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Practice and Analysis of Rock Blasting Model Experiments in Blasting Engineering Education

Li Chengjie[1,a,*], Xu Ying[1,b], Cheng Bing[2,c], Xie Shoudong[1,d]

[1]*School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan, China*
[2]*School of Chemical and Blasting Engineering, Anhui University of Science and Technology, Huainan, China*
[a]*austlcj@163.com,* [b]*651832861@qq.com,* [c]*2022053@aust.edu.cn,* [d]*284079750@qq.com*
[*]*Corresponding author*

Abstract: *Traditional blasting engineering courses are limited by abstract theoretical concepts and limited experimental training. In order to address these challenges, this study developed a quasi-plane strain blasting experimental teaching system under confining pressure loading. We independently developed an integrated experimental device for cylindrical charge blasting. The device combines lateral constraint, high-speed photography, and ultra-dynamic strain testing; additionally, we combined digital image correlation full-field strain analysis with dynamic strain gauge point measurements. This methodology enables the visualized observation of blast-induced crack propagation and comprehensive data analysis of strain wave propagation patterns. Teaching practice demonstrated that the developed system, which employs a "teacher demonstration–student practice" hierarchical teaching model, enabled students to visually grasp blasting damage zone characteristics and stress wave attenuation laws. Thus, the system significantly enhances theoretical understanding and scientific research innovation capabilities; it provides a replicable practical paradigm to address the challenges of high safety risks and operational complexity in traditional blasting experiments.*

Keywords: *Blasting Engineering; Experimental Teaching Reform; DIC Technology; Dynamic Strain Measurement; Crack Propagation Mechanism*

1. Introduction

The drilling and blasting method is a standard technique in modern engineering such as tunnel excavation, open-pit mining, and roadbed formation. The method is widely used because of its technical maturity and robustness to various engineering scenarios [1,2]. Consequently, Blasting Engineering has been a fundamental course in higher education curricula for civil, mining, and safety engineering programs [3]. Experimental instruction, which is a critical platform for investigating rock blasting dynamics under dynamic loads, enhances students' comprehension of explosive stress wave propagation and fracture mechanisms. Experimental instruction also helps students cultivate practical engineering skills alongside scientific research literacy [4]. Safe and efficient experimental teaching systems have become a pivotal focus in blasting education reform to address the pedagogical demands for understanding rock blasting damage mechanisms. Traditional blasting engineering education faces notable challenges: the inherent complexity of blasting theories involving stress wave propagation, and energy dissipation often leads to cognitive barrier and diminished learning motivation when relying solely on lecture-based instruction [5]. Furthermore, stringent regulations on explosive materials severely restrict conventional experimental training, thereby impeding the development of practical competencies.

To address these limitations, this study developed a columnar charge blasting experimental system that integrates confining pressure loading, high-speed photography, and ultra-dynamic strain measurement. A quasi-plane strain blasting experimental curriculum was designed to systematically investigate rock damage characteristics, strain wave propagation patterns, and crack evolution mechanisms under blasting loads. This pedagogical approach combines digital image correlation (DIC)-based full-field strain analysis with dynamic strain gauge measurements, enabling multi-dimensional data acquisition and cross-validation. Teaching practice demonstrated that the observation of crack propagation visualization and the analysis of strain–time history curve significantly improved students' understanding of damage zoning characteristics and stress wave attenuation patterns. The hierarchical

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"demonstration–practice" teaching model effectively cultivates the capabilities of scientific research innovation and team collaboration awareness, providing a replicable practical paradigm for nurturing innovative talents in blasting engineering.

2. Cylindrical Charge Blasting Test System

2.1 System Components

The rock blasting experimental teaching course employs a self-developed blasting loading system from the Impact Dynamics Laboratory at Anhui University of Science and Technology. As illustrated in Figure 1, the system comprises three primary subsystems: a lateral loading system, a high-speed photography system, and an ultra-dynamic strain acquisition system. The lateral loading system contains hydraulic jacks, reaction frames, front/rear retaining plates, and hydraulic gauges. The high-speed photography system consists of a high-speed camera, auxiliary lighting, and dedicated image processing software. The ultra-dynamic strain acquisition system comprises strain gauges, bridge circuits, an ultra-dynamic strain amplifier, and digital oscilloscopes. This blasting loading system is operationally simple and reliably safe. It enables systematic investigation into dynamic response characteristics under columnar charge conditions with lateral confinement, effectively simulating blasting environments at various rock mass depths.

