

Article

Study on Progressive Damage Characteristics of Pre-Cracked Weak Sandstone Under Uniaxial Creep

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Abstract

Addressing the engineering challenge of creep instability in weakly cemented fractured sandstones within extremely soft coal-bearing formations under long-term loading in western mining areas, using weakly cemented sandstone from a coal mine in Xinjiang as the study subject. This research employs uniaxial graded loading creep tests combined with full-information acoustic emission technology and DIC high-speed strain field observation to investigate the creep deformation patterns (The full name of “DIC” is the three-dimensional high-speed dynamic and static stress–strain analysis system of the DIC strain field measurement and analysis system. For the convenience of expression, this system will be uniformly referred to as DIC in the following text), damage evolution characteristics, and failure mechanisms of sandstone under intact, pre-fabricated 30° fractures, and pre-fabricated 60° fractures. Results indicate: Fractures significantly weaken rock strength and long-term stability. Unfractured specimens primarily exhibit columnar splitting tensile failure, while pre-fractured specimens show pronounced shear failure. Shear cracks accounted for 83.67% of failures in 30° pre-fractured specimens and decreased to 63.44% in 60° pre-fractured specimens. Intact specimens exhibited acoustic emission ringing responses during accelerated creep stages, whereas fractured specimens showed ringing responses as early as the first loading stage. During graded loading, ringing counts in pre-fractured specimens continuously accumulated, with cumulative counts significantly exceeding those of intact specimens. Pre-fabricated cracks induced significant stress concentration effects at the ends, causing failure cracks to propagate preferentially along the crack direction and forming a non-uniform deformation field bounded by the crack. The study revealed the micro-macro evolution patterns of progressive damage during creep in extremely weak fractured rock, providing theoretical support for early warning and control technologies against creep instability in tunnel rock masses of weakly cemented strata in western regions.



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Keywords: fractured soft rock; damage evolution; extremely weak rock; acoustic emission; creep characteristics

1. Introduction

Currently, China's energy development focus is gradually shifting toward the western regions. In western mining areas, the roof and floor strata of coal-bearing formations predominantly consist of extremely soft rocks such as mudstone, shale, and muddy sandstone, constituting typical ultra-soft coal-bearing strata [1–3]. These rock layers exhibit characteristics including low strength, poor cementation, susceptibility to weathering, sensitivity to disturbance, and a tendency to become muddy and disintegrate upon contact with water. These properties increase the difficulty of tunnel excavation and control [4]. Particularly under long-term loading, they exhibit significant rheological behavior, leading to mining safety incidents such as uneven deformation of surrounding rock, roof collapses, and roof falls [5,6]. This represents a major phased challenge constraining coal mine safety production in western regions. Therefore, accurately understanding and predicting rock mass creep characteristics holds significant theoretical and engineering value for ensuring the long-term stability and safety of mining projects.

In recent years, researchers both domestically and internationally have conducted extensive research in the field of rock creep, yielding fruitful results. Regarding the creep of fractured hard rock, Wang et al. [7] established an improved Kelvin nonlinear creep model through creep fracture tests on epoxy-reinforced fractured rock masses, revealing the creep-fracture coupling characteristics of fractured rock masses. Regarding the creep characteristics of fractured granite, relevant studies [8] have found that factors such as fracture dip angle, stress conditions, temperature, and moisture content significantly influence creep behavior. The failure times for saturated specimens with dip angles of 30° and 60° were approximately 1.05% and 0.84% of those for dry specimens, respectively. Kou et al. [9] developed a fractional-order damage creep model for fractured rock masses based on fractional calculus theory, accounting for the coupled effects of initial damage and externally induced damage. This model accurately describes the characteristics of the accelerated creep stage. In studies examining the creep behavior of fractured rock under freeze–thaw cycles, Gao et al. [10] observed that freeze–thaw cycles significantly influence the creep response of fractured rock. Axial strain, instantaneous strain, and creep strain all increase with the number of freeze–thaw cycles. These investigations have primarily focused on hard or medium-strength rocks such as granite and sandstone. Regarding comprehensive studies on the mechanical properties of soft rock, Deng et al. [11] investigated the creep characteristics of red-bed soft rock through water-rock coupled triaxial creep tests. They found that seepage action led to reductions in triaxial strength and long-term strength, while Poisson's ratio and seepage velocity increased rapidly. Li et al. [12] employed an improved Burgers-parallel bonding contact creep model to investigate the creep deformation and failure mechanisms of deep-seated soft rock, revealing its creep characteristics under varying initial confining pressures and unloading ratios. Regarding the creep behavior of extremely soft rocks, Sun et al. [13] demonstrated that highly fractured coal exhibits pronounced rheological characteristics: large creep strains, rapid creep rates, and susceptibility to accelerated creep failure. At natural moisture content, cumulative strain reached 2.99% after 328 h, with a steady-state creep rate as high as 4.89×10^{-5} /h. These characteristics markedly differ from those of other rock types. Furthermore, numerous researchers [14–16] have conducted systematic research on the creep deformation characteristics and control technologies of deep soft rock tunnel surrounding rock, establishing creep constitutive models that account for micro-damage. However, these studies primarily focus on intact or micro-fractured soft rock, with limited attention given to the creep behavior of soft rock containing significant macro-fractures.

A review of existing research reveals that studies on rock creep primarily focus on two areas: First, investigations into the creep characteristics and mechanisms of fractured hard rock (such as granite and sandstone), emphasizing the influence of factors like fracture geometry and stress paths on creep behavior [7–10]; Second, studies on the mechanical properties of intact or weakly damaged soft rocks (e.g., mudstone, sandy mudstone, coal rock), emphasizing the creep response of soft rocks under conditions such as water-rock coupling and high stress [11–17]. The research subjects are predominantly rocks from deep strata in the central and eastern China regions. However, research on the creep behavior of weakly cemented fractured soft rock bodies in western China regions—which exhibit both “fracture structures” and “extremely soft rock” characteristics—remains relatively scarce. In practical engineering, particularly within complex geological environments such as shallow-buried weak strata, strongly weathered zones, and coal-bearing formations, extremely soft rock bodies containing structural surfaces like joints and fractures are widely distributed. Such rock masses typically exhibit uniaxial compressive strengths below 15–25 MPa and softening coefficients as low as 0.3–0.5. They readily soften and disintegrate upon water exposure while developing through-going or semi-through-going joints, exhibiting more complex creep behavior under loading [18–24]. The presence of fractures not only reduces the rock mass’s bearing capacity but also provides pathways and sites for water infiltration and stress concentration, exacerbating the creep deformation and long-term instability risks of extremely soft rock [25–29]. However, this study can enrich the research content on the mechanical properties of extremely weak rocks, and provide more targeted references for the study of progressive damage characteristics of extremely weak rocks. In addition, by prefabricating cracks in the samples, attention can be paid to the study of rock mechanical properties under multiple conditional factors.

Based on the aforementioned research status, this study investigates extremely fractured soft rock using combined acoustic emission monitoring and DIC high-speed camera equipment. Through laboratory creep tests and theoretical analysis, it systematically studies the creep deformation characteristics of extremely fractured soft rock under varying stress levels and fracture parameters, revealing its creep mechanism. This provides valuable theoretical guidance for controlling the creep behavior of fractured soft rock and the surrounding rock in weak tunnels.

