Effect of Bedding Angle on Energy and Failure Characteristics of Soft–Hard Interbedded Rock-like Specimen under Uniaxial Compression

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Abstract: To investigate how bedding planes affect the energy evolution and failure characteristics of transversely isotropic rock, uniaxial compression tests were conducted on soft–hard interbedded rock-like specimens with varying bedding angles (α) using the RMT-150B rock mechanics loading system. The test results indicate that throughout the loading process, the energy evolution shows obvious stage characteristics, and the change of α mainly affects the accelerating energy dissipation stage and the full energy release stage. With the increase of α, the ability of rock to resist deformation under the action of energy shows the characteristics of “strong–weak–strong”. The energy dissipation process is accelerated by medium angle bedding planes (α = 45° ~ 60°). The precursor points of the ratios of dissipation energy to total energy (RDT) and elastic energy to dissipation energy (RED) can be used to effectively predict early failure. With the gradual increase of α, the difficulty of crack development is gradually reduced. The changes of energy storage limitation and release rate of releasable elastic energy are the immanent cause of different macroscopic failure modes of specimens with varying α.

Keywords: soft–hard interbedded rock-like specimen; energy evolution; failure precursor; macroscopic failure; bedding angle

1. Introduction

Since the beginning of the 21st century, under the backdrop of long-term, rapid, and high-quality economic development in China, the demand for high-speed cross-regional resource flows has significantly increased, leading to a rapid development trend in the construction of the national transportation network [1,2]. In the central and western regions of China, tunnels are often built through weak surrounding rock formations. These formations typically include sandstone, sandy mudstone, muddy sandstone, slate, gneiss, carbonaceous slate, shale, and other layered weak rocks with distinct anisotropic mechanical properties and failure modes [3,4]. Among these, soft–hard interbedded rock is a typical example, and its complex rock structure poses significant challenges to the design and construction of deep-buried layered weak rock tunnels in the western regions of China. Therefore, it is of great significance to carry out the research and prediction of the failure mechanism of soft–hard interbedded rock for the safety of ongoing construction projects.

At present, a large number of effective experimental studies on layered rock masses have been carried out by scholars both domestically and internationally. For instance, Tien et al. [5,6] conducted uniaxial and triaxial compression experiments in the laboratory, studied the influence of varying α on the mechanical properties and elastic modulus of rock, and gave its failure criterion. Nasseri et al. [7] performed uniaxial and triaxial compression tests on schist to examine the applicability of nonlinear strength criteria in predicting compressive strength and elastic modulus. Hakala et al. [8] conducted
uniaxial compression tests and Brazilian splitting tests on gneiss, investigating five elastic parameters of transversely isotropic rocks. Heng et al. [9] carried out direct shear tests on shale specimens, analyzing the variation of shear parameters with bedding angles and studying the impact of bedding plane orientation on the shear strength and failure mechanism of shale. Based on laboratory experiments, Shen et al. [10] developed a failure model for analyzing the failure probability of anti-dip interlayer rock slopes. The study indicates that the shoulder, toe, and weak layers of the slope are more prone to failure, while the slope posterior remains relatively stable. Liu et al. [11] studied the impact of mechanical properties and thickness of rock layers on the bending fracture behavior of underground rock caverns through three-point bending tests. They found that as the tensile strength of hard rock, cohesion of soft rock, and the layer thickness ratio increase, the peak load of the bending fracture of the samples also increases. Sun et al. [12] used the No. 3 inclined shaft of the Muzhaling Tunnel as an engineering example to conduct large-scale geomechanical model tests of tunnel excavation and loading, revealing that an increase in the lateral pressure coefficient leads to bedding plane sliding and surrounding rock deformation. Additionally, based on numerical simulations, they discovered that as the bedding plane spacing increases, the maximum displacement decreases and progressively increases from the floor to the roof. These studies have provided a clear understanding of the deformation and failure of layered rock masses under different conditions. The essence of rock failure is a state of instability driven by energy. Therefore, researching the energy evolution mechanism of rocks helps to reveal the damage evolution process and deformation mechanisms of rocks. For instance, Zhou et al. [13] studied the variation pattern of critical strain energy density and discovered that the critical strain energy density factor of rock exhibits an exponential relationship with the loading rate. Peng et al. [14] determined the stability of crack initiation and propagation in cross-connected specimens with openings by examining different stages of energy dissipation ratios. Dong et al. [15] investigated the differences in the fracture process of artificial composite rock containing interface flaws with varying interface angles based on energy dissipation theory and damage evolution models. Guo et al. [16] analyzed the coal–rock composite structures and found that during failure process of the specimen, the failure of coal and its energy release occur earlier than that of rock, with the energy release from rock exacerbating the failure of coal. For layered rock masses, scholars have also conducted extensive research in the field of energy studies. For example, Rui et al. [17] quantitatively characterized the energy evolution of Longmaxi shale during uniaxial loading and found that microcrack generation and propagation are quite limited before rock failure, with the rock being primarily destroyed by rapidly released energy. Ceng et al. [18] applied incremental cyclic tensile loads at different frequencies to sandstone and found that peak tensile strain, residual strain, and energy dissipation increased with the number of cycles. Zhang et al. [19] studied the energy evolution process and distribution characteristics of diabase under different confining pressures and proposed a method for evaluating the brittle–ductile transition of transversely isotropic rocks based on energy evolution characteristics. Gao et al. [20] proposed a strength failure criterion based on energy mutation through uniaxial compression experiments on shale, which does not require consideration of the failure mode. Additionally, many scholars have made significant achievements in predicting rock failure based on energy theory. For example, Wang et al. [21] conducted tests on rock energy storage performance and attempted rockburst prediction based on strain energy. Liu et al. [22] proposed a new indicator for evaluating rock failure precursors in coal–rock under different confining pressures based on energy dissipation rate. Hou et al. [23] used the mutation point of the elastic loss ratio as a precursor for predicting rock failure. Ullah et al. [24] employed acoustic emission signals and energy evolution to predict the failure of various types of rock under freeze–thaw weathering and estimated the evolution of microcracks. The aforementioned work fully demonstrates the positive significance of studying the energy characteristics of
loaded rocks for guiding engineering practices. However, current research on the energy evolution of layered rock masses primarily focuses on naturally layered rocks composed of a single type of bedrock, with relatively few studies on soft–hard interbedded rocks. Moreover, most research separates the energy characteristics during rock loading from the rock fracture process and macroscopic failure modes, often only addressing one specific aspect.

