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Research Progress on Dynamic Response Mechanism and Damage Control of Jointed Rock Mass Blasting

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Abstract: ***The dynamic response of jointed rock masses under blasting loads is a critical scientific issue for safe and efficient tunneling and mining engineering. This paper systematically reviews the synergistic mechanisms between blast stress waves and gas propelling agents in rock fragmentation, elucidating how joints regulate energy propagation, crack propagation, and damage evolution during blasting. Research findings indicate that joints enhance blasting responsiveness through three mechanisms: reflecting/transmitting stress waves, altering crack propagation directions, and dissipating energy to amplify anisotropy; gas propelling agents drive quasi-static crack propagation, while joint length and orientation control the "guidance-suppression" effect on crack development; coupled high stress-joint interactions intensify rock mass damage zoning. Through numerical simulations (LS-DYNA/RHT models), experimental studies (dynamic dissipation line technique, CT reconstruction), and engineering practices, this paper proposes recommended blasting parameter design and damage control strategies. Future research should focus on multi-field coupling models, intelligent algorithms, and blasting theories under complex deep geological conditions, advancing rock mass blasting from empirical design to precision engineering.***

Keywords: Jointed rock mass, Blasting mechanism, Fracture propagation, Damage evolution.

1. Introduction

Blasting excavation is a critical construction process in tunnel and mining engineering. The natural fracture network endows rock masses with discontinuity and anisotropy, making the dynamic response mechanisms of blasting extremely complex. Traditional theories suggest that this phenomenon results from the combined effects of blasting stress waves and gas emissions: Blasting stress waves generate initial dynamic rupture, while gas emissions drive quasi-static crack propagation. However, fractures are inherently discontinuous structural surfaces within rock masses. They alter the blasting rupture mechanism and damage distribution by influencing stress wave propagation paths, regulating crack expansion directions, and dissipating blasting energy. Recent advancements in technologies such as high-speed photography, 3D printing, and discrete element simulation have advanced research on fracture mechanisms in jointed rock masses. This paper focuses on the regulatory mechanisms governing stress wave propagation, gas emission-driven processes, dynamic crack expansion, and damage accumulation in jointed rock masses. It systematically reviews experimental methods, numerical models, and engineering applications from perspectives including interactions between blasting stress waves and joints, evolution patterns of gas emissions with joint guidance effects, crack propagation and damage evolution modes in fractured rock masses, as well as damage control strategies and case studies. The aim is to provide theoretical support for optimizing blasting designs and controlling surrounding rock damage.

2. Mechanism of Rock Blasting

In tunnel drilling and blasting excavation, natural rock masses contain numerous fractures, joints, and weak interlayers that exhibit discontinuity and anisotropy. This complexity leads to extremely intricate damage mechanisms under blast impact loads, sparking extensive research on blasting damage mechanisms by scholars worldwide. Most researchers attribute rock fragmentation primarily to the combined action of stress waves generated by explosive detonation and gas emissions. These two factors complement each other, playing dominant roles at different stages of dynamic rock failure: Blast-induced stress waves initiate initial dynamic failure through crack formation, while gas emissions drive subsequent crack propagation through quasi-static pressure.

2.1 Blast Stress Waves

The high-pressure shock wave generated by detonation exceeds the dynamic compressive strength of the rock mass near the borehole wall, causing intense compression and fragmentation of the nearby rock mass into a crushed zone. During this process, the shock wave attenuates into a compressional stress wave due to energy dissipation, propagating outward. The radial compression forces induce radial displacement of rock particles, thereby generating significant tangential tensile stress in the medium. When this tangential stress exceeds the rock's dynamic tensile strength, a fracture zone dominated by radial cracks forms. Additionally, when the compressive stress wave reaches free surfaces or discontinuous interfaces, reflections occur. If these reflected tensile waves surpass the rock's tensile strength, they induce layer fractures or further expand radial cracks. As the blast center distance increases, the energy of the compressive stress wave gradually dissipates. The peak pressure drops below the rock's elastic limit, and the waveform becomes flatter, transforming into low-frequency, low-amplitude seismic waves that continue propagating outward. This causes elastic vibrations in the rock mass, resulting in recoverable elastic deformation without new fractures, forming a vibration zone. The rock mass blasting damage mechanism [1] is illustrated in Figure 1 (where R0 represents the borehole radius).