2. Materials and Methods

2.1. Preparation of Pre-Fractured Soft Rock Samples

The specimens used in this study were soft sandstones extracted from a coal mine in the Heshtolage Town area of Tacheng Prefecture, Xinjiang, China. This region features typical weakly cemented rock formations characterized by poor cementation, low strength, and well-developed joints and fractures. The extremely weak rock defined in this study is classified in accordance with the Code for Classification of Engineering Rock Mass (GB/T 50218-2014). It is generally accepted that rock with an unconfined compressive strength (UCS) of less than 5 MPa can be categorized as extremely weak rock, and the specimens employed in this study have a UCS below this value. The specimen preparation process is illustrated in Figure 1. First, samples were drilled on-site using a drilling rig (Step a), promptly numbered, recorded, and sent for processing (Step b). Cylindrical standard specimens were prepared according to rock mechanics testing standards (Step c). Ultrasonic screening was applied to reduce experimental randomness (Step d), followed by fracture calibration of the screened specimens (Step e), and finally, a combination of micro-drilling and wire cutting is used to cut through-fractures in the specimens (Step f). Test specimen numbering follows the principle of capitalizing the first letter of

the test name's pinyin, followed by the fracture angle and specimen number. Detailed specimen preparation parameters are provided in Table 1.

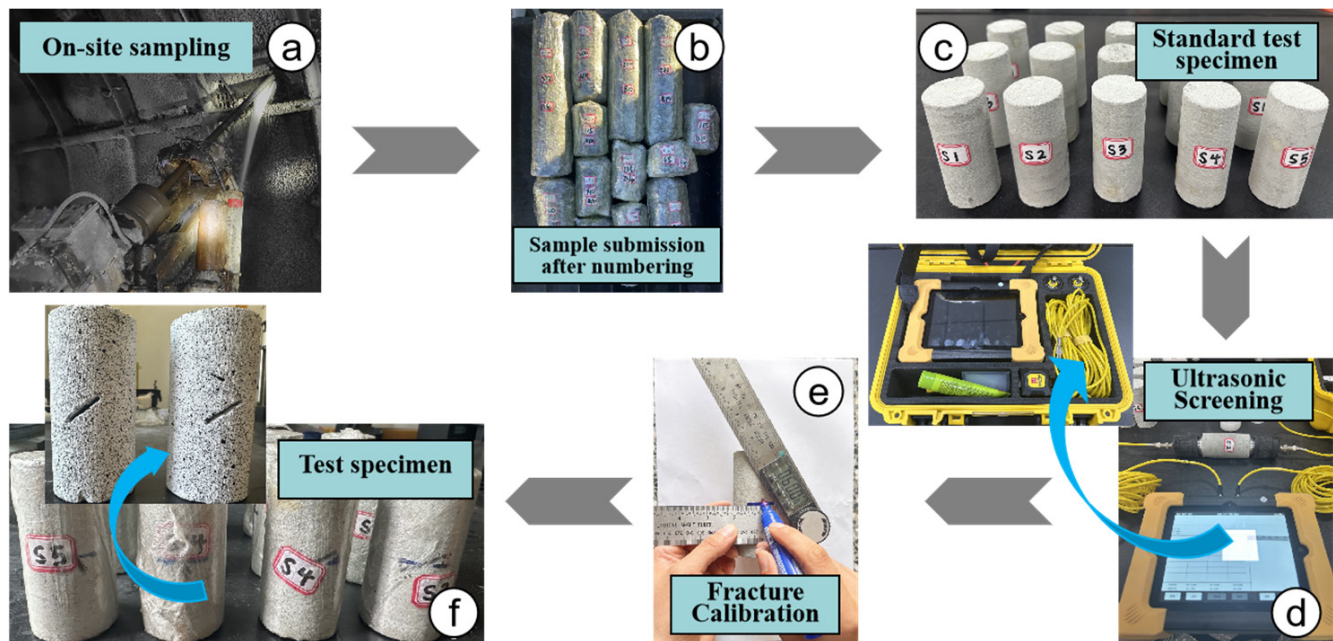


Figure 1. Sample Preparation Process.

Table 1. Preparation Parameters and Physical and Mechanical Properties of Test Specimens.

Types of Test Specimens	Specimen Number	Fracture Angle (°)	Fracture Length (mm)	Fracture Width (mm)	Specimen Height and Diameter (mm)
sandstone	D-N-1	/	/	/	100 × 50
sandstone	D-N-2	/	/	/	
sandstone	D-30-1	30°	20	1.5	
sandstone	D-30-2				
sandstone	D-60-1	60°	20	1.5	
sandstone	D-60-2				

2.2. Testing Equipment

This test employs an integrated experimental system comprising an MTS mining rock mechanics testing machine, a full-information acoustic emission system, and a DIC high-speed camera, as shown in Figure 2. The system centers on the MTS mining rock mechanics testing machine (labeled e in the figure), with an acoustic emission device (labeled c) mounted on the specimen and a DIC high-speed camera acquisition system (labeled d) installed. During testing, both MTS press data acquisition (labeled b) and acoustic emission signal acquisition (labeled a) are displayed in real time. The MTS mining rock mechanics testing system features a maximum compression capacity of 4600 kN and displacement accuracy of ± 0.01 mm. It supports three closed-loop control modes—stress, strain, and displacement—enabling the calculation of parameters including maximum compressive strength, shear strength, tensile strength, elastic modulus, and yield strength. The full-information acoustic emission signal detector features 8 external parameter channels with a sampling frequency of 60 Hz, enabling capture of internal rock damage responses—including stage-specific damage levels and locations. The DIC high-speed camera operates at 1280×1024 resolution and 13000FPS, with

displacement accuracy reaching 0.01 pixels, allowing capture of rock deformation, crack propagation, and failure characteristics.