This study focuses on laboratory-prepared soft–hard interbedded rock-like (SHIR) specimens with different bedding angles. Using an RMT-150B rock mechanics system, uniaxial compression tests were conducted to explore the influence of these bedding angles on the energy characteristics of specimens. Specifically, the research examines the accumulation, dissipation, and release patterns of energy during the deformation and failure processes of SHIR specimens under uniaxial compression. It aims to uncover the inherent connections between energy evolution and rock fracture damage as well as macroscopic failure. The findings of this study can provide valuable insights for the design, construction, disaster mitigation, and stability analysis of underground engineering projects such as tunnels under complex geological conditions.

2. Experimental Method

2.1. Specimen Preparation

Compared to field specimens, rock-like materials are widely used in similar physical modeling experiments due to their ease of acquisition, strong reproducibility, and mechanical properties that closely resemble natural rocks. Scholars often use materials such as fine sand, cement, gypsum, diatomaceous earth, lime, kaolin, and organic resins to create rock-like specimens for relevant research. The specimens of soft–hard interbedded rocks in this experiment were similarly prepared using rock-like materials. Through the tests of material mass ratio, two optimal material ratios were finally selected: for the hard rock-like material, the ratio was quartz sand:cement:gypsum:water = 1:0.6:0.1:0.5, and for the soft rock-like material, the ratio was quartz sand:cement:gypsum:water = 1:0.2:0.4:0.65.

The preparation process of specimens is depicted in Figure 1. Rock-like materials are measured and mixed in specific proportions, with ink added to the soft layer material to distinguish it from the hard rock. The mixture is then poured layer by layer alternately into molds, with approximately 120 min between adjacent layers to ensure proper solidification of the mixture. After pouring, once the synthetic rock blocks reach a certain strength, they are removed for curing. After the rock-like blocks have cured to a certain strength, a core drill with a diameter of 50 mm is used to drill samples from the blocks at five angles (0°, 30°, 45°, 60°, and 90°) in a clockwise direction. Three samples are prepared for each angle. Finally, following the testing methods recommended by the International Society for Rock Mechanics, the drilled cores are cut and polished into standard cylindrical rock specimens with a diameter of 50 mm and a height of 100 mm [25]. The processed specimens are categorized and numbered accordingly, using “S-α” to denote each specimen. In this notation, “S” represents specimen, and “α” denotes bedding angle. For example, S-45 indicates the soft–hard interbedded rock-like (SHIR) specimen with a bedding angle of 45°.
2.2. Experimental System and Scheme

The RMT-150B rock mechanics loading system from the Wuhan Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, was utilized in this study (as shown in Figure 2). This loading system is characterized by a vertical hydraulic jack with a maximum output force of 1000 kN and a maximum compression deformation of 50 mm. The control system allows real-time acquisition of the relationship between force and displacement during rock loading. In addition to the loading system, the experimental system includes a CCD camera, light source, and image acquisition host. The CCD camera captures real-time images during the rock loading process, recording the fracture process of the rock. For axial loading in this experiment, the displacement control of 0.005 mm/s is adopted. Prior to testing, a CCD camera is fixed on one side of the rock specimen, capturing images at a rate of 1 frame per second (fps) during specimen loading, with an image resolution set at 1024 pixels × 1024 pixels. This experiment involves three groups totaling 15 specimens for uniaxial compression tests. Each group includes five varying $\alpha$ ($0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, and $90^\circ$). To minimize data dispersion and avoid excessive repetition in analysis, specimens with compressive strength values closest to the mean are selected for detailed analysis based on each $\alpha$. 

Figure 1. Preparation process of the specimens.
3. Energy Characteristics of SHIR Specimens with Different α

3.1. Principles and Calculation Methods of Energy

In materials, fracture damage and eventual failure are driven by energy. According to thermodynamics, energy conversion is an inherent characteristic of physical processes, and material failure is an unstable phenomenon driven by energy [26]. In this experiment, the energy evolution of SHIR specimens is illustrated in Figure 3. It is generally understood that heat exchange between rocks and the surrounding environment during deformation and failure processes can be neglected, hence externally input energy primarily converts into elastic energy and dissipation energy [27]:

\[ U = U^e + U^d \]  

(1)

In the equation above, \( U \) represents total strain energy input from surroundings, \( U^e \) denotes recoverable elastic strain energy, and \( U^d \) stands for dissipation energy.
During the process of deformation and failure, rocks continuously exchange energy with their surroundings. Energy conversion mainly involves four stages: energy input, energy accumulation, energy dissipation, and energy release [14]. During the compaction stage, part of the externally input energy accumulates in the rock as $U^e$, while another part is consumed by the closure of original microcracks and microfissures. In the elastic stage, $U^e$ stored in the rock continues to increase. In the plastic stage, cracks begin to initiate and propagate; the proportion of $U^e$ decreases gradually, and $U^d$ begins to increase. In the post-peak stage, cracks further propagate and interconnect, resulting in macroscopic rock failure, and most of the previously stored $U^e$ is released. The formulas for calculating the various strain energies are as follows [28]:

