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Dynamic responses of coal-rock-bolt composite with axial pre-stress and confining pressure

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ABSTRACT

The stability of coal-rock-bolt composite (CRB) structures is critical in deep coal mining, particularly concerning damage mechanisms under combined static and dynamic loading conditions. This study investigates the dynamic failure mechanism of CRBs subjected to varying axial pre-stress and confining pressures using integrated Split Hopkinson Pressure (SHPB) tests and numerical simulations. Under dynamic loading, the CRBs exhibited a characteristic three stage mechanical response: elastic deformation, yield, and post-peak softening. Axial pre-stress was observed to systematically reduce the effective strain rate achieved during impact, whereas confining pressure increased it. These applied constraints influence energy dissipation by inhibiting lateral deformation and altering failure modes, leading to a significant increase in dissipated energy. Under identical dip angles and strain rates, confining pressure substantially enhanced the dynamic strength of the CRB specimens, while axial pre-stress demonstrated a negligible influence on peak strength under the tested conditions. Furthermore, confining pressure mitigated bolt fracture by restricting shear displacement at the coal-rock interface. Conversely, increasing axial pre-stress was found to exacerbate V-shaped deformation patterns within the specimen, with the severity positively correlating with pre-stress magnitude. Finally, an increase in strain rate resulted in a reduction in specimen section elevation, a decrease in bolt fracture depth, and a greater propensity for localized failure modes under dynamic loading.

1. Introduction

In deep mining environments, the stability of coal-rock-bolt (CRB) composite structures is significantly challenged by dynamic disturbance loads. The inherent complexity of predicting and mitigating damage is exacerbated by increasing mining depths, which lead to elevated in-situ stress conditions. Two principal components of this stress field, confining pressure and axial pre-stress, strongly affect the response and stability of CRB structures under such dynamic events. Therefore, a comprehensive investigation into how these pre-existing stress stresses modulate the dynamic failure behavior of CRB structures is essential for improving the safety and operational efficiency of deep mining activities [1,2].

Existing research extensively examines the mechanical behavior and failure mechanisms of coal-rock composite structures, often focusing on stability analysis and the influence of structural parameters and multi-field coupling effects. Studies indicate that an increase in the coal-rock height ratio (CRHR) significantly reduces the composite's compressive

strength and elastic modulus, while concurrently increasing its energy adsorption capacity under dynamic loading. Associated failure modes reportedly transition from complete fragmentation ('debris-type') to more localized damage ('local') as CRHR increases [3–6]. While improving the rock layer's strength enhances the overall composite strength and stiffness, it also fundamentally alters crack propagation mechanisms within the coal layer. For example, within low-strength rock composites, coal fracture transitions from predominantly shear-driven to mixed tensile-shear modes, whereas in high-strength rock composites, a mixed tensile-shear mode consistently prevails [7–10]. Interface angle appears to have a limited influence on the primary mechanical parameters [11], whereas pre-existing cracks significantly weaken dynamic strength and alter the fractal dimensions of the resulting fracture network [12–14]. Additionally, multi-field interactions are critical, as increasing confining pressure enhances resistance to impact loading [15], while the coupling of dynamic disturbances and gas pressure can exacerbate system instability, potentially involving rapid energy release events, particularly under

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high initial gas pressures [7]. Failure initiation is commonly observed within the weaker coal layer, subsequently propagating into the rock mass, with shear failure modes often reported as dominant [6,16].

Existing research further elucidates the critical relationship between energy evolution principles within coal-rock composites and strategies for engineering hazard prevention and control. The difference in peak energy storage density between coal and rock layers, acting as the primary media for elastic energy, has been shown to correlate positively with the intensity of dynamic failure events. Leveraging this understanding, models such as the Differential Energy Instability Model (DEIM) have been proposed, utilizing metrics like the ratio of energy difference to instability duration to quantify impact propensity and assess the system's proximity to critical instability [17–19]. Monitoring techniques are important for tracking these energy states [20,21]. Acoustic Emission (AE) analysis, particularly using parameters like the multi-fractal spectrum width $\Delta\alpha_m$, helps characterize crack propagation complexity, while P-wave velocity measurements (correlated with elastic modulus) allow for inference of energy storage capacity. Observations such as the unimodal distribution of AE energy rates under high rock strength conditions suggest patterns of concentrated energy accumulation followed by abrupt release [22–24]. Numerical simulations employing codes such as RFPA2D, UDEC-Trigon, and Abaqus corroborate the importance of explicitly modeling rock-coal-rock interactions, confirming their significant role in elastic strain energy accumulation, post-peak softening behavior, and overall impact risk assessment [7,8]. These theoretical and observational insights directly inform practical engineering interventions. For instance, controlled fracturing techniques aimed at optimizing crack geometries may be employed to weaken overlying hard strata and delay coal mass instability [12,13]. Designing effective dynamic disaster prevention measures in deep mines, such as reinforcing support schemes specifically at coal-rock interfaces, relies heavily on principles grounded in energy release rates and crack propagation thresholds derived from such research [13,16].

In summary, while prior research has significantly advanced the understanding of mechanical properties, energy evolution, and multi-field coupling effects in unanchored coal-rock structures, these investigations have largely relied on static or quasi-static loading conditions (e.g., uniaxial or triaxial tests). Consequently, a critical knowledge gap persists concerning the dynamic response mechanism of anchored systems, specifically coal-rock-bolt (CRB) composites, particularly when subjected to the combined static pre-stress and dynamic loading characteristics of deep mining environments. Addressing this limitation, the present study employs dynamic impact testing methodologies (e.g., SHPB) to investigate CRB specimens under systematically varied axial pre-stress and confining pressure levels, incorporating defined anchorage configurations. The primary objective is to elucidate and comparatively analyze the distinct influences of axial pre-stress and confining pressure on the dynamic stability of coal-rock combinations with bolts. The findings aim to establish a robust theoretical foundation for optimizing the design and performance of roadway support systems in challenging deep mining conditions.

2. Experiment setup and methodology

2.1. Specimen preparation and experimental system

The reliability of the experimental results was ensured at the source through dual quality control measures: strictly calibrated high-precision experimental equipment and rigorous homogenization control of specimens. Coal-rock-bolt (CRB) composite specimens, schematically illustrated in Fig. 1, were prepared for testing. Preparation involved initially drilling 50 mm diameter cylindrical cores from larger blocks of intact coal and sandstone. These cores were then precisely cut at specified interface dip angles ($\alpha = 15^\circ, 30^\circ, 45^\circ$, and 60°). The cut sections were polished to ensure close contact and subsequently bonded together using a 1:1 ratio dolomite-based adhesive. This adhesive possesses a reported compressive-shear bond strength of ≥ 8 MPa [25]. The bonding process resulted in cylindrical composite specimens with a final diameter of 50 mm and a height of 100 mm, conforming to a standard 2:1 aspect ratio. Following bonding, a central borehole with a nominal diameter of approximately 3.05 mm was drilled axially through the entire length of each specimen using a precision drill press equipped with a 3 mm bit. A 3 mm diameter copper rod, serving as a bolt analog [26–28], was inserted into the borehole. Epoxy resin was then carefully injected to serve as the anchoring agent, ensuring a secure bond between the copper rod and the surrounding coal and rock material.

2.2. SHPB tests

Dynamic compression tests under varying static pre-loads were conducted using a Split Hopkinson Pressure Bar (SHPB) system, as illustrated in Fig. 2. The apparatus consisted primarily of a striker, an incident bar, and a transmitted bar, all fabricated from 40Cr alloy steel with a Young's modulus of 210 GPa. The prepared CRB specimen was carefully positioned coaxially between the polished ends of the incident and transmitted bars. This configuration allowed the specimen to be subjected to controlled high-strain loading, simulating dynamic disturbance events encountered in mining. Prior to dynamic impact, a specified level of static axial pre-stress was applied quasi-statically to the specimen using a dedicated hydraulic loading system integrated with SHPB apparatus via components connected to the bar flanges [29].

Dynamic loading was initiated by launching the striker using compressed air, causing it to impact the free end of the incident bar. This generated an incident compressive stress wave that propagated along the incident bar towards the specimen. Upon reaching the bar-specimen interfaces, a portion of the wave was reflected back into the incident bar as a reflected tensile wave, and a portion was transmitted through the specimen into the transmitted bar as a transmitted compressive wave. Data acquisition adhered to ISRM-suggested methods [30]. Strain gauge pairs were attached at appropriate locations on the surfaces of the incident and transmitted bars to measure the strains associated with these propagating waves. The signals from these gauges, typically configured in half or full Wheatstone bridge circuits for optimal

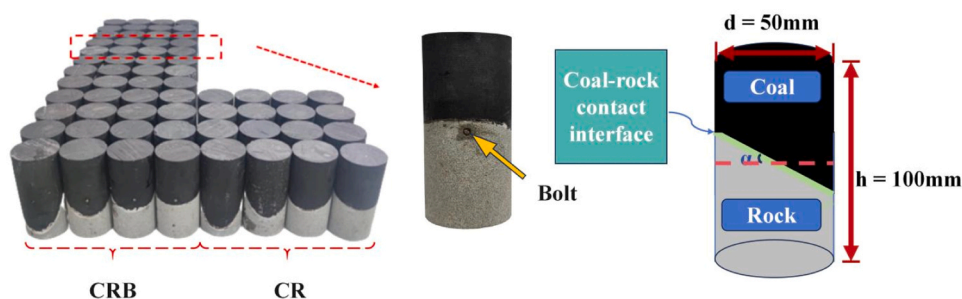


Fig. 1. The photograph and size of the test samples.