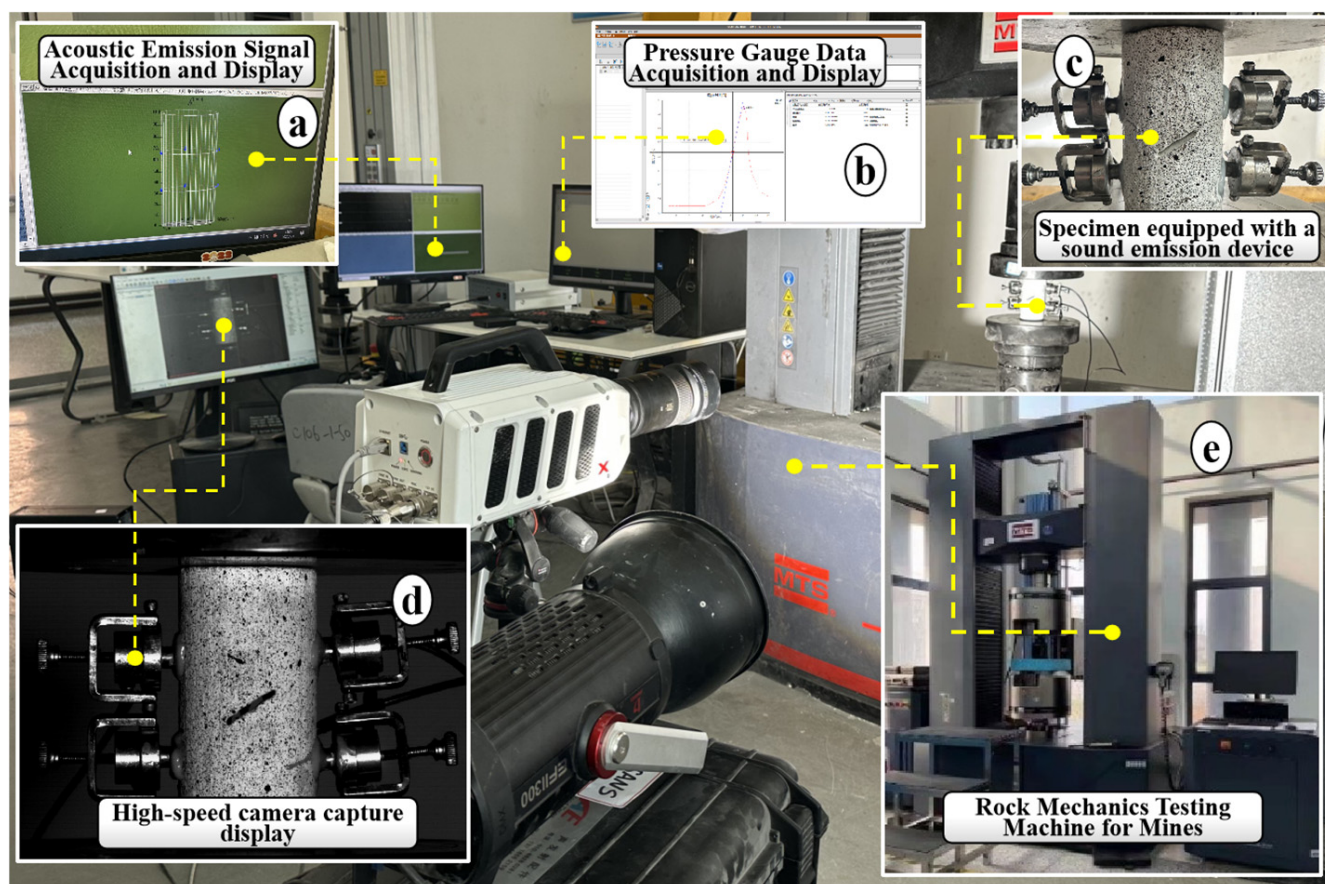


Figure 2. Schematic Diagram of the Integrated Experimental System.

2.3. Test Procedures and Protocol

This study employed the MTS Mine Rock Mechanics Testing System to conduct uniaxial graded loading creep tests on fractured soft rock, following ASTM D7070-16 “Standard Test Method for Creep of Rock Core Specimens at Constant Stress and Temperature” [30]. Creep loading grades were determined based on the average compressive strength of each specimen category. The tests were conducted with simultaneous acoustic emission monitoring and high-speed DIC camera recording. The experimental protocol is as follows:

(1) Initial rock foundation mechanical testing yielded an average uniaxial compressive strength of 6.2 MPa for non-destructive specimens. This value provides a critical reference for load grading in subsequent creep tests. It also confirms that this batch of specimens belongs to weakly cemented, friable sandstone with low strength, suggesting concurrently high rheological properties.

(2) Testing the uniaxial compressive strength of pre-fractured specimens revealed that rock with a fracture angle of 30° exhibited a strength of 3.92 MPa (approximately 64% of ultimate compressive strength, UCS), while rock with a fracture angle of 60° demonstrated a strength of 4.95 MPa (approximately 82% of UCS). These results align with previous studies indicating that the uniaxial compressive strength of rock with a 30° joint angle is typically 64% of the intact rock’s uniaxial compressive strength, while that of rock with a 60° joint angle is generally 82% of the intact rock’s uniaxial compressive strength, confirming the established relationship between joint angle and rock uniaxial compressive strength [31,32].

(3) Based on the aforementioned ratio, load levels are set for each stage of graded loading. The first stage load is 30% of the uniaxial compressive strength, with subsequent load increments set at 20% of the uniaxial compressive strength. Therefore, the loading gradient is set at a ratio of 30%, 50%, 70%, and 90% of the uniaxial compressive strength of each group of samples. Specific parameter settings are detailed in Table 2. Once the stress reaches the set stress level at each stage, it is maintained constant, allowing the damaged specimen to undergo creep deformation until failure.

Table 2. Test Load Grade Parameter Settings.

Sample Type \ Load Rating	Level I/MPa	Level II/MPa	Level III/MPa	Level IV/MPa
D-N	1.87	3.16	4.38	5.63
D-30	1.19	1.98	2.78	3.57
D-60	1.56	2.54	3.56	4.58

(4) During the initial stage of the test, the control mode was set to displacement control. The specimen was loaded to 0.5 MPa (10% ultimate compressive strength), then unloaded to 0.1 MPa. This cycle was repeated twice to eliminate any initial gaps. During the loading phase, the sampling interval is 1 s.

(5) Each load level in the test was maintained for 2 h. During the constant load phase, the sampling frequency was 0.1 Hz/s. When load levels changed, the loading rate was 0.01 MPa/s. After the test concluded, to facilitate the acquisition of specimen deformation characteristics and mechanical parameters, representative specimens were selected for analysis and summary based on the test results.

3. Results

3.1. Specimen Failure Mode

Failure Mode in Uniaxial Creep Testing

During uniaxial creep failure of extremely weak rock, vertical cracks originating internally and superficially within intact rock specimens (as shown in Figure 3a) propagate through the specimen within an extremely brief timeframe, immediately followed by failure. This failure is accompanied by a crisp sound and manifests as columnar cleavage failure. For specimens with pre-fabricated fractures, internal fractures and inclined shear fractures at the surface, pre-fabricated fracture locations gradually interconnected, leading to failure. Typical failure specimens are shown in Figure 3b,c. These specimens exhibited numerous developed fractures, with failure predominantly occurring as shear failure. The failure fractures were relatively concentrated, accompanied by a certain amount of rock debris shedding. It was observed that the smaller the angle of the pre-fabricated fracture, the more pronounced the shear failure morphology of the specimen. As the angle increases, the specimen failure pattern approaches columnar cleavage failure. The observed failure types align with the findings of Zhang et al. [33] and Bai et al. [34] on pre-fractured rock. However, compared to hard rock specimens, this extremely weak specimen exhibits secondary fractures with greater quantity and longer propagation paths, accompanied by abundant rock debris.

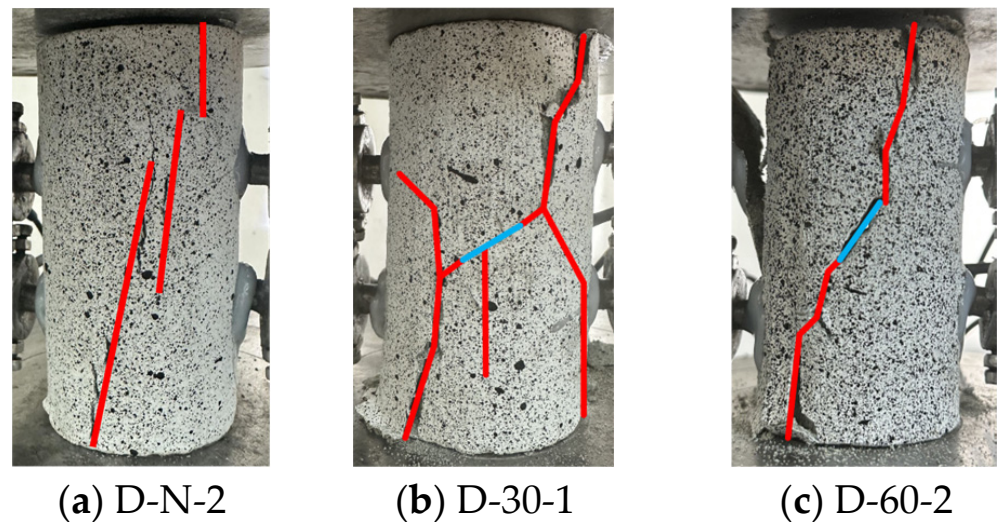


Figure 3. Specimen Failure Mode. (a) Complete pattern destruction (b) Failure mode with 30° prefabricated crack pattern (c) Failure mode with 60° prefabricated crack pattern.

3.2. Creep–Acoustic Emission Characteristics of Fractured Soft Rock

The uniaxial creep curve of the specimen accompanied by acoustic emission signals is shown in Figure 4. The experimental curve encompasses the entire creep development process. To provide a more intuitive analysis of the strain increment and creep rate at each load level, the variation patterns of strain increment per unit time and creep rate under different load levels are plotted in Figure 5.