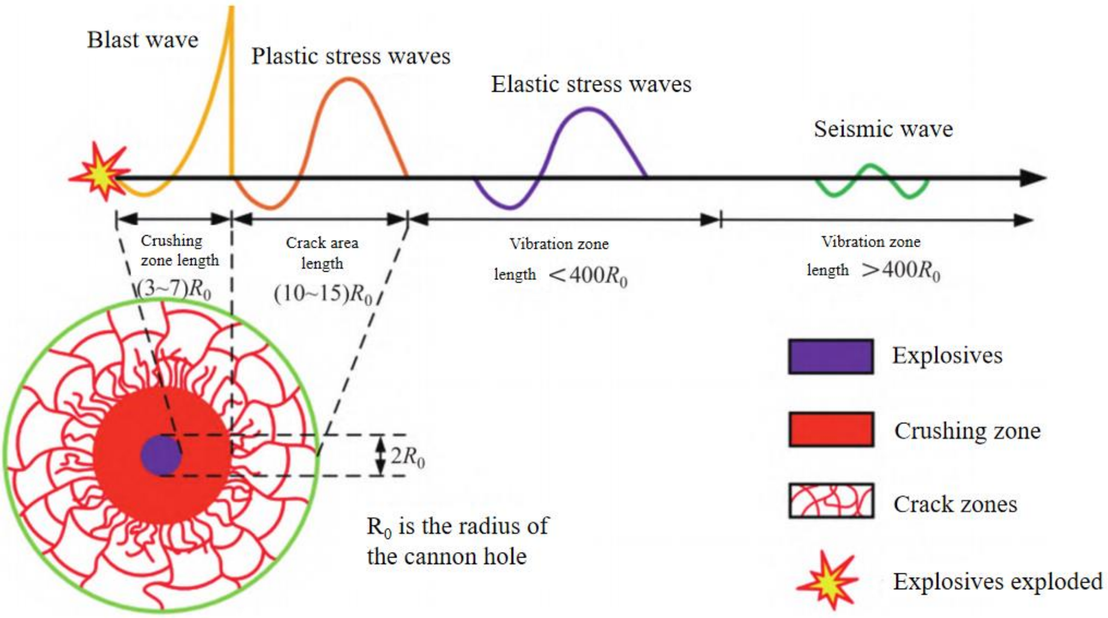

Figure 1: Mechanism of rock blasting [1]

Blasting stress waves are the core technical parameters in blasting operations. Research on their propagation and attenuation patterns directly determines rock fragmentation efficiency, tunnel stability, and blasting design optimization, which has long been a focus of international scholars. Li et al. [2] investigated granite blasting responses through cylindrical rock tests using Manganin pressure sensors to measure impact pressures at different distances, deriving exponential decay patterns for peak shockwave pressures. Yan et al. [3] conducted theoretical analysis and field monitoring to address air blast wave propagation mechanisms and control technologies in tunnel drilling, obtaining insights into propagation characteristics, hazard properties, prediction methods, and control strategies for tunnel blasting. However, natural rock masses contain naturally formed joints, bedding planes, and faults. When blasting stress waves penetrate these structures, complex transmission and reflection phenomena occur at joint surfaces, hindering wave propagation. Therefore, studying joint effects on blasting wave transmission is essential. Chen et al. [4] established explosion stress wave propagation patterns in jointed rock masses through model experiments, demonstrating how joint fill media influence wave propagation and energy absorption while optimizing blasting parameters. Zhang et al. [5] analyzed delayed blasting performance impacts from rock joints and fractures, establishing nonlinear joint blasting models and conducting finite element simulations to evaluate joint mass stress fields and blasting effectiveness. Yari et al. [6] employed a three-dimensional discrete element method to simulate the propagation patterns of blast stress waves in fractured rock masses, demonstrating that fractures hinder wave propagation by reducing energy dissipation and velocity. Du et al. [7] conducted experimental and numerical studies on blast stress wave propagation in fractured rock masses, revealing that fracture-filling media prolong stress wave propagation duration and cause energy attenuation. They further proposed optimized blasting parameter methods based on these findings.