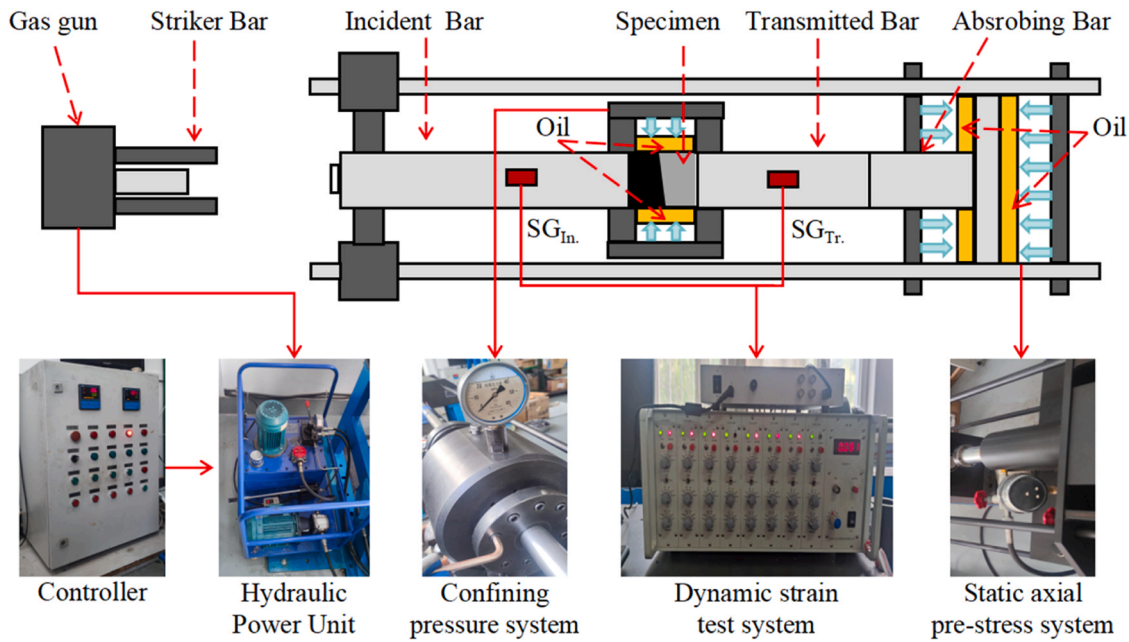


Fig. 2. The SHPB test system.

sensitivity and temperature compensation, were conditioned, amplified, and recorded using a high-speed oscilloscope or digital data acquisition system.

The in-situ stress environment surrounding CRB structures in deep mining is inherently complex and multi-axial. A single CRB typically experiences a one-dimensional stress state. In most cases, CRBs are subjected to a biaxial stress state, while a small portion experiences a three-dimensional stress state. To investigate the influence of key static stress components on the dynamic response, this study simulated three distinct loading configurations using the SHPB apparatus: pure dynamic loading (D-CRB), combined static axial pre-stress and dynamic loading (Z-CRB), and combined static confining pressure and dynamic loading (W-CRB).

The static axial pre-stress levels were carefully selected to ensure specimens remained stable under the static load alone prior to dynamic impact. Consequently, during the experiment, axial pre-stress values were set at 20%, 40%, 60%, and 80% of the quasi-static uniaxial compressive strength determined for the specific CRB specimens (which varied depending on the interface angle, α). The static confining pressures were applied at three discrete levels at 6.5 MPa, 10.0 MPa, and 13.5 MPa, respectively. The basic parameters for the prepared composite specimens are detailed in Table 1.

2.3. Validation of SHPB experiment

The analysis of SHPB test data is predicated upon the assumptions of one-dimensional stress wave propagation within the pressure bars and the achievement of dynamic stress equilibrium across the specimen during loading. To evaluate stress balance during the test, the sum of incident and reflected stresses is compared with the transmitted wave. Prior to testing, a thin layer of lubricant (petroleum jelly) was applied to both ends of each specimen to minimize interfacial friction effects. Fig. 3 presents a typical dynamic force balance check plot obtained from a CRB dynamic compression test. The sum of incident and reflected stresses closely aligns with the transmitted stress, except for a deviation during the loading process, indicating good stress equilibrium throughout the test.

Table 1

The basic parameters of the combinations.

Combination	No.	Interface angle (°)	Axial pre-stress (MPa)	Confining pressure (MPa)
D-CRB	15-0-0*	15	0.0	0.0
	30-0-0	30	0.0	0.0
	45-0-0	45	0.0	0.0
	60-0-0	60	0.0	0.0
Z-CRB	15-6.4-0	15	6.4	0.0
	15-12.8-0	15	12.8	0.0
	15-19.2-0	15	19.2	0.0
	15-25.6-0	15	25.6	0.0
	30-5.4-0	30	5.4	0.0
	30-10.8-0	30	10.8	0.0
	30-16.2-0	30	16.2	0.0
	30-21.6-0	30	21.6	0.0
	45-2.6-0	45	2.6	0.0
	45-5.2-0	45	5.2	0.0
	45-7.8-0	45	7.8	0.0
	45-10.4-0	45	10.4	0.0
	60-1.4-0	60	1.4	0.0
	60-2.8-0	60	2.8	0.0
	60-4.2-0	60	4.2	0.0
	60-5.6-0	60	5.6	0.0
W-CRB	15-0-6.5	15	0.0	6.5
	15-0-10	15	0.0	10.0
	15-0-13.5	15	0.0	13.5
	30-0-6.5	30	0.0	6.5
	30-0-10	30	0.0	10.0
	30-0-13.5	30	0.0	13.5
	45-0-6.5	45	0.0	6.5
	45-0-10	45	0.0	10.0
	45-0-13.5	45	0.0	13.5
	60-0-6.5	60	0.0	6.5
	60-0-10	60	0.0	10.0
	60-0-13.5	60	0.0	13.5

* Note: The '15' represents the interface dip angle, the first '0' represents the axial pressure, and the last '0' represents the confining pressure.

3. Results and discussion

3.1. Dynamic stress-strain curves

Figs. 4–6 present the dynamic stress-strain curves obtained for D-CRB, Z-CRB, and W-CRB specimens, respectively, tested across the four

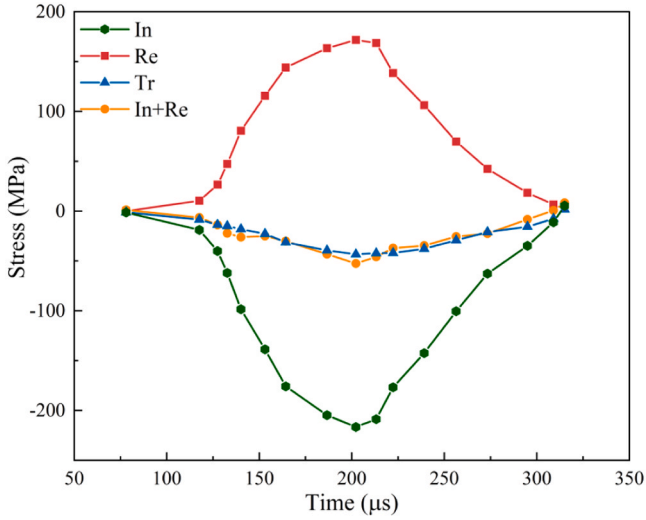


Fig. 3. The stress-time history curves for the verification of dynamic stress balance.

interface angles α . Universally, the samples exhibited a three-stage mechanical response under dynamic loading, characterized by initial elastic deformation, a yielding phase leading to peak stress, and subsequent post-peak softening. This phenomenon aligns with the stress-strain curve characteristics of the coal-rock combination in the literature [31,32]. During initial loading, the micro-pores in the sample close,

marking the elastic stage. The linear elastic stage is brief, with most stages showing nonlinear plastic characteristics due to the short duration of the dynamic impact load. Furthermore, axial and confining pressures cause initial micro-cracks in the composite sample to close. Over time, the sample reaches peak strain, with the post-peak softening stage characterized by decreased stress with increased strain. This behavior results from energy release accumulated during loading, generating a reverse compressive stress wave in the incident rod.