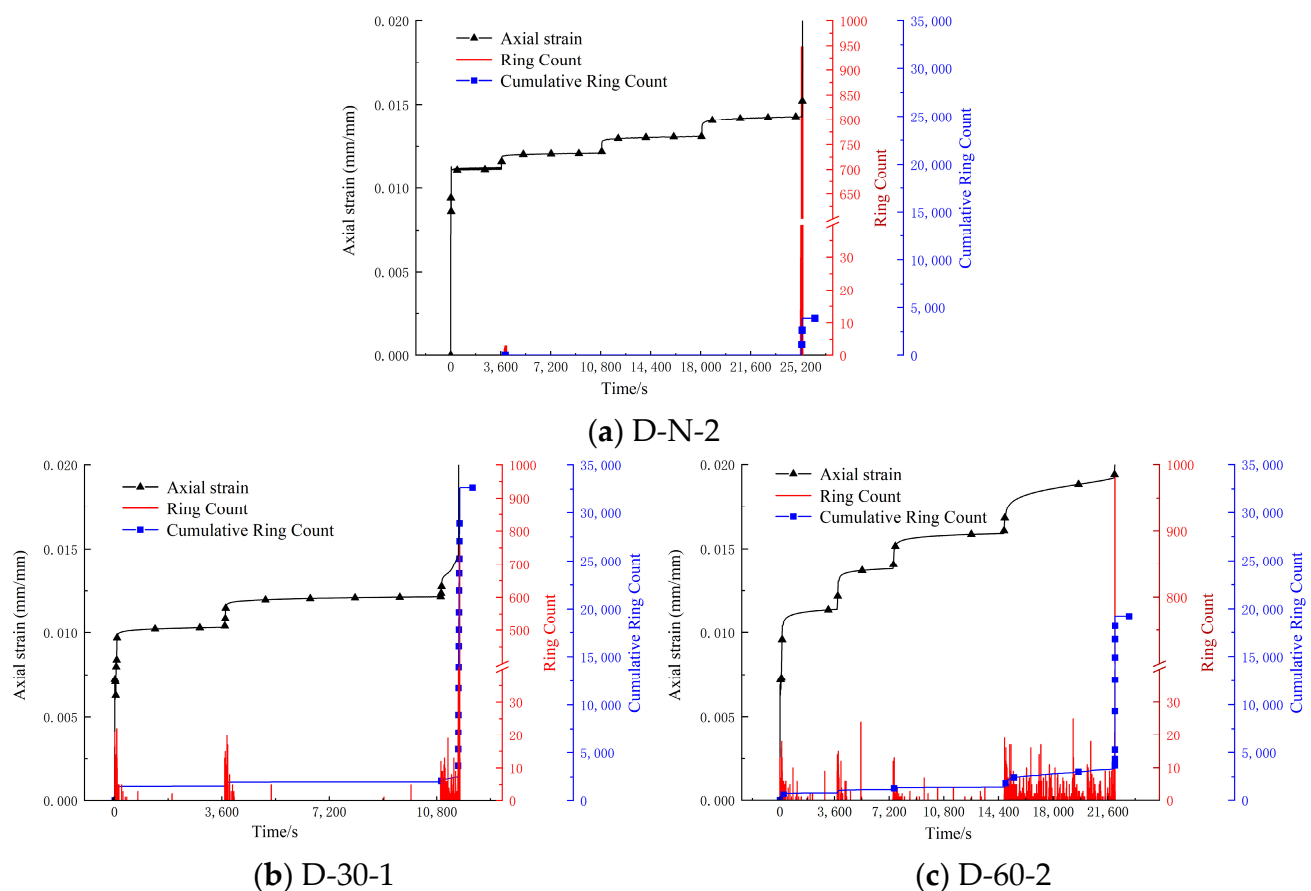


Figure 4. Uniaxial Creep–Acoustic Emission Signal Diagram of Test Specimen.

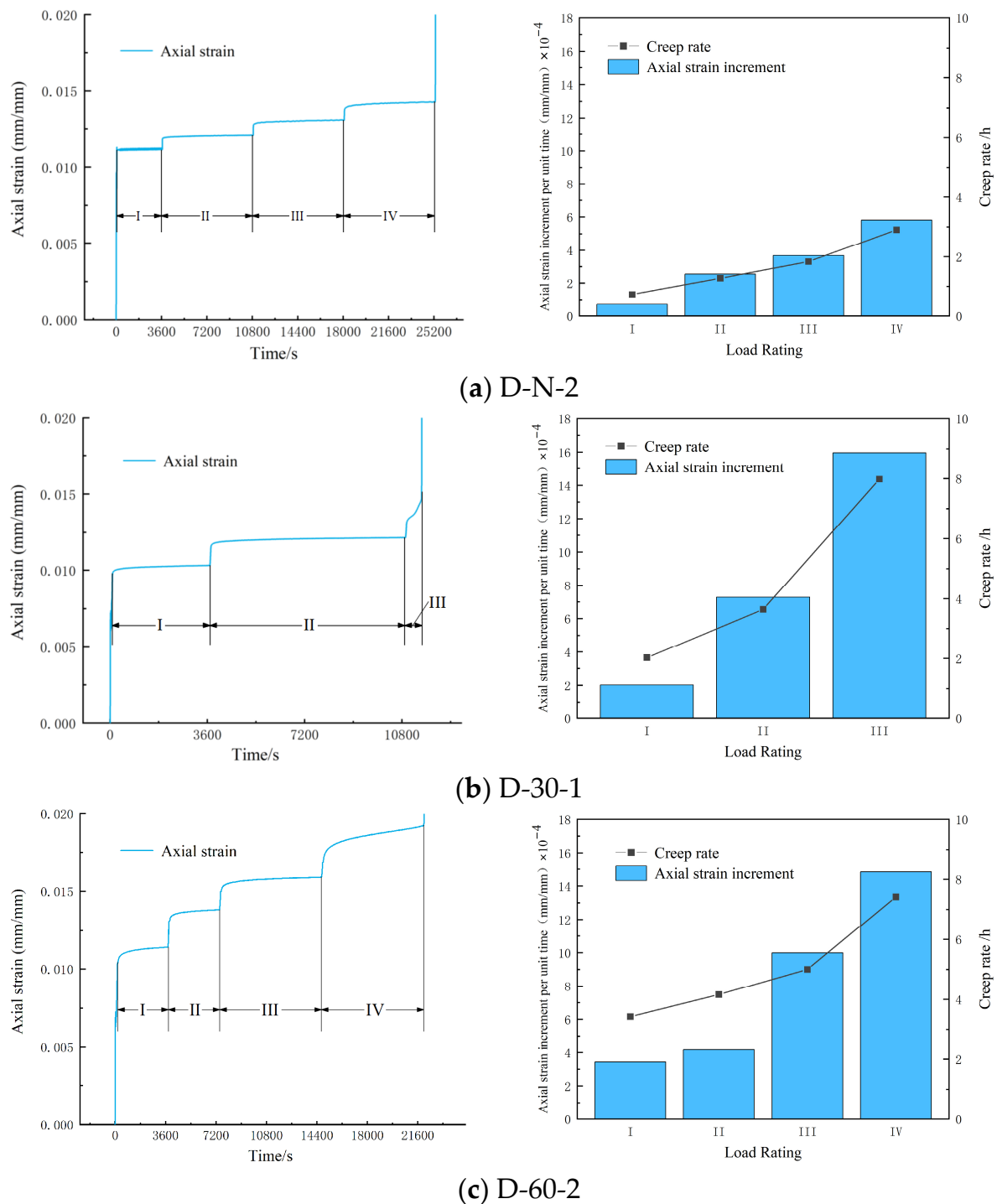


Figure 5. Relationship between Incremental Strain per Unit Time and Creep Rate of Test Specimens.

