

Experimental Study on Dynamic Mechanical Properties of Layered Rock Under Cyclic Impact Loading

Wenxin Jia¹, Yian Ma², Chong Xu³, Jiaqi Guo¹

¹School of Civil Engineering, Henan Polytechnic University, Jiaozuo, Henan, China

²Xi'an-Chengdu Passenger Dedicated Line Shaanxi Co., Ltd., Xi'an, Shaanxi, China

³China Railway First Survey and Design Institute Group Co., Ltd., Xi'an, Shaanxi, China

Copyright: © 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Bedding planes impart pronounced anisotropic mechanical behavior to layered rock masses, and their deformation and failure modes are also governed by these planes. Consequently, tunnels excavated in layered rock masses are susceptible to asymmetric large deformations, collapses, and other disasters, directly threatening the safe construction of nationally significant projects. Currently, the drilling and blasting method remains the dominant construction technique for mountain tunnels, during which the layered surrounding rock is inevitably subjected to repeated blasting dynamic loads, substantially affecting its stability. In light of this, this study focuses on layered rock masses and employs a combination of laboratory experiments and theoretical analysis to investigate the effects of bedding plane angle, number of impacts, and impact load amplitude on the dynamic mechanical properties of layered rock masses. The principal findings are as follows: Split Hopkinson pressure bar (SHPB) cyclic impact tests reveal that the dynamic stress–strain curves of layered rock masses exhibit a distinct “rebound” phenomenon as the number of impacts increases, followed by a transition to a “semi-open” loop shape.

Keywords: Layered rock; Cyclic impact loading; Dynamic mechanical properties; Stress-strain curve; Dip angle

Online publication: Oct 16, 2026

1. Introduction

During tunnel excavation, layered rock masses, as the most common type of surrounding rock structure, are subjected not only to static loads such as in-situ stress but also to cyclic impact disturbances induced by blasting excavation. Owing to the presence of bedding planes, such rock masses exhibit pronounced anisotropy, and their mechanical behavior and failure modes are considerably more complex than those of homogeneous rock masses. Under cyclic impact loading, the interaction between bedding planes and stress waves can trigger abrupt changes in the dynamic mechanical properties of layered rock masses, easily leading to instability and failure of the surrounding rock. Therefore, investigating the dynamic mechanical

properties of layered rock masses with different bedding plane inclinations under cyclic impact loading holds significant theoretical importance and engineering value for ensuring the safety of underground projects.

In recent years, researchers worldwide have conducted extensive studies on the dynamic mechanical behavior of rocks. Advancements ranging from experimental technique development to the revelation of mechanical properties have laid a foundation for understanding the performance evolution of rock masses under complex loading conditions. Regarding dynamic testing methods for rocks, Li Xibing and Zhang et al. have provided systematic reviews of dynamic testing techniques and mechanical behavior of rocks ^[1,2]. Fan Chao et al. summarized the application achievements of the split Hopkinson pressure bar (SHPB) in testing the dynamic mechanical properties of rocks ^[3]. Ren Wenke et al. and Wang Jiangbo et al. investigated SHPB incident wave shaping techniques and similarity laws, respectively, providing a basis for improving test accuracy ^[4,5]. In terms of cyclic impact studies on homogeneous rocks, Jin Jiefang et al. conducted research on stress–strain curves and stress wave characteristics of rocks under cyclic impact, establishing a data acquisition and analysis framework for cyclic impact tests ^[6]. With respect to the dynamic mechanical properties of layered rock masses, scholars have carried out explorations targeting different bedding structures and loading conditions. Yang Renshu et al. prepared layered composite rock masses and performed SHPB dynamic compression tests, finding that differences in wave impedance lead to significantly different mechanical responses and failure patterns under different propagation directions ^[7]. Ma Qinyong et al. performed SHPB tests on deep roadway sandstone containing joints with varying inclinations, revealing the influence of joint inclination on the dynamic strength of sandstone rock masses ^[8]. Fan Zhao and Zhang Jing conducted impact tests on rock masses with different bedding plane inclinations and analyzed the anisotropic effects of bedding inclination on dynamic mechanical parameters ^[9,10]. Furthermore, Yin Zhiqiang et al. revealed the influence of static load on the dynamic mechanical properties and stress wave propagation in jointed coal-rock masses, while Zhang Xiaowu et al. systematically analyzed the anisotropy of mechanical properties and energy evolution in layered rocks ^[11,12]. For composite rock masses, Shang Hui studied the dynamic mechanical properties of concrete–sandstone composite specimens, revealing the influence of interface inclination on the dynamic strength of the composites ^[13]. Wu Jianyang and Wu Baolin investigated the mechanical properties of composite layered rocks and soft–hard interbedded rock masses under dynamic loading ^[14,15]. Wang Zhide et al. carried out impact tests on filled jointed rock masses and soft–hard interbedded rock masses, respectively, revealing the significant influence of joint inclination and soft–hard layer combination on the dynamic bearing capacity ^[16,17]. These studies have enriched the understanding of the dynamic mechanical behavior of complex layered structures.