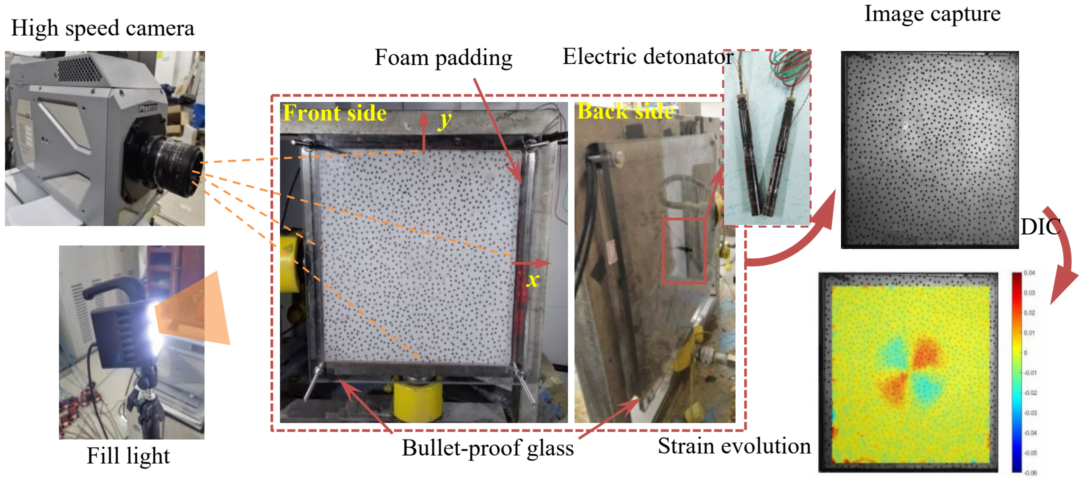

Figure 1: Experimental system of charge blasting loading.

2.2 Experimental Principle

The experimental system shown in Figure 1 was employed to apply different lateral pressures on plate-shaped rock specimens, simulating the stress states of rocks at various burial depths. Detonating cords or detonators were utilized as explosive sources to investigate the blasting-induced fracture characteristics of rock materials and the stress wave propagation behavior under cylindrical charge conditions. High-speed photography was used to capture the dynamic crack propagation process, and the attenuation law of strain waves was obtained from the evolution of surface strain fields. Subsequently, DIC technology was used to analyze the blasting process images acquired by the high-speed cameras, deriving variations in the surface strain field. Simultaneously, strain pulse signals were collected through strain gauges attached to the specimen surfaces. The following sections detail the testing principles of DIC and ultra-dynamic strain measurement.

2.2.1 Principle of DIC Technology

DIC is a non-contact optical measurement method that analyzes image deformation to measure surface displacement and strain on objects [6]. It uses cameras to capture digital images of specimens before and after deformation, recording speckle patterns on the specimens' surface. The pre- and post-deformation images are divided into sub-regions, and correlation algorithms are applied to identify the best-matching positions between corresponding sub-regions in the reference undeformed and target deformed images. Displacement vectors for each sub-region are the calculated based on the matching results, yielding a 2D or 3D displacement field across the specimen's surface. In this experiment, the

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target measurement area covered the full-field region of the specimen's surface.

2.2.2 Principle of Ultra-Dynamic Strain Measurement

The surface strain acquisition of the specimen consists of strain gauges attached to the surface, a bridge box, and the uT8916 distributed network synchronous acquisition system. In our test, a quarter-bridge wiring configuration was used for the bridge box, and a total of 10 channels were set up to measure axial deformation and radial strain at five locations. Based on the Wheatstone bridge principle, a single-arm working mode was adopted, and the specimen's strain $\varepsilon(t)$ can be expressed accordingly as follows [7]:

$$\varepsilon(t)=\frac{4\Delta U(t)}{K_1 K_2 U_0} \tag{1}$$

Where $\Delta U(t)$ is the output voltage, K_1 represents the sensitivity coefficient of the strain gauge, and K_2 denotes the amplification factor of the strain gauge amplifier.