When explosive stress waves encounter resistance at joints, significant changes occur in crack propagation, energy transfer, and damage evolution of surrounding rock. Research on jointed rock mass stress wave-coupled fracture mechanisms holds crucial engineering implications for optimizing tunnel blasting design, improving energy utilization efficiency, and controlling rock damage. Zhou et al. [8] established numerical models to analyze how joint geometry parameters affect blasting effectiveness, revealing patterns of reflection coefficients, energy ratios, and crack propagation influenced by joint location, crack width, and blast source distance. Huang et al. [9] utilized ANSYS/LSDYNA software and RHT material models to investigate the effects of blast source-to-crack distance and crack width on stress wave transmission coefficients and crack propagation patterns. Li et al. [10] conducted dynamic analysis of inclined open-joints through beam-shaped borehole tests and ABAQUS simulations, exploring dynamic fracture behavior and stress concentration mechanisms that drive wing cracks and secondary fractures at joint ends. Song et al. [11] studied stress wave attenuation and crack evolution in deep-hole blasting through numerical simulations and field observations, revealing relationships between joint inclination angles, transmission coefficients, and fractal dimension. Zhai et al. [12] employed ANSYS/LSDYNA to model blast responses in high-stress field conditions, demonstrating that initial ground stress and joint distribution significantly influence stress wave propagation. Their findings highlight substantial impact of ground stress on rock damage severity and energy transfer mechanisms.

2.2 Explosive Gas

Explosive gases play a crucial quasi-static driving role in rock mass fracturing. The high-temperature, high-pressure gases generated by explosive detonation rapidly penetrate initial fractures induced by blast shock waves. Through sustained gas pressure compressing fracture walls, they create splitting effects that significantly accelerate quasi-static crack propagation. Simultaneously, stress concentration at crack tips accelerates tip expansion rates, resulting in radial cracks with a gradient distribution pattern: dense wide inner zones and sparse narrow outer zones. Existing joints in rock masses guide crack propagation along their surfaces, with greater joint length enhancing this effect [13]. However, explosive gases and dynamic blast stress waves jointly determine the final fracturing morphology and size distribution of rock masses, making their interactions inseparable. Yang et al. [14] introduced high-speed camera technology to establish a digital image correlation experimental system, conducting two-dimensional model tests and visual analysis to investigate mechanisms of blast stress waves and gases in forming crushing zones and fracture zones. Results indicate that blast stress waves directly cause crushing zone formation while explosive gases serve as the primary driver for fracture zone development. Notably, explosive gases effectively reduce crushing zone dimensions, extend fracture extension lengths, and enhance peak medium stress. To better investigate the evolution patterns and mechanisms of blast gases, Ren et al. [15] employed a shadow experiment system to experimentally study the dynamic evolution processes of columnar explosive packages at different detonation positions. Their findings revealed that blast gas evolution consists of three stages: expansion, flow, and free diffusion. The detonation position significantly influences shock wave propagation characteristics and gas distribution. A clustering effect was observed in blast gases, with its intensity ranking as follows: mid-point detonation> 1/3-point detonation> apex detonation. This effect enhances radial gas flow in clustered areas, causing the radial flow distance of gases at detonation positions to be significantly greater than at other locations. Yang et al. [16] addressed the mechanism of underwater borehole blasting-induced water shock waves by considering interactions between blast gases and water. Through theoretical analysis, SPH-FEM coupled numerical simulations, and field experiments, they identified three mechanisms: transmissive/refractive stress wave propagation, gas jetting along boreholes, and burst gas overflow from rock mass bulging. They also discovered that blockage conditions significantly affect peak shock pressure.

3. Blasting Damage Characteristics of Jointed Rock Mass

During blasting excavation of jointed rock masses, structural surfaces such as fractures, bedding planes, and joints create significant heterogeneity and anisotropy within the rock mass. These surfaces exert pronounced control over fracture propagation, damage evolution, and blast vibration transmission, demonstrating strong "structural surface orientation": Fractures tend to propagate along joint surfaces or in directions with small angles relative to joints; rock mass damage near jointed surfaces is more severe; blast vibration waves undergo reflection and transmission at joints, causing variations in vibration intensity and frequency that ultimately alter the blasting effectiveness.