Currently, research on the dynamic mechanical properties of layered rock masses mostly focuses on single-impact conditions, whereas studies on dynamic properties under cyclic impact are relatively scarce. Existing cyclic impact research primarily addresses homogeneous rocks. Although some scholars have conducted cyclic impact tests on layered slate with different bedding inclinations and identified stage characteristics of damage evolution, studies that comprehensively consider the influence of multiple factors, such as impact velocity and bedding inclination, on the dynamic mechanical behavior of layered rock masses remain very limited. Hence, conducting multi-level velocity cyclic impact tests on layered rock masses with different bedding inclinations to reveal their dynamic stress–strain response characteristics as well as strength and deformation evolution laws can not only enrich the theory of layered rock mass dynamics but also provide an important basis for the stability assessment and support design of layered surrounding rock engineering. In view of this, this study employs an electromagnetically driven split Hopkinson pressure bar (SHPB) apparatus to prepare layered rock mass specimens with four bedding plane inclinations (0°, 30°, 60°, and 90°) using rock-like materials such as cement, quartz sand, and gypsum. Constant-velocity cyclic impact tests are

conducted at impact velocities of 3, 3.35, 3.65, and 4 m/s. This research aims to reveal the dynamic mechanical properties of layered rock masses with different bedding inclinations under cyclic impact loading, with a view to providing a theoretical basis and technical support for optimizing blasting parameters and controlling surrounding rock stability in the drill-and-blast construction of tunnels in layered surrounding rock.

2. Cyclic impact tests on layered rock

2.1. Layered rock specimen

At present, many scholars commonly employ rock-like materials such as cement, gypsum, diatomite, and quartz sand to prepare rock-like specimens. The physical and mechanical properties of these materials (e.g., density, strength, elastic modulus, Poisson's ratio, and failure characteristics) are similar to those of natural rocks, while also offering good workability and controllability. In view of these advantages and the requirements of the intended experiments, the present tests, based on the research achievements of our university, use C42.5 ordinary Portland cement, 80–120 mesh quartz sand, gypsum, and tap water to fabricate layered rock mass specimens^[18]. The constituent materials are shown in **Figure 1**, and the mix proportion of cement, quartz sand, gypsum, and water is 1:0.6:0.1:0.5 by weight.



Figure 1. Materials for synthesis.

According to the standard suggested by the International Society for Rock Mechanics (ISRM), the drilled cores were cut and ground into cylindrical specimens with a diameter of 50 mm and a height of 50 mm, as shown in **Figure 2**^[10,19].

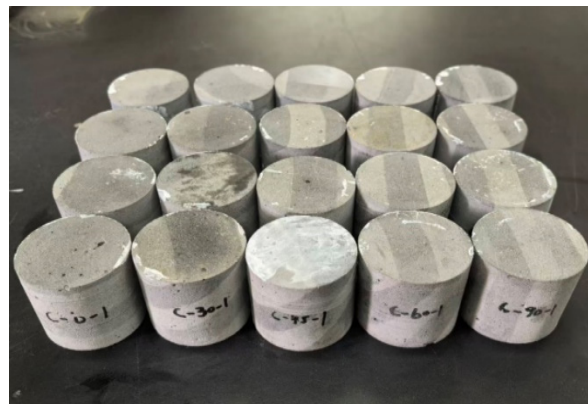


Figure 2. Layered rock mass specimen.

2.2. SHPB test apparatus

The cyclic impact tests on layered rock mass specimens with different bedding plane inclinations were

conducted using an electromagnetic-driven split Hopkinson pressure bar (SHPB) apparatus, developed independently by Henan Polytechnic University, in conjunction with acoustic monitoring equipment. The apparatus consists of three parts: a driving system, a loading system, and a data acquisition system. The driving system comprises a control cabinet and an electromagnetic coil. The loading bar system is composed of a striker bar (400 mm), an incident bar (2000 mm), a transmitted bar (1400 mm), and an absorber bar (400 mm). All bars are made of 40Cr alloy steel with a diameter of 50 mm, an elastic modulus of 210 GPa, a density of 7.93 g/cm³, and a longitudinal wave velocity of 5190 m/s. The data acquisition system includes strain gauges, a dynamic strain meter, and an optical velocimeter. Additionally, a high-speed camera (resolution 1920 × 1980, frame rate 22000 fps, exposure time 3 μs) and an LED fill light were positioned beside the specimen to record the entire deformation process. During testing, the layered rock mass specimen was placed between the incident bar and the transmitted bar, with a thin layer of petroleum jelly applied to the end faces to minimize friction^[8]. The electromagnetic coil drives the striker bar to impact the incident bar, and the amplitude of the generated incident wave is controlled by the striker velocity. Due to the wave impedance mismatch at the bar–specimen interfaces, reflected and transmitted waves are formed and recorded by the strain gauges mounted on the respective bars, then acquired in real time by the dynamic strain meter. To suppress wave oscillation and facilitate constant strain rate loading, a 1-mm-thick annealed copper disk was used as a pulse shaper, which absorbs energy through plastic deformation and reduces the peak slope of the stress wave^[4,5]. See **Figure 3**.