Focusing initially on the influence of a strain rate under a specific condition (e.g., D-CRB, Fig. 4), a pronounced sensitivity to loading rate was observed. For the $\alpha = 15^\circ$ samples, peak strain varied non-monotonically with increasing strain rate: values of 0.30%, 0.42%, 0.34%, and 0.28% were recorded at nominal strain rates of 101.3 s^{-1} , 146.3 s^{-1} , 181.1 s^{-1} , and 201.1 s^{-1} , respectively. The peak stress achieved at the lowest strain rate (101.3 s^{-1}) was observed to be lower compared to those at higher rates. At this lowest rate, the post-peak softening phase also displayed distinct transient stress fluctuations (termed "stress abrupt transitions", characterized by brief stress increases or sharp drops). These fluctuations became less evident or disappeared entirely at the higher strain rates ($\geq 146.3 \text{ s}^{-1}$ for $\alpha = 15^\circ$). Comparative analysis across different interface angles revealed similarities for $\alpha = 30^\circ$ and $\alpha = 45^\circ$ samples, whose stress-strain evolution generally mirrored that of the $\alpha = 15^\circ$ sample regarding strain rate sensitivity (including the non-monotonic peak strain trend) and the diminishing occurrence of the "stress abrupt transition" phenomenon at higher strain rates (typically above 140 s^{-1}), leading to smoother post-peak curves. In contrast, samples with the steepest interface angle ($\alpha = 60^\circ$) exhibited notably different behavior. These samples displayed more frequent and pronounced "stress abrupt transitions" across the

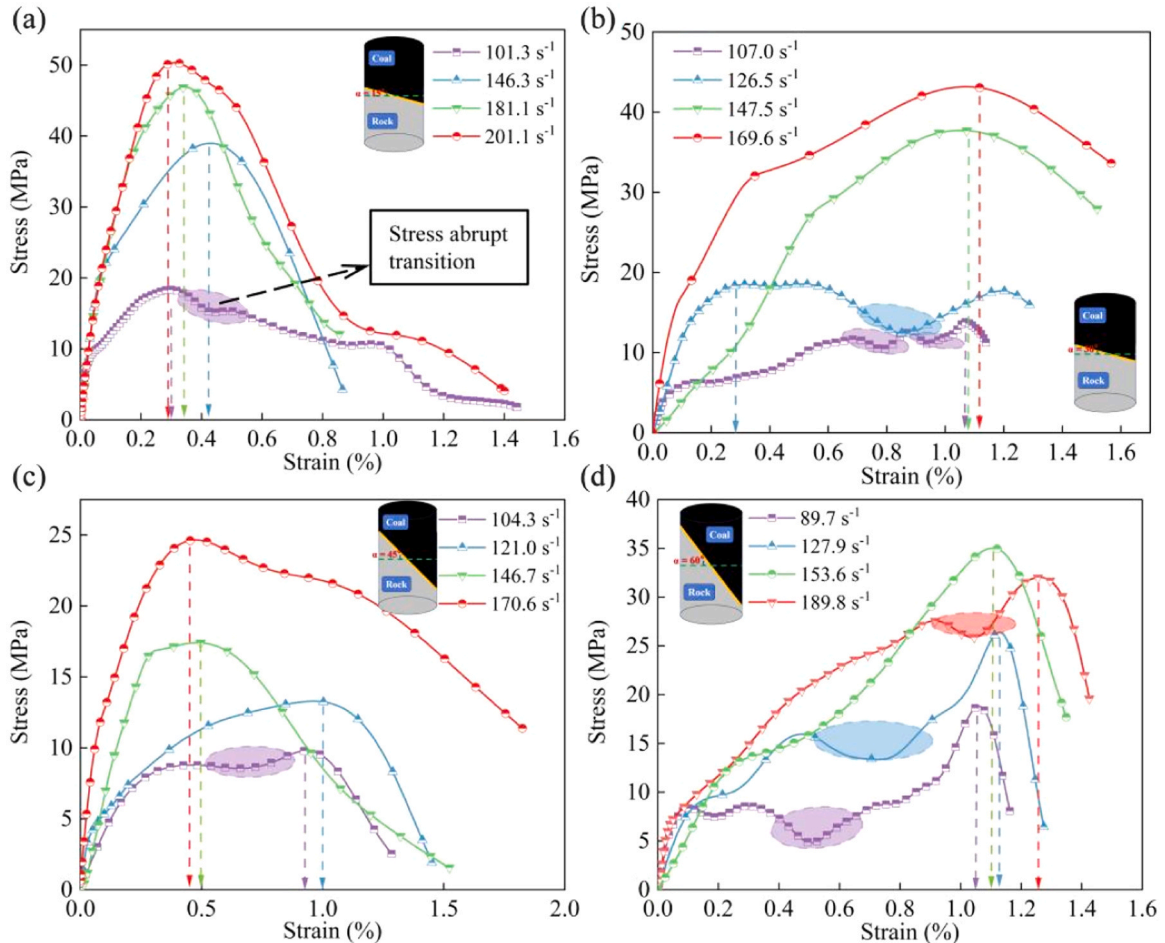


Fig. 4. The dynamic stress-strain curves of the D-CRB with different strain rates: (a-d) respectively for the interface angles are the 15° , 30° , 45° , and 60° .

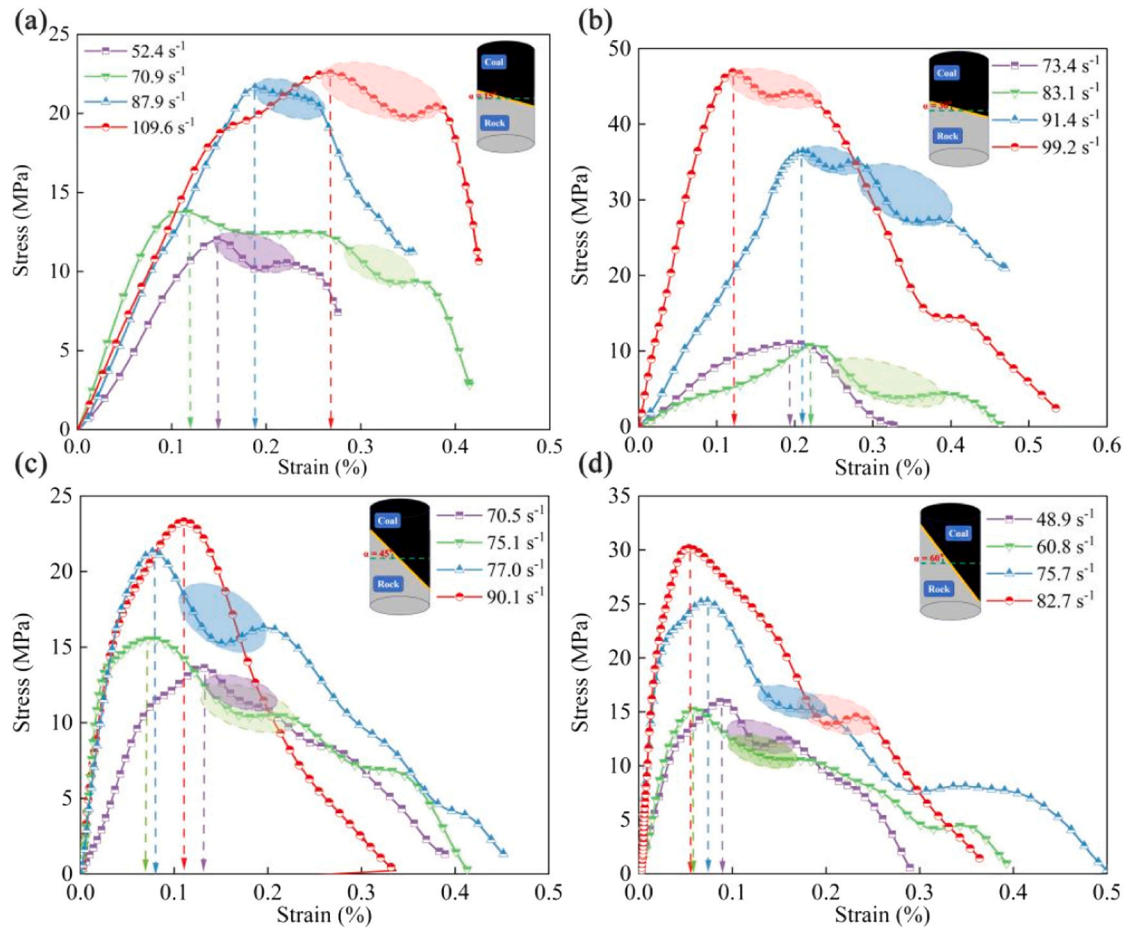


Fig. 5. The dynamic stress-strain curves of the Z-CRB with different strain rates: (a-d) respectively for the interface angles are the 15° , 30° , 45° , and 60° .

tested strain rates. Furthermore, the peak strain attained by $\alpha = 60^\circ$ samples was significantly higher compared to those with lower α values under similar loading rates. These observations suggest that increasing the interface dip angle (α), particularly to values like 60° , compromises the structural integrity and stability of the CRB composite under dynamic loading conditions.

Fig. 5 elucidates the influence of static axial pre-stress on the dynamic mechanical behavior of CRB specimens (Z-CRB configuration). A key observation from the experimental data is that, for a given impact velocity, the application of axial pre-stress systematically reduces the resultant strain rate achieved within the sample. Similar to W-CRB, Z-CRB also exhibited the characteristic three-stage deformation process (elastic, yield, post-peak softening). However, the prominence of the "stress abrupt transition" phenomenon during the post-peak phase of Z-CRB tests was found to generally increase with increasing interface inclination angle (α). The occurrence of this phenomenon also showed a dependency on both α and strain rate: for $\alpha = 15^\circ$ and $\alpha = 60^\circ$, transitions were observed across the range of tested strain rates, primarily in the post-peak stage. Conversely, for $\alpha = 30^\circ$, these transitions were mainly observed within the approximate strain rate range of 80–100 s^{-1} , while for $\alpha = 45^\circ$, they occurred predominantly between 70 and 90 s^{-1} .

