Research Article

Experimental Investigations on Crack Propagation Characteristics of Granite Rectangle Plate with a Crack (GRPC) under Different Blast Loading Rates

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The experimental system of 3D digital image correlation (3D-DIC) is set up to eliminate a certain extent of out-of-plane motion for accurate measuring the full-field strain field during crack propagation, and the effect of blast loading rates of fracture behavior of granite rectangle plate with a crack (GRPC) is investigated. The experimental results indicated that the maximum values of the strain concentration zone do not fully represent the crack tip during the whole process of crack propagation. The axial strain threshold value tip (ASTVT) plotting with lines and coordinate contours corresponding with the actual crack at the shooting area can be used to describe the position of the crack. The axial strain 1.3% is more practical to obtain crack velocity and average crack velocity, and the average crack velocity decreases as the blast loading rates increase. Through observing the relationship between crack width and time, it can be found that there are three stages, and the crack width increases as the blast loading rates increase.

1. Introduction

Blasting is one of the main rock breaking methods that is widely used in rock excavation, and rock blasting fragmentation time is an important component of the delay time of differential blasting, which is related to the fracture velocity and fracture process of rock [1]. On the one hand, granites are a common rock type in the open bench blasting, and thermal shocks, frost action, and salt crystallization leading to cracking of granites are widely studied [2–5]; on the other hand, the fracture characteristics of granite under explosive dynamic loading are one of the core problems of rock dynamic mechanics, and then the research in this area has practical application significance [6]. Contemporarily, the research on the rock failure mechanism under explosive loading mainly focuses on the singularity of the crack tip, the variation law of stress and strain fields, and the crack propagation behavior [7]. For example, Zhu et al. [8] proposed a new method to test the dynamic fracture toughness

under explosive loading by utilizing a rectangular slab concrete specimen with mode-I crack; the crack tip initiation time was measured by using a strain gauge, and the pressure obtained from the two strain gauges near the hole was applied as the dynamic boundary condition by using the finite element method to calculate crack tip open displacements and crack tip dynamic intensity factors. Liu et al. [9] proposed a single internal crack circular disc (SICCD) specimen with poly methyl methacrylate/methacrylic acid (PMMA) to investigate the fracture toughness parameters and propagation behavior of mode-I crack under blasting load by using crack propagation gauges (CPGs); the crack propagation velocity, dynamic initiation toughness, propagation toughness, and fracture parameters of mode-I crack were obtained through the experimental-numerical method. Sun et al. [7] introduced symmetry experimental model with PMMA to implement the visualized positioning of the crack tip and obtained the more accurate record of full-field strain, and it is concluded that the maximum strain value point in

the main strain field cannot be used as the judgment basis of the crack tip. Wan et al. [10] used PMMA to customize a rectangle plate with a crack and edge notches (RPCENs) to study the fracture toughness of mode-I crack under blasting load, and they concluded that the crack propagation velocity is variable and related to the fracture surface roughness, the nucleation rate, and propagation toughness. Xu et al. [11] studied the effect of blast waves on the precrack with a cracked medium, and they found that the precrack underwent different developments under three kinds of stress waves. The obvious characteristic of these models is that the borehole is the loading boundary of the blast stress wave, and then a precrack extending to the borehole wall is used to investigate the crack propagation behavior.

In terms of experimental technique to measure the crack initiation and propagation process, there are strain gauge, CPGs, geometric grating method, moiré interference method, photoelastic method, electronic speckle interference method, and two-dimension digital image correlation (2D-DIC) method [12–16]. Ju et al. [17] summarized the measurement techniques used to determine the crack initiation and crack tip location. Zhang Zhao [18] demonstrated that the measurements of strain gauge and 2D-DIC are in good agreement and 2D-DIC is reliable, especially, 2D-DIC can continue to measure the strain on the sample surface after the failure of the strain gauge. By comparing with various test methods, 2D-DIC has the advantages of simple sample preparation, easy measurement system construction, and surface deformation field measurement. And 2D-DIC is a common successful experimental technique to determine the crack processes that occur to the surface of a rock specimen under dynamic loading. For instance, by combining 2D-DIC with the split-Hopkinson pressure bar (SHPB), the notched semicircular bend (NSCB) was selected to obtain the vertical strain field and the vertical displacement field around the tip of the prenotched crack; besides, Zhang and Zhao [19] deemed that a high-speed camera is reliable than traditional SHPB methods of obtaining the crack propagation results from the range of higher loading rates. Sutton et al. [20] published a review on dynamic NSCB-SHPB tests with the 2D-DIC method, and they summarized the calculation principle of 2D-DIC and introduced what reliable information about the fracture propagation process can be provided by 2D-DIC. However, 2D-DIC theoretically is restricted to planar surfaces, predominantly in-plane deformations, and cases where the recording camera can be set perpendicular to the object surface [20], i.e., out-of-plane motions affect the measurement of the object deformation. 3D-DIC can eliminate this factor; for example, Xing et al. [21] proved that the distribution of strain developed by 2D-DIC and 3D-DIC at the same position on the sandstone surface under dynamic compression shows a different pattern with the maximum strain error of 0.18%.