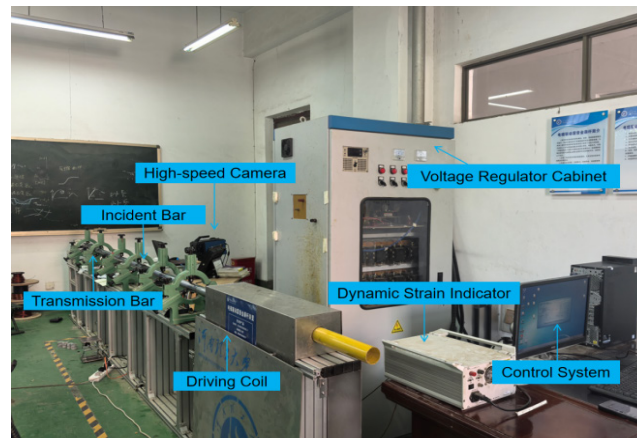


Figure 3. SHPB experimental apparatus.

2.3. Experimental scheme

To investigate the mechanical properties and damage evolution of layered rock masses subjected to cyclic disturbance by stress waves, cyclic impact dynamic tests were carried out on layered rock mass specimens using the electromagnetic-driven SHPB apparatus. In this test, four impact velocities were preset, ranging from low to high as 3 m/s, 3.35 m/s, 3.65 m/s, and 4 m/s. Constant-amplitude cyclic impact tests were performed on layered rock mass specimens with four different bedding plane inclinations (0°, 30°, 60°, and 90°). At a given impact velocity, the test for a group was terminated once the specimen underwent complete failure. The specific impact scheme is presented in **Table 1**. For each impact velocity, three parallel specimens were tested, and the final results were taken as the average to ensure data stability. Furthermore, to ensure that the peak intensity of the incident wave remained identical during each cyclic impact, the charging voltage of the control cabinet and the position of the striker bar within the driving coil were kept constant at a given velocity. In addition, during each cyclic impact test, a high-speed camera was used to record the crack initiation, propagation, and coalescence processes on the surface of the layered rock mass specimen, as well as to capture its final failure pattern.

Table 1. Experimental scheme for cyclic impact tests on layered rock mass

Loading mode	Specimen number	Impact velocity
Cyclic impact	C- β -1	3.00m/s
	C- β -2	3.35m/s
	C- β -3	3.65m/s
	C- β -4	4.00m/s

3. Analysis of testing results

3.1. Dynamic stress equilibrium

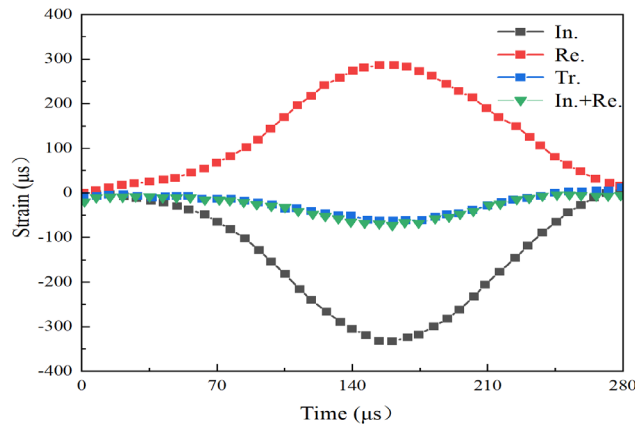
The SHPB impact test procedure is based on two fundamental assumptions. First, during the test, the striker bar is driven by electromagnetic force to impact the incident bar, and the resulting stress waves propagate in both the incident bar and the transmitted bar as one-dimensional elastic stress waves, with the bars maintained in a one-dimensional stress state. Second, after the stress wave undergoes several round-trip reflections between the two end faces of the specimen, the stress distribution across any cross-section of the specimen and the loads at both ends of the specimen reach a dynamic equilibrium, thereby placing the specimen in an approximately uniform one-dimensional stress state^[20]. Based on these assumptions, the stress, strain, and strain rate of the specimen can be calculated using the following formulas:

$$\sigma(t) = \frac{E_c A_c}{2A_s} (\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)) \quad (1)$$

$$\varepsilon(t) = \frac{c_e}{L_s} \int_0^t [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)] dt \quad (2)$$

$$\dot{\varepsilon} = \frac{c_e}{L_s} [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)] \quad (3)$$

where E_c denotes the elastic modulus of the bars, A_c and A_s denote the cross-sectional areas of the bars and the specimen, respectively, c_e denotes the longitudinal wave speed of the one-dimensional stress wave in the bars, L_s denotes the specimen length, and $\varepsilon_I(t)$, $\varepsilon_R(t)$, and $\varepsilon_T(t)$ denote the strain signals corresponding to the incident, reflected, and transmitted waves, respectively. See **Figure 5**.

**Figure 5.** Dynamic stress equilibrium curve.

Taking the dynamic stress equilibrium of the layered rock mass specimen at an impact velocity of 4 m/s as an example, as shown in **Figure 5**, it can be observed that the superimposed curve of the incident and reflected waves agrees well with the transmitted wave curve, indicating that the dynamic stresses at both ends of the specimen are nearly identical during the impact process and simultaneously demonstrating the accuracy of the test results obtained in this study.