3.1 Crack Growth

Under blast loading, the initiation, development, and propagation of cracks in rock masses fundamentally involve dynamic fracture mechanics. Joints, as primary discontinuities in rock masses, significantly alter crack propagation patterns by modifying stress fields at crack tips, directing crack propagation along joint planes or inducing path deviations. Simultaneously, they act as energy barriers or conductive channels that influence stress wave propagation and energy dissipation, ultimately determining crack propagation behavior and mass fragmentation mechanisms. Whether joints inhibit or promote crack propagation depends on three key factors: the relative orientation between joints and blast-generated principal stress fields, the mechanical properties of joints (such as opening degree, filling degree, and roughness), and the characteristics of blast loading. Accurate identification of joint systems is crucial for predicting crack propagation range, size distribution, and profile quality during blasting processes.

To investigate rock crack propagation in blasting, Bendezu et al. [17] compared three methods—expansion finite element method, conventional finite element method, and cell deletion method—for simulating crack propagation induced by hard rock blasting. Their study revealed that the expansion finite element method demonstrated significant advantages in capturing non-smooth crack features, markedly improving both numerical accuracy and computational efficiency. In contrast, the conventional finite element method required frequent mesh remeshing, while the cell deletion method proved more suitable for rock fragmentation research rather than crack propagation analysis. Li et al. [18-19] conducted experiments using PMMA specimens and performed AUTODYN numerical simulations to investigate the effects of dual-pore spacing and dual-blasting hole spacing on crack propagation paths. Their findings indicated that smaller pore spacing enhanced crack suppression, while larger dual-blasting hole spacing hindered crack coalescence. Three crack coalescence mechanisms were identified: mutual, direct, and indirect. Regarding crack propagation in jointed rock masses, multiple domestic and international researchers employed numerical simulations. Fei et al. [20-21] utilized RHT models and software like ANSYS/LSDYNA to establish rock mass models with various joint geometries, investigating crack propagation mechanisms under blasting loads. Their analysis of joint width, curvature, inclination angle, length, and blasting hole spacing revealed that increased joint width and curvature promoted crack propagation between blast holes and joints. Additionally, greater joint inclination angles exhibited stronger inhibitory effects on blasting effectiveness, demonstrating the shielding effect of joints and crack deflection phenomena. Furthermore, increased joint length promotes crack propagation parallel to the joints but inhibits wing crack growth [22]. As shown in Figure 2 (with all parameters except L value identical), four main cracks develop and propagate in a cross-shaped pattern. The cracks extending in the opposite direction of the joints show relatively minor joint influence but tend to branch near adjacent boundaries. For cracks propagating perpendicular to the joints, their extension paths deviate due to increased joint length, while branching remains prevalent. Chen et al. [23] developed a non-local damage fracture phase field model considering rock mass heterogeneity. By incorporating fracture parameter heterogeneity characteristics and modifying governing equations, their numerical simulations demonstrated the model's capability to simulate crack propagation under compressive loading in pre-fractured rock samples.

