced, while K_I/K_{II} is progressively reduced, and thereby the crack deflection angle gradually approaches -70° . These prediction results show qualitative consistency with the experimental observations in this work. For example, as shown in Figure 10b,c, the measured crack deflection angles are -73° and -77° , respectively. The agreement between the theoretical predictions and experimental measurements demonstrates that the fracture mechanics model can reasonably explain the crack propagation mechanism controlled by the bedding planes in oil shale. It should be pointed out that this theoretical model is built upon the linear elastic homogeneous approximation, whereas the actual oil shale is composed of weak bedding planes with organic matter, mineral heterogeneity, and localized defects, and thus there may still be some deviations between the theoretical predictions and the actual measurements, but both results exhibit a consistent changing trend.

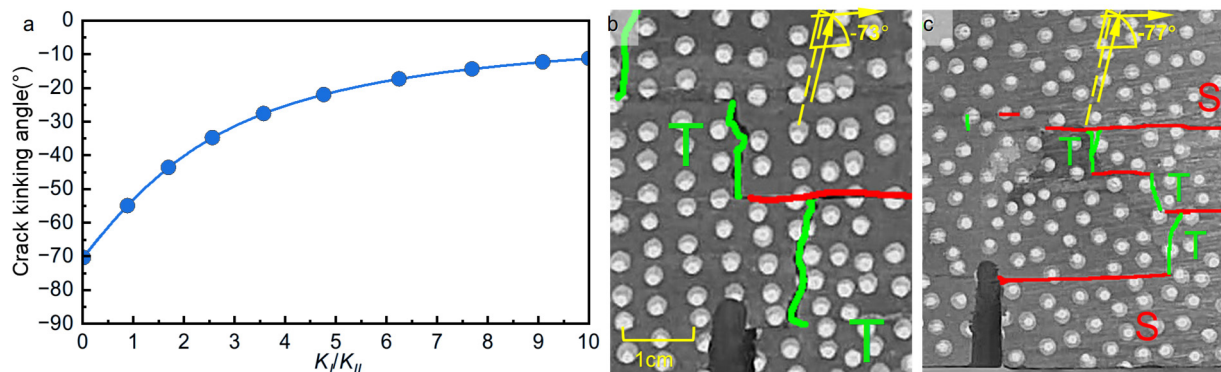


Figure 10. Crack deflection angles corresponding to K_I/K_{II} : (a) calculation results; (b) measurement results of specimen 1; (c) measurement results of specimen 2.

In Section 2.1.2, the tested oil shale contains a remarkably high proportion of clay minerals (muscovite and kaolinite, totaling approximately 48.5 wt.%). Muscovite possesses a typical layer-silicate structure with extremely well-developed cleavage planes, while kaolinite is characterized by its weak microscopic interlayer bonding. During the sedimentary compaction process of oil shale, these flaky clay minerals tend to be directionally distributed parallel to the macroscopic bedding planes. Consequently, when the tensile crack front approaches these clay-rich interfacial zones, the intrinsically low frictional coefficient and structural weakness of the muscovite and kaolinite significantly diminish the localized shear strength and fracture energy of the interface. This mineralogical characteristic fundamentally provides the material basis for the aforementioned local stress field adjustment and the observed macroscopic phenomenon: rather than penetrating the high-brittleness matrix, the crack preferentially deflects and undergoes interfacial slip

along the weak bedding planes. Therefore, the high susceptibility to slip is inherently determined by the synergistic effect of macroscopic bending stresses and microscopic clay mineral distributions.

From a micromechanical perspective, the finite thickness and relatively low stiffness of the organic matter layer significantly affect the mechanics of crack deflection. When the main tensile crack tip propagates into a relatively soft organic layer with finite thickness, a crack tip blunting effect may be induced due to the localized yielding or ductile deformation of the organic constituents, which mitigates the extreme stress concentration at the crack tip. Consequently, the actual interfacial crack propagation behavior involves not only brittle slip but also complex energy dissipation within the finite thickness of the weak region. Nevertheless, because the thickness of these organic layers is still macroscopically negligible relative to the sample dimensions and the overall crack propagation path, the linear elastic theoretical model and the simplified mixed-mode I-II assumption remain highly effective in capturing the macroscopic trend of the crack trajectory selection and the global deflection angle. The localized stress buffering by the finite-thickness organic layers merely delays the instantaneous rupture, explaining the dense, discrete localized high-energy acoustic emission events observed just before and during the macroscopic slip.