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + \int_0^{\varepsilon_2} \sigma_2 d\varepsilon_2 + \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3$$  \hspace{1cm} (2)$$

$$U^e = \frac{1}{2} \sigma_1 \varepsilon_1^e + \frac{1}{2} \sigma_2 \varepsilon_2^e + \frac{1}{2} \sigma_3 \varepsilon_3^e$$  \hspace{1cm} (3)$$

$$U^d = U - U^e$$  \hspace{1cm} (4)$$

In the equations above, $\sigma_i$ ($i = 1, 2, 3$) represents principal stresses, and $\varepsilon_i$ and $\varepsilon_i^e$ ($i = 1, 2, 3$) denote strains and elastic strain energy in the principal stress directions. According to Hooke’s Law, Equations (2) and (3) under uniaxial compression conditions can be rewritten as [29]

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1$$  \hspace{1cm} (5)$$

$$U^e = \frac{\sigma_0^2}{2E_0}$$  \hspace{1cm} (6)$$

In the equations above, $E_0$ represents the initial elastic modulus during the loading process of the specimen.

### 3.2. Evolution Process of Energy

According to the calculation method of energy, variation of $U$, $U^e$, and $U^d$ of SHIR specimens with varying $\sigma$ under uniaxial compression conditions can be obtained. Energy evolution curves are shown in Figure 4. Based on the variation characteristics of curves, three characteristic points (compaction stress $\sigma_{p\text{ir}}$, yield stress $\sigma_p$, and peak stress $\sigma_p$) are determined. Point $A$ corresponding to $\sigma_{p\text{ir}}$ not only represents the inflection point of the stress–strain curve from concave to straight line, but also denotes the first intersection point of the $U^e$ curve and the $U^d$ curve. Point $B$ at $\sigma_p$ indicates the point where stress and $U^e$ begin to transition from linear to nonlinear increments. Point $C$, corresponding to $\sigma_p$, represents the point where stress reaches its maximum value. Therefore, based on
these characteristic points, energy evolution curves of specimens with varying $\alpha$ can be categorized into four stages: initial energy dissipation stage ($O-A$), stable energy storage stage ($A-B$), accelerating energy dissipation stage ($B-C$), and full energy release stage ($C-D$).

Figure 4. The energy evolution of SHIR specimens with different $\alpha$ during loading process: (a) S-0; (b) S-30; (c) S-45; (d) S-60; (e) S-90.
At the initial energy dissipation stage, the $U$ curve and the $U^e$ curve exhibit a concave upward distribution, with $U^d$ slightly greater than $U^e$. This is because of the closure and friction of pre-existing microcracks and micropores within the SHIR specimens, resulting in minor internal damage to the rock. At this stage, the energy conversion efficiency of the rock is relatively low, mainly dominated by energy dissipation. As strain continues to increase, the slope of the $U^e$ curve gradually increases while the slope of the $U^d$ curve approaches 0. After the stress reaches $\sigma_{pd}$ (point A), the $U^e$ curve begins to exceed the $U^d$, and the specimen enters the stable energy storage stage. The $U^e$ curve at this stage shows a linear growth trend similar to the $U$ curve. The rock exhibits strong energy storage capacity, where most of the external input energy is converted into elastic energy for storage, while dissipation energy remains relatively constant. As strain continues to increase, $U^e$ far exceeds $U^d$. However, when stress reaches $\sigma_{pu}$ (point B), the rock enters the accelerating energy dissipation stage. The $U^e$ curve begins to deviate from the $U$ curve, and its slope gradually decreases. The $U^d$ curve starts to increase significantly, promoting the generation and propagation of cracks. When stress reaches $\sigma_p$ (point C), the rock enters the full energy release stage. The $U$ continues to increase, and a large amount of elastic energy is released rapidly, while $U^d$ increases sharply. This indicates that the stored elastic energy is converted into dissipation energy, and the cracks inside the rock continue to propagate and connect, causing the rock to lose its load-bearing capacity.

From Figure 4, it can also be concluded that changes of $\alpha$ have little impact on the initial energy dissipation stage and the stable energy storage stage. During the early loading stage, the rock generates a small amount of $U^d$ due to pre-existing defects and primarily stores elastic energy once it reaches the linear elastic stage of the stress–strain curve. The variation of $\alpha$ mainly affects the accelerating energy dissipation stage and the full energy release stage. At the accelerating energy dissipation stage, a significant amount of $U$ is converted into $U^d$ with increasing displacement, and this trend is more pronounced at lower $\alpha$. For the specimens S-0 and S-30, $U^d$ already exceeds $U^e$ in this stage. For specimens with $\alpha = 45^\circ$–$90^\circ$, the increase of $U^d$ is mainly concentrated in the full energy release stage. The rock nearly completes the sharp decline of $U^e$ and the sharp increase of $U^d$ within a short time after failure, gradually transitioning from plasticity to brittleness.