3.2. Dynamic mechanical properties

The stress–strain curves of rock mass specimens with different bedding plane inclinations (0° , 30° , 60° , and 90°) under cyclic impact at different velocities of 3 m/s, 3.35 m/s, 3.65 m/s, and 4 m/s are presented in **Figures 6** and **7**. As can be seen from **Figures 6**, **7**, **8**, and **9**, the dynamic mechanical properties of the layered rock mass specimens exhibit a significant correlation with both the cyclic impact velocity and the bedding plane inclination angle.

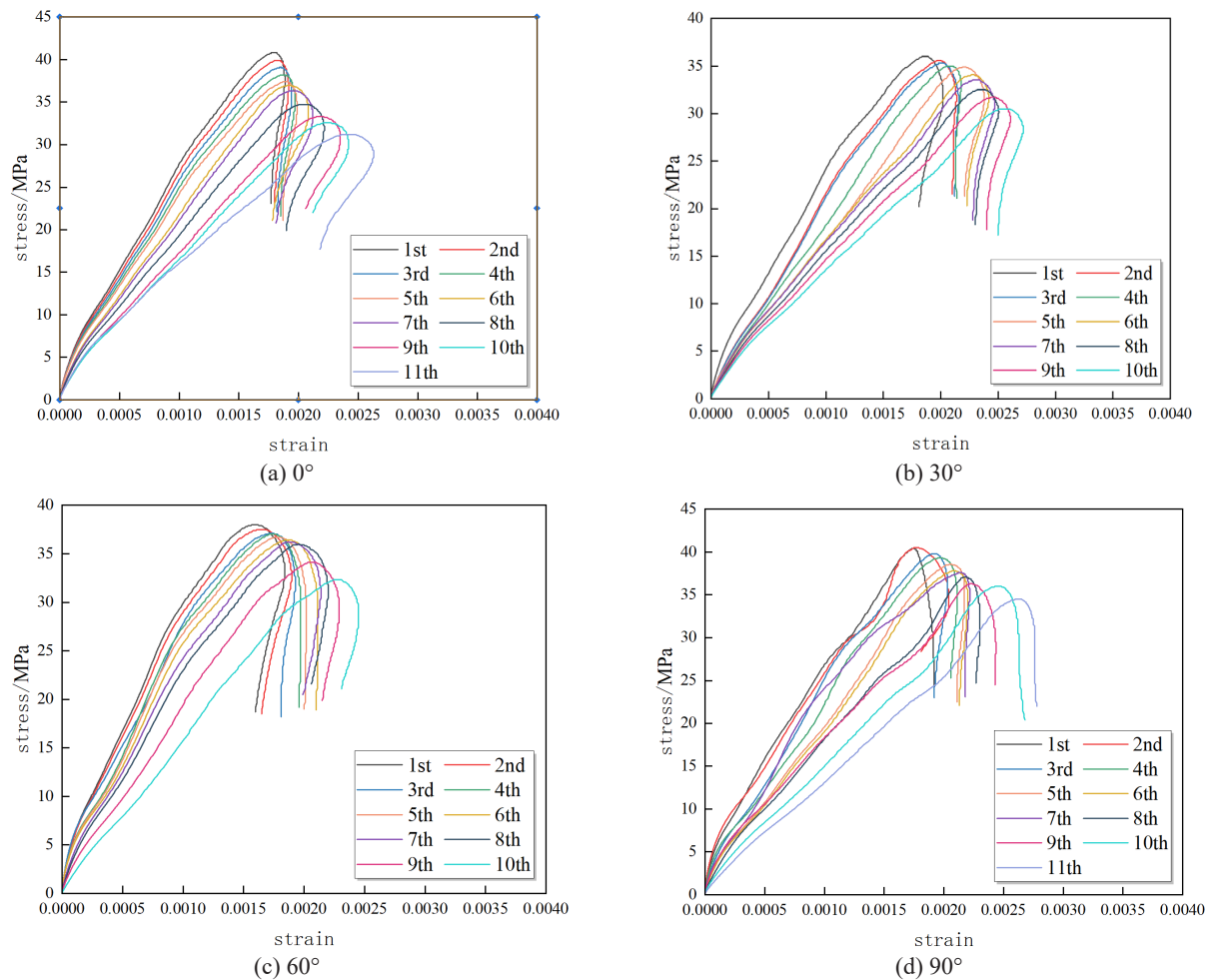


Figure 6. Stress-strain curve of layered rock mass at an impact velocity of 3 m/s.

At an impact velocity of 3 m/s, the layered rock mass specimens with different bedding plane inclinations sustained the greatest number of impacts, and their peak stress and peak strain exhibited no significant changes during the early stage of cyclic loading. This indicates that under low-velocity impact loading, the damage induced

within the rock specimen is relatively minor. The reason is that under this stress wave loading condition, the specimen remains in the linear response stage and has not yet reached its damage threshold.