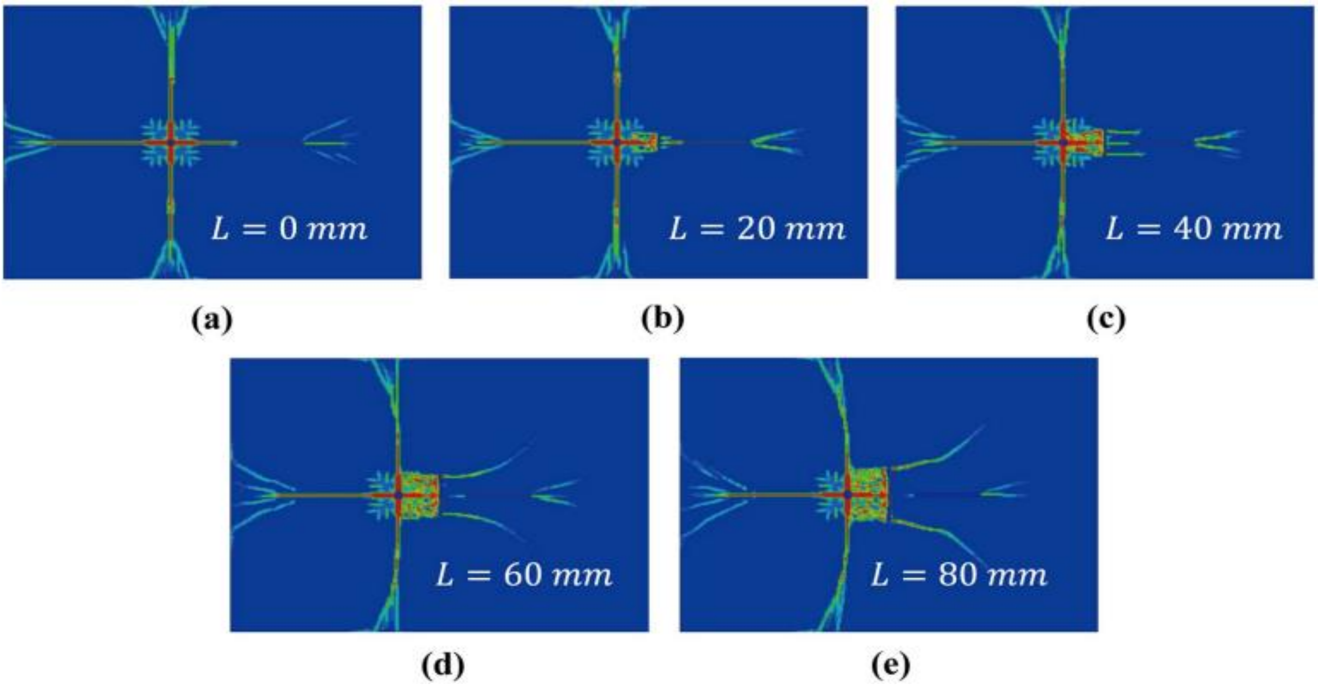

Figure 2: Final failure modes of rock samples with different joint lengths L after blasting: a L = 0 mm, b L = 20 mm, c L = 40 mm, d L = 60 mm, e L = 80 mm [22]

However, numerical simulation models often simplify complex realities and suffer from low credibility. To enhance the persuasiveness of simulation predictions, researchers must base their simulations on experimental data. Li et al. [24] conducted field blasting tests using a novel CO2 phase-change fracturing device to obtain dynamic pressure curves. By establishing a numerical model with LSDYNA software, they compared three types of fracturing devices: conventional, new, and head-type, analyzing how joint filling status, length, thickness, and blast source distance affect rock mass fracturing under different working conditions. Their findings revealed that new fracturing devices produce more uniform crack distribution and stronger rock mass impact effects. Head-type fracturing devices effectively guide crack propagation direction, promote secondary crack network formation, and significantly enhance rock mass permeability. Xu et al. [25] combined digital dynamic fission experiments with numerical simulations to explore the interaction mechanisms between two dynamically expanding cracks under blasting loads. Dynamic stress intensity factors KIId and T stress play crucial roles in crack deflection direction and interaction. They discovered that when cracks are within critical proximity, local stress fields exhibit significant superposition effects, leading to increased dynamic stress intensity factors and crack velocities. This controls crack interaction behavior, with cracks initially exhibiting repulsive effects before transitioning to attractive ones, which diminishes as vertical distance increases. Shen et al. [26] analyzed parallel joints' influence on crack propagation mechanisms through experiments and numerical simulations. Results showed that small spacing parallel joints inhibit crack propagation, while large spacing facilitates crack expansion along pre-set directions. Shen et al. [27] conducted blasting loading tests and PFC 2D discrete element numerical simulations on red sandstone specimens containing three types of preformed joints, revealing the controlling role of joint symmetry forms on crack propagation morphology and velocity during blasting, and elucidating the mechanisms by which joints guide and obstruct blast-induced crack propagation. Liang et al. [28] combined wave-crack synchronous testing system experiments with CDEM numerical simulation methods to conduct visual studies, demonstrating the complex effects of joints on blast stress wave propagation and crack propagation, and clarifying the mechanisms by which joint length and ground stress conditions influence blasting effectiveness. With advancing research, high-stress tunnel blasting has become a focal point. Deep rock mass crack propagation is influenced by both joints and ground stress. Through numerical simulation, theoretical analysis, and experimental studies, this paper explores how joint parameters and ground stress affect blasting effectiveness in fractured rock masses. Results indicate that joints guide and promote crack propagation along their surfaces, while ground stress exerts directional influence on crack propagation toward maximum stress directions [29-32]. Under deep high-stress conditions, rational optimization of blasting parameters can improve fragmentation efficiency and effectively control rock mass damage extent, providing theoretical basis and technical guidance for blasting design in deep fractured rock mass engineering.