The three-dimensional digital image correlation (3D-DIC) method was put forward by Luo et al. [22], and the basic principle is to combine the principle of binocular stereovision with digital image correlation matching technology, restore the three-dimensional space coordinates of

the points before and after deformation, and then obtain the surface morphology and three-dimensional deformation information of the object [23]. Completing a test with 3D-DIC, a few pointers helping us to get the best results in the shortest period time is worth pointing out [24]: (1) the preferred surface texture should be nonperiodic; (2) a simple task lamp of 50–100 watts will give excellent light levels for many moderately sized specimens; (3) it should be aware of the orientation and potential camera placement, and then the next step will be to set focus; (4) it will also be necessary to adjust the brightness of the image as you make the image sharp through the focus adjustment; (5) selecting a grid that approximately fills the field of view, and calibration images will be useful as long as all three of the hollow marker dots are visible; and (6) setting appropriate subset and step is important for DIC to analysis, and then output the data. At present, 3D-DIC has also been used in measuring dynamic crack propagation. For example, Fan et al. [25] proposed that 3D-DIC is a practical and reliable method to determine crack initiation time and dynamic fracture toughness. Xu et al. [26] applied a linear-shaped jet to a cylindrical concrete mold, and full-field three-dimensional deformation characteristics of the splitting development of the specimen were analyzed by 3D-DIC.

From the existing research, the study of rock dynamic fracture response is focused on the fracture toughness parameters and propagation behavior of mode-I crack under the same blasting load. In this paper, a granite rectangular plate with a crack (GRPC) is introduced to investigate crack propagation behavior based on 3D-DIC under different blast loading rates.

2. Materials and Methods

2.1. Granite Materials. Experimental samples are Wulian Flower Granite (G3761; Wulian County, Rizhao City, Shandong province, China). Polarizing microscope tests (LEICA DM2500 p) are done in Yuneng geological service (Langfang, China) for obtaining the main minerals of granite, as shown in Figure 1, and the test parameter is 10×2.5 (eyepiece multiples $\times$ objective multiples). The main minerals of the rock are plagioclase (Pl; the main grain size is 2–5 mm, some grain size is 0.5–2 mm, and the content is about 25%), potassium feldspar (Kfs; the main grain size is 2–5 mm, and some grain size is 5–10 mm, and the content is about 45%), and quartz (Qtz; the main grain size is 2–5 mm, some grain size is 0.5–2 mm, and the content is about 20%), while the secondary minerals are biotite (Bt; the main grain size is 0.2–2 mm, and the content is about 7%) and amphibole (Hbl; the main grain size is 0.5–2 mm, and the content is about 2%). The auxiliary minerals are magnetite, zircon (Zrn), and apatite (Spn). The altered minerals are sericite, tetrahedrite, and chlorite. Based on the International Society for Rock Mechanics (ISRM) standards, parallelism and perpendicularity of two end planes are smaller than 0.2 mm, cylindrical specimens cut into 50×100 mm and 50×25 mm for uniaxial static compressive strength tests and static tensile strength tests are cored from the same rock block without obvious joint

FIGURE 1: Polarizing microscope images. (a) Plane-polarized light and (b) cross-polarized light.

surface, and the quasi-static properties of granite are tested by the hydraulic screen-display universal testing machine (WEP-600) and in the Laboratory of Civil and Resource Engineering School at University Science and Technology Beijing (Beijing, China). The BX 120-10AA strain gages (sensitive grid size is 10×2 mm) are used to test deformation. Five replicate tests are performed for each property; the static mechanical parameters of granite are shown in Table 1, and the P-wave velocity tested for sample 1 by using an acoustic emission detector (PCI-2) is 4386 m/s.