4.2. Microscopic and Macroscopic Characteristics of Fracture Toughness of Oil Shale

Based on the above results, the failure in oil shale under three-point bending cannot lead to the formation of a single vertically penetrating crack, but a complex crack network consisting of vertical tensile cracks and horizontal cracks along the bedding planes is generated. Meanwhile, the AE classification results demonstrate that the crack initiation and propagation in the early stage are dominated by the tensile fracture events, whereas the occurrence of shear fracture events is continuously enhanced in the vicinity of peak and in the post-peak stages. This indicates that the weak bedding planes cannot determine whether the crack initiation occurs, but they can significantly affect the path selection and failure mode during the subsequent crack propagation process. In this study, to further explore the influences of weak bedding planes on unstable crack propagation, the fracture toughness of oil shale was estimated using nanoindentation parameters and three-point bending peak loads, respectively.

4.2.1. Microscopic Fracture Toughness of Oil Shale Matrix

In this study, the nanoindentation measurements were carried out using a Hysitron TI980 nanoindenter (Bruker GmbH, Bremen, Germany). A Berkovich diamond indenter with a tip curvature radius of 100 nm was used. The maximum indentation load was set to 10 N with a load resolution of 1 μ N and a displacement resolution of 0.01 nm. During the testing process, the loading-holding-unloading mode was adopted. The indenter approached the specimen surface at a speed of 20 nm/s. When the load reached the preset maximum load P_{max} , the load was held for 5 s and then unloaded to 0. Five maximum load levels were adopted, i.e., 100 mN, 200 mN, 600 mN, 1000 mN and 1500 mN, respectively, while the corresponding results are presented in Figure 11.

Based on the nanoindentation testing results, the apparent fracture toughness of the material can be estimated by the indentation fracture mechanics model (Equation (7)):

$$K_{IC} = \chi \left(\frac{E}{H} \right)^{1/2} \frac{P}{c^{3/2}} \quad (7)$$

where K_{IC} is the fracture toughness (Pa·m), χ is an empirical constant taken as ~ 0.016 for a Berkovich indenter, E is the elastic modulus of the material, H is the hardness, P is the maximum load (N) and c is the characteristic crack size (m).

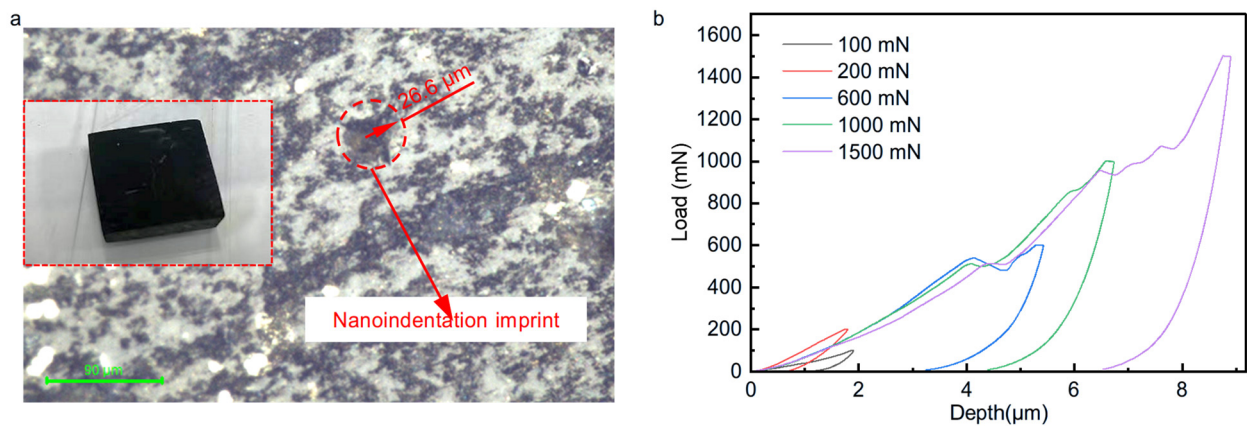


Figure 11. Physicochemical tests of oil shale: (a) rock specimen for nanoindentation test and corresponding micrograph; (b) nanoindentation testing results.