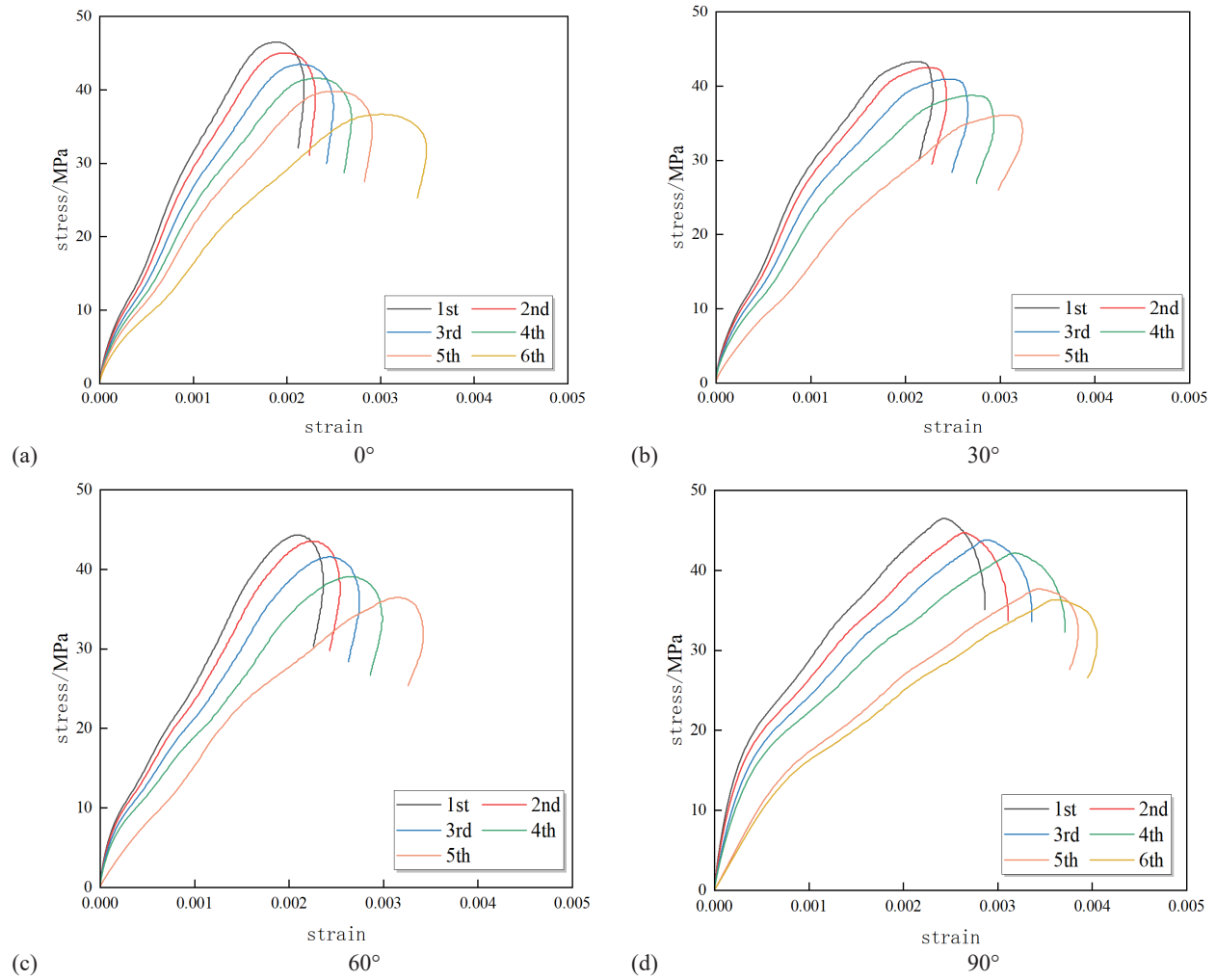
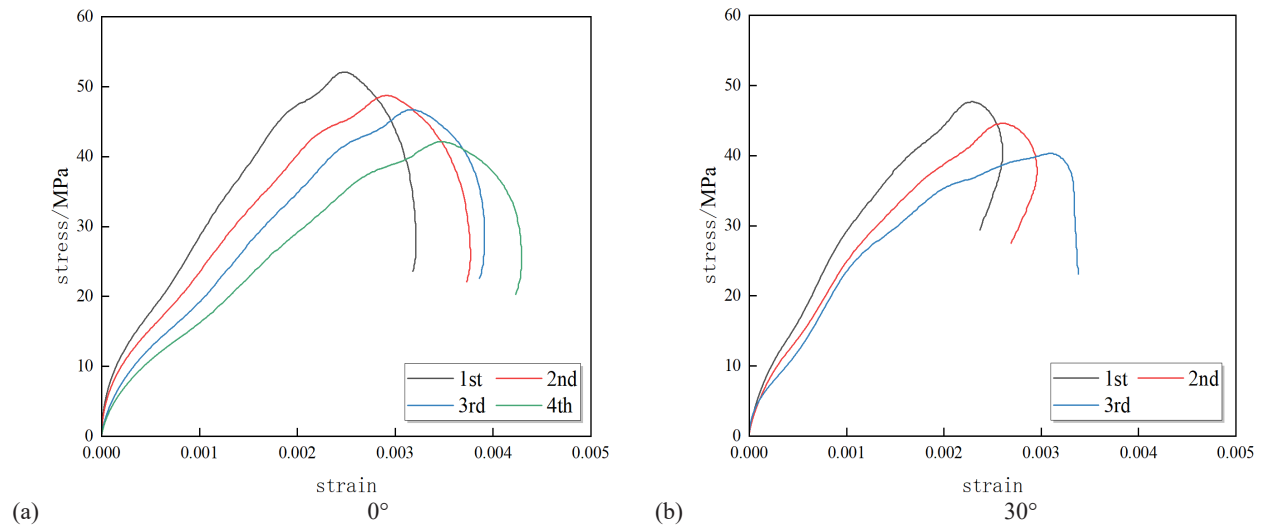


Figure 7. Stress-strain curve of layered rock mass at an impact velocity of 3.35 m/s.