### 3.3. The Bedding Effect of Energy at the Characteristic Points

Table 1 presents the values of various types of strain energies at characteristic points during the failure process of SHIR specimens with different $\alpha$, enabling analysis of the influence of $\alpha$ on the energy evolution patterns of rocks (see Figure 5). It is observed that as the characteristic stress increases, the energy difference between different $\alpha$ gradually increases. With increasing $\alpha$, the $U$, $U^e$, and $U^d$ decrease first and then increase at the $\sigma_{pd}$ and $\sigma_{pu}$ during the loading process of rocks, reaching a minimum with $\alpha = 60^\circ$ and a maximum with $\alpha = 90^\circ$, showing an overall V-shaped trend in the energy curves. As loading continues, the $U^d$ of the rock at peak stress initially decreases and then increases. However, the $U$ and $U^d$ show an upward trend with the lower $\alpha$ ($\alpha = 0^\circ$–$30^\circ$). As the $\alpha$ increases, these two types of energy subsequently decrease and then suddenly increase, resulting in an overall N-shaped trend in the energy curves. The above-mentioned observations indicate that the presence of bedding planes affects the energy evolution characteristics of rocks. Compared to the horizontal bedding plane, the slightly inclined bedding planes ($0^\circ < \alpha < 30^\circ$) enhance the capability of rock to absorb and dissipate energy to a certain extent, while a medium $\alpha$ ($\alpha = 45^\circ$–$60^\circ$) significantly diminishes the energy absorption capacity and storage limitation of rock, thereby reducing its overall strength and minimizing energy dissipation during the deformation and failure process. With increasing $\alpha$, the resistance of the rock to energy-driven deformation and failure shows an overall evolution characterized by a “high–low–high” pattern.
Table 1. Energy values of SHIR specimens at the characteristic points with different α.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>$U$ (kJ/m$^3$)</th>
<th>$U^e$ (kJ/m$^3$)</th>
<th>$U^d$ (kJ/m$^3$)</th>
<th>$U^e$ (kJ/m$^3$)</th>
<th>$U^d$ (kJ/m$^3$)</th>
<th>$U^e$ (kJ/m$^3$)</th>
<th>$U^d$ (kJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-0</td>
<td>1.17</td>
<td>0.60</td>
<td>0.57</td>
<td>14.75</td>
<td>14.14</td>
<td>0.61</td>
<td>91.52</td>
</tr>
<tr>
<td>S-30</td>
<td>0.54</td>
<td>0.28</td>
<td>0.26</td>
<td>11.03</td>
<td>10.69</td>
<td>0.34</td>
<td>98.00</td>
</tr>
<tr>
<td>S-45</td>
<td>0.48</td>
<td>0.25</td>
<td>0.23</td>
<td>4.97</td>
<td>4.77</td>
<td>0.20</td>
<td>7.48</td>
</tr>
<tr>
<td>S-60</td>
<td>0.47</td>
<td>0.24</td>
<td>0.23</td>
<td>1.70</td>
<td>1.54</td>
<td>0.16</td>
<td>1.82</td>
</tr>
<tr>
<td>S-90</td>
<td>4.59</td>
<td>2.29</td>
<td>2.30</td>
<td>53.74</td>
<td>50.70</td>
<td>3.04</td>
<td>229.05</td>
</tr>
</tbody>
</table>

Figure 5. $U$, $U^e$ and $U^d$ of SHIR specimens with different α at the characteristic points: (a) $U$; (b) $U^e$; (c) $U^d$.

In addition, according to Table 1, the detailed ranges of total strain energy, elastic energy, and dissipated energy at peak stress can be determined. Calculating the proportion of various types of rock energies at the peak stress reveals that a different α leads to variations of energy distribution at peak stress, reflecting the influence of α on energy accumulation and dissipation in rocks. For specimens S-0 and S-30, the elastic energy at peak stress accounts for 41.67% and 25.32% of the total energy, respectively, indicating that specimens with a lower α ($α = 0°$~$30°$) exhibit significant plastic deformation and damage before reaching peak stress, where more elastic strain energy is converted into dissipation energy. Conversely, the proportion of elastic energy at peak values exceeds dissipation...
energy when $\alpha = 45^\circ$~$90^\circ$, indicating that before reaching the peak strength, the energy input from the outside is mainly converted into elastic energy and stored.

3.4. The Evolution Characteristics of Energy Ratios

Many researchers analyze energy ratios to study the complex energy conversion and deformation processes within rocks [30,31]. This study analyzes three energy ratios of SHIR specimens with varying $\alpha$; the formulas for calculation are as follows:

$$R_{\text{DT}} = \frac{U_d}{U}$$  \hspace{1cm} (7)

$$R_{\text{ET}} = \frac{U_e}{U}$$  \hspace{1cm} (8)

$$R_{\text{ED}} = \frac{U_e}{U_d}$$  \hspace{1cm} (9)

In the formulas above, the $R_{\text{DT}}$ represents the ratio of $U_d$ to $U$. The $R_{\text{ET}}$ denotes the ratio of $U_e$ to $U$. The $R_{\text{ED}}$ signifies the ratio of $U_e$ to $U_d$.