Table 1 lists the nanoindentation testing results of oil shale specimens and the calculated fracture toughness. The measurement results demonstrate that the indentation depth, contact stiffness, contact area, reduced modulus and hardness of oil shale exhibit significant variations under different indentation loads. These differences are closely associated with the intrinsic heterogeneity of oil shale, demonstrating that different indentation locations may correspond to various mineral compositions or organic matter regions, and thus noticeable differences in localized mechanical responses can be detected. The reduced modulus E_r is mainly distributed within the range of 24.36–35.08 GPa, while the hardness H is mainly distributed within the range of 0.73–3.42 GPa. The mechanical parameters exhibit certain fluctuations under different loads and indentation locations, which are attributed to the uneven distributions of mineral particles, organic matter, and pore structures within the oil shale. The apparent fracture toughness K_{IC} of the oil shale is relatively low within the range of 0.54–1.17 $\text{MPa} \cdot \text{m}^{1/2}$, suggesting that after eliminating the influences of macroscopic bedding structure, the oil shale matrix is a highly brittle material with inferior crack resistance.

Table 1. Nanoindentation results for oil shale at different indentation loads.

Load (mN)	h_c (μm)	h_{max} (μm)	h_{eff} (μm)	E_r (GPa)	H (GPa)	h_f (μm)	c (μm)	K_{IC} ($\text{MPa} \cdot \text{m}^{1/2}$)
100.00	1.64	1.91	1.92	24.80	1.04	1.00	5.52	0.60
200.00	1.27	1.80	1.81	32.43	3.42	0.49	4.31	1.10
600.00	4.89	5.43	5.48	24.36	0.79	3.08	15.12	0.90
1000.00	5.84	6.45	6.50	31.07	0.94	4.20	18.36	1.17
1500.00	8.32	8.90	8.94	35.08	0.73	6.80	45.33	0.54
Mean ± SD (n = 5)	4.39 ± 2.65	4.90 ± 2.73	4.93 ± 2.74	29.55 ± 4.26	1.38 ± 1.02	3.11 ± 2.29	17.73 ± 14.82	0.86 ± 0.26

Note: h_c is the contact depth; P_{max} is the maximum load; S is the contact stiffness; A is the projected contact area; h_{max} is the maximum indentation depth; h_{eff} is the effective depth; E_r is the reduced modulus; H is the hardness; and h_f is the residual depth.

4.2.2. Macroscopic Fracture Toughness of Oil Shale

The oil shale is no longer regarded as an ideal continuous medium at the macroscopic scale, and instead it is a complex rock mass consisting of discontinuous structures, such as bedding planes. The fracture toughness of the specimen can be calculated using the three-point bending peak load (Equation (8)):

$$K_I = \frac{PS}{BW^{3/2}} f\left(\frac{a}{W}\right) \quad (8)$$

where P is the maximum fracture load (N), S is the support span (mm), B is the specimen thickness (mm), W is the specimen height (mm), $f(\frac{a}{W})$ is the geometric correction function, and a is the initial notch length (mm). In this experiment, the specimen dimensions were 40 mm × 40 mm × 160 mm, and the support span was 120 mm, while the notch depth was 10 mm.

The three-point bending calculations demonstrate that the fracture toughness of the three specimens can be determined as 0.795, 2.216, and 1.244 MPa·m^{1/2}, respectively, and an average of 1.42 MPa·m^{1/2} is achieved. In terms of magnitude, these results are highly consistent with the microfracture toughness of the matrix estimated by nanoindentation results, and thereby these results obtained by two approaches suggest that the oil shale is a low-toughness and brittle material. Compared with the microscale results, the overall macroscopic fracture toughness is slightly higher, indicating that the macroscopic crack initiation and instability process is not only controlled by the localized crack resistance of the matrix but also affected by the overall geometric constraints of oil shale specimens and influencing factors such as the bedding planes.