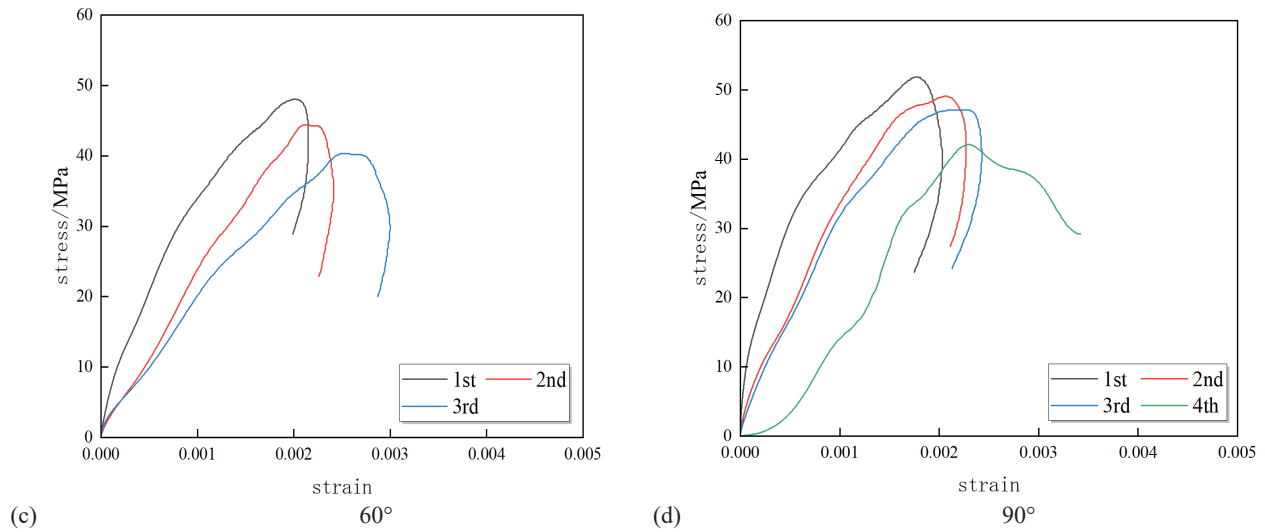
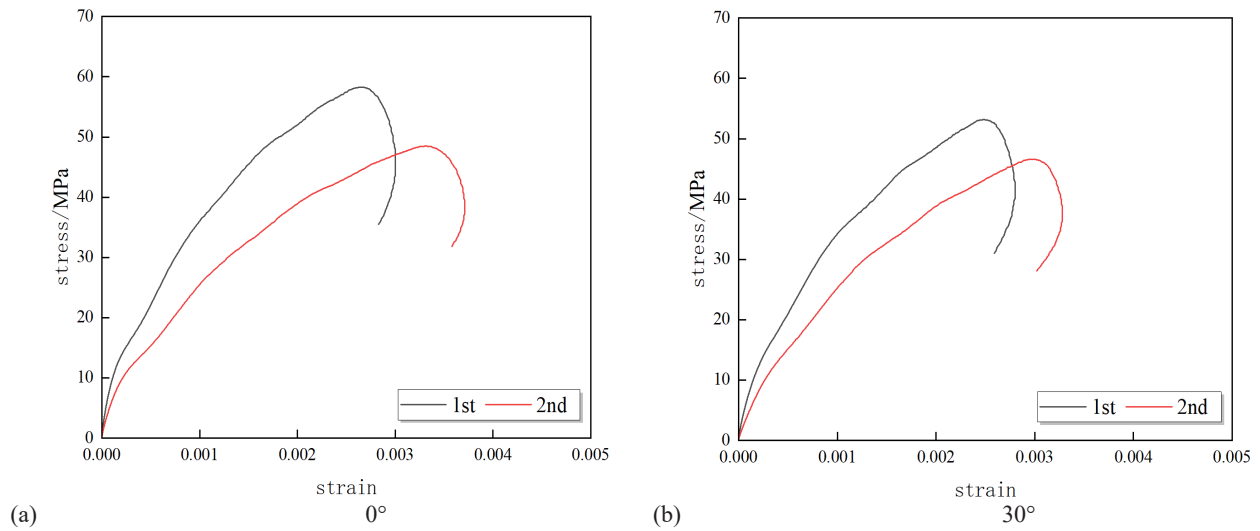


Figure 8. Stress-strain curve of layered rock mass at an impact velocity of 3.65 m/s.