Fig. 6 presents the dynamic stress-strain characteristics for CRB specimens tested under confining pressure. The application of confining pressure was observed to significantly reduce the "stress abrupt transition" phenomenon, resulting in smoother post-peak curves and more clearly defined deformation stage boundaries. Under comparable impact conditions, the W-CRB specimens sustained substantially higher (180–245 s^{-1}) peak stresses, often surpassing 200% of those recorded

for equivalent D-CRB and Z-CRB samples, typically achieved at high strain rates (observed range 180–245 s^{-1}). A comparative analysis across the stress-strain curves indicates that the "stress abrupt transition" phenomenon is linked to the applied constraint conditions. In the absence of lateral confinement, stress wave propagation in the D-CRB specimen varies with interface inclination, inducing instabilities in crack initiation and propagation, manifesting as abrupt stress fluctuations. Confining pressure enhances lateral restraint, which appears to stabilize the failure process, promote more distributed damage, inhibit abrupt crack coalescence, and thus lead to smoother stress-strain curves. Conversely, while axial pre-stress may improve the initial contact tightness across the coal-rock interface, the resulting asymmetric stress distribution, particularly pronounced at higher interface inclinations, seems to exacerbate structural instability under dynamic impact, leading to more frequent and pronounced "abrupt transitions" compared to the unconfined D-CRB case.

3.2. Energy properties

Fig. 7 presents the energy evolution characteristics of CRB specimens, tested with varying interface inclinations under combined dynamic and static loading conditions. In SHPB analysis, the incident energy imparted by the impact is categorized into reflected energy, transmitted energy, and dissipated energy [33,34]. A general trend observed across most conditions was that, with increasing strain rate, the proportion of reflected energy tended to decrease, while the proportions of both transmitted and dissipated energy tended to increase. Furthermore, comparing the different loading configurations revealed that, for similar impact velocities, the incident energy associated with

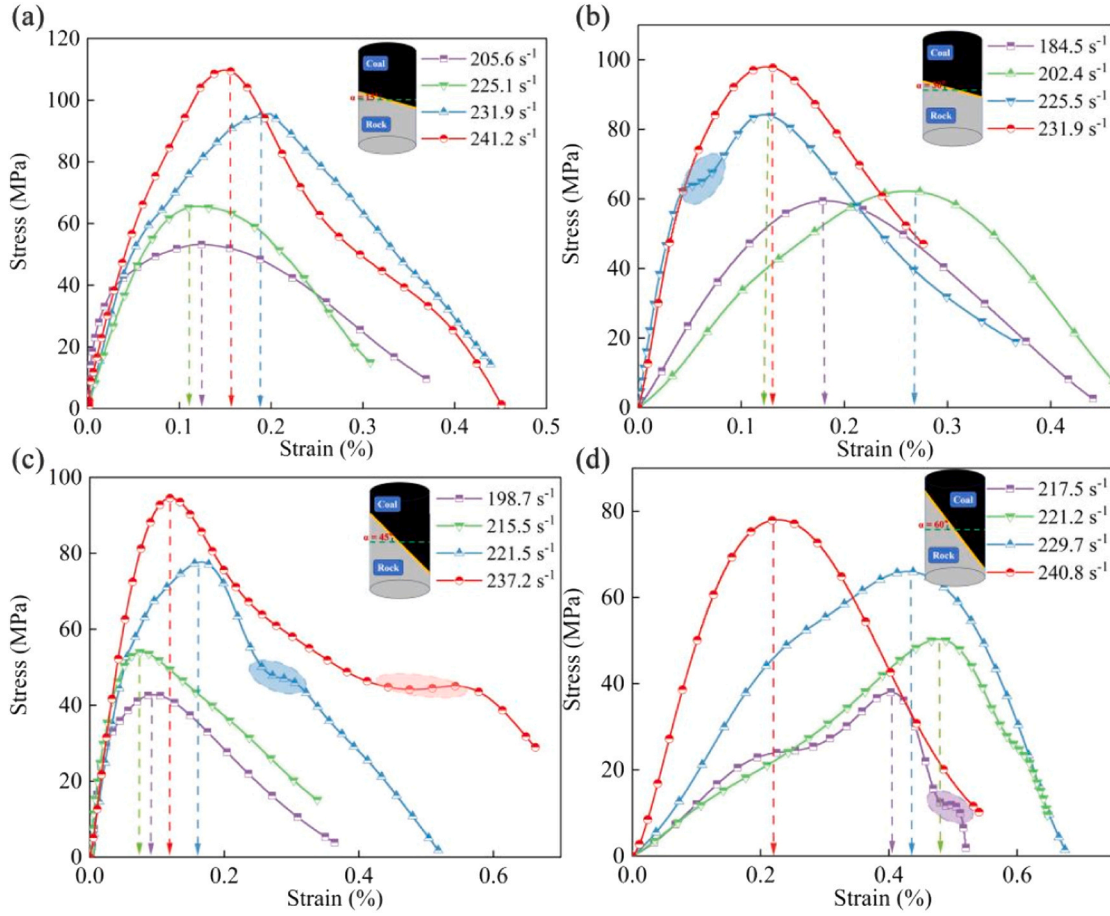


Fig. 6. The dynamic stress-strain curves of the W-CRB with different strain rates: (a-d) respectively for the interface angles are the 15°, 30°, 45°, and 60°.

D-CRB tests was typically lower than for Z-CRB tests, whereas W-CRB tests involved significantly higher incident energies compared to Z-CRB tests.

For specimens with $\alpha = 15^\circ$, the incident energy in D-CRB tests ranged from 60.7 J to 107.0 J. Within this range, the relative proportions of reflected, transmitted, and dissipated energy remained relatively stable, varying by less than approximately 1% ($\Delta \leq 1\%$). For the corresponding Z-CRB specimens ($\alpha = 15^\circ$), increasing the strain led to a marked decrease in the reflected energy proportion (from 80% down to 62%), accompanied by increases in the dissipated energy proportion (from 7% up to 13%) and transmitted energy proportion (from 13% up to 25%). The average incident energy for W-CRB specimens ($\alpha = 15^\circ$) was substantially higher (by 190 J) than for Z-CRB specimens, and the decrease in reflected energy proportion with increasing strain rate was less pronounced (from 71% down to 63%). Similar stability in energy partitioning was observed for the D-CRB specimens with $\alpha = 30^\circ$, where the proportions varied by less than $\pm 3\%$ across the tested range. For Z-CRB specimens ($\alpha = 30^\circ$), a specific test at a strain rate of 91.4 s⁻¹ showed a dissipated energy proportion of 13% and a transmitted energy proportion of 22%. The energy partitioning trends for W-CRB specimens at $\alpha = 30^\circ$ generally mirrored those observed at $\alpha = 15^\circ$, although the overall incident energy magnitudes involved were considerably higher.

For specimens with an interface inclination $\alpha = 45^\circ$, the D-CRB configuration exhibited an apparently anomalous energy distribution at a specific high strain rate (104.3 s⁻¹), where the proportion of dissipated energy decreased sharply to 1%, corresponding to a relatively low incident energy of 58.9 J. For the Z-CRB configuration ($\alpha = 45^\circ$), the transmitted energy proportion displayed a non-monotonic trend, peaking at 23% at an intermediate strain rate of 77.0 s⁻¹, higher than values recorded at both lower (70.5 s⁻¹) and higher (90.1 s⁻¹) strain rates. In

contrast, the dissipated energy proportion for W-CRB specimens ($\alpha = 45^\circ$) reached a minimum of 4% at a strain rate of 198.7 s⁻¹, subsequently showing a linear increase with further increases in strain rate within the tested range.

For the steepest interface inclination tested ($\alpha = 60^\circ$), D-CRB specimens showed increasing energy absorption with loading rate – increasing the strain rate from 89.7 s⁻¹ to 153.6 s⁻¹ resulted in increases of 4% in transmitted energy and 1% in dissipated energy proportions. At a higher strain rate of 216.0 s⁻¹, these proportions increased further, reaching values approximately 8% and 5% higher, respectively, than at the lowest strain rate. The Z-CRB specimens ($\alpha = 60^\circ$), tested with incident energies ranging from 139 J to 215 J, demonstrated relatively stable energy partitioning, with dissipated energy proportions remaining consistently between 9% and 10% and transmitted energy proportions between 17% and 19%. For W-CRB specimens ($\alpha = 60^\circ$), increasing strain rate led to a decrease in reflected energy proportion (from 77% to 72%) and an increase in transmitted energy proportion (from 14% to 17%), while the dissipated energy proportion remained relatively stable around 10%.

In summary, applying axial pre-stress and, particularly, confining pressure influences the dynamic response. These constraints limit lateral deformation, thereby modifying the damage modes and failure processes within the CRB specimens. Consequently, the distribution of incident energy into reflected, transmitted, and dissipated components is altered. A significant overall trend observed is an increase in the proportion of dissipated energy under both Z-CRB and W-CRB conditions compared to the D-CRB baseline. The results align with Yang et al. (2022) and Chen et al. (2023), confirming that static stresses enhance the CRB structure's ability to absorb and dissipate impact energy through internal damage mechanisms [23,34].