The curves of energy ratios calculated against strain variations are shown in Figure 6, exhibiting similar trends for the same energy ratio curves of SHIR specimens with different $\alpha$. During the compaction stage, $R_{\text{ET}}$ decreases while $R_{\text{DT}}$ increases. In the elastic stage, as stress continuously increases, $R_{\text{ET}}$ consistently rises while $R_{\text{DT}}$ decreases. Upon reaching the yield stress, as the rock enters the plastic stage, $R_{\text{ET}}$ plummets and $R_{\text{DT}}$ increases steadily. The sudden change of curves can be used as a precursor to the early failure point of rock [24]. Based on the analysis above, the $R_{\text{ET}}$ curve shows a trend of decrease-rise-decrease throughout the deformation and failure process, whereas the $R_{\text{DT}}$ curve exhibits an increase-decrease-increase trend. These changes occur simultaneously but in opposite directions, allowing the change trend of one value to be inferred by analyzing the other of the values. Furthermore, careful observation of Figure 6 reveals that after the closure and frictional sealing of inherent pores within the rock, it enters the elastic stage, where the $R_{\text{DT}}$ curve initially increases before starting to decrease. The rate of decrease in the $R_{\text{DT}}$ curve at this stage shows no clear pattern with changes in $\alpha$, primarily because the elastic modulus of rock depends mainly on the rock matrix rather than the bedding planes [32]. Therefore, the energy storage capacity and elastic energy conversion rate of rock in this loading stage have no obvious change rule. When the rock enters the plastic stage, the slope of the $R_{\text{DT}}$ curve has a significant difference with the change of $\alpha$. After the $R_{\text{DT}}$ curves of specimens with S-45 and S-60 increase slightly, the slope approaches 1 near the peak stress. This indicates that a medium $\alpha$ accelerates the energy dissipation process of rock, leading to a sudden increase in the damage accumulation rate. After reaching peak stress, the $R_{\text{DT}}$ curves of specimens S-0 and S-30 continue to rise in the post-peak stage until they reach 1, whereas for specimens S-45, S-60, and S-90, the $R_{\text{DT}}$ values almost reach 1 upon reaching peak stress. This further indicates that with increasing $\alpha$, the rock transitions from plasticity to brittleness.

From Figure 6, it also can be observed that the $R_{\text{ED}}$ curve exhibits an increasing-decreasing trend throughout the entire deformation and failure process. Initially, the $R_{\text{ED}}$ curve shows slight fluctuations in the early loading stage, and from the compaction stage to the elastic stage, $R_{\text{ED}}$ steadily increases, with the slope of the curve continuously rising. As the stress approaches the yield strength, the $R_{\text{ED}}$ curve begins to fluctuate and rapidly decrease, indicating a decline in the rate of elastic energy accumulation, accompanied by a continuous increase in dissipation energy. The sudden decrease in $R_{\text{ED}}$ and the fluctuations in the curve also serve as signals for the early failure of the rock [30]. During the plastic and post-peak stages, $R_{\text{ED}}$ steadily decreases, indicating a continuous interaction between the accumulated elastic energy and dissipation energy, leading to the continuous expansion and propagation of cracks, ultimately resulting in rock fracture. Additionally, it is evident that for medium $\alpha$ ($\alpha = 45^\circ$~$60^\circ$), the range of $R_{\text{ED}}$ values is significantly smaller compared
to other rocks. This suggests that rocks with these $\alpha$ store relatively little elastic energy, further influencing the release of energy during rock failure.

Figure 6. $R_{DT}$, $R_{ET}$, and $R_{ED}$ curves of SHIR specimens with different $\alpha$: (a) S-0; (b) S-30; (c) S-45; (d) S-60; (e) S-90.

4. Failure Characteristics of SHIR Specimens with Different $\alpha$

4.1. Fracture Process and Failure Precursors of SHIR Specimens

To further investigate the fracture process and crack propagation characteristics of SHIR specimens with varying $\alpha$, the concept of Energy Dissipation Ratio (EDR) has been introduced, with the calculation formula as follows [33]:

$$EDR = \frac{U_{I_2} - U_{I_1}}{I_2 - I_1}$$

(10)

In the formula, $I_1$ and $I_2$ represent two adjacent time points, and $U_{I_1}$ denote the dissipation energy corresponding to these adjacent time points.
Through studying the variation patterns of the EDR curve and combining the aforementioned analysis of energy ratio evolution characteristics of SHIR specimens with different α at various stages, this section employs a CCD camera to observe in real-time the crack status on the rock surface, thereby characterizing the extent of crack propagation at each stage. To streamline and avoid redundancy, typical specimens S-0, S-45, and S-90 were selected for analysis. The EDR and energy ratio (RDT and RED) curve variations under uniaxial compression conditions, along with the evolution of surface crack processes, are depicted in Figure 7. T, S, and S_0, respectively, represent tensile cracks, shear cracks, and surface spalling cracks. The red line indicates the crack propagation path, while σ_π, σ_πi, and σ_p denote the compaction stress, yield stress, and peak stress during the rock loading process, with σ_T representing the stress at complete rock failure. In addition, the turning point where RED starts to decline and RDT begins to rise is defined as the precursor point, and the point where EDR first exhibits high amplitude is defined as the high EDR point.

Figure 7. Evolution of stress, EDR, RDT, RED, and cracks in SHIR specimens: (a) S-0; (b) S-45; (c) S-90.
Figure 7a shows the EDR and energy ratio (R_{DT} and R_{ED}) curve variations of specimen S-0 and the process of surface crack propagation. In Section 3.4, the energy ratio curves of specimens with different $\alpha$ have been analyzed in detail, so it will not be repeated here. At Stage I, the energy dissipation in the rock is minimal. The EDR fluctuates near zero with a low amplitude, and there are essentially no visible cracks on the surface of the rock. With increasing load, entering Stage II, the amplitude distribution of EDR remains mostly unchanged, and the rock undergoes slight deformation, characterized by minor surface spalling near the bedding planes of the rock. When the stress reaches $\sigma_{pi}$ (11.3 MPa), the amplitude of EDR gradually increases and remains at a high level, indicating continuous generation and expansion of internal cracks within the rock. When the stress reaches $\sigma_p$ (20.8 MPa), the distribution range of surface cracks (S_{cracks}) on the rock expands further. Subsequently, as the stress begins to decrease, there is a sudden increase in the amplitude of EDR at 152.0 s, resulting in a significant positive value. This reflects the intensification of damage and fracture in the rock, leading to severe destruction of its original structure. Subsequently, EDR continues to fluctuate continuously, with cracks continuously expanding and intersecting with each other, ultimately leading to complete instability and failure. As the stress decreases to $\sigma_f$ (8.5 MPa), the rock exhibits numerous surface spalling cracks and tensile fractures.