As the impact velocity increases, the number of impacts required to cause failure of the layered rock mass specimens gradually decreases; at an impact velocity of 4 m/s, the number of cyclic impacts sustained by the rock specimens drops to two. This indicates that under high-velocity impact loading, the resistance of the layered rock mass specimens to external loading decreases substantially, demonstrating the mechanical characteristic whereby the specimens undergo continuously increasing deformation and progressive strength deterioration under cyclic impact loading.



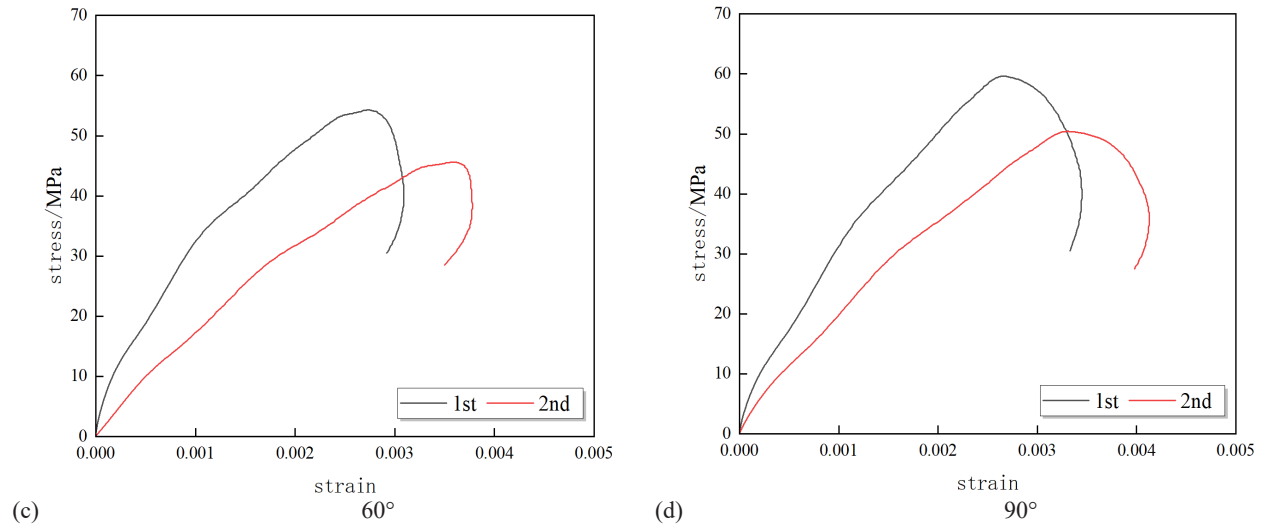


Figure 9. Stress-strain curve of layered rock mass at an impact velocity of 4 m/s.

From the perspective of the same cyclic impact velocity, the stress–strain curves of layered rock mass specimens with different bedding plane inclinations exhibit similar characteristics. In the early stage of cyclic impact, the stress–strain curves display a distinct “rebound” phenomenon. As the number of impacts increases, the peak stress gradually decreases, the peak strain gradually increases, and the stress–strain curves show a tendency to shift progressively to the right; concurrently, the rebound behavior disappears, and the curves transition to a “semi-open” type.

Comparing specimens with different bedding plane inclinations under the same cyclic impact velocity reveals clear differences in the dynamic mechanical properties. Specimens with inclinations of 0° and 90° require the greatest number of impacts to reach failure, whereas those at 30° and 60° require the fewest. Correspondingly, in terms of peak stress, the 0° and 90° specimens possess the highest dynamic stress strength, while the dynamic mechanical strength of the 30° and 60° specimens is relatively lower. The primary reason is that inclined bedding planes disperse the concentration of the stress wave, causing energy attenuation and reducing the effective stress within the layered rock mass specimen. Moreover, at the endpoints or irregularities of the bedding planes, dynamic stress concentration is prominent; intermediate inclination angles facilitate the coalescence of stress concentration effects within the specimen, thereby inducing macroscopic fracture. It is worth noting that when conducting blasting excavation in tunnels within rock masses exhibiting bedding plane inclinations of 30° – 60° , the intensity of blasting vibration should be controlled and the layout of blasting holes optimized to prevent excessive propagation of stress waves along the bedding planes.

4. Conclusions

Under cyclic impacts, the dynamic mechanical properties of layered rock are jointly governed by impact velocity and bedding angle, exhibiting a significant synergistic control effect of rate and structure.

- (1) Impact velocity determines the rate of damage accumulation and the failure process. At low velocities, the specimen sustains minimal damage, and the stress–strain curve exhibits a “rebound” phenomenon in the early stage while remaining in the linear phase. As the velocity increases, the number of impacts

required for failure drops sharply, and the curve gradually shifts to the right, transitioning to a “half-open” shape, reflecting intensified deformation and continuous strength deterioration.

- (2) Bedding angle controls the strength and failure mode of the rock mass. Specimens with 0° and 90° bedding angles exhibit high strength and require more impacts to fail. In contrast, specimens with 30° and 60° bedding angles show lower strength and fail more quickly, because the inclined bedding planes tend to induce stress concentration and form through-going fractures, leading to energy attenuation and reduced effective stress.
- (3) The combination of high impact velocity and moderate bedding angles is the most destructive. At bedding angles of 30–60°, the stress wave concentration effect is prominent, and the load-bearing capacity of the specimen decreases significantly. During tunnel blasting excavation under such conditions, special attention should be paid to controlling vibration intensity and optimizing blast-hole layout to prevent excessive propagation of stress waves along the bedding planes.