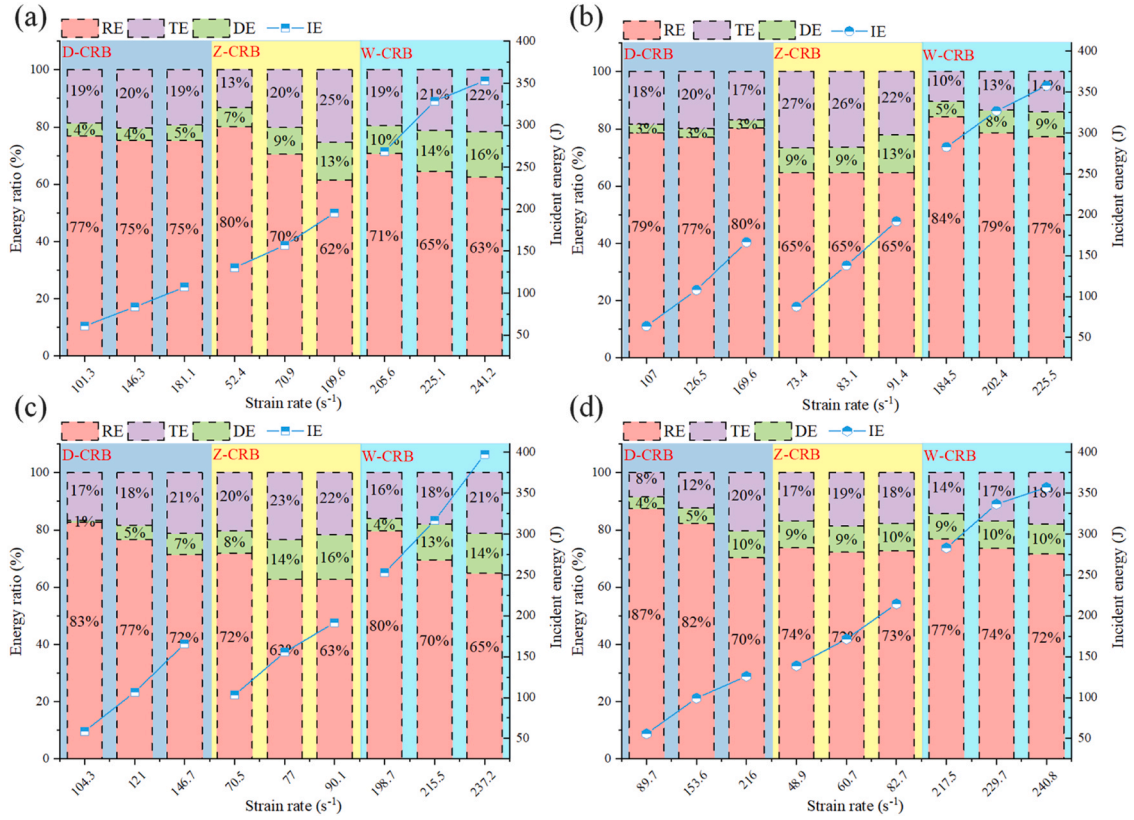


Fig. 7. The variation of the energy distribution percentage (each part of the energy to the incident energy) and incident energy with strain rates for the (a) 15°, (b) 30°, (c) 45°, and (d) 60° specimens.

3.3. Dynamic mechanical properties

Fig. 8 presents the dynamic compressive strength of CRB specimens as a function of the interface inclination angle (α), with data points color-coded according to the achieved strain rate, allowing visualization of strain rate effects within each loading configuration. Under dynamic loading alone, the CRB exhibits a non-monotonic relationship between α and dynamic strength. The lowest strengths were typically observed at the shallowest angle ($\alpha = 15^\circ$, approximately 30 MPa) and the steepest angle ($\alpha = 60^\circ$, around 70 MPa), while specimens with intermediate interface angles ($\alpha = 45^\circ$) generally exhibited higher dynamic strength under these conditions. When static axial pre-stress was applied (Z-CRB configuration), the specimens with $\alpha = 30^\circ$ appeared to benefit significantly from pre-stress, achieving substantial dynamic strengths. At a

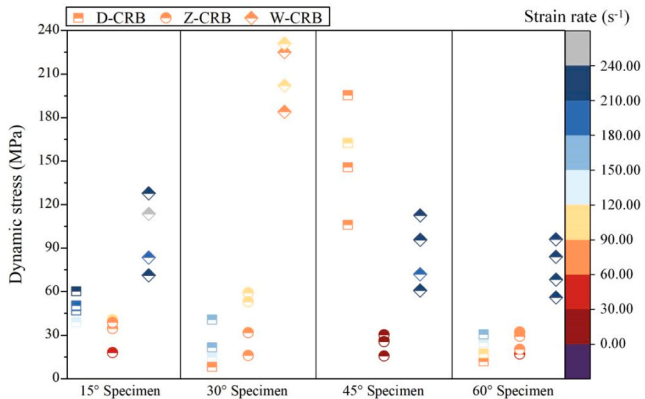


Fig. 8. The variation of the dynamic strength of CRB under different dynamic and static combined loads.

strain rate of 99.2 s^{-1} , the dynamic strength reached 59.1 MPa. Within the Z-CRB test series, specimens with $\alpha = 60^\circ$ generally ranked second highest in terms of achieved dynamic strength. In contrast, specimens with $\alpha = 15^\circ$ and $\alpha = 45^\circ$ under axial pre-stress displayed comparatively lower dynamic strengths, often similar to one another. However, a subtle trend emerged at higher strain rates (specifically, for tests exceeding 150 s^{-1} within the Z-CRB group) – specimens with $\alpha = 45^\circ$ exhibited a marginal strength advantage ($\Delta = +3.8\%$) over those with $\alpha = 15^\circ$.

The application of confining pressure resulted in a dramatic increase in dynamic strength, particularly evident for specimens with $\alpha = 30^\circ$. These specimens achieved strengths up to 231 MPa (at a strain rate of 116 s^{-1}), representing values 287%–412% higher than those recorded for specimens with other interface angles. Specimens with $\alpha = 60^\circ$ consistently exhibited the lowest dynamic strength, with 56.1 MPa recorded at a high strain rate of 217.5 s^{-1} . However, this was notably higher than the observed strength for the corresponding Z-CRB specimen ($\alpha = 60^\circ$) tested under comparable conditions (approximately 36 MPa).

Ren et al. (2025) find that bolts in CRB absorb external load and energy, reducing the angle's effect. Their presence significantly boosts CRB's dynamic strength, mainly due to the strain rate effect [32]. This is consistent with the results observed in this experiment. At similar strain rates, W-CRB specimens consistently demonstrated significantly higher dynamic strength than their Z-CRB counterparts, indicating the pronounced strengthening effect of confining pressure. By creating a three-dimensional stress field, the confining pressure increases the frictional resistance and the energy required for crack initiation and propagation. Additionally, confinement restricts lateral expansion, improving particle interlocking and suppressing shear displacement within the coal and rock mass, thereby enhancing overall resistance to dynamic failure. While axial pre-stress alone might improve initial

interface contact, the resulting biaxial stress state under dynamic impact is less effective at inhibiting failure. The asymmetric loading relative to the inclined interface may even promote or exacerbate shear slip along the CRB contact surface, contributing to the relatively lower dynamic strengths observed in Z-CRB tests compared to the confined W-CRB tests.

4. Observation of the fracture surfaces

4.1. Setup of 3D laser scanning experiment

The quantitative characterization of fracture surface morphology provides vital insights into the failure processes and mechanisms governing material behavior. To further elucidate the fundamental failure mechanisms of the CRB composites under the combined static and dynamic loading conditions investigated, this study utilized three-dimensional (3D) laser scanning technology. This technique enables the precise digital reconstruction and subsequent quantitative analysis of the fracture surface topography, focusing specifically on the primary failure zones developed within the specimens post-impact. The experimental system is illustrated in Fig. 9.

The fracture surface topography measurements were conducted using a PS50 three-dimensional surface profilometer system. This instrument comprises an optical measuring probe coupled with a CCD image acquisition module, mounted on a precision motorized scanning stage, and integrated with a dedicated data processing system. It facilitates non-contact, high-speed acquisition of 3D surface topography data. Key specifications of the standard system configuration include a maximum automatic scanning area of 50 mm × 50 mm, a minimum step resolution of 0.1 μm, and a maximum scanning velocity of 20 mm/s. Instrument operation, parameter control, and subsequent data analysis are managed via specialized control software.

For the specific requirements of this study, the scanning area (X/Y range) was defined as 30 mm × 30 mm, centered relative to the original bolt hole location which served as the origin for the reference coordinate system. Specific feature locations, designated points A (distal contact) and B (proximal contact) were selected for detailed morphological analysis (Fig. 10). This targeted scanning approach ensured efficient capture of the relevant topographic characteristics associated with failure across the heterogeneous material interface.