3. Experimental Course Design

The experimental sessions are integrated into the total course hours to supplement theoretical instruction, aiming to deepen students' understanding of blasting theories. However, the number of experimental hours should not be excessive [8]. Because students typically lack foundational knowledge of rock explosion dynamics and are unfamiliar with experimental procedures, detailed planning of each experimental phase is essential to achieve pedagogical objectives, ensure safety, and optimize outcomes.

3.1 Pre-experiment Preparations

3.1.1 Specimen Preparation

Specimens were polished prior to the experiment to ensure surface integrity and homogeneity. The test employed relatively homogeneous sandstone with a density of 2 710 kg·m^{-3} and a Poisson ratio of 0.20. The plate specimen for blasting tests measured 300×300×50 mm, with flatness tolerance controlled within 0.05 mm for all surfaces. The speckle pattern on the observation surface (the front face) required extended preparation time and was prearranged, while the back face was affixed with resistance strain gauges. A 7 mm-diameter borehole, slightly larger than the detonator diameter, was drilled at the geometric center of the back face to a depth of 45 mm but not fully penetrated to prevent premature release of detonation products during filming.

3.1.2 Experimental Setup Preparation

Before the experiment began, the loading equipment, high-speed camera, and ultra-dynamic strain gauge were transported to the test site for pre-assembly. A 1 g electric detonator served as the explosive source, with passive confinement applied to the specimen. Foam material was inserted between the specimen's lateral surfaces and padding blocks to mitigate stress wave reflection and tensile effects. Front and rear bulletproof glass plates provided confinement to ensure explosive forces primarily acted along the borehole's radial direction, while simultaneously enhancing the blasting test safety and filming convenience.

3.2 Experimental teaching content

3.2.1 On-site Introduction to Blasting Experimental System

During the experiment, the instructor used physical demonstrations to introduce the composition of the loading system, high-speed imaging system configuration, DIC technique principles, and strain measurement methodology to students. Prior to the blasting tests, video and images were used to explain DIC principles and demonstrate speckle pattern fabrication. The following critical points were emphasized to ensure successful acquisition of surface strain field evolution, crack propagation data, and compliance with cylindrical charge blasting conditions:

(1) Specimen dimensions for blasting model tests typically have limitations. Hence, lateral constraints were implemented with foam panels inserted to mitigate reflected wave effects, thereby satisfying the cylindrical charge conditions in an infinite rock mass. Additionally, because the rock mass stress is

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considered a plane stress problem, deformation along the borehole axis must be restricted. This was achieved by applying constraints through front and rear retaining plates to limit specimen deformation along the borehole axis during blasting.

(2) Speckle pattern density distribution is a critical prerequisite for reliable strain field processing. Insufficient density may induce elevated mismatch rates in displacement calculations, potentially obscuring localized small-scale deformations or high-strain gradients that could distort true strain distributions. Additionally, selecting the right frame rate for the high-speed camera is crucial for strain field analysis: the image acquisition requires a sufficiently high definition within the complete blasting deformation timeframe to ensure that the strain evolution data obtained are temporally continuous and spatially resolved.

(3) Given the inherent stochasticity of blasting test results, strain gauge measurements were employed as supplementary validation for the DIC-derived strain fields. Students were assigned comparative analysis tasks to investigate discrepancies and correlations between DIC and ultra-dynamic strain measurement methodologies through a literature review. Subsequent classroom discussions were then scheduled for knowledge consolidation.

