Research Article

Experimental Study of Fracture Characterizations of Rocks under Dynamic Tension Test with Image Processing

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To investigate the fracture characterizations of rocks under high strain rate tensile failure, a series of dynamic Brazilian tests was conducted using Split Hopkinson pressure bar (SHPB), and a high-speed digital camera at a frame rate of 50,000 frames per second (FPS) with a resolution of 272×512 pixels was adopted to capture the real-time images and visualize the failure processes. Using the extracted cracks and image processing technique, the relationship between loading condition (impact velocity), crack propagation process (crack velocity, crack fractal characteristic, and crack morphological features), and dynamic mechanical properties (absorbed energy and strain-stress parameters) was explored and analyzed. The experimental results indicate that (1) impact velocity plays a critical role in both crack propagation process and dynamic mechanical properties, (2) the crack fractal dimension is positively correlated with crack propagation velocity and has a linear relationship with the proposed morphological feature of crack, (3) mean strain rate and max strain of rocks under SHPB loading both decrease with the increase of crack propagation velocity, and (4) the energy absorbed by the rocks increases with increasing impact velocity and has a strong negative correlation with a proposed novel crack descriptor. Experimental studies pertaining to the measurement of crack propagation path and velocity, in particular, some crack feature extraction approaches, present a promising way to reveal the fracture process and failure mechanisms of rock-like materials.

1. Introduction

Fully understanding the dynamic rock mechanics is of great importance in dealing with a wide range of civil engineering applications, e.g., earthquakes, mining, sub-way tunnel excavation, blasting events, and protective construction project [1, 2]. The properties of rocks under dynamic loading tests always are very different from those of static tests due to the transient nature of high strain rate loading; therefore, several testing methods for determining the dynamic properties and fracture behavior of rocks have been conducted over the past few decades, e.g., Brazilian disc (BD) [3, 4], semicircular bending (SCB) [5, 6], notched semicircular bending (NSCB) [7–9], cracked chevron notched BD (CCNBD) [10], cracked chevron NSCB (CCNSCB) [11], flattened BD (FBD) [12], and holed cracked FBD (HCFBD) [13]. Additionally, the dynamic mechanical behavior of rock materials under different test conditions has been extensively studied, e.g., dynamic

uniaxial compressive test, dynamic triaxial compressive test, dynamic tensile test, and dynamic shear test. For example, Lundberg [14] performed some compression tests on rock-like materials using the SHPB technique. Isheyskiy and Marinin [15] investigated the strength of blasted rocks accounting for fracture zones and explored the relationship between uniaxial compressive strength of average rock and energy consumption. Gary and Bailly [16] applied some improved loading technique to determine the triaxial compressive strength of rock-like materials. Zhao et al. [17] investigated the dynamic shear strengths of rock-like materials using a pneumatic-hydraulic machine.

Moreover, it has been generally recognized that rock and rock-like materials are much weaker in tension than compression. Therefore, accurate determination of dynamic response and fracture properties of rocks under high strain rate tensile failure is important. In general, dynamic tension testing methods are being continuously improved from the

original quasistatic ones to precisely determine the dynamic tensile strength which can be approximately classified into two categories: direct tensile and indirect tensile testing methods [1]. Compared with the direct testing method to measure the tensile strength of rock material, an indirect testing method provides a more convenient and accurate alternative not only for the specimen preparation but also for the experimental design [18].

More specifically, the primary testing methods to determine the dynamic tensile strength of rock are basically extended from corresponding quasistatic ones and mainly include BD or FBD method, bending [19] or SCB method [5], spalling method [20–22], etc. Specifically, Zhou et al. [3] and Zhao et al. [4] conducted several tests on rock specimens with BD configuration using a SHPB and investigated the dynamic indirect tensile strength of rocks under different loading conditions. Dai et al. [5, 6] explored the rate dependence of tensile strength of rocks under SHPB impact loading using SCB. Biolzi and Labuz [23] investigated the deformation of a rock specimen in the classical four-point bend (FPB) fracture tests. Wang et al. [24] also assessed the FPB method for testing the tensile strength and fracture toughness of rocks by using the SHPB apparatus. Klepaczko and Brara [20] performed a dynamic tensile test for concrete using spalling method. In addition to the above indirect tension test, Asprone et al. [25] investigated the dynamic behavior of rock-like materials using the dynamic DT (Direct tension) method. Among these, the BD test is widely used for measuring the static and dynamic fracture toughness of rock and rock-like materials under the Split Hopkinson pressure bar (SHPB) loading. SHPB is a highly reliable apparatus and widely utilized to quantify the dynamic properties of rocks under high strain rates since it was invented by Kolsky in 1949 [26], and many efforts have been made to improve the measurement results [27, 28]. Moreover, these experiments always are conducted to explore the dynamic mechanical properties of rocks as well as crack initiation, propagation, and coalescence under different SHPB loading rates [11, 29–31]. For example, Zhang and Zhao [32] performed an experimental investigation about quasistatic and dynamic fracture behavior of rock materials by a servohydraulic and SHPB loading system. Bertram and Kalthoff [33] investigated the Mode-I propagation processes for limestone material under different crack speeds and explained the characteristics of the crack propagation path of brittle materials based on the experimental results. Also in Mode-I rock fracture process, Dai et al. [11] and Chen et al. [34] employed SHPB and laser gap gauge to study the dynamic fracture properties of rock-like materials with CCNSCB and SCB configuration, respectively. Forquin [35] proposed a crack velocity measurement method using optical correlation technique for concrete and rock-like materials under dynamic tensile loading test. Zhao et al. [36] also adopted a high-speed digital camera to record the crack propagation process of coal materials under SHPB impact loading and explored its fractal characteristics. Gomez et al. [37] performed a photoelastic dynamic