Figure 7b depicts the EDR and energy ratio (R_{DT} and R_{ED}) curves for specimen S-45, illustrating the process of surface crack propagation. At Stages I and II, EDR amplitude is nearly zero, indicating minimal crack initiation in the rock. When the stress reaches $\sigma_{pi}$ (6.8 MPa), shear cracks appear at the edges of the bedding planes. As the stress reaches $\sigma_p$ (7.6 MPa), EDR amplitude sharply increases, with shear cracks penetrating the specimen, leading to unstable failure of the rock. This is because the shear strength of the bedding planes is much lower than that of the rock matrix; the failure of rock under loading depends solely on the bedding planes, independent of the rock matrix [32].

Figure 7c illustrates the EDR and energy ratio (R_{DT} and R_{ED}) curves for specimen S-90, showing the process of surface crack propagation. At Stages I and II, EDR mainly ranges between $-0.001$ and $0.001$ MJ/m$^{-3}$, indicating minimal crack formation on the rock surface. When the stress reaches $\sigma_{pi}$ (31.6 MPa), tensile cracks appear at the bedding planes, while no cracks form on the surface of the rock matrix. At this stage, as stress continues to increase, under uniaxial compression conditions, the rock undergoes lateral strain and outward expansion. The tensile strength at the interface between soft and hard rock layers is much lower than that of the two material matrices, leading to preferential splitting failure, and the rock matrix still retains its load-bearing capacity [34]. With continuous loading, EDR amplitude expands to between $-0.001$ to $0.005$ MJ/m$^{-3}$ at 126.1 s, indicating continuous displacement and slip of internal defect surfaces within the rock. When the stress reaches $\sigma_p$ (59.9 MPa), it sharply drops to 0, indicating complete crack penetration and sudden instability of the rock. This releases a significant amount of energy, causing severe structural damage to the rock. New tensile cracks propagate along bedding planes, causing extensive spalling of the rock matrix, ultimately resulting in complete failure of the rock.

The above analysis indicates that the changes of $\alpha$ significantly influence the rock fracture and damage processes. Sudden rises or drops in R_{DT} and R_{ED} curves can serve as precursors to rock failure, while the increased amplitude of EDR fluctuations can indicate the accelerated propagation of cracks; previous scholars have studied these characteristics [31,35,36]. In this study, Table 2 provides detailed stress and time data for precursor and peak points of different specimens. It is evident that R_{DT} and R_{ED} curves effectively predict rock failure; where the stress of the precursor point is equal to $\sigma_{pi}$, combined with experimental images, the location of the first damage and the type of cracks produced by different rocks can be determined. It can be observed that rocks with different $\alpha$ all experience initial failure near the bedding plane, but the types of cracks that appear first vary: specimens S-0 and S-30 first exhibit surface spalling cracks, specimens S-45 and S-60 exhibit shear cracks, and specimen S-90 exhibits tensile cracks. Additionally, due to differ-
ences in the fracture processes of specimens, EDR shows distinct trends. For specimens S-0 and S-30, high-amplitude EDR fluctuations mainly occur at Stage IV, with EDR before the peak much lower than after the peak, indicating more cracks forming after the peak. For specimens S-45 and S-60, EDR peaks when stress reaches $\sigma_p$ and then gradually decreases, suggesting that most cracks concentrate during the instantaneous failure of rock. In the case of the specimen S-90, EDR begins fluctuating as early as Stage II, with the amplitude increasing further in Stage III, indicating that numerous cracks have already formed within the rock by this stage. The above analysis indicates that as the $\alpha$ increases, the main stages of rock failure gradually shift from Stage IV to the earlier Stages II and III. An increase of $\alpha$ promotes the initiation, propagation, and coalescence of cracks within the rock.

Table 2. Values of stress and time at precursor points and peak stress points of SHIR specimens with different $\alpha$.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Precursory Point (Time, s)</th>
<th>Stress at Precursory Point ($\sigma_r$, MPa)</th>
<th>Time at Peak Stress Point (s)</th>
<th>Stress at Peak Stress Point ($\sigma_p$, MPa)</th>
<th>$\sigma_r/\sigma_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-0</td>
<td>51.35</td>
<td>11.27</td>
<td>139.77</td>
<td>20.85</td>
<td>0.54</td>
</tr>
<tr>
<td>S-30</td>
<td>36.02</td>
<td>10.30</td>
<td>159.82</td>
<td>19.16</td>
<td>0.54</td>
</tr>
<tr>
<td>S-45</td>
<td>35.87</td>
<td>6.82</td>
<td>40.64</td>
<td>7.60</td>
<td>0.90</td>
</tr>
<tr>
<td>S-60</td>
<td>22.46</td>
<td>5.52</td>
<td>22.86</td>
<td>5.67</td>
<td>0.97</td>
</tr>
<tr>
<td>S-90</td>
<td>57.47</td>
<td>30.61</td>
<td>141.68</td>
<td>59.88</td>
<td>0.51</td>
</tr>
</tbody>
</table>