The macroscopic fracture toughness estimated from the three-point bending peak load shows a relatively large scatter among specimens (0.795–2.216 MPa·m^{1/2}, with a mean value of 1.42 MPa·m^{1/2}). This variability is expected for oil shale and is closely related to the heterogeneity of bedding planes and organic-rich weak interfaces. Although the specimen geometry, notch depth and bedding orientation were strictly controlled, the local bedding spacing, the continuity of weak bedding planes, and the distribution of pre-existing microcracks/laminations may differ from specimen to specimen. Such heterogeneity can shift the onset location of crack deflection and the extent of interfacial slip, thereby changing the peak load recorded in the three-point bending test and, consequently, the calculated K_{Ic} . In particular, a specimen in which the propagating crack intersects a more continuous and weaker bedding plane is more prone to premature deflection and interfacial slip, leading to a lower apparent macroscopic fracture toughness, whereas a specimen with a less continuous or locally stronger bedding plane requires a higher load to trigger deflection and unstable fracture, resulting in a higher apparent value. In addition, as observed during specimen preparation, oil shale is susceptible to delamination along bedding planes; minor differences in machining-induced or stress-relief-induced interlayer separation may also contribute to the scatter in peak-load-based K_{Ic} .

It should be pointed out that this phenomenon, whereby macroscopic toughness slightly exceeds microscopic toughness, does not imply that the layered structure can improve the overall crack resistance of the material. Conversely, it demonstrates that the three-point bending peak load can characterize the comprehensive response of the oil shale specimen before reaching macroscopic unstable crack propagation, rather than the localized crack initiation resistance of a single matrix unit. During the actual failure process, after the occurrence of crack initiation at the notch tip, the crack propagation first passes through a certain matrix region. When the crack propagation approaches near the weak bedding planes, the corresponding propagation direction is adjusted, while a portion of the driving force is used for crack deflection, secondary crack formation, and interfacial slip activation, and thus the macroscopic fracture toughness is essentially an equivalent fracture parameter that includes the effect of crack path evolution.

4.2.3. Synergistic Effects of Microscopic Brittle Matrix and Macroscopic Bedding Structure

The combination of microscopic and macroscopic results demonstrates that the essential characteristics of the fracture toughness of oil shale exhibit a pronounced scale effect. Specifically, at the microscopic scale, the relatively low fracture toughness of the matrix can determine that the material is highly susceptible to crack initiation under bending tensile

stress, and thus, the crack initiation stage is dominated by the mode I tensile fracture. In contrast, at the macroscopic scale, the crack propagation caused by the introduction of bedding structure no longer follows the shortest penetration path in a single homogeneous medium, and instead it is governed by the competition between the matrix propagation and the weak interface deflection.

In other words, the relatively low microscopic toughness accounts for the susceptibility of crack initiation, whereas the weak bedding planes explain the deflection of crack propagation from a straight line. When the weak bedding planes with inferior mechanical properties and lower fracture energy are presented ahead of the crack, the resistance required for the crack to continue propagating through the matrix exceeds that along the weak interface, while the crack deflection occurs after the crack approaches the weak bedding planes, and thus the tensile-dominated process is gradually transited to a mixed-mode I–II fracture governed by interfacial slip. Based on the above discussion, this elucidation is highly consistent with the macroscopic crack morphology, the temporal sequence evolution of AE tensile/shear events, and the crack deflection mechanism obtained from the stress intensity factor analysis in Section 4.1.

In addition to the stress-intensity-factor perspective discussed in Section 4.1, the competition between crack penetration through the oil shale matrix and deflection into the weak bedding planes can be interpreted in an energy-based manner. In fracture mechanics, a candidate crack path becomes favorable when the available driving force, quantified by the energy release rate G , exceeds the corresponding resistance, quantified by the critical energy release rate G_c . Because the bedding planes in oil shale often contain organic-matter-rich weak interfaces and clay minerals, their effective resistance is expected to be lower than that of the intact matrix. Therefore, when the crack tip approaches a weak bedding plane, and the local crack tip field becomes mixed-mode I–II, the interfacial slip route can become energetically preferred, promoting crack deflection and the observed mixed tensile–shear failure.