splitting experiment and studied the dynamic behavior of concrete and granite with tensile damage.

Since dynamic fracture of rock material is a very complex behavior, some traditional contact measurement approaches like resistance strain gauges cannot provide enough information to reveal the dynamic fracture process of rock. Therefore, many noncontact and optical measurement techniques have been adopted and developed as a promising way in the experiment to record the fracture process and further reveal the fracture process and failure mechanisms of rock materials [38]. These techniques can be approximately classified into following groups, i.e., CT (computed tomography) [39, 40], SEM (scanning electron microscope) [41, 42], X-ray phase contrast imaging (PCI) [43, 44], LGG (laser gap gauge) [34, 45], DIC (digital image correlation) [46–48], and DIT (dynamic infrared tomography) [49]. Among them, using the high-speed & high-resolution camera is the most convenient way to capture the fracture process of rock material.

Nevertheless, with regard to the crack evolution characteristics and failure process, the investigation is more challenging than that of stress-strain on the rock specimen in SHPB experiments since there are no effective characteristic parameters that can quantitatively describe crack propagation. To the best of our knowledge, research studies into the relationship between crack propagation and mechanical properties are relatively few. Therefore, we proposed a data processing method based on Ratsnake graphic annotation software [50] and Halcon machine vision software [51] to extract crack propagation features which are further compared with the dynamic mechanical properties of rocks. The main aim of this study is to visualize the relationship between crack propagation process and mechanical properties of rock using extracted multicracks and then, to investigate and reveal the future fracture behavior of the rock materials.

2. Experiment Procedures

2.1. Experimental Design and Rock Specimens. The dynamic Brazilian tensile test is conducted using the SHPB system at China University of Mining and Technology Beijing (CUMTB), and the schematic and physical map of the experimental setup are shown in Figures 1 and 2, respectively.

The SHPB system mainly consists of power system, bars, strain wave collector, and high frame rate camera. In order to satisfy the one-dimensional stress wave propagation wave, the length of the bars should be 30 times of the bar diameter [3]. Therefore, the length and the diameter of the bars utilized in the experiment are 2000 mm and 50 mm, and the length and diameter of the bullet are 400 mm and 50 mm. In addition, all the bars used in the SHPB test are 35CrMn steel material with $7,800 \text{ kg/m}^3$ density, 206 GPa Young's modulus, and 0.28 Poisson's ratio.

To visualize the fracture process and further reveal fracture mechanism, FASTCAM SA5 (16G) camera was employed to capture the fractured images of rock, which adopts the CMOS sensor with a $20 \mu\text{m}$ pixel delivering an

FIGURE 1: Schematic map of the SHPB experimental system.

FIGURE 2: Physical map of the SHPB experimental system.

ISO light sensitivity of 10,000 monochrome and 4,000 colors. When the frame rate is set to 1,000,000 FPS, the resolution of the captured image is only 16×64 pixels; on the other hand, when the resolution is set to 1024×1024 , the maximum frame rate is only 7000 FPS which cannot capture the fracture process of a rock specimen under SHPB impact loading. Therefore, the camera is set to 272×512 pixels resolution at a frame rate of 50,000 FPS in the experiment.

The rock samples utilized in the experiment are manufactured by sandstone selected from a quarry in the Fangshan area of Beijing, China. According to the ISRM suggestion for BD specimens preparation, the rock

specimens were cut from the same rock block without obvious bedding and manufactured to a cylinder with a dimension of 50 mm in diameter and 25 mm in length. Moreover, two ends of the rock specimen were finely ground to be flat within an accuracy of ± 0.05 mm and perpendicular to the longitudinal axis no more than $\pm 0.25^\circ$. At last, the surface of the rock samples is smooth by Vaseline lubricant.