2.2. Granite Rectangular Plate with a Crack (GRPC). The GRPC is cut by professional rock cutting tools from a granite cuboid with $400 \times 400 \times 80$ mm; the GRPC contains a mode-I crack and a circular hole, as shown in Figure 2. The length of the crack tip with 10 mm is incised by using a diamond wire saw, and the width of the crack tip is approximately 1 mm. The reason for the choice of the crack tip is that the failure should take place only between the initial notch tip and the back-face of the specimen [27], as shown in Figure 3(a). A set of split-type smoke shielding devices is designed to avoid the impact of blasting gas on camera shooting effect (“Front” and “Back” in Figure 1), the cylindrical charge charging with PETN in plastic straw is used to ensure uniform force on the borehole wall, the charge length is selected the same as the thickness of GRPC (80 mm), and the charging mode is chosen as radial decoupling charge (the decoupling coefficients are 3.82, 3.5, and 3.0, respectively), as shown in Table 2. To ensure the cylindrical charge is located at the center of the borehole, the insulating tape is wound around the front and back (position in connection with the detonating cord) of the cylindrical charge. Finally, the detonator detonates the detonating cord, and then the detonating cord detonates the PETN.

2.3. Experimental System. As shown in Figure 4, the experimental system of 3D-DIC is set up in the State Key Laboratory of Explosion Science and Technology at the Beijing Institute of Technology (Beijing), and the main components of this experimental system are two high-speed cameras (Photron Fastcam SA5), standard Nikon lens, VIC-3D analysis software,

the lighting system (Godox SL-200W) synchronous trigger system, and a computer. The texture of the granite itself is chosen as a speckle pattern [29], the distance between the cameras and the GRPC is 2.0 m, and the shooting angle of the two cameras is 10 degrees. When the detonator detonates, a square signal transmits to the synchronous system, and thus the signal triggers the cameras.

Calibrating a VIC-3D system is straightforward and has been streamlined into a nearly automatic process. The procedure for the 3D system involves moving, imaging, and analyzing a rigid calibration target in front of a stereo camera pair. This precisely calculates the cameras’ intrinsic and extrinsic parameters while triangulating the positions of the cameras and removing lens distortions. This ultimately removes any measurement bias and defines a three-dimensional coordinate system on the surface of the specimen. The standard calibration target set is provided with each VIC-3D™ system and covers fields of view from 30 mm and above. Each target features an ultramatte finish, a rigid and durable design, and they are specially coded for automatic spacing detection in VIC-3D v7 and later. These targets can be used for calibrating high-speed and low-speed systems and for both high and low-resolution cameras [30]. In this paper, calibration of the stereovision system is performed using 32 images of a translated and rotated planar dot pattern with a spacing of 10 mm (12×9 – 10.0 mm).

As shown in Figure 5, the camera shooting parameters and postprocess parameters are set as follows: the photograph frames are set as $60,000 \mu\text{fps}$ (the time interval between the two images is $16.67 \mu\text{s}$), the image resolution is set as $320 \text{ pixels} \times 320 \text{ pixels}$, the origin of coordinates is located in the center of the shooting surface (black hand-painted frame), the shooting area is approximately $120 \text{ mm} \times 120 \text{ mm}$, the calculated zone of interest (ZOI) is approximately $100 \text{ mm} \times 110 \text{ mm}$, the line of interest (LOI) locates on the ZOI with the spacing of 10 mm, the reference subset of pixels in the 3D-DIC computation is chosen to be $33 \text{ pixels} \times 33 \text{ pixels}$, and a subset step of 3 pixels is used. 3D-DIC mainly analyzed the strain field in crack propagation but not crack initiation, and 3D-DIC analysis is not affected by blasting gas because the speed of crack propagation is higher than that of blasting gas expansion.

FIGURE 3: The failure pattern [27].

TABLE 2: Charge parameters.