Funding

Key Project of the Key Project of the Science and Technology Research and Development Program of China State Railway Group Co., Ltd. (Project No.: N2024G049)

Disclosure statement

The author declares no conflict of interest.

References

- [1] Li X, Gu D, Lai H, 1993, On the Reasonable Loading Stress Waveforms Determined by Dynamic Stress-Strain Curves of Rocks by SHPB. *Explosion and Shock Waves*, 1993(2): 125–130.
- [2] Zhang B, Zhao J, 2014, A Review of Dynamic Experimental Techniques and Mechanical Behaviour of Rock Materials. *Rock Mechanics and Rock Engineering*, 47(4): 1411–1478.
- [3] Fan C, Yu K, Meng Q, et al., 2018, Stability Evaluation of Weak Slopes Under Heavy Precipitation. *Soil Engineering and Foundation*, 32(5): 552–558.
- [4] Ren W, Li W, Wang J, et al., 2021, Quantitative Study on Influence of Pulse Shaper on Split Hopkinson Pressure Bar (SHPB) Incident Waveform. *Transactions of Beijing Institute of Technology*, 41(9): 901–910.
- [5] Wang J, Li W, Ren W, et al., 2022, Experimental and Numerical Study on the Incident Pulse Similarity Law and Pulse Shaping Technique in SHPB Test. *Journal of Vibration and Shock*, 41(6): 169–176 + 221.
- [6] Jin J, Li X, Chang J, et al., 2013, Stress-Strain Curve and Stress Wave Characteristics of Rock Subjected to Cyclic Impact Loadings. *Explosion and Shock Waves*, 33(6): 613–619.
- [7] Yang R, Li W, Fang S, et al., 2019, Experimental Study on Impact Dynamic Characteristics of Layered Composite Rocks. *Chinese Journal of Rock Mechanics and Engineering*, 38(9): 1747–1757.
- [8] Ma Q, Su Q, Ma D, et al., 2020, SHPB Experimental Study on Dynamic Characteristics and Failure Behaviors of Sandstone Containing Weakly Filled Joints With Various Angles in Deep Roadways. *Chinese Journal of Rock Mechanics and Engineering*, 39(6): 1104–1116.
- [9] Fan Z, 2021, Experimental Study on Dynamic Mechanical Properties of Layered Purple Sand Rock Under Uniaxial Impact, thesis, Xiangtan University.

- [10] Zhang J, 2024, Mechanical Properties and Crack Propagation Characteristics of Layered Rock Mass Subjected to Coupled Static-Dynamic Compression, thesis, Shijiazhuang Tiedao University.
- [11] Yin Z, Wang J, Zhang Z, et al., 2022, Influence of Static Load on Dynamic Mechanical Properties and Stress Wave Propagation of Jointed Coal Rock Masses. *Chinese Journal of Rock Mechanics and Engineering*, 41(S2): 3152–3162.
- [12] Zhang X, Xu J, Liu Z, et al., 2023, On Mechanical Properties and Energy Evolution Anisotropy of Layered Rocks. *Journal of Hunan University of Science and Technology (Natural Science Edition)*, 38(2): 1–9.
- [13] Shang H, 2025, Research on the Dynamic Mechanical Characteristics of Concrete-Sandstone Variable-Angle Composites Under Impact Loading, thesis, Anhui University of Science and Technology.
- [14] Wu J, 2024, Study on Mechanical Properties and Failure Mechanism of Composite Layered Rock Under Dynamic Load, thesis, Anhui University of Science and Technology.
- [15] Wu B, 2023, Experimental Study on Mechanical Properties of Soft and Hard Composite Rock Mass Under Impact Load, thesis, Xi'an University of Science and Technology.
- [16] Wang Z, Zhou Q, Qian M, et al., 2026, Dynamic Characteristics of Hard-Soft Interbedded Rock Mass Under Impact Loading. *Blasting*, 1–20.
- [17] Wang Z, Xing Y, Wu Y, et al., 2026, Research on the Mechanism of Impact Failure of Rock Mass With Different Inclination Filling Joints. *Journal of Wuhan University of Technology*, 48(1): 58–65.
- [18] Wang Z, Guo J, Gao F, et al., 2024, Acoustic Emission Characteristics and Crack Types Evolution of Soft and Hard Interbedded Rock-Like Specimens Under Uniaxial Compression. *Chinese Journal of High Pressure Physics*, 38(6): 37–51.
- [19] Shi Y, Guo Y, Feng G, et al., 2025, Effect of Different Rock Strength on the Uniaxial Compression Bearing Characteristics of Rock-Backfill Body-Rock Combination. *Chinese Journal of Rock Mechanics and Engineering*, 44(5): 1326–1339.
- [20] Wang S, Cheng C, Gong J, et al., 2025, Dynamic Mechanical Properties of Magnesium Oxychloride-Based Titanium Gypsum Concrete After High-Temperature Exposure. *Construction and Building Materials*, 472: 140841.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.