The analysis demonstrates that structural surfaces such as joints and bedding planes in rock masses play dual roles in guiding and hindering crack propagation. When designing blasting projects for jointed rock masses, engineers must account for the influence of joints. Wu et al. [33-35] employed field sampling to document trace line distributions and internal joint structures of target rock masses, then applied this data to construct detailed blasting models using ANSYS/LSDYNA software. Their validation through blasting experiments confirmed the model's feasibility. Ma et al. [36] established a composite failure criterion model combining compression-shear and tensile-shear mechanisms to analyze post-blasting stress field distribution and crack propagation patterns near blasting holes under different joint characteristics. Their findings revealed that when joints form a 45° angle with blast holes, over-excavation and under-excavation phenomena are most severe; angles of 0° or 90° show minimal impact; while lower joint strength and wider joints demonstrate enhanced resistance to blast stress waves and tensile failure. Through major engineering cases, they optimized tunnel blasting schemes for jointed rock masses and successfully validated the optimized plan [37]. Combining slit blasting technology with experimental modeling, numerical simulations, and field applications, researchers discovered that weakly constrained PVC materials exhibit instantaneous high strength during impact, effectively guiding energy accumulation. Smaller joint angles facilitate crack propagation along their orientation. The application of weakly constrained slit pipes in layered rock mass tunnel blasting has proven successful. Wei et al. [38] conducted experimental modeling analysis under full-face excavation blasting conditions for deep circular tunnels. Their study investigated the effects of joint length and spacing on instantaneous unloading processes in jointed rock masses, identifying two distinct cracking patterns: terminal joint initiation and mid-joint propagation. These findings provide both theoretical foundations and practical engineering references for understanding dynamic responses and failure mechanisms in deep tunnel excavation involving jointed rock masses.

3.2 Damage Evolution

Rock mass blasting excavation is a complex dynamic process where the failure mechanisms fundamentally differ from those under static loading conditions. The dynamic failure of rock mass blasting, characterized by high strain rates, dominance of strong stress waves, significant inertial effects, and unique zonal damage patterns with complex fracture modes, inevitably damages intact rock masses. This leads to degradation of physical-mechanical properties, reduced strength, compromised integrity, and ultimately threatens long-term stability. In such conditions, native joints and other structural surfaces alter stress wave propagation paths through reflection and refraction, inducing preferential crack propagation along these surfaces. High-frequency filtering dissipates energy, significantly enhancing the anisotropy of blasting-induced damage [39]. Only through comprehensive research on rock mechanics behavior and damage evolution under dynamic loading [40] can we better understand the essence of blasting failure. This knowledge enables the development of more realistic constitutive models and failure criteria for jointed rock masses [41-42], providing theoretical foundations for refined numerical simulations. Such advancements guide safer, more efficient, and cost-effective blasting design and construction control, achieving dual objectives: precise excavation contour formation and effective surrounding rock protection.