Test no.	Charge length (mm)	Charge diameter (mm)	Charge weight (g)	Density of PETN (g/cm ³)	Detonation velocity (m/s) [28]
1	80	5.5	1.51	0.7949	4762.13
2	80	6.0	1.98	0.8758	5061.46
3	80	6.5	2.42	0.9121	5195.77

According to reference [28], detonation velocity (km/s) = 3.19 + 3.7 * Density of PETN (g/cm³) - 0.37.

FIGURE 4: Schematic diagram of the experimental system.

FIGURE 5: Zone of interest (ZOI) and line of interest (LOI).

FIGURE 6: Crack evolution and full-field strain at different stages for test 1. (a) Crack evolution, (b) axial strain, and (c) principal strain.

FIGURE 7: Actual crack and fracture appearance after the explosion. (a) Actual crack in the shooting area for test 1, (b) actual crack in the shooting area for test 2, (c) actual crack in the shooting area for test 3, (d) actual crack, and (e) fracture appearance.

terms of transformation pattern except for the numerical differences.

As shown in Figures 7(a) and 7(c), the length of the crack from O to A is all 20 mm, and the length of the crack from O to E is 120 mm and 124 mm, respectively. It is assumed that the right deflection of the crack is positive and the left deflection is negative, and the crack deflection angle during crack propagation is described in the figure. It can be seen in Figure 7(e) that fracture appearance is flat for test 2 and test 3.

3.2. Axial Strain on the LOI. Figure 9 and 10 present the axial strain on the line of interest at different times for test 1 and test 3. From the peak position in the graphs, the maximum value position of the strain concentration zone corresponding to the X-axis value can be obtained and the X-axis value of crack position is also obtained. If the LOI line is used as the monitoring line and the crack is considered to be a linear scale, then the crack path can be described. For

example, for test 1, the X-axis values are 3.66 mm (LOI 1), 5.44 mm (LOI 2), 6.92 mm (LOI 3), 6.75 mm (LOI 4), 5.84 mm (LOI 5), 3.73 mm (LOI 6), 2.82 mm (LOI 7), and 7.95 mm (LOI 8), respectively; for test 3, the X-axis values are 1.83 mm (LOI 2), -1.04 mm (LOI 3), -0.98 mm (LOI 4), -1.14 mm (LOI 5), -5.78 mm (LOI 6), -10.87 mm (LOI 7), and -14.49 mm (LOI 8), respectively. Then, the location of the crack can be known by incorporating the X-axis values measured by LOI and the Y-axis values of LOI, and the crack path can be obtained by connecting these coordinate points. Therefore, the shorter the LOI spacing is, the more accurate the data likely to be are.

Furthermore, the LOI 6 locates at the inflection point (point D in Figure 7(a) and point C in Figure 7(c)) in test 1 and test 3. For test 1, the axial strain value at LOI 6 is 0.0154 at $2450 \mu s$, and the axial strain values on the LOI 5 is 0.0139 at $2450 \mu s$. According to Figure 6(b), the front end of the maximum strain concentration zones matches approximately the crack tip at $2383 \mu s$, and the maximum value of the axial strain is 0.0143. On the contrary, point C in

FIGURE 8: (a) Crack evolution and (b) full-field axial strain at different stages for test 3.

FIGURE 9: Continued.

FIGURE 9: Continued.

FIGURE 9: Axial strain on the line of interest at a different time for test 1. (a) LOI 1, (b) LOI 2, (c) LOI 3, (d) LOI 4, (e) LOI 5, (f) LOI 6, (g) LOI 7, and (h) LOI 8.

FIGURE 10: Continued.

FIGURE 10: Axial strain on the line of interest at a different time for test 3. (a) LOI 1 (abnormal data points are eliminated), (b) LOI 2, (c) LOI 3, (d) LOI 4, (e) LOI 5, (f) LOI 6, (g) LOI 7, and (h) LOI 8.