3.2.2 Charge Detonation Process Demonstration

After helping students comprehend the relevant knowledge points, a charge blasting demonstration commenced. The experiment was conducted at the Anhui University of Science and Technology Explosion Testing Site. For the purposes of experimental safety and teaching effectiveness, teachers informed visiting students about safety requirements in advance. The specific experimental procedures are as follows:

(1) Strain system connection. Check the attachment of strain gauges, connect them to the bridge box, and link the system to a dynamic strain meter and oscilloscope. The instructor first demonstrates wiring for one strain gauge; then, students perform the remaining connections to develop practical skills. The instructor corrects operational errors and explains potential impacts of improper handling.

(2) Camera configuration. Position the high-speed camera at a specified distance from the specimen, aligning the lens perpendicularly to the specimen surface. Set camera parameters, configure the automatic acquisition mode, determine the frame rate, and position fill lights. This step is performed by the instructor with real-time explanations.

(3) Explosive source preparation. Use display boards to explain the structure and initiation principles of electronic detonators. The instructor inserts and secures the detonator into the specimen’s rear side, connecting it to the blasting machine.

(4) Detonation. Evacuate students to a safe observation zone. Verify the readiness of all measurement systems before initiating detonation.

(5) Data preservation. Post-detonation, save recorded data from the high-speed camera and oscilloscope. Properly archive files, disassemble equipment, and return detonators to storage.

3.2.3 Experimental Results Presentation

The high-speed camera’s playback function was utilized to preliminarily demonstrate the crack propagation and fragmentation processes in the specimen to students. Strain–time history curves acquired through oscilloscopic measurements were used to illustrate the propagation and attenuation characteristics of explosive-induced strain waves. Detailed experimental results are elaborated in subsequent theoretical sessions.

(1) Crack propagation process

As shown in Figure 2, approximately 20 μs after detonator initiation, a minor bulge formation was initially observed at the specimen’s center, followed by the emergence of fine cracks. These cracks exhibited progressive elongation and width expansion. Macroscopic crack patterns became established at around 200 μs, with crack lengths remaining essentially constant between 200 and 300 μs while widths gradually increased until stabilization, ultimately forming distinct radial cracks.

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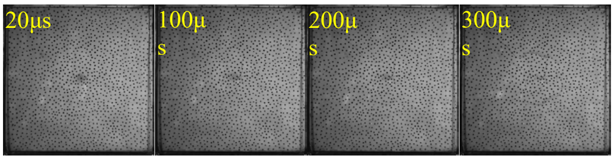
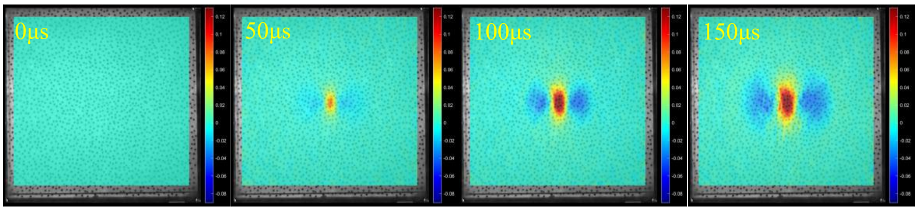


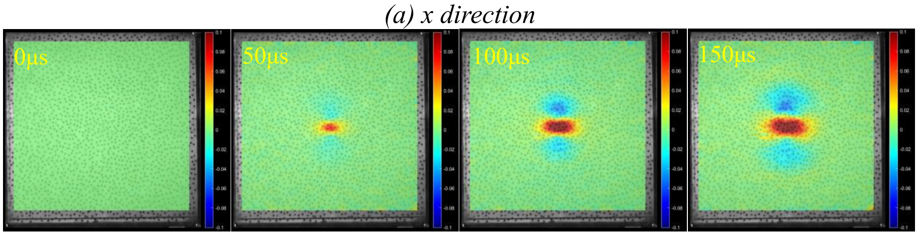
Figure 2: Expanding crack propagation process.