As shown in Figure 4a, the acoustic emission signals from the specimen primarily concentrate during stress loading changes and before creep instability occurs. During the constant load phase, the specimen exhibits minimal acoustic emission response, with relatively low cumulative ringing counts. Concurrently, Figure 5a indicates that at lower load levels, the intact specimen demonstrates small strain increments and slow creep deformation rates. As the stress level increases, the strain increment during the constant load stage gradually increases. By the second loading stage, the creep deformation rate begins to show a gradual upward trend, which becomes increasingly pronounced as the

stress level continues to rise. The strain increment is particularly significant during the creep deformation instability stage.

The results of uniaxial creep accompanied by sonic emission signals for specimens with a 30° pre-cracked angle are shown in Figure 4b. Specimens with pre-cracked surfaces exhibited partial sonic emission feedback even at lower load levels. Concurrently, Figure 5b indicates larger strain increments during the constant load stage, with more pronounced accelerated creep preceding creep failure. The curve slope is relatively steeper, and acoustic emission signals are more frequent, particularly concentrated during stress changes and before creep failure. The cumulative ring count is significantly higher than that of the intact specimen.

The results of uniaxial creep accompanied by acoustic emission signals for specimens with a 60° pre-cracked angle are shown in Figure 4c. It can be observed that during the acceleration stage before creep instability, the ringing count of sample D-60-2 rapidly accumulates and increases. The cumulative ring counts across all stages were significantly higher than those of the intact specimen but lower than those of the specimen with a 30° pre-crack. As shown in Figure 5c, the specimen exhibited a low strain rate at low stresses. Only when the applied load approached the failure limit did the strain rate increase markedly. Specimen D-60-2 exhibits lower sensitivity to stress changes compared to specimen D-30-1, yet remains more sensitive than the intact specimen D-N-2. These results show notable differences from the hard rock creep studies by Xu et al. [35] and Lu et al. [31].

A comprehensive analysis of Figure 5 reveals that specimen D-N-2 exhibits a significant increase in strain increment per unit time during the second load level compared to the first load level, with a marked acceleration in creep rate during the fourth load level. Specimen D-30-1 shows substantial variation in strain increment per unit time across the three load levels, and its creep rate changes significantly with increasing load level. Sample D-60-2 exhibits substantial variation in strain increment per unit time under Level III loading, with creep rate markedly accelerating at Level IV loading. Comparative analysis reveals that the strain increment per unit time and creep rate of samples D-30-1 and D-60-2 under Levels I and II loading are comparable to those of sample D-N-2 under Levels III and IV loading. The strain increments and creep rates of Specimens D-30-1 and D-60-2 at load levels III and IV were substantially greater than those of D-N-2. The variation patterns of strain and creep rate with load level in this extremely soft rock differ markedly from the creep strain findings reported by Zhang et al. [36] and Liu et al. [37] for harder rocks.

4. Discussion

4.1. Analysis of Strain-Displacement Characteristics Using a High-Speed Camera for Rock DIC

In DIC high-speed camera analysis software, surface composite displacement refers to the composite displacement vector calculated for each point in three-dimensional space by analyzing the dynamic changes in the speckle pattern on an object's surface. The resulting surface composite displacement image enables in-depth analysis of specimen characteristics across multiple dimensions, including deformation features, strain distribution, and dynamic response. Figure 6 illustrates the surface composite displacement diagram for unconfined uniaxial creep testing of a specimen. The black short lines in Figure 6 represent the prefabricated fractures in the specimens.

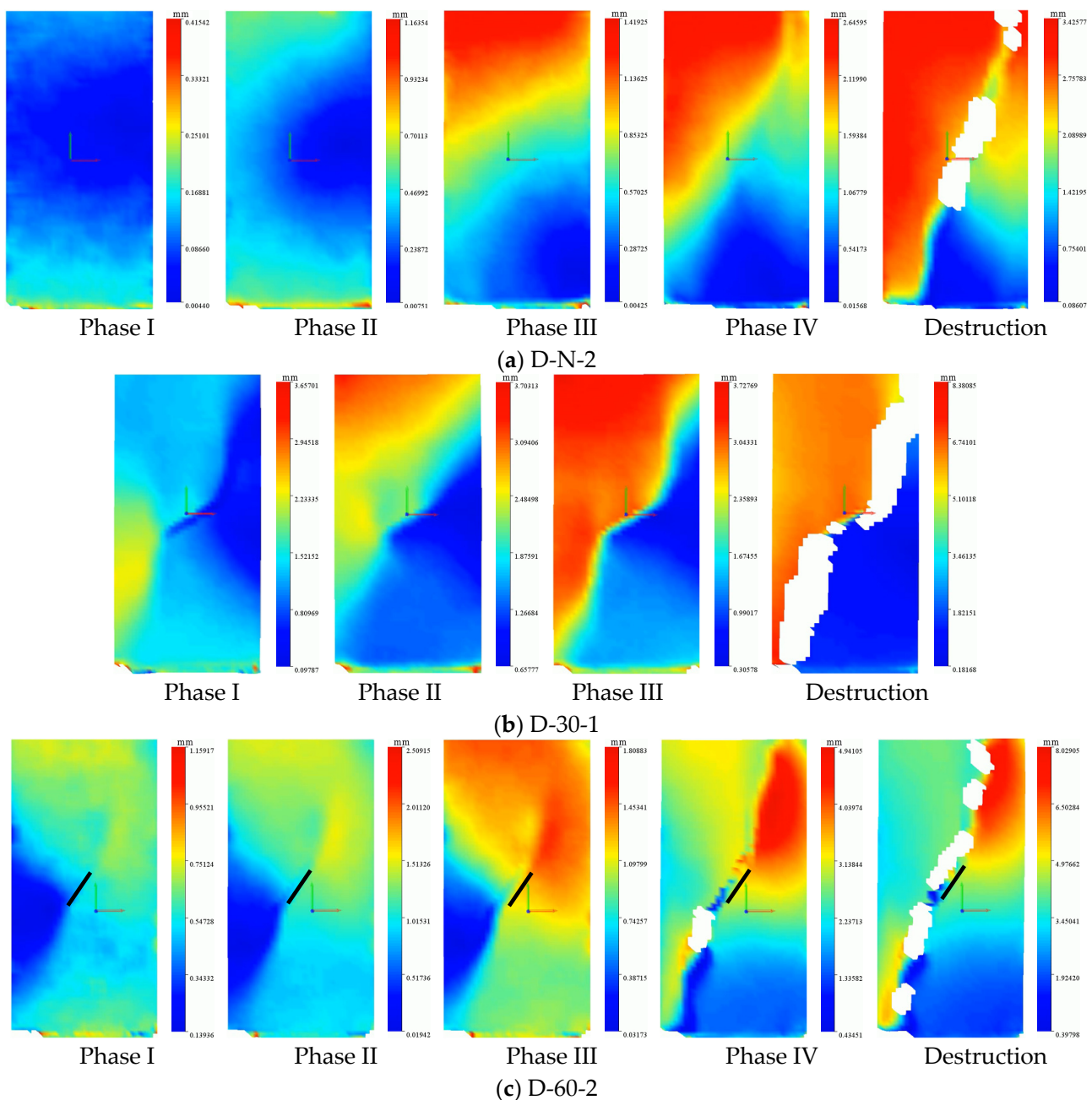


Figure 6. Unconfined Surface Displacement of Specimen Under Uniaxial Creep.