Figure 7(a) locates approximately within LOI 5, and the crack tip propagates approximately to point C at $2433 \mu\text{s}$. The axial strain value at LOI 5 is 0.0109 at $2433 \mu\text{s}$. According to Figures 9(e) and 9(f), the axial strain values on LOI 6 is 0.0102 at $2417 \mu\text{s}$, and the axial strain values on LOI 5 is 0.0084 at $2417 \mu\text{s}$. For test 3, the axial strain value on LOI 7 is 0.0155 at $1933 \mu\text{s}$, and the axial strain values on LOI 6 is 0.0125 at $1933 \mu\text{s}$. Similar to the analysis above, the axial strain value in Figure 10(b) is 0.0146 at $1800 \mu\text{s}$. Something like this, it can be identified that the crack occurs preferentially on LOI 6 in test 1 and on LOI 7 in test 3.

3.3. Crack Velocity. It has been known that the maximum value of the strain concentration zone does not fully represent the crack tip during the whole process of crack propagation, and the critical values of axial strain are 0.0143 , 0.0146 , and 0.0109 when the maximum axial strain concentration zone matches approximately the crack tip. Therefore, 1.0% , 1.1% , 1.2% , 1.3% , and 1.4% of axial strain is chosen as a threshold value to detect the axial strain threshold value tip (ASTVT) to measure the position of the crack tip and crack velocity. The evolutionary processes of axial strain for different strain threshold values for test 1 and test 3 are shown in Figures 11 and 12. It can be observed that the length of ASTVT and the width of the axial strain concentration zone increase with time when the axial strain threshold value is fixed, and the length of ASTVT and the width of axial strain concentration zone decrease as the axial strain threshold value increases.

ASTVT plotting with lines and coordinate contours corresponding with the actual crack in the shooting area can be used to describe the position of the crack, as shown in Figure 13. It can be found that ASTVT plotting with lines in test 3 matches well with the actual crack position, and the trajectory of ASTVT is consistent with the crack morphology

for test 1 and test 3. In addition, through observing the coordinate contours corresponding with the actual crack (the line of the red arrow representing the Y-axis), it can also be found that ASTVT plotting with lines in test 1 has an error of 2 mm with the actual crack position, which is maybe due to a mismatch between the coordinates established by the camera and those set by the human (black block diagram in Figure 5). In a word, it can be affirmed that ASTVT plotting with lines is helpful to determine the actual crack position.

The coordinates of the crack tip (visible method) or ASTVT at time t_i is (x_i, y_i, z_i) , and within the schedule $\Delta t_i = t_i - t_{i-1}$, the crack velocity v_i can be approximately regarded as the instantaneous velocity when the crack grows to the measuring point c_i . It satisfies the following equation:

$$s_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2}, \quad (1)$$

$$v_i = \frac{s_i}{\Delta t_i}, \quad (2)$$

$$v_{\text{avg}} = \sum_{i=2} \frac{v_i}{(i-1)}, \quad (3)$$

where s_i is the crack tip or ASTVT displacement and v_{avg} is the average crack velocity.

The crack velocity is 400 m/s , 500 m/s , and 410 m/s from point A to point E in Figure 7(a), and the crack velocity is 484.8 m/s , 882.4 m/s , and 518.1 m/s from point A to point D in Figure 7(c). The average crack velocity is 436.7 m/s for test 1 and 628.4 m/s for test 3. As shown in Figure 14, the crack velocity experiences a peak process in both visible method and ASTVT. It can also be seen that the peak value of ASTVT mismatches the visible method for test 1, the peak value of ASTVT matches the visible method when the axial strain threshold value is 1.3% for test 3, and the horizontal

FIGURE 11: Evolutionary process of axial strain for different strain threshold values for test 1. (a) 1.0%, (b) 1.1%, (c) 1.2%, (d) 1.3%, and (e) 1.4%.

FIGURE 12: Continued.

FIGURE 12: Evolutionary process of axial strain for different strain threshold values for test 3. (a) 1.0%, (b) 1.1%, (c) 1.2%, (d) 1.3%, and (e) 1.4%.

FIGURE 13: The position of axial strain threshold value tip. (a) Test 1 and (b) test 3.