2.2. SHPB Test. SHPB is an ideal apparatus for testing the dynamic response of materials, and its principle is based on the one-dimensional (1D) stress wave propagation. To accurately calculate the dynamic properties of rock material under SHPB loading, the following three assumptions also require to be satisfied [1]: (1) propagation of elastic waves in the bars satisfied 1D stress wave theory which determined by the bar dimensions; (2) neglecting the friction and inertia effects on the rock specimen which can be fulfilled approximately with the suggested testing procedures; (3) specimen reaches stress equilibrium. For a classic SHPB test, when the bullet impacts the incident bar, a compressive pulse is generated and propagates towards the rock sample. With the above recorded incident $\varepsilon_i(t)$, reflected $\varepsilon_r(t)$, and transmitted $\varepsilon_t(t)$ strain signals, the stress $\sigma(t)$, strain $\varepsilon(t)$, and strain rate $\dot{\varepsilon}(t)$ of rock material under different impact velocities can be expressed as

$$\sigma(t) = \frac{AE}{2A_S} [\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)], \quad (1)$$

$$\varepsilon(t) = \frac{C}{L_S} \int_0^t [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] dt, \quad (2)$$

$$\dot{\varepsilon}(t) = \frac{C}{L_S} [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)], \quad (3)$$

where A and A_S are the cross-sectional area of the bar and rock specimen, respectively. E is Young's modulus of the bar, C is the longitudinal stress wave speed of the bar, and L_S denotes the length of rock specimen.

Also, the dynamic forces on the incident and transmitted ends, P_1 and P_2 , can be computed as

$$\begin{aligned} P_1 &= AE(\varepsilon_i + \varepsilon_r), \\ P_2 &= AE\varepsilon_t. \end{aligned} \quad (4)$$

3. Methodology

Figure 3 shows the framework of our proposed method, which mainly consists of two parts, i.e., crack feature extraction and dynamic mechanical properties calculation. Firstly, the video of the fracture process of rock specimens is split into several images which will be postprocessed by the crack extraction module. To achieve the accurate extraction of cracks, a novel and efficient image annotation software tool, Ratsnake [50], is adopted to identify and extract cracks on rock surface accurately. According to the principles of connected domain approach used in semantic image segmentation application, images of extracted cracks of rock specimens under SHPB impact loading are obtained. Then by Halcon [51] machine vision software, a number of novel crack features have been proposed and calculated to describe the fracture process of rock under different loading rates. At the same time, dynamic mechanical properties also have been computed based on the above formulas. Finally, a correlation matrix was constructed based on Pearson's correlation coefficient.

As illustrated in Figure 4, the correlation matrix heat-map has been calculated based on the experimental data to visualize the relationship between loading condition, crack propagation process, and dynamic mechanical properties of rocks under different SHPB impact velocities.

Given paired data $\{(x_1, y_1), \dots, (x_n, y_n)\}$ consisting of n pairs, Pearson's correlation coefficient r_{xy} is defined as

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}}, \quad (5)$$

where n is the sample size, x_i, y_i are the individual points indexed with i , and $\bar{x}, \bar{y}$ are the sample mean values of x and y points.

In the correlation matrix heat-map, larger positive values were represented by dark red colors denoting a strong positive correlation between two variables while larger negative values were represented by dark blue colors

which indicate a strong negative correlation between two variables.

4. Results and Discussion

4.1. Crack Propagation Process

4.1.1. Crack Propagation Velocity. Over the past few decades, there have been some investigations for crack propagation velocities of rock materials under dynamic loading which provide a promising way to explore the fracture mechanisms of rock materials [1, 18]. However, relatively few crack extraction approaches based on image processing have been conducted on rock specimens to describe the failure process and explore the fracture mechanism due to the technical difficulties associated with crack feature extraction and computation.

In this study, the crack propagation velocity V and V_{Ap} were calculated according to the crack length and crack area (the number of crack pixels) [52], as shown in Figures 5 and 6.

To visualize the relationship between these two crack velocity variables, Figure 7 plots V_{Ap} as a function of V as well as the fitting curve. It can be seen that V_{Ap} increases almost linearly with the increased of V under SHPB loading.

4.1.2. Crack Fractal Characteristic. Since cracks on rock surface are an important index to measure the state of rock material and fractals exhibit the ability for measuring the complex topological pattern, many significant endeavors have been made to investigate the fractality of cracks to the mechanics of fracture [53, 54].