(2) Strain field characteristics

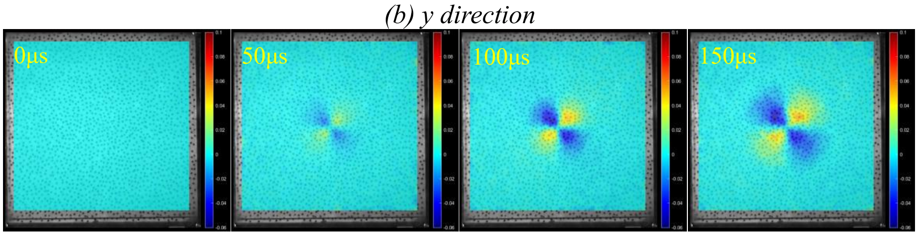
Figure 3 presents a strain contour map along the *x*-axis (horizontal), *y*-axis (vertical), and *xy*-directions (±45° and ±135°) during blasting, with sequential frames captured at 50 μs intervals. The analysis reveals that radial strains in all monitored directions exhibited approximately symmetric distributions centered at the borehole, with comparable strain magnitudes. As observed in the figure, the radial strains in the x-direction, y-direction, and xy-direction of the specimen exhibit approximately symmetric distributions centered at the blast hole. Meanwhile, strain amplitudes in different directions show comparable magnitudes with negative values, indicating that specimen deformation propagates radially from the blast hole center in compressive strain form at equivalent velocities. This result demonstrates that the blasting strain wave propagates approximately as a cylindrical wave. The central region of the specimen displays larger deformation characterized by tensile strain, which results from the concentrated energy effect of detonator explosion that induces outward ejection tendencies in the central medium. However, the development of tensile deformation is constrained by the presence of front and rear bulletproof glass panels.



(a) x direction



(b) y direction



(c) xy direction

Figure 3: Contour map of blast-induced strain field evolution in specimens.

Since the explosive strain wave propagates approximately in the form of a cylindrical wave around the borehole, the data along the horizontal symmetry axis O*x* of the specimen are selected for study. According to the characteristics of the strain–time history curve, the OC segment is divided into three sections: OA, AB, and BC, corresponding to rock deformation regions Ω_1, Ω_2, and Ω_3, respectively. These regions are referred to as the influence zone of the energy-gathering structure, radial compression zone, and reflected tensile disturbance zone, as shown in Figure 4(a). Compared to the Ω_1 and Ω_3 regions, the Ω_2 region represents the wave action zone of the strictly defined radial compressive stress. Additionally, the experimental results demonstrate that the strain–time history curves obtained from strain gauge measurements exhibit consistent trends with DIC test results. Therefore, subsequent analysis will focus solely on DIC data within the Ω_2 region.

Overall, the radial strain of the specimen initially increases rapidly with time, reaches a peak value, and then gradually decreases, ultimately resulting in irreversible deformation in the radial direction, as shown in Figures 4(b) and 4(c). As the distance increases, the peak compressive strain at various

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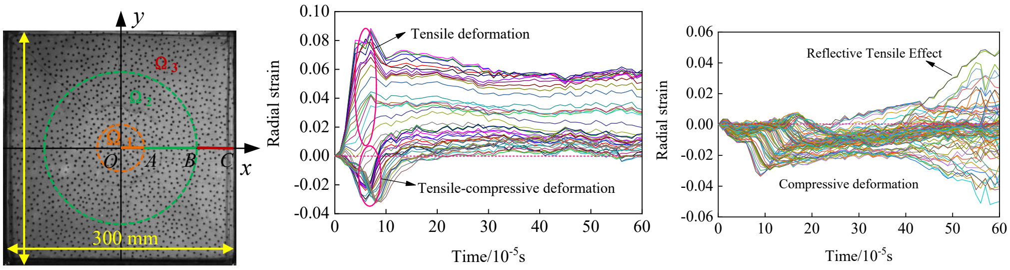
measurement points progressively diminishes. The strain rate at the descending edge of the curve gradually decreases, while the strain rates at the ascending edges remain relatively similar. The duration of the descending edge is shorter than that of the ascending edge. In reality, the descending edge of the strain–time curve corresponds to the rapid compressive work performed by stress waves. When the accumulated energy in the rock medium reaches a certain level, the compressive deformation begins to recover, which corresponds to the formation of the ascending edge.