4.2. Fracture morphology

A representative 3D reconstruction of a post-impact CRB fracture surface is illustrated in Fig. 11a. The overall surface topography exhibits a general slope, with elevation typically decreasing from the distal towards the proximal side relative to the original coal-rock interface. A distinct, often irregular, cavity is evident at the center of the scanned surface, corresponding to the location where the embedded bolt fractured during dynamic loading. The varying fracture depths of the bolt result in differences in the scanned elevation. As the strain rate increases, the elevation decreases from 5 mm down to 2 mm, with the minimum observed bolt fracture depth occurring at the highest tested strain rate of 240.8 s⁻¹. This inverse relationship between fracture depth

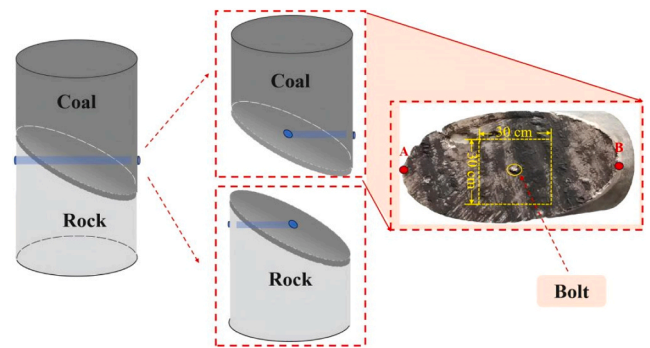


Fig. 10. The diagram of the scanning section for the fracture.

and strain rate suggests that as the strain rate increases, the shear effect of the bolt along the contact surface becomes more pronounced.

To quantitatively characterize the fracture surface topography, height distribution histograms and Abbott-Firestone (A-F) curves were generated from the 3D scanned data (Fig. 11b). The height distribution histogram illustrates the frequency or probability density of different elevations across the scanned surface. The A-F curve, also known as the bearing area curve, plots the cumulative probability (bearing ratio), typically representing the percentage of the surface area residing above a certain height threshold, as a function of that height or depth [35]. Analysis of specimens tested at different strain rates revealed distinct topographical characteristics. The height distribution histogram shows that surface elevations of the sample (217.5 s⁻¹) are primarily concentrated between 0 and 0.27 mm. Approximately 10% of the data points fall within the higher elevation range of 0.27 mm to 2.71 mm. The corresponding A-F curve exhibits a characteristic shape - an initial relatively steep section representing the highest surface peaks, followed by a more gradual slope through the core roughness region, potentially flattening further in the valley region. The overall height range of the sample (229.7 s⁻¹) spanned from 0 mm to 2.8 mm. The histogram indicates a peak distribution density between 1.62 mm and 1.80 mm, with this modal range accounting for approximately 22.5% of the data points. About 10% of the surface points reside within the 1.4 mm and 1.8 mm height interval. The height range for the sample (240.8 s⁻¹) is the smallest, with elevations concentrated primarily between 0 mm and 1.44 mm. The histogram displays a typical unimodal distribution (frequency initially increasing then decreasing with height). The A-F curve analysis indicated that 20% of the surface area existed above an elevation of 0.62 mm.

To analyze the orientation patterns of the generated fracture surfaces, the point cloud data obtained from the 3D scans was processed using the Facets plugin within the CloudCompare software. This tool automatically segments the point cloud, identifies local planar regions (facets), and extracts their orientation data (dip direction and dip angle). This structural orientation data was then imported into DIPS software for stereographic projection and analysis. DIPS was used to generate contour maps and analyze the orientation distribution patterns of structural planes [36]. Fig. 11c presents these cloud maps for specimens tested at different strain rates. The discontinuous surfaces of the four samples are primarily concentrated at the central position (bolt fracture), with the discontinuous surface range of the sample (217.5 s⁻¹) exhibiting a relatively tight cluster, indicating a dominant, well-defined failure orientation. As the strain rate increases, the discontinuous surface extends downward from the center. The discontinuous surface of the sample (229.7 s⁻¹) expands from the center to both ends, with the direction exhibiting some shift or elongation on the stereonet. Upon reaching 240.8 s⁻¹, the pole distribution becomes significantly more dispersed. While a primary orientation cluster might still be discernible, numerous scattered poles and potentially secondary, weaker clusters appear across the stereonet. This indicates a more complex fracture

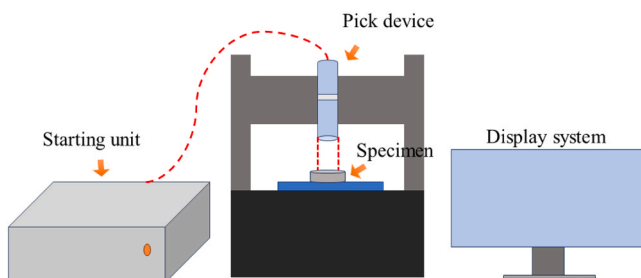


Fig. 9. The diagram of the 3D surface morphology instrument.

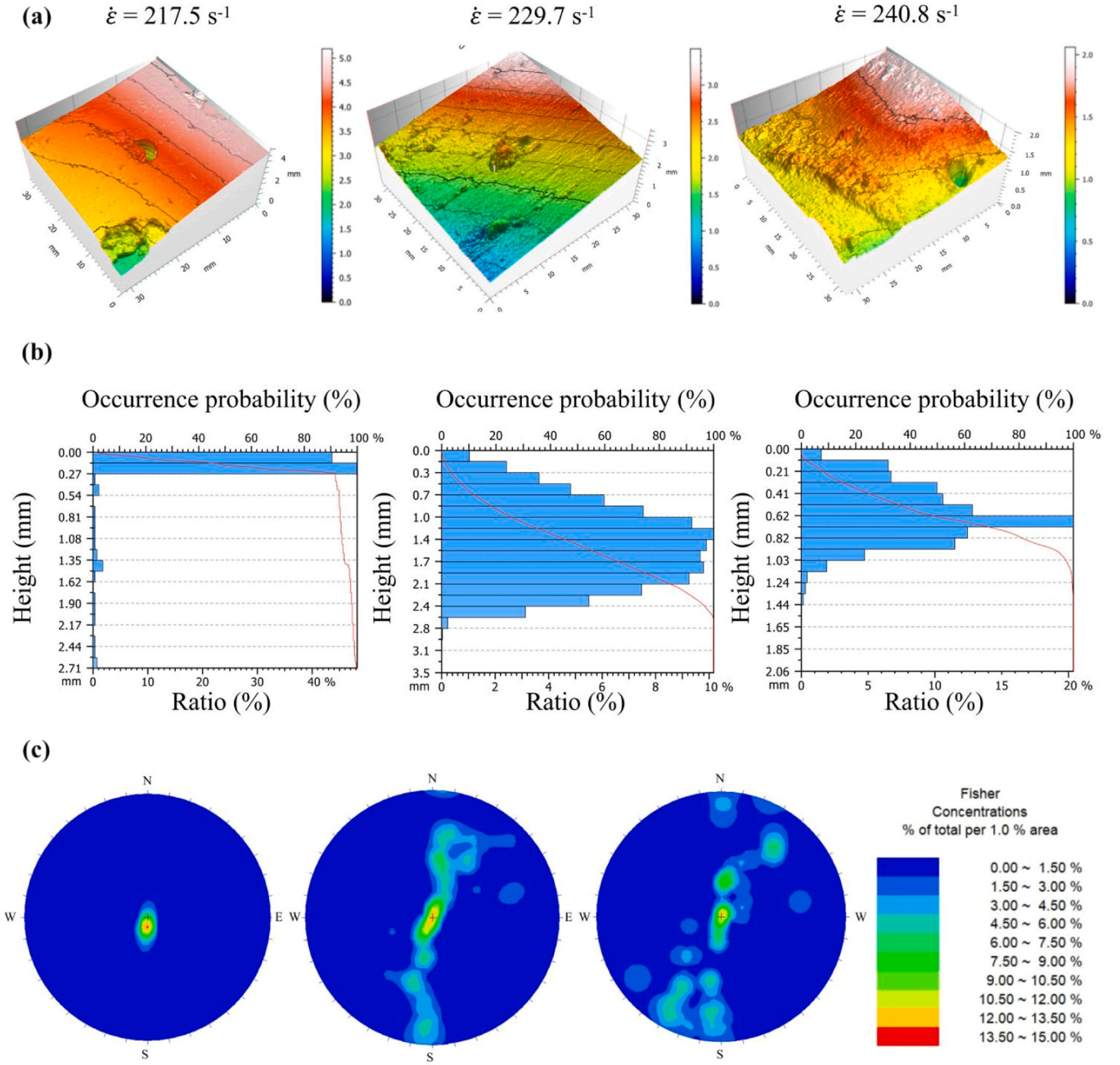


Fig. 11. (a) The 3D view of the fracture surface; (b) the Abbott-Firestone curves and height distribution histograms; (c) isoline maps distribution on shear fracture planes. The strain rates are 217.5 s^{-1} (left), 229.7 s^{-1} (middle), and 240.8 s^{-1} (right), respectively.

network with multiple contributing orientations. The observed trend of increasing pole scatter and the emergence of multiple orientation clusters with increasing strain rate supports the interpretation that higher loading rates promote more distributed and localized fracturing. Instead of failure being dominated by a single macro-plane, the damage becomes more complex, involving fractures with diverse orientations. This increased complexity in the fracture network contributes to the overall irregularity observed in the final failure surface morphology at higher strain rates and suggests an enhanced propensity for localized failure modes under more intense dynamic loading.