FIGURE 14: Crack velocity. (a) Test 1 and (b) test 3.

stage of crack velocity after the peak is all in the vicinity of 200 m/s by using ASTVT to measure. Through calculating the average crack velocity, the following can be obtained: the average crack velocity is 400.8 m/s (1.0%), 433.8 m/s (1.1%), 469 m/s (1.2%), 438.6 m/s (1.3%), and 481.6 m/s (1.4%) for test 1, and the average crack velocity is 293.8 m/s (1.0%), 310 m/s (1.1%), 359.6 m/s (1.2%), 332 m/s (1.3%), and 307.2 m/s (1.4%) for test 3. It is found that the average crack velocity matches both visible method and ASTVT when the axial strain threshold values are 1.1% and 1.3% for test 1. Combining the position of crack and ASTVT at 2433 μs, 1.3% is more appropriate.

3.4. Evolution of Horizontal Displacement Field and Crack Width. The crack propagation process is characterized by the continuous evolution of the measured surface displacement field from disorder to order and the continuous displacement field concentration in the crack area, as shown in Figure 15.

Wu et al. [31] proposed the method to determine the crack opening displacement; in this paper, the crack opening displacement along LOI 4 is calculated to avoid the effects of blasting gas. It satisfies the following equation:

$$W = U_R - U_Q, \quad (4)$$

where W is the crack width; U is the horizontal displacement, and the points R and Q in Figures 16(a) and 16(b) are chosen according to the method of Wu et al. [31].

As shown in Figure 16(c), through observing the relationship between crack width and time, it can be found that there are three stages, i.e., initial stage (under line A), abrupt stage (rectangle B) or delayed stage (rectangle C), and linear stage, and the crack width of test 3 is larger than test 1. The linear stage coincides with the crack velocity (1.3%) rising phase in time. The average crack velocity of test 3 is smaller than test 1

according to Figure 14, and the width of the axial strain field of test 3 is larger than test 1 according to Figures 11 and 12. Using the equation of state of ideal gases to evaluate of borehole wall pressure [32] and the ratio of charge length to detonation velocity to estimate peak pressure rise time, the blast loading rates are obtained that 40.48 MPa/16.8 μs = 2.41 MPa/μs for test 1 and 91.27 MPa/15.4 μs = 5.93 MPa/μs for test 3. Then it can be demonstrated that, the crack width increases as the blast loading rates increase, and the average crack velocity decreases as the blast loading rates increase.

3.5. Fracture Process Zone. The fracture process zone (FPZ) in rocks is defined as the region affected by microcracking and frictional slip surrounding the visible crack tip propagating under stress [33]. Strain or displacement can be used as the defining standard of FPZ region [31]. If the axial strain threshold value (1.0%, 1.1%, 1.2%, 1.3%, and 1.4%) is used as the defining standard of the FPZ region, it can be found that the width of FPZ (axial strain concentration zone) increases with time when the axial strain threshold value is fixed. Then the width of FPZ is the same on the same X coordinate after 2450 μs for test 1 and 1867 μs for test 3, and the width of FPZ is also basically the same on the different Y coordinate except ASTVT. For example, the width of FPZ is approximately 18 mm (1.0%) and 15 mm (1.4%) at 2500 μs for test 1. If displacement is used as the defining standard of FPZ region, the X coordinate of point Q and point R is different according to Figures 15(a) and 15(b) ($X_R - X_Q < 20$ mm for test 1, and $X_R - X_Q > 20$ mm for test 3, where X_R is the X coordinate of point R and X_Q is the X coordinate of point Q). Wu [31] has demonstrated that the final macrocrack trajectory is in good agreement with the propagation path of the FPZ determined by the DIC technique; therefore, it can be demonstrated that the width of FPZ increases as the blast loading rates increase and FPZ generates along the trajectory of crack.

FIGURE 15: Evolution of horizontal displacement field. (a) Test 1 and (b) test 3.

FIGURE 16: Displacements along LOI 4. (a) Test 1, (b) test 3, and (c) crack width.