Analysis of Figure 6a reveals that specimen D-N-2 exhibits minimal strain displacement under low load levels. When stress exceeds 50% of the specimen's strength, strain displacement undergoes abrupt changes, resulting in a new stress distribution pattern. During deformation, the upper half of the specimen first contacts the testing machine's indenter, initiating displacement deformation. This triggers rapid propagation of the damage crack, followed closely by significant displacement in the lower half. The overall displacement of the upper half consistently exceeds that of the lower half. Consequently, when the specimen fails due to instability, the macroscopic crack propagates from the upper section and rapidly traverses the entire specimen.

Analysis of Figure 6b,c reveals that the lower portion of the surface composite displacement image, marked by the blue boundary line of the pre-fabricated crack, represents the specimen's weak point. With the boundary extending from both ends of the pre-fabricated crack toward the specimen edge, the upper half of the specimen exhibits greater overall

strain displacement as stress levels increase. Conversely, the lower half—the portion inclined along the crack's normal direction—shows minimal displacement influence. The failure pattern further indicates severe damage in the upper section, while the lower section remains largely intact. Thus, the pre-existing crack acts as a boundary: the actively loaded section suffers severe damage, while the crack itself markedly interrupts stress propagation and strain displacement. Consequently, specimen failure propagates and develops along the direction of the pre-existing crack.

4.2. Acoustic Emission RA-AF Crack Characteristic Analysis

The R_A - A_F relationship in acoustic emission (denoted as R_A and A_F in the formula) is an analytical method based on characteristic parameters of acoustic emission signals, used to investigate material fracture mechanisms. The calculation formula is as follows:

$$\begin{cases} R_A = \frac{R_T}{A} \\ A_F = \frac{N}{D_{UR}} \end{cases} \quad (1)$$

In the formula: R_T denotes rise time; A represents peak amplitude; N indicates ringing count; D_{UR} signifies duration; the R_A value characterizes signal abruptness; the A_F value reflects signal frequency distribution. The R_A - A_F relationship evaluation employs the maximum A_F/R_A ratio k of AE events as the failure mode classification threshold. This evaluation method is equally applicable to extremely weak rock specimens [38]. Based on the characteristic that acoustic emission signals exhibit high A_F and low R_A during tensile failure, while shear failure shows the opposite pattern, failure modes with $A_F/R_A > k$ are defined as tensile crack failure, and those with $A_F/R_A < k$ as shear crack failure, as shown in Figure 7.

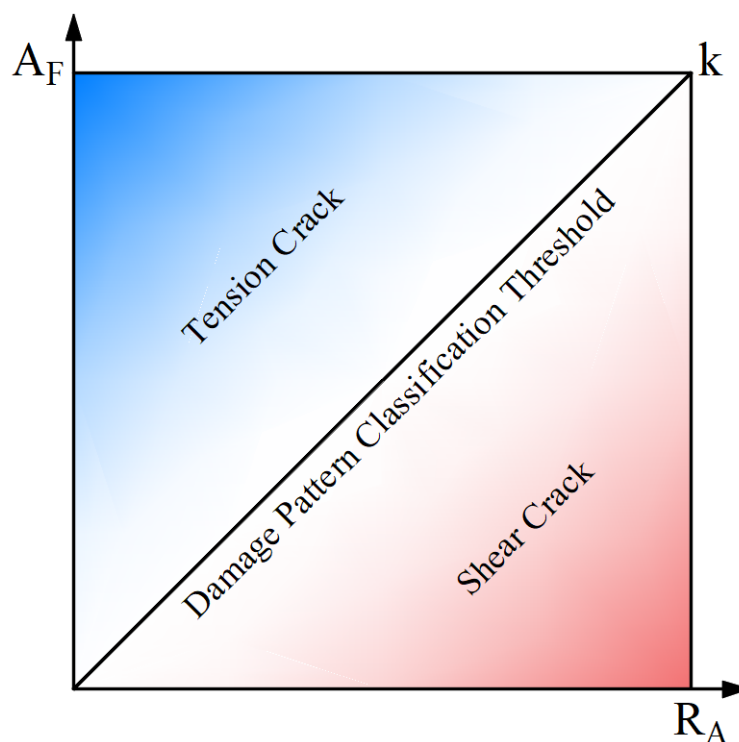


Figure 7. R_A - A_F Signal Destruction Pattern Classification Thresholds.

Considering the brittle-plastic characteristics of weakly cemented sandstone and the calculation and analysis of experimental results, a k value of 9 is obtained. Meanwhile,

with reference to previous studies on similar soft rocks, it is confirmed that this k value falls within a reasonable range. Thus, $k = 9$ is selected as the division boundary. Observing the cumulative crack type characteristics diagram of specimens (Figure 8), the intact specimen (Figure 8a) exhibits a failure mode dominated by tensile failure, while the pre-cracked specimens (Figure 8b,c) display a failure mode dominated by shear failure. The findings on experimental failure modes align with the conclusions drawn by Zhu et al. [39] regarding the acoustic emission characteristics of cracked sandstone failure.

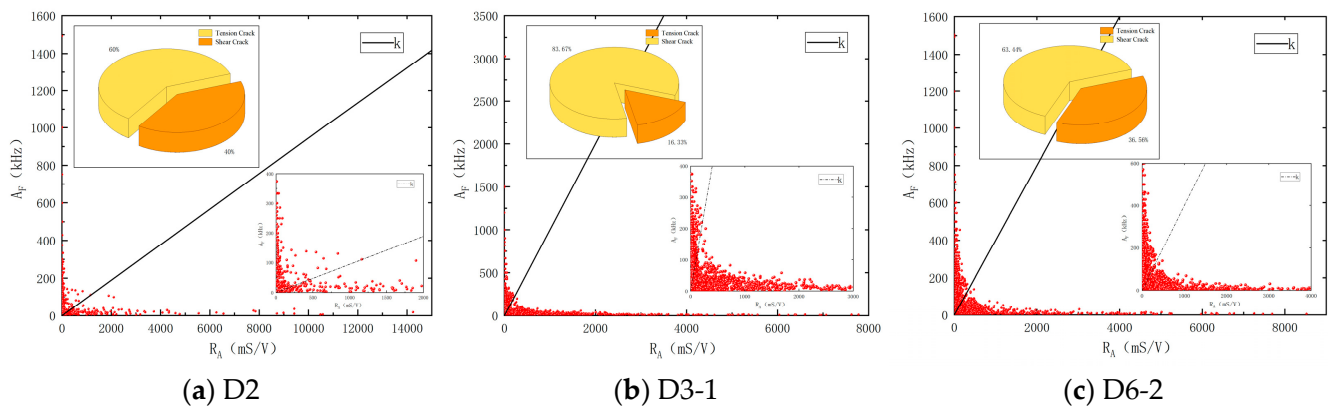


Figure 8. Cumulative Characteristics of Crack Types in Test Specimens.

Analysis of the RA-AF evolution statistical diagram for uniaxial creep specimen failure (Figure 9) reveals that as the pre-crack angle increases from 30° to 60° , the proportion of shear failure cracks decreases from 83.67% to 63.44%. This indicates that larger pre-crack angles make shear slip less likely to occur in specimens, while the proportion of tensile crack failure continues to rise. That is, when cracks are present in the specimen, the failure mode shifts from tensile failure to a distinct shear failure.