5. Simulation of SHPB tests

5.1. Numerical model

During testing, it is challenging to observe the entire deformation process of the bolt in CRBs. To analyze the effects of axial pre-stress and confining pressure on the dynamic response of bolts in CRBs, this study employed the Drucker-Prager yield criterion, selected for its ability to capture the influence of confining pressure and strain rate. The finite element model, depicted in Fig. 12a, precisely replicated the dimensions

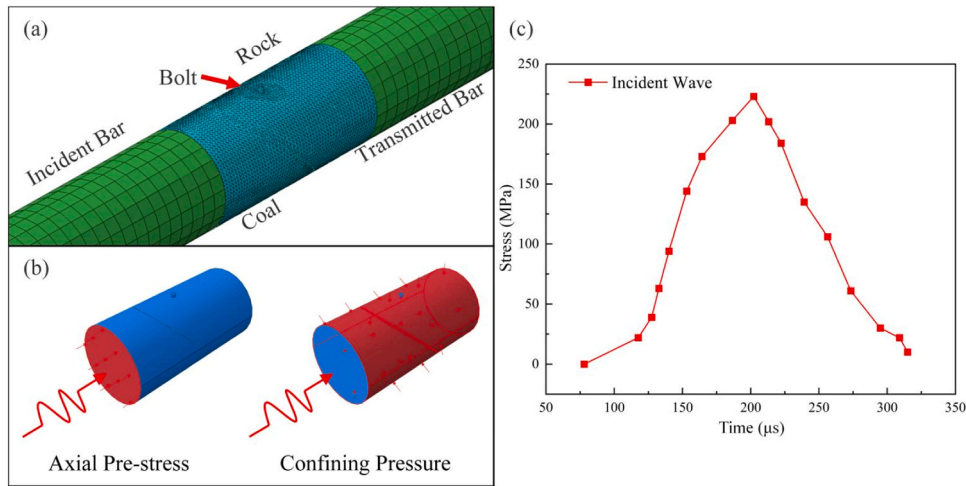


Fig. 12. The schematic of the (a) numerical model, (b) boundary condition, and (c) the input stress waveform.

of the experimental CRB specimens and relevant sections of the incident and transmitted bars. Accurate simulation of stress wave propagation necessitates careful mesh design. Consequently, the finite element mesh was significantly refined, particularly within the CRB specimen and along the axis of the pressure bars. Element sizes were chosen to ensure adequate spatial resolution, typically aiming for at least 10 elements per characteristic wavelength of the input stress pulse to minimize numerical dispersion [37,38]. The simulation procedure mirrored the experimental sequence to replicate the combined static and dynamic loading conditions. First, quasi-static boundary conditions representing either axial pre-stress or confining pressure were applied to the relevant surfaces of the CRB specimen and allowed to reach equilibrium, as illustrated in Fig. 12b. Subsequently, the dynamic loading event was simulated by applying a prescribed velocity or stress input boundary condition at the incident end of the modelled pressure bar. This input waveform, shown in Fig. 12c, was directly derived from the incident stress wave measured during the corresponding laboratory SHPB experiments, ensuring fidelity between the simulated dynamic impact and the physical test. The bolt was modeled using an 8-node linear reduced-integration hexahedral element (C3D8R). The primary advantage of C3D8R is its low computational cost in frictional analysis, owing to its relatively small number of element nodes and the adoption of a reduced integration scheme, which significantly reduces solution time. Additionally, the numerical performance of C3D8R is robust in contact analysis, with its flat element surfaces facilitating accurate contact detection and slip identification, thereby minimizing convergence issues such as penetration. Detailed parameters for coal, sandstone, and bolt specimens are listed in Table 2.

5.2. Contact relationship and interface model

The surface-to-surface contact is employed to simulate the interaction between the bolt and the surrounding rock. This method can model slip, voids, and friction, with the rock, being the stiffer material, selected as the Master surface. The outer surface of the bolt is designated as the Slave surface. This configuration is based on the numerical

implementation of the contact constraint: during the computational process, the software detects penetration from the surface node to the master surface and applies the corresponding penalty function or constraint to prevent such penetration. Choosing a stiffer surface as the master provides a nearly constant geometric reference, thereby significantly reducing the potential for slave node penetration. This, in turn, ensures the accuracy of the contact force calculations and enhances both numerical stability and convergence efficiency during the solution process. This approach is crucial for optimizing the accuracy and computational robustness of contact analysis. In the interaction properties, the normal behavior is set to "Hard contact", which allows for contact pressure transfer but prevents penetration. For tangential behavior, the "Penalty" method is selected, with a friction coefficient (μ) of 0.4, determined experimentally. The surface-to-surface contact method is also applied to model the interface between coal and rock. This modeling approach is analogous to that used for the bolt-rock interface, with the rock surface acting as the master and the coal seam surface as the slave. The normal behavior is again set to "Hard contact", and the tangential behavior utilizes the "Penalty" method. The friction coefficient was set to $\mu = 0.5$, as reported in literature [5].

5.3. Verification of numerical model

Verification of the numerical model's fidelity in replicating the physical experiments is essential before using it to further analysis [39–42]. This was achieved through a trial-and-error process to adjust the simulated stress-strain curve and failure behavior to match laboratory results. For example, Fig. 13a compares the experimental and numerical results for a representative Z-CRB specimen ($\alpha = 45^\circ$, axial pre-tress = 7.8 MPa). The comparison focuses on both the dynamic stress-strain curves and the final failure patterns. Good agreement was obtained between the simulated and experimental stress-strain curves, particularly regarding peak stress, initial stiffness, and general post-peak behavior, confirming the model's ability to capture the overall mechanical response. Furthermore, the simulated failure pattern qualitatively matches the primary features observed in the post-test experimental specimen. Additionally, under specific conditions (e.g., $\alpha = 45^\circ$ and confining pressure of 6.5 MPa), bolt fracture is evident in the simulation, as shown in Fig. 13b.

5.4. Numerical results and analysis

Understanding the axial stress state within the bolt is vital for assessing its stability and load-bearing capacity under dynamic loading [43]. This section utilizes the validated numerical model to analyze the

Table 2

The physical and mechanical parameters of coal, rock and bolt.

Material	ρ (g/cm ³)	E (GPa)	$\sigma_{\max}$ (MPa)	σ_r (MPa)	σ_s (MPa)	A_e (%)
Coal	1.48	2.03	14.29	10.04	-	-
Rock	2.79	12.73	83.01	24.71	-	-
Bolt	8.90	184.00	-	-	392	8

Note: ρ is the density; E is the elastic modulus; $\sigma_{\max}$ is the peak strength; σ_r is the residual strength; σ_s is the yield strength; A_e is elongation rate at the yield point.

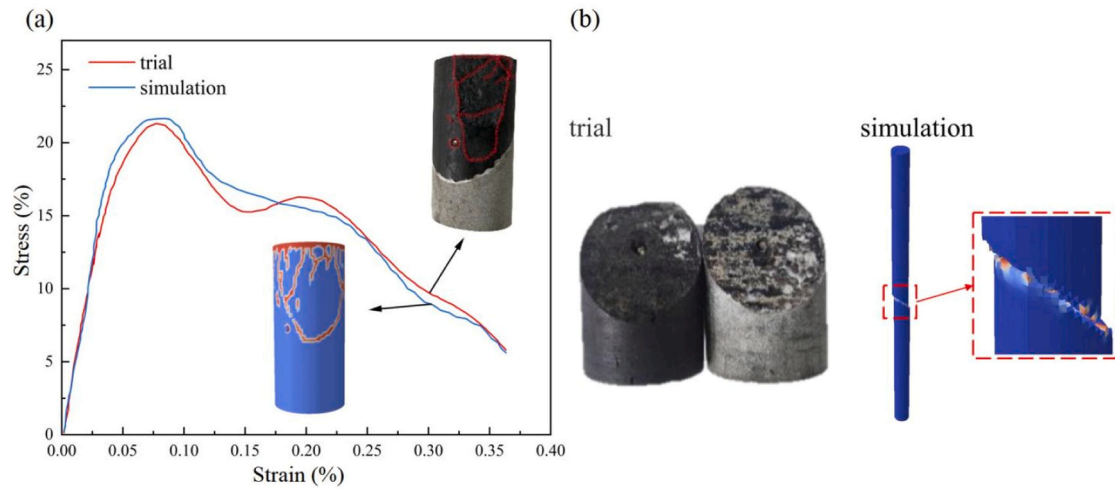


Fig. 13. The comparison of the numerical simulation with SHPB test: (a) stress-strain curves; (b) bolt failure.