4. Conclusions

In this study, the GRPC is introduced to investigate the crack propagation characteristics under different blast loading rates, and an experimental system of 3D-DIC is set up to eliminate a certain extent of out-of-plane motion for accurate measuring the full-field strain field during crack propagation. The main conclusions obtained from the study are as follows:

- (1) There is a moment that the maximum value of strain concentration zone matches the visible crack tip; however, with the passage of time, the maximum value of the strain concentration zone does not fully represent the crack tip during the whole process of crack propagation. And then the location of the crack can be described by incorporating the X-axis values and the Y-axis values measured from the peak value of the axial strain in the LOI.
- (2) The length of ASTVT and the width of the axial strain concentration zone increase with time when the axial strain threshold value is fixed, and the length of ASTVT and the width of the axial strain concentration zone decrease as the axial strain threshold value increases.
- (3) ASTVT plotting with lines and coordinate contours corresponding with the actual crack in the shooting area can be used to describe the position of the crack. The trajectory of ASTVT is consistent with the crack morphology.
- (4) The different strain threshold value and the visual method calculating average crack velocity are compared; in this study, the axial strain 1.3% is more practical to obtain crack velocity and average crack velocity, and the average crack velocity decreases as the blast loading rates increase.
- (5) Through observing the relationship between crack width and time, it can be found that there are three stages which are initial stage, abrupt stage or delayed stage, and linear stage, and the crack width increases as the blast loading rates increase.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] Q. Zhang, K. L. Luo, and Q. Z. Lu, "Cracking and blast breaking process of rock," *Mining and Metallurgical Engineering*, vol. 17, pp. 6–9, 1997.
- [2] A. Zalooli, D. M. Freire-Lista, M. Khamehchiyan et al., "Ghaleh-khargushi rhyodacite and goid andesite from Iran: characterization, uses, and durability," *Environmental Earth Sciences*, vol. 77, no. 8, p. 315, 2018.
- [3] D. M. Freire-Lista, R. Fort, and M. J. Varas-Muriel, "Thermal stress-induced microcracking in building granite," *Engineering Geology*, vol. 206, pp. 83–93, 2016.
- [4] D. M. Freire-Lista, R. Fort, and M. J. Varas-Muriel, "Freeze-thaw fracturing in building granites," *Cold Regions Science and Technology*, vol. 113, pp. 40–51, 2015.
- [5] S. Ghasemi, M. Khamehchiyan, A. Taheri et al., "Crack evolution in damage stress thresholds in different minerals of granite rock," *Rock Mechanics and Rock Engineering*, vol. 53, pp. 1–16, 2019.
- [6] W. T. Xu, Z. M. Zhu, and L. G. Zeng, "Testing method study of mode-I dynamic fracture toughness under blasting loads," *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, pp. 2767–2772, 2015.
- [7] Q. Sun, X. D. Li, T. F. Yao et al., "Experimental study on crack propagation of brittle materials based on DIC under explosive loading," *Explosion and Shock Waves*, vol. 39, pp. 1–11, 2019.
- [8] Z. M. Zhu, W. T. Xu, and R. Q. Feng, "A new method for measuring mode-I dynamic fracture toughness of rock under blasting Loads," *Experimental Techniques*, vol. 40, no. 3, pp. 899–905, 2016.
- [9] R. F. Liu, Z. M. Zhu, M. Li et al., "Study on initiation and propagation of mode I crack under blasting," *Chinese Journal of Rock Mechanics and Engineering*, vol. 37, pp. 1–11, 2018.
- [10] D. Y. Wan, Z. M. Zhu, R. F. Liu et al., "Measuring method of dynamic fracture toughness of mode I crack under blasting using a rectangle specimen with a crack and edge notches," *International Journal of Rock Mechanics and Mining Sciences*, vol. 123, pp. 1–12, 2019.
- [11] P. Xu, R. S. Yang, Y. Guo et al., "Experimental and numerical investigation of the interaction between blast wave and pre-crack in a defected material," *Applied Optics*, vol. 58, pp. 9718–9727, 2019.
- [12] V. B. Chalivendra and A. J. Rosakis, "Interaction of dynamic mode-I cracks with inclined interfaces," *Engineering Fracture Mechanics*, vol. 75, no. 8, pp. 2385–2397, 2008.
- [13] H. V. Tippur, "Coherent gradient sensing (CGS) method for fracture mechanics: a review," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 33, no. 12, pp. 832–858, 2010.
- [14] F. Pierron, M. A. Sutton, and V. Tiwari, "Ultra high speed DIC and virtual fields method analysis of a three point bending impact test on an aluminium bar," *Experimental Mechanics*, vol. 51, no. 4, pp. 537–563, 2011.
- [15] X. F. Yao and W. Xu, "Recent application of caustics on experimental dynamic fracture studies," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 34, no. 6, pp. 448–459, 2011.
- [16] J. E. Field, S. M. Walley, W. G. Proud, H. T. Goldrein, and C. R. Siviour, "Review of experimental techniques for high rate deformation and shock studies," *International Journal of Impact Engineering*, vol. 30, no. 7, pp. 725–775, 2004.
- [17] M. H. Ju, J. C. Li, Q. L. Yao et al., "Rate effect on crack propagation measurement results with crack propagation