Hence, from the perspective of fracture resistance, the three-point bending failure of oil shale can be recognized as a staged failure process controlled by the combination of low toughness-induced matrix crack initiation and low strength bedding-induced crack propagation. The former can determine the crack initiation under relatively low external loads, whereas the latter can determine that crack deflection from the original path during the propagation process, and eventually, the complex crack network is formed, which is characterized by the interleaved distribution of vertical tensile cracks and horizontal interface cracks.

4.3. Mixed-Mode I–II Fracture Process in Oil Shale

Based on the aforementioned analysis, Figure 12 illustrates the evolution of crack paths in oil shale under three-point bending conditions, and this process can be described as follows. First, the crack initiation occurs at the pre-existing notch tip within the matrix through the mode I tensile fracture behavior. Second, as the crack approaches the horizontal weak bedding planes, the stress field at the crack tip is disturbed by the interfacial mechanical mismatch, and thereby a transition from mode I-dominated propagation to mixed-mode I–II propagation is induced, leading to the occurrence of crack deflection. Eventually, when the crack penetrates the weak bedding planes, the low shear resistance and low fracture resistance of the interface are conducive to the slip propagation along the bedding planes, leading to the formation of macroscopic deflection-slip mixed-mode failure.

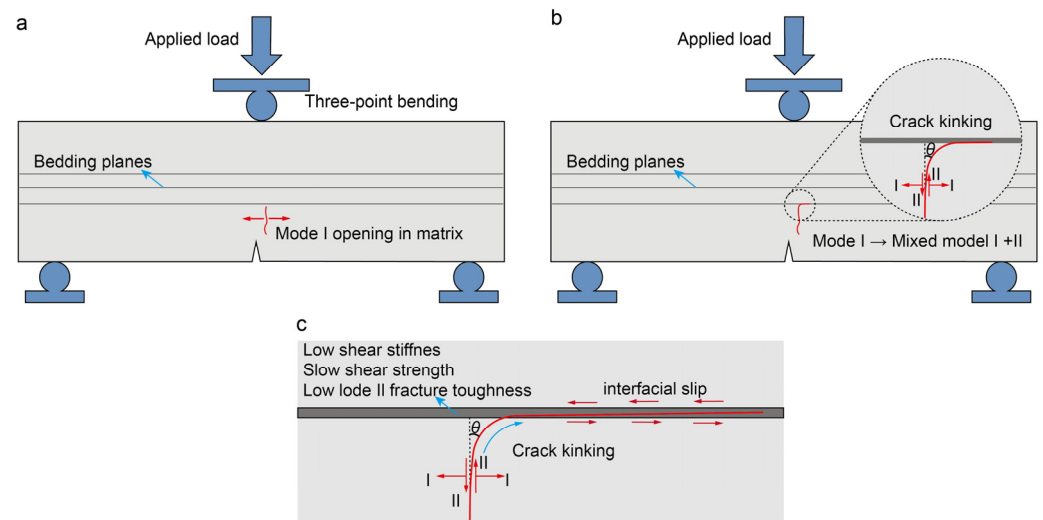


Figure 12. Conceptual schematic model of crack path evolution in oil shale under three-point bending, developed based on experimental observations combined with AE monitoring and fracture mechanics interpretation. The schematic is intended to qualitatively summarize the proposed mechanism rather than to represent a fully and quantitatively validated process: (a) mode I crack initiation; (b) mixed-mode I + II fracture and crack deflection near weak bedding planes; (c) crack propagation along organic-rich interlayers.

4.4. Limitations

In addition, a practical limitation of this study is related to the observability and the AE instrumentation configuration. The crack paths discussed here are primarily identified from surface crack traces and the post-failure macroscopic morphologies (Figures 6 and 7). Given the three-dimensional nature of fracture in laminated rocks, internal cracking and out-of-plane branching may occur without being fully represented by surface observations. Moreover, AE monitoring was conducted using a single sensor, which does not allow reliable event localization or correction for wave-velocity anisotropy associated with bedding. Consequently, the AF–RA-based classification should be interpreted as a qualitative indicator of the dominant fracture mechanism (tensile-dominated versus shear-involved activity) rather than a one-to-one spatial mapping between individual AE events and specific segments of the deflected crack. Future work will employ multi-sensor AE source location and complementary full-field/3D characterization techniques to better constrain the spatial correspondence among crack deflection, interfacial slip, and AE responses.