(a) Blasting Deformation Zone Division (b) Strain–Time History Curve of OA Segment (c) Strain–Time History Curves of AB and BC Segments

Figure 4: Characteristics of the strain–time history curve around the blast hole in the specimen.

3.3 Experimental Discussion and Assessment

Given the relative complexity of this experimental procedure, which involved many steps pre-completed by instructors, a discussion and assessment session was established to reinforce students' in-depth understanding of the blasting experiment content. During the summary of experimental conclusions, students were presented with scientific questions regarding operational procedures and rock blasting fracture mechanisms. Examples include the following: Why were bulletproof glass constraints required on the front and back surfaces of the specimen, and what impacts would the absence of such constraints create? Can the attenuation process of blasting stress waves be deduced from the evolution of strain fields on the specimen surface during blasting? What is the post-blast fracture state of rock under cylindrical charge conditions, and how can one identify and define the blasting crushed zone, cracked zone, and elastic vibration zone? These questions require students to fully engage with the experimental course, integrate theoretical knowledge of blasting engineering, and conduct post-class literature research using academic databases. Additionally, to evaluate students' comprehension, experimental reports were submitted within one week after the experiment. Report contents included the following: principles of DIC and dynamic strain gauge measurements, cylindrical charge blasting experimental procedures, experimental data recording and result analysis.

3.4 Analysis of Experimental Teaching Effectiveness

In undergraduate blasting engineering education, the indoor cylindrical charge blasting experiment connects theory with practice, which is crucial. Its teaching effectiveness was significantly enhanced through a "teacher-led and student-involved" hierarchical instructional model. Addressing the safety risks and operational complexities inherent in traditional blasting experiments, this course adopts a progressive teaching design featuring "teacher demonstrations + student stepwise practice". Instructors demonstrate standardized procedures including specimen preparation, speckle pattern preparation, installation/debugging of high-speed cameras and strain measurement systems, as well as charge detonation. Students collaboratively participate in practical operations such as constraint device installation, strain gauge configuration, and data acquisition system debugging. Teaching practice showed that approximately 80% of students gained more intuitive understanding of rock blasting dynamic response characteristics through hands-on completion of specimen constraint and dynamic strain measurement system setup. This integrated approach of combining theoretical courses with indoor cylindrical charge blasting experiments effectively alleviated students' perception of theoretical learning monotony while substantially improving their practical skills in experimental design and research interest.

To further enhance undergraduates' early-stage research capabilities, the teaching team plans to incorporate numerical simulation technology, expanding instructional dimensions through data interaction between 3D blasting simulations and laboratory experiments. Current limitations such as equipment shortages and lengthy experimental cycles will be addressed through optimized group rotation mechanisms and pre-experiment video tutorials, ensuring continuous improvement in experimental teaching outcomes.

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4. Conclusions

This study aimed to deepen students' understanding of rock mass dynamic response mechanisms and blasting damage evolution characteristics. A quasi-plane strain blasting experiment under confining pressure loading conditions was designed. This course specifically addresses common student challenges such as insufficient theoretical knowledge of shock wave propagation and limited experience in dynamic testing technologies. By integrating high-speed photography with ultra-dynamic strain synchronous measurement techniques, the experiment systematically reveals stress wave propagation laws and damage-fracture characteristics in deep rock mass blasting. The experimental course resolves the technical bottleneck of reproducing infinite rock mass boundary effects in traditional teaching while establishing a data cross-validation model that combines DIC full-field strain measurement with point-based dynamic strain gauge monitoring. Teaching practice demonstrated that this course significantly enhances students' practical engineering skills and research literacy. Through high-speed image analysis of crack propagation processes, students can quantitatively describe the formation and extension of blast-induced cracks in rocks. The multi-stage characteristics of strain–time history curves further enable students to comprehensively grasp stress wave attenuation patterns. Additionally, open-ended discussions on confinement effects, strain field evolution, and fracture zoning during experimental debriefings effectively stimulate students' in-depth exploration of blasting mechanisms. Substantial improvements in scientific innovation awareness were achieved, successfully realizing the pedagogical objectives of blasting engineering courses.

Acknowledgements

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