- gauge, digital image correlation, and visual methods," *Engineering Fracture Mechanics*, vol. 219, pp. 1–14, 2019.
- [18] Q. B. Zhang and J. Zhao, "Determination of mechanical properties and full-field strain measurements of rock material under dynamic loads," *International Journal of Rock Mechanics and Mining Sciences*, vol. 60, pp. 423–439, 2013.
 - [19] Q. B. Zhang and J. Zhao, "Effect of loading rate on fracture toughness and failure micromechanisms in marble," *Engineering Fracture Mechanics*, vol. 102, pp. 288–309, 2013.
 - [20] M. A. Sutton, J. H. Yan, V. Tiwari, H. W. Schreier, and J. J. Orteu, "The effect of out-of-plane motion on 2D and 3D digital image correlation measurements," *Optics and Lasers in Engineering*, vol. 46, no. 10, pp. 746–757, 2008.
 - [21] H. Z. Xing, Q. B. Zhang, D. Ruan, S. Dehkhoda, G. X. Lu, and J. Zhao, "Full-field measurement and fracture characterisations of rocks under dynamic loads using high-speed three-dimensional digital image correlation," *International Journal of Impact Engineering*, vol. 113, pp. 61–72, 2018.
 - [22] P. F. Luo, Y. J. Chao, M. A. Sutton, and W. H. Peters, "Accurate measurement of three-dimensional deformations in deformable and rigid bodies using computer vision," *Experimental Mechanics*, vol. 33, no. 2, pp. 123–132, 1993.
 - [23] Y. J. Chen, S. J. Sun, and C. M. Ji, "Development and application of 3D digital image correlation (3D DIC) in deformation measurement of materials," *Journal of Aeronautical Materials*, vol. 37, no. 4, pp. 90–100, 2017.
 - [24] C. Solutions, *Vic-3D V7 testing guide*, 2016.
 - [25] Y. Fan, Y. Wei, Y. Xue et al., "On the application of digital image correlation testing technology in hopkinson bar loading," *Journal of Experimental Mechanics*, vol. 30, pp. 591–598, 2015.
 - [26] Z. Y. Xu, J. Yang, and L. J. Guo, "Study of the splitting crack propagation morphology using high-speed 3D DIC," *Explosion and Shock Waves*, vol. 36, pp. 400–406, 2016.
 - [27] V. Veselý, L. Řoutil, and S. Seitzl, "Wedge-splitting test – determination of minimal starting notch length for various cement based composites part I: cohesive crack modelling," *Key Engineering Materials*, vol. 452–453, pp. 77–80, 2011.
 - [28] Y. X. Ou, *Exploseves*, Beijing Institute of Technology Press, Beijing, China, 2014.
 - [29] C. He and J. Yang, "Experimental and numerical investigations of dynamic failure process in rock under blast loading," *Tunnelling and Underground Space Technology*, vol. 83, pp. 552–564, 2019.
 - [30] "Acqtec," <http://www.acqtec.com/article/detail/64>.
 - [31] Z. Wu, H. Rong, J. Zheng, F. Xu, and W. Dong, "An experimental investigation on the FPZ properties in concrete using digital image correlation technique," *Engineering Fracture Mechanics*, vol. 78, no. 17, pp. 2978–2990, 2011.
 - [32] O. Yilmaz and T. Unlu, "Three dimensional numerical rock damage analysis under blasting load," *Tunnelling and Underground Space Technology*, vol. 38, pp. 266–278, 2013.
 - [33] A. Zang, F. C. Wagner, S. Stanchits, C. Janssen, and G. Dresen, "Fracture process zone in granite," *Journal of Geophysical Research: Solid Earth*, vol. 105, no. B10, pp. 23651–23661, 2000.