Furthermore, the current study leans primarily on parameter-based AE analysis and lacks comparisons with alternative AE analytical methods, such as waveform analysis and acoustic source location. As these advanced techniques could provide additional spatial information to directly map the damage zone and verify the crack deflection process, future research should expand the sample size, calibrate the classification threshold for specific shale types, and incorporate these complementary spatial and spectral analysis methods to further validate the mixed-mode fracture mechanism revealed in this work.

5. Conclusions

In this study, the oil shale was selected as the research object, while the crack path evolution, the crack type transition, and the energy release characteristics were systematically investigated by the combination of three-point bending and AE monitoring. The main conclusion can be drawn as follows:

(1) The failure of oil shale under three-point bending shows obvious brittle instability characteristics. In the pre-peak stage, the specimen exhibits an approximately overall linear

elastic response, while the damage variable is gradually enhanced, and the AE activity remains weak. As the load approaches the peak value, the AE event, damage variable, and energy release are rapidly enhanced, whereas the load is sharply reduced in the post-peak stage, demonstrating the typical sudden fracture instability.

(2) The failure essence of oil shale is derived from the crack path selection between the matrix and weak interfaces rather than a single vertical penetration process. Specifically, the crack propagation mainly initiates via mode I tensile fracture in a near-vertical direction at the notch tip. However, as the main crack approaches the weak bedding planes, the mechanical mismatch between the interface and the matrix alters the stress field at the crack tip, inducing a transition from mode I-dominated to mixed-mode I-II propagation. Consequently, the crack is susceptible to deflect and slip along the weak bedding planes characterized by low shear resistance, eventually forming a complex network comprising interleaved vertical tensile cracks and horizontal bedding slip cracks.

(3) The crack classification and energy analysis based on the AE monitoring demonstrate that during the three-point bending process of oil shale, the crack initiation and early propagation stages are dominated by the tensile fracture event, indicating that the tensile fracture event exhibits an absolute dominance in terms of quantity (i.e., accounting for 72–89%). In terms of energy release characteristics, all single high-energy release events correspond to the tensile fracture events, suggesting that the tensile fracture can be identified as the primary source of energy release during the three-point bending process of oil shale. The overall energy of individual shear fractures is lower than that of individual tensile fracture events, but the occurrence of shear fracture events is continuously enhanced in the vicinity of peak and in the post-peak stages, reflecting the persistent involvement of slip and displacement along bedding weak planes after the occurrence of crack deflection.

(4) The findings of this study offer vital practical insights for the exploitation of oil shale. The identified transition mechanism from matrix tensile initiation to mixed-mode interfacial slip implies that the weak bedding planes can be purposefully utilized in hydraulic fracturing design to induce crack branching and form complex fracture networks. Meanwhile, the localized high-energy release associated with shear slip along bedding highlights the necessity of closely monitoring acoustic emission activities to assess delamination risks and implement customized structural support, thereby mitigating unexpected failure induced by weak interfaces. Furthermore, to fully understand the spatial evolution of such complex networks, future studies are recommended to incorporate micro-CT analysis to directly confirm the internal 3D structure of the cracks and the volumetric nature of the mixed-mode failure.

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Abbreviations

The following abbreviations are used in this manuscript:

AF	Average frequency
CSTBD	Cracked straight-through brazilian disk
ICDD	International Centre for Diffraction Data
RA	RA value (rise time divided by amplitude)
SCB	Semicircular bending
XRD	X-ray diffraction
D	Damage variable
K_I	Mode I stress intensity factor
K_{II}	Mode II stress intensity factor
K_{IC}	Fracture toughness
E_r	Reduced modulus
H	Hardness
P_{max}	Maximum load
h_c	Contact depth
h_{max}	Maximum indentation depth
h_{eff}	Effective depth
h_f	Residual depth

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