To investigate the blasting damage characteristics of jointed rock masses, Xie et al. [43] conducted numerical simulations using the RHT model implemented in ANSYS/LSDYNA to analyze how blast initiation points and joint distribution influence dynamic damage evolution. Under bottom initiation, explosive energy propagates concentratedly toward the borehole entrance, achieving fragmentation and ejection objectives. Upward shifting the initiation point improves stress distribution and damage patterns. Layered joints exacerbate damage on the impact surface while hindering stress wave propagation, resulting in asymmetric damage distribution. Xiao et al. [44] experimentally studied joint effects through a digital laser dynamic dissipation system, revealing that larger joint spacing reduces medium damage. However, at 60mm joint spacing, the joint's regulatory effect on crack propagation gradually diminishes. Joints accelerate damage between boreholes and joints while suppressing external medium destruction. As hole-joint spacing increases, reflected stress waves decay progressively, diminishing their influence on crack propagation velocity and dynamic stress intensity factor KId. Wang et al. [45] employed 3D printing and CT scanning to conduct blasting tests on joint-bearing rock mass models. Through 3D reconstruction analysis, they found that increased joint inclination leads to greater specimen damage and fractal dimension, while weakening the joint's crack propagation inhibition effect. Zhang et al. [46-47] investigated the effects of joint orientation and blasting distance on the evolution of blast-induced damage zones in jointed rock slopes using continuous medium numerical simulation, digital borehole imaging, and blasting vibration testing. Anti-collinearity joint slopes exhibited lower deformation and shear strain variations, while low-and high-angle joint slopes showed gradually decreasing critical strength reduction coefficients. Under pre-split blasting conditions, the development degree and width of internal fractures in rock masses progressively decreased with increasing blasting distance, showing no significant impact beyond 9 meters from the blasting point. Gao et al. [48] conducted numerical simulations to study damage and peak particle velocity (PPV) decay characteristics induced by double-hole blasting under different in-situ stress conditions. Results indicated that as ground stress increased, the damage range and main crack length in jointed rock masses were inversely proportional. The PPV values first increased then decreased with enhanced ground stress. Figure 3 presents damage cloud images of four types of jointed rock slopes under zero in-situ stress conditions, revealing distinct damage patterns across different joint angles. Joints played a significant guiding role in damage propagation. All rock masses with different joint angles exhibited damage ranges extending along the joint direction in opposite directions. Rock mass at the joint ends farther from the blasting hole was more susceptible to destruction due to blast shock waves. However, unlike the case of single-hole blasting, no obvious extension and development of wing cracks were observed at the end of joints in double-hole blasting. This may be because the shock waves released by the two blast holes superimposed on each other at the end region of the joint, and the stresses offset each other, resulting in reduced tangential tensile stress that is difficult to induce wing cracks.