4.2. Macroscopic Failure Characteristics of SHIR Specimens Based on Energy

Figure 8 illustrates the energy storage limitation ($U^e$), elastic energy release rate after the peak ($U^e$), and failure characteristics of SHIR specimens with different $\alpha$ under uniaxial compression. With increasing $\alpha$, the energy storage limitation initially decreases and then increases, while the rate of elastic energy release gradually rises. Moreover, specimens with different $\alpha$ exhibit distinct macroscopic failure characteristics under uniaxial compression. Combining the geometric shapes and propagation mechanisms of cracks, crack propagation modes can be categorized into tension cracks (T), shear cracks (S), and surface spalling cracks ($S^s$) [37]. In Figure 8, main cracks and secondary cracks are depicted in thick red and yellow lines, respectively, with white indicating hard rock and gray indicating soft rock, while shaded areas denote regions of surface spalling. The $\alpha$ significantly influences the growth of cracks in rocks, allowing for the classification of macroscopic failure modes into tensile failure of the rock matrix, shear slipping failure along bedding planes, and tensile splitting failure along bedding planes. At lower $\alpha$ ($\alpha = 0^\circ$~$30^\circ$), main cracks primarily propagate along the loading direction, with secondary cracks and surface spalling predominantly occurring near the rock matrix adjacent to bedding planes. As $\alpha$ increase gradually ($\alpha = 45^\circ$~$60^\circ$), main cracks primarily propagate and expand through shear sliding along bedding planes, with few secondary cracks observed. At the maximum $\alpha$ ($\alpha = 90^\circ$), main cracks similarly propagate along bedding planes. The bedding planes are parallel to the loading direction, resulting in tensile splitting failure along bedding planes, alongside internal generation of secondary cracks leading to detachment of rock surface blocks. From the above observations, it is evident that different $\alpha$ have a significant impact on the macroscopic failure of rocks. When $\alpha = 0^\circ$~$30^\circ$, the bedding planes are nearly horizontal. The soft and hard rocks on either side of the bedding planes experience uneven deformation due to vertical loads, leading to extensive tensile failure primarily controlled by the hard rock. When $\alpha = 45^\circ$~$60^\circ$, due to the relatively low shear strength of the bedding planes, the rock matrix has not yet developed significant cracks, and the specimen loses its load-bearing capacity due to sliding along the bedding planes. When $\alpha = 90^\circ$, the bedding planes are parallel to the loading direction, and both the bedding planes and the rock matrix share the vertical load. However, due to the lower tensile strength of the bedding planes, the specimen experiences large-scale splitting failure along the bedding planes. The
macroscopic failure of rocks is controlled by the bedding planes, with different $\alpha$ leading to distinct types of failure.

The more energy storage before the peak, the greater the energy release during the post-peak, and the characteristics of energy release are directly related to the macroscopic failure of the rocks. Therefore, there is an inherent connection between energy storage, release, and macroscopic failure of rocks [38]. Variations in strength and energy characteristics of SHIR specimens with different $\alpha$ under uniaxial compression lead to different macroscopic failure modes. In this experiment, rocks with $\alpha = 45^{\circ}~60^{\circ}$ require the least strength and energy for failure, characterized by shear sliding along bedding planes. Rocks with $\alpha = 0^{\circ}~30^{\circ}$
primarily fail through tensile failure of the rock matrix, requiring higher strength and energy. Although the macroscopic failure mode of rock with $\alpha = 90^\circ$ is characterized by tensile splitting failure along bedding planes, it can be seen from Figure 7c that before the stress of specimen S-90 reaches the yield stress during the loading process, the tensile crack has begun to produce and expand along the bedding plane, with the accumulation of elastic energy driving deformation and failure of the rock matrix. Furthermore, the greater the elastic energy accumulated before the peak stress, the larger the energy released during rock instability failure, leading to the formation of more cracks that interconnect to form surface spalling areas, providing additional release paths. Specimens S-0 and S-30 exhibit ductile failure with high energy storage limitations and lower rates of elastic energy release, characterized by stable energy release in the post-peak stage. Specimen S-0 shows extensive surface spalling in both soft and hard rock matrices, while specimen S-30 exhibits relatively less surface spalling, mostly in the soft rock matrix. Specimens S-45 and S-60 have lower energy storage limitations and show minimal surface spalling, whereas specimen S-90 exhibits the most severe surface spalling, and the rock failure is brittle. Upon reaching peak stress, the elastic energy stored prior to failure in specimen S-90 is instantaneously released, resulting in a nearly infinite rate of elastic energy release and extensive detachment of rock matrix blocks.

5. Discussion

5.1. Engineering Significance of the Study for Slope and Tunnel Stability

Natural layered slopes are mainly classified as prograde, reverse, and vertical slopes, with their stability largely determined by lithology and the geological structures within the rock, such as bedding planes and pre-existing defects. These structures promote crack development, leading to slope failure, which in turn triggers natural disasters and rock engineering damages, resulting in unnecessary economic losses and personal safety hazards. Based on energy analysis, this study examined the failure modes of soft–hard interbedded rock-like specimens with varying $\alpha$ (Figure 8). When the $\alpha$ is low, the bedding planes rarely develop cracks, and the failure is primarily due to the rock matrix, accompanied by stable energy release. As the $\alpha$ increases, sliding failure of the bedding planes becomes more likely. When the $\alpha$ reaches $90^\circ$, the specimen fails due to bedding plane splitting, accompanied by a sudden release of energy and fracturing of the rock matrix. The above analysis partially reflects the damage within layered slopes during geological activities. The phenomenon where bedding planes and soft layers are more prone to failure is consistent with other studies on layered slopes [10,39]. In addition, when a tunnel passes through heterogeneous strata, each point around the tunnel experiences a combination of varying magnitudes of tangential stresses and different orientations of discontinuities [34]. Therefore, determining the types and locations of rock mass failures is crucial for enhancing construction safety, optimizing support design, and ensuring the long-term stability of the tunnel.