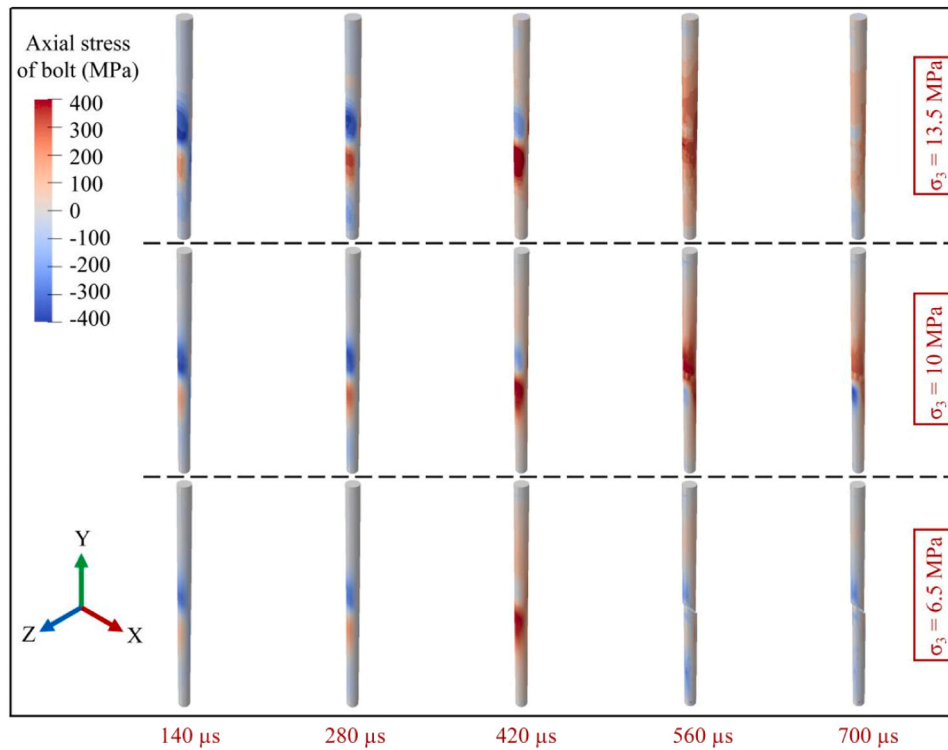


Fig. 14. The influence of the confining pressure on bolt stress in CRB.

evolution of axial stress along the bolt embedded within CRB specimens (specifically focusing on $\alpha = 45^\circ$ examples) subjected to dynamic impact under varying static confinement levels. Fig. 14 displays the simulated effect of dynamic loading on the axial stress distribution within the bolt under different confining pressures. Numerical simulations reveal that during initial loading, the portion of the bolt closer to the incident bar typically experiences compressive axial stress due to the incoming wave, while the portion further along (distal end) develops tensile stress. As the loading progresses and differential deformation occurs between the coal and rock segments across the inclined interface, relative shear displacement is induced. This displacement effectively stretches the bolt across the interface, causing the axial stress along most, or all, of the bolt's length to transition into a tensile state. Afterwards, the bolt fractures mainly from lateral pressure by coal and rock, shifting to compressive stress. At an intermediate confining pressure (10 MPa),

simulations indicated slight bolt yielding or fracture occurring later, near the end of the primary loading phase, while at the lowest confining pressure (6.5 MPa), the bolt fractured relatively early in the loading process, typically near the coal-rock interface. Conversely, at the highest confining pressure (13.5 MPa), the bolt remained intact throughout the simulation duration. These numerical findings indicate that increasing confining pressure significantly inhibits coal-rock dislocation during loading, reducing the magnitude of the tensile axial forces generated within the bolt and lowering the risk of bolt fracture.

Fig. 15 illustrates the simulated evolution of axial stress within the bolt for CRB specimens subjected to dynamic impact under varying levels of static axial pre-stress. The simulation indicates compressive axial stress developing near the impact end and tensile stress towards the distal end of the bolt immediately following impact. However, as loading continues, the behavior diverges. Significant tensile axial

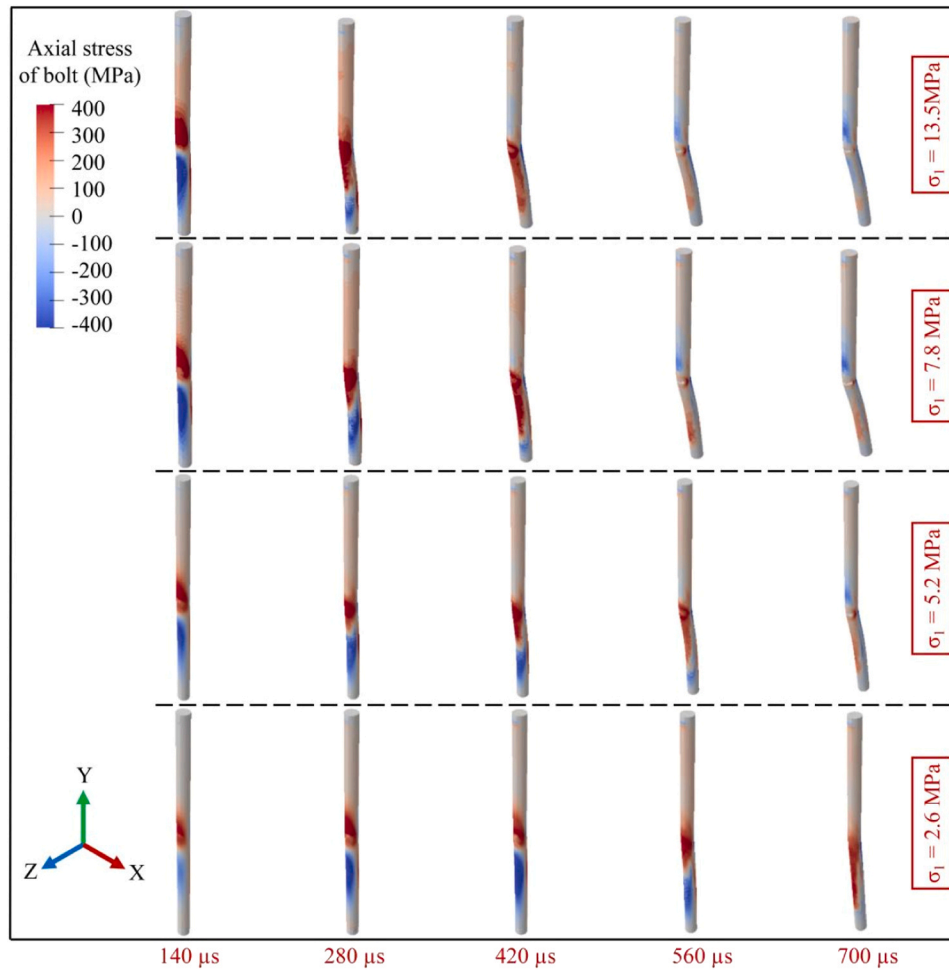


Fig. 15. The influence of the axial pre-stress on bolt stress in CRB.

stresses develop and intensify, particularly concentrated near the inclined coal-rock interface, driven by the shear displacement between the coal and rock segments. This differential movement induces substantial bending deformation in the bolt, rather than immediate fracture. The simulations show this deformation manifesting as a pronounced V-shape, originating near the interface and becoming more severe as the magnitude of the initial axial pre-stress increases. For the specific case of $\alpha = 45^\circ$ specimens under Z-CRB conditions, the numerical simulations indicate that the bolt often remains intact, despite the significant V-shaped deformation. In these scenarios, the CRB composite reaches its load-carrying capacity, leading to preferential failure initiating within the coal material, often near the loading end. This localized failure of the coal appears to effectively unload or reduce the load transferred to the segment of the bolt embedded within it. By limiting the peak tensile stress or stress concentration experienced by the bolt, particularly near the critical interface region, this coal failure mechanism contributes to preserving the bolt's integrity, preventing fracture even under severe bending.

6. Conclusions

This study investigated the dynamic response of coal-rock-bolt (CRB) composite structures under various combined dynamic and static loading conditions using integrated SHPB experiments and numerical simulations. The research analyzed the influence of static axial pre-stress and confining pressure on the stress-strain behavior, energy partitioning characteristics, dynamic mechanical properties, and failure modes of CRB specimens with varying interface angles. Numerical modelling

provided insights into the internal mechanics, particularly bolt behavior. Additionally, post-failure fracture surface topography and orientation patterns were characterized using 3D laser scanning and stereographic analysis. The key findings of this study are:

- (1) CRB specimens consistently exhibit a three-stage mechanical response under dynamic loading: elastic deformation, yielding leading to peak stress, and post-peak softening. For a given impact velocity, the application of static axial pre-stress was observed to systematically reduce the achieved strain rate within the specimen, whereas the application of confining pressure generally resulted in higher achieved strain rates compared to unconfined tests.
- (2) Both axial pre-stress and confining pressure significantly influence energy partitioning during dynamic impact. By inhibiting lateral deformation and altering internal damage mechanisms, these static constraints lead to a marked increase in the proportion of incident energy dissipated within the specimen compared to unconstrained conditions.
- (3) Confining pressure exerts a pronounced strengthening effect on CRB specimens. Under comparable interface angles and strain rates, the dynamic compressive strength was significantly enhanced by confinement, indicating improved resistance to dynamic load. In contrast, static axial pre-stress demonstrated a negligible influence on the peak dynamic strength under the tested conditions.
- (4) The bolt mitigates crack propagation and interface dislocation by connecting the coal strata in series, thereby significantly

enhancing the dynamic strength of CRB. Simultaneously, the bolt absorbs impact energy through its own elastic-plastic deformation, effectively preventing the surrounding coal-rock matrix from catastrophic failure.

- (5) Confining pressure effectively suppresses bolt fracture by limiting relative shear displacement across the coal-rock interface during dynamic loading. Conversely, axial pre-stress exacerbates bending deformation of the bolt, leading to a pronounced V-shape, the severity of which correlated positively with the pre-stress magnitude.

CRediT authorship contribution statement

Linxin Wang: Writing – original draft, Funding acquisition, Data curation. **Tianzuo Huang:** Resources, Formal analysis, Data curation. **Fuqiang Ren:** Writing – review & editing, Methodology, Funding acquisition. **Yuan Chang:** Methodology, Data curation. **Zhenyang Xu:** Resources, Methodology, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

All data included in this study are available upon reasonable request by contact with the corresponding author.

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