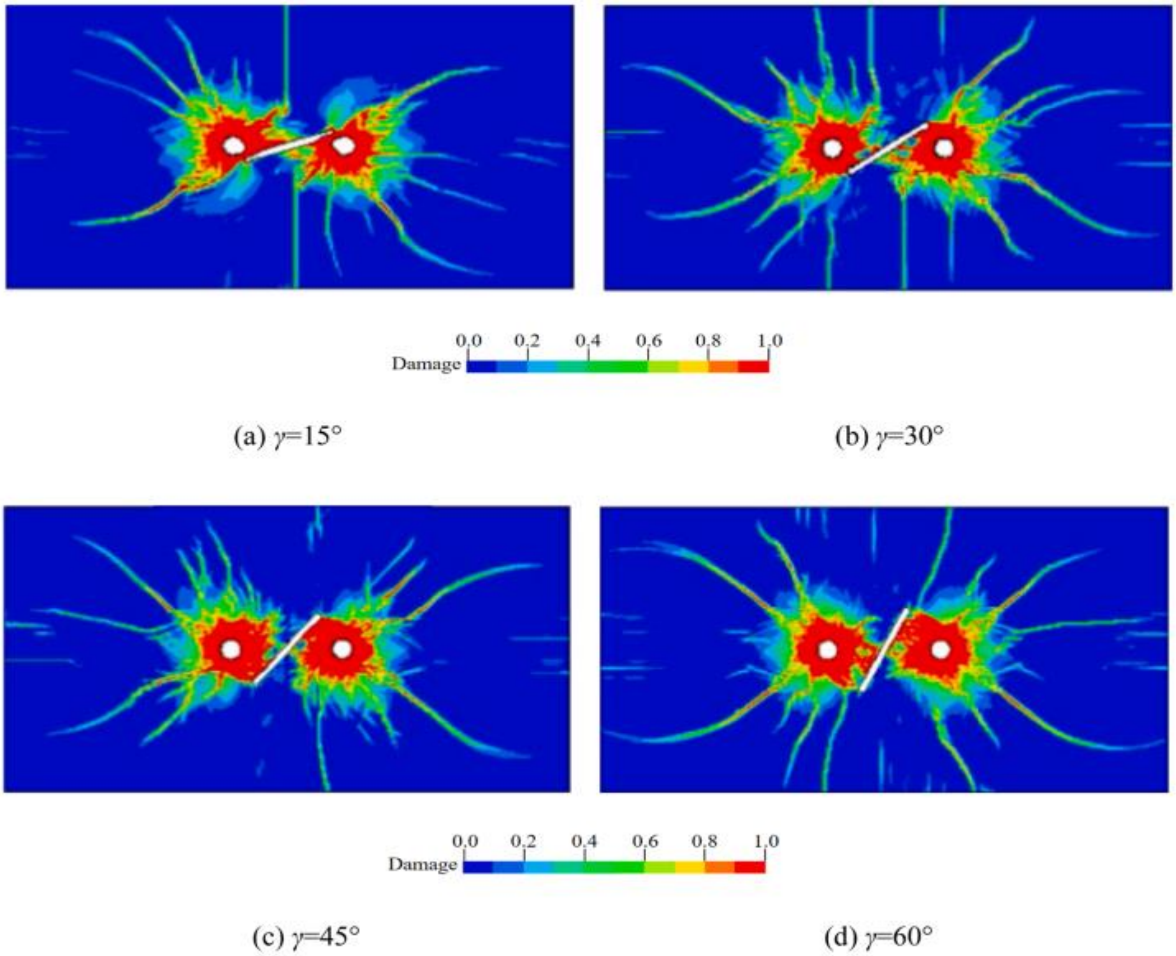

Figure 3: Damage of double-hole blasting in rock mass under the variation of joint dip Angle without ground stress. γ represents the joint dip Angle [48]

As demonstrated in the analysis, studying the effects of different joint parameters (joint width, dip angle, and spacing) on dynamic damage evolution of rock masses under blasting loads [49-50] is crucial for determining appropriate blasting parameters (e.g., maximum single-bolster quantity and single-cycle advance length) [51-53], selecting optimal excavation sequences, conducting lithological analysis, controlling rock mass disturbance caused by blasting loads [54], and implementing effective support measures [55]. Numerical simulation methods such as finite element method, discrete element method, and discontinuous deformation analysis (DDA) have been widely applied to simulate damage evolution processes in jointed rock masses under blasting loads. These simulations are validated and refined using field monitoring data (including acoustic testing and deformation monitoring) to achieve more accurate prediction and control of blasting-induced damage.

4. Look into the Distance

Based on the current research progress, blast stress waves undergo transmission, reflection, and attenuation at joints, which govern crack initiation and crack deflection at joint ends, resulting in anisotropic distribution of fracturing and damage. Geometric parameters of joints (such as dip angle, spacing, and length) control the evolution of main crack length, damage distribution areas, and propagation of blast vibrations, exhibiting strong "structural plane orientation". For multi-joint conditions where tunnel blasting contour lines are difficult to precisely shape, construction costs are high, over-excavation/under-excavation volumes in complex geological conditions are challenging to control, and joint information acquisition accuracy remains low, future research could focus on the following key breakthrough directions:

4.1 Multi-physical Field Coupling Mechanism

Develop and investigate a dynamic coupling model of "strain-induced fracture-crevice-blasting" to quantify how fractures influence stress wave attenuation and crack deflection in high-strain environments, thereby revealing the dynamic development patterns of deep rock mass blasting damage. By integrating non-local damage theory, phase-field methods, or fluid-structure interaction algorithms, we establish cross-scale numerical simulation models to better elucidate the dynamic adjustment mechanisms of fractures in rock mass blasting processes.

4.2 Intelligent Blasting Parameter Design and Optimization

By integrating machine learning with digital twin technology, we utilize field mapping data of joints (including trace line distribution, joint dip angle, and spacing statistics) to train an optimized blasting parameter model. This enables intelligent prediction of charge configuration, detonation timing and sequence, as well as damage extent. The approach drives the transformation of blasting design from empirical methods to digitalization, thereby enhancing tunnel blasting efficiency and quality while achieving precision in tunnel blasting engineering.

4.3 Deep Complex Environmental Adaptation Technology

China's tunnel construction is progressively advancing into the complex mountainous regions of western China. Researchers are developing directional blasting control technologies for jointed rock masses under high stress and high seepage flow conditions, including optimizing engineering compatibility between weakly constrained slurry pipes and phase-change fracturing devices. The project also explores real-time monitoring systems for blasting vibrations and surrounding rock damage, establishing a dynamic matching mechanism between damage evolution and post-construction support systems.

4.4 The Integration of Emerging Technologies

Develop three-dimensional characterization technologies such as CT-InSAR joint scanning and distributed optical fiber sensing for blast damage analysis. By 3D printing specific joint rock samples and integrating DIC with acoustic emission techniques, this approach deciphers the dynamic feedback mechanisms of fractures within specimens, providing experimental data to bolster theoretical models.

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