5.2. Impact and Application of Rock Energy Characteristics on Failure Prediction for Engineering Construction

In the southwestern mountainous regions of China, the terrain is highly undulating and deeply cut, with a widespread distribution. Additionally, the mountains are subjected to significant tectonic stress due to the mutual compression of continental plates, leading to complex geomorphological, hydrological, and geological conditions in these areas. Consequently, tunnel construction in these regions must focus on addressing the challenges associated with “long, large, deep, difficult, and hazardous” conditions [40,41]. In engineering construction, rocks are often subjected to continuous disturbances from blasting, excavation, mechanical vibrations, and earthquakes, which can lead to instability and failure. To effectively predict rock failure and understand its progressive failure process, a range of advanced monitoring technologies is required. This study provides an in-depth analysis of the energy input, storage, dissipation, and release in interbedded soft–hard rock-like specimens during loading (Figures 4–6), which is crucial for understanding the
fracture and failure process of these rocks and predicting their failure (Figure 7). Additionally, the increase of dissipation energy is well synchronized with the increase of acoustic emission signal intensity [42,43]. Therefore, by combining acoustic emission monitoring technologies, comprehensive information on the entire crack initiation and development process can be obtained in real time and continuously. This allows for timely evaluation and prediction of rock instability, offering a valuable reference for the early warning and prevention of rock mass failure.

6. Conclusions

In this study, uniaxial compression tests were conducted on soft–hard interbedded rock-like specimens with different bedding angles (α) to investigate the energy evolution characteristics of rocks. Based on energy analysis, the influence of bedding planes on rock fracture processes and macroscopic failure was discussed. The following conclusions were drawn:

1. The energy evolution process of rocks exhibits distinct stages. It can be divided into four stages: initial energy dissipation stage, stable energy storage stage, accelerating energy dissipation stage, and full energy release stage. The variation of α primarily affects the latter two stages of energy evolution. The trend of the energy ratio curves of rocks remains unchanged with varying α. Medium angle bedding planes (α = 45°–60°) accelerate the energy dissipation process of rocks.

2. Different types of energy at the characteristic stresses exhibit distinct bedding effects. For specimens where α = 0°–30°, the input energy before reaching peak stress mainly converts into dissipation energy. In contrast, for specimens where α = 45°–60°, the input energy before reaching peak stress primarily converts into elastic energy. Medium angle bedding planes (α = 45°–60°) severely weaken the absorption capacity and energy storage limitation of rocks. The resistance of rocks to energy-driven deformation and damage shows an evolutionary pattern of “high–low–high”.

3. During the loading process, rock failure can be effectively predicted by the abrupt changes of energy ratio curves. Regardless of the α, initial failure of the rocks occurs near the bedding planes. For low angle specimens (α = 0°–30°), surface spalling cracks first appear, while for medium angle specimens (α = 45°–60°), shear slipping cracks are the initial mode of failure. High angle specimens (α = 90°) experience tensile splitting cracks first. As the α increases, it promotes the initiation and development of cracks within the rock, causing the main stages of rock failure to occur progressively earlier.

4. The macroscopic failure of rocks is controlled by the bedding planes and shows a good correlation with energy storage and release, categorized into rock matrix tensile failure, shear slipping failure along bedding planes, and tensile splitting failure along bedding planes. With the increase of α, the energy storage limitation first decreases and then increases, while the release rate of elastic energy gradually increases. A higher energy storage limitation in rocks corresponds to more pronounced surface spalling upon final instability and failure. With an increasing α, surface spalling initially decreases and then increases in rocks.

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References


16. Guo, W.Y.; Zhang, D.X.; Zhao, T.B.; Li, Y.R.; Zhao, Y.Q.; Wang, C.W.; Wu, W.B. Influence of rock strength on the mechanical characteristics and energy evolution law of gypsum-rock combination specimen under cyclic loading-unloading condition. *Int. J. Geomech.* 2022, 22, 04022034. [CrossRef]


18. Chen, D.F.; Li, Y.G.; Huang, D. Mechanical behavior of the weak bedding plane within sandstone subjected to dynamic load of cyclic tension. *Bull. Eng. Geol. Environ.* 2021, 80, 424. [CrossRef]


22. Liu, X.; Xue, Y.; Zheng, Y.; Li, H. Research on failure precursor based on characteristics of energy dissipation rate for rock. *Front. Earth Sci.* 2022, 9, 35. [CrossRef]


33. Ma, L.Q.; Khan, N.M.; Cao, K.W.; Rehman, H.; Salman, S.; Rehman, F.U. Prediction of sandstone dilatancy point in different water contents using infrared radiation characteristic: Experimental and machine learning approaches. *Lithosphere* 2022, 2021, 3243070. [CrossRef]


38. Guo, J.Q.; Zhang, H.Y.; Sun, F.Y.; Fan, J.Q.; Shi, X.Y. Experimental investigation of nonlinear energy evolution and failure characteristics of granite under different water content states. *Geoﬂuids* 2022, 2022, 7969009. [CrossRef]


42. Lai, X.P.; Ren, J.; Shan, P.F.; Zhang, Y.; Zhang, N.; Feng, C. Damage monitoring and energy evolution analysis of self-equilibrium coal under vertical load. *Measurement* 2022, **203**, 10. [CrossRef]


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