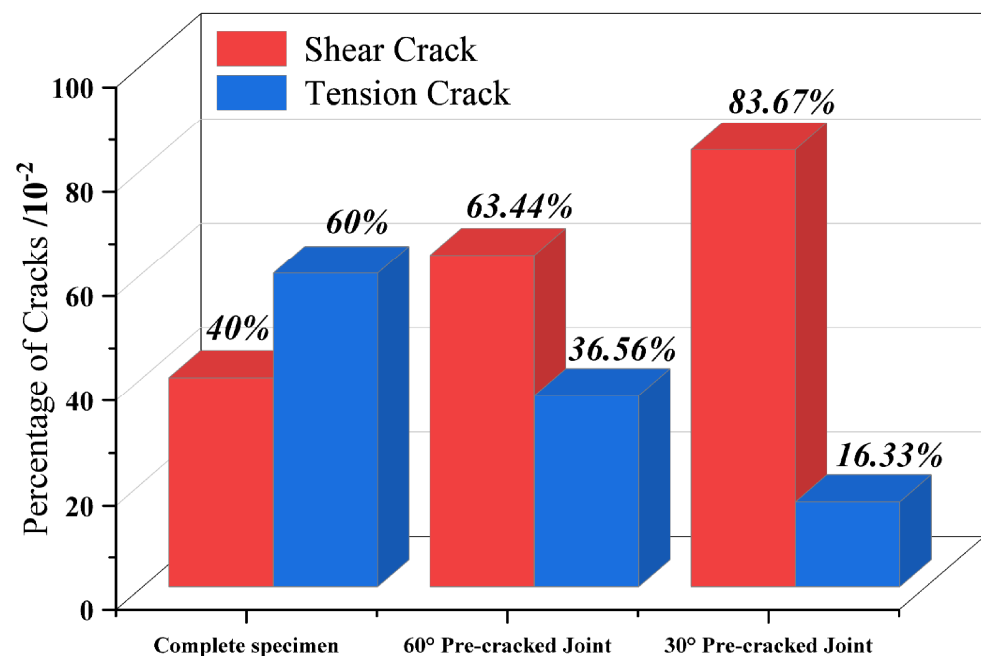


Figure 9. RA-AF Evolution Statistics for Single-Axis Creep Test Specimen Failure.

The evolution patterns of RA-AF during uniaxial creep testing are shown in Figure 10. Throughout the entire test process, analysis of Figure 10a reveals that for specimen D-N-2, where columnar splitting failure predominates, the number of tensile cracks consistently

exceeds that of shear cracks. Analysis of Figure 10b reveals that for specimen D-30-1, where shear failure was clearly dominant, the number of shear cracks consistently exceeded that of tensile cracks. During the failure instability stage, the number of shear cracks further surged; Analysis of Figure 10c shows that for specimen D-60-2, where shear failure dominated, the number of shear cracks exceeded tensile cracks prior to instability. At the point of instability, both crack types were nearly equal in number, but shear cracks significantly increased and became dominant at failure. This explains the previously observed pattern: as the crack angle increases, the failure mechanism of specimens gradually shifts from shear failure to tensile failure.

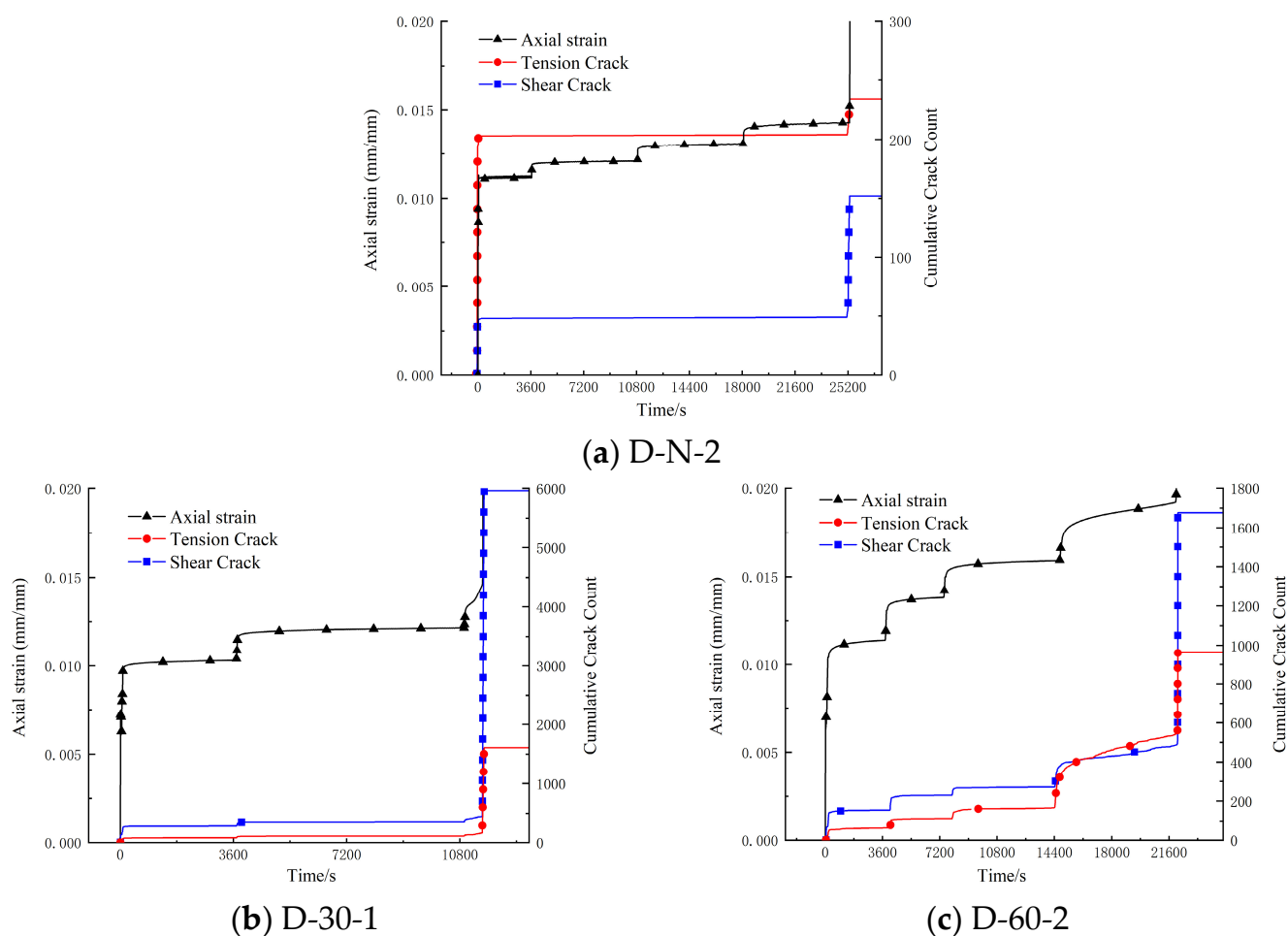


Figure 10. Evolution Patterns of Different Crack Cumulants in Test Specimens.

Figure 11 shows the distribution characteristics of acoustic emission localization points in intact specimens and specimens with pre-fabricated cracks during uniaxial creep testing. It is evident that acoustic emission events gradually increase both within and on the surface of the rock specimens during loading, consistent with the development and propagation of macroscopic cracks in the specimens. Simultaneously, it is evident that specimen D-N-2 exhibits relatively stable creep behavior. Specimen D-30-1 releases energy more distinctly during creep instability, followed by specimen D-60-2. Furthermore, the damage energy release locations for specimens D-30-1 and D-60-2 are primarily concentrated near the cracks, exhibiting a radial distribution pattern centered around the pre-existing cracks, which then spreads and attenuates.

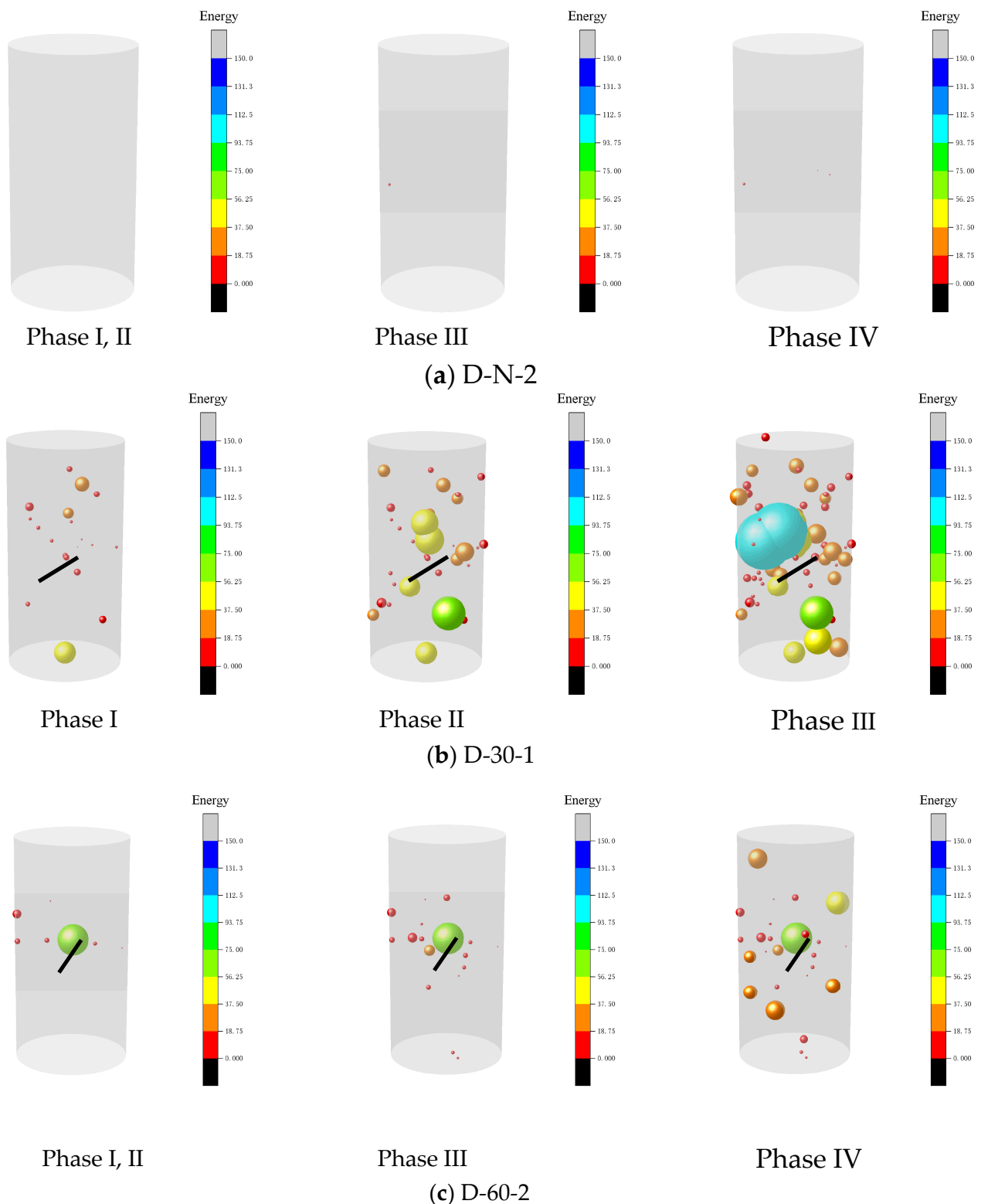


Figure 11. Evolution of Acoustic Emission Localization Points in the Specimen.

4.3. Analysis of the Progressive Damage Mechanism in Creep of Fractured Sandstone

Analysis of the combined test results reveals that the creep behavior of extremely weak rock exhibits distinct characteristics of weak cementation. When stress loads are below 30% of the rock's strength, the rock maintains relatively good integrity, with only minor damage occurring near pre-existing fractures. At low stress levels, the rock is minimally affected by damage [40]. The specimen remains in a relatively stable creep

state. The presence of pre-existing fractures and the accumulation of damage within the specimen exert minimal influence on the deformation and stress stability of the rock. The specimen exhibits only subtle fluctuating signals due to the generation of new micro-fractures. When stress loads exceed 50% of the strength of extremely weak rock, the specimen—being classified as extremely weak rock—exhibits an extremely low strength and extremely poor cementation, rendering it highly sensitive to stress variations [41]. Stress concentration occurs at the ends of pre-existing fractures, causing damaged fractures to progressively propagate and extend. Cumulative damage accelerates specimen deformation and failure. The pre-existing fractures and their propagation directions become distinct weak points where damage accumulates extensively. Secondary fractures develop rapidly, and the creep rate gradually increases. Furthermore, the weakly cemented nature of extremely soft rocks results in inadequate bonding between internal particles [42]. This facilitates rapid propagation and interconnection of internal fractures under stress, leading to swift damage response. Consequently, distinct acoustic emission signals are observed during stress loading and prior to specimen creep instability. When stress loads reach approximately 85% of rock strength, cumulative damage in the specimen exceeds its load-bearing capacity. Macro-fractures begin to manifest, the specimen's creep rate increases significantly, and the creep rate accelerates markedly. The specimen transitions toward accelerated creep failure, ultimately failing within a short timeframe. Macroscopic crack paths traverse the entire specimen along pre-existing cracks, with secondary cracks propagating and developing around these pre-existing cracks. Large amounts of fine sandstone debris collapse within the rock, and displacements and slippage occur between skeletal particles within the specimen [43]. The failure generally exhibits a shear failure pattern, with this extremely weak sandstone specimen demonstrating brittle failure.

5. Conclusions

This study focuses on extremely weak sandstone with prefabricated cracks. The experimental process adopts the method of uniaxial creep graded loading test, combined with DIC high-speed photography and full information acoustic emission monitoring equipment analysis, to explore the progressive damage characteristics of extremely weak sandstone with prefabricated cracks. Through the analysis and summary of the experimental results, the following conclusions are drawn.

(1) Analysis of rock deformation under stress reveals that rock strength with 60° and 30° joints decreases to 82% and 64% of intact rock strength, respectively. As joint angles decrease, rock strength progressively declines. Extremely weak fractured rock exhibits low sensitivity to stress variations when stress loads are below 30% of its strength. As stress loads approach 50% of strength, distinct weak zones emerge, becoming highly sensitive to stress changes and accelerating damage accumulation. When stress loads exceed 85% of rock strength, the rock loses long-term load-bearing capacity and destabilizes.

(2) As the pre-crack angle increased from 30° to 60°, the proportion of shear failure cracks decreased from 83.67% to 63.44%. The presence of cracks caused a significant shift in specimen failure modes: intact specimens primarily exhibited columnar cleavage failure, while specimens with pre-crack primarily exhibited shear failure.

(3) The deformation and instability of extremely weak pre-fractured rock primarily result from the accumulation of damage at fracture locations, which promotes the development of micro-fractures. This leads to a reduction in the specimen's overall load-bearing capacity. Under long-term constant loading conditions, damaged fractures gradually interconnect, further accelerating the rock's creep rate and ultimately causing the specimen to fail through instability.

(4) Based on the mechanism by which joint fractures affect the overall strength of rock, during loading deformation, rock displacement occurs along pre-existing fractures. Stress concentration at these fractures leads to cumulative damage, causing specimen strain to increase continuously during the constant load phase as the load level rises. Simultaneously, the presence of pre-existing fractures reduces rock strength and lowers the damage threshold, maintaining a state of continuous damage. Consequently, the specimen becomes more sensitive to stress variations. This conclusion provides valuable reference for research on rock mass control in extremely weak fissured rock tunnel environments.

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