In mathematics, a fractal dimension is used to evaluate the fractal patterns by quantifying their complexity as a ratio of the change in detail to the change in scale [55]. Unlike topological dimensions, the fractal dimension can take noninteger values. Particularly, there are many formal mathematical definitions for fractal dimension, e.g., box-counting dimension, information dimension, and correlation dimension. Among them, the box-counting dimension is calculated by counting how this number changes as it makes the grid finer by applying a box-counting algorithm. In more detail, by the box-counting dimension computation method, the fractal dimension of an object can be computed as [56]

$$N = C \cdot S^D, \quad (6)$$

where D is fractal dimension, S the scale of the object (cracks), N the number of boxes of scale S required to cover the object (cracks), and C a constant number. Taking the logarithm, it can be rewritten:

$$\ln N = \ln C + D \cdot \ln S. \quad (7)$$

Therefore, the box-counting dimension D can be defined as

$$D = -\lim_{s \rightarrow 0} \frac{\ln N}{\ln S}. \quad (8)$$

FIGURE 3: An overview of the proposed approach for the investigation of dynamic fracture process of rock materials under SHPB impact loading. (a) an input video of rock fracture process; (b) an algorithm for multicracks extraction; (c) crack extraction results for a fracture process video; (d) dynamic strain-stress response of rock specimens; (e) the formula of Pearson's correlation coefficient; (f) matrix of crack evolution features; (g) matrix of dynamic mechanical properties; (h) a correlation matrix heat-map of relationship between crack evolution features and dynamic mechanical properties.

FIGURE 4: An illustration of the correlation matrix heat-map with loading condition, crack propagation process, and dynamic mechanical properties.

Figure 8 presents an illustration for crack coverage using different scale boxes ($S = 8, 16, 32, 64$), while Figure 9(a) plots the linear fitting results of $\ln N$ and $\ln S$, which shows the fractal dimension is 1.14 for current cracks on rock surface. Based on the plots of $\ln N$ and $\ln S$, the

fractal dimension of the crack can be accumulated by formula (8).

In general, the higher fractal dimension indicates a more curved and intricate crack propagation path. Therefore, according to the above method, the fractal dimension of

FIGURE 5: An illustration of crack propagation velocity computation using crack length.

FIGURE 6: An illustration of crack propagation velocity computation using crack area.

cracks in each frame of the rock fracture process has been increasing. Figure 9(b) gives a quantitative description of the crack propagation process of rock specimens under different impact velocities. It can be observed from it that the fractal dimension of cracks increases gradually during the fracture process of rocks, and the value of the fractal dimension of cracks on rock surface ranges from 0.8 to 1.2.

Figure 10 shows the relationship between crack propagation velocity and fractal dimension velocity. It has been found that both crack propagation velocities V and V_{A_p} increase with increasing V_D for rocks under different impact velocities.

4.1.3. Crack Morphological Features. In addition to adopting the crack area A_p and fractal dimension D to quantitatively describe the crack characteristics, two morphological features that can further analyze the crack evolution path and failure process are also proposed based on image processing technique. Figure 11 demonstrates a crack morphological process for crack initiation, propagation, and coalescence. In order to present a quantitative description of the distribution and shape factor of cracks, Anisometry and Compactness which derived from image morphology are proposed. In specific, Anisometry is derived from the geometric moments for each crack and defined as

FIGURE 7: Relationship between V and V_{A_p} of rock specimens under SHPB loading.

$$\text{Anisometry} = \frac{R_a}{R_b}, \quad (9)$$

where R_a denotes the main radius of maximum ellipse of the crack and R_b represents the secondary radius of the ellipse. Similarly, Compactness is also a shape factor which value ranges from 0 to 1 and can be expressed as

$$\text{Compactness} = \max(1, C'), \quad (10)$$

$$C' = \frac{L^2}{4 \cdot F \cdot \pi},$$

where L is the total length of the contour and F is the area of the region.

As shown in Figure 12(a), V_{Comp} is decreasing with the increase of V_D as a whole. It can also be seen from Figure 12(b) that the values of V_{Anis} decrease almost linearly with the increase of impact velocity, which indicates that longitudinal crack length produced by the rock is less than transverse's under higher impact velocity.

4.1.4. Distribution of Cracks. It has been generally recognized that, for a valid and typical dynamic Brazilian

FIGURE 8: An illustration of different box scales to fully cover cracks.

FIGURE 9: (a) Number of covered boxes versus box size; (b) fractal characteristics of crack for rock material under different velocities.

test, crack should be first appeared along the impact direction somewhere near the center of the specimen and then propagates bilaterally to the loading ends. According to the row and column index of the crack center, Figure 13 shows the coordinate distribution of crack center in the process of rock failure. It can be observed from Figure 13 that most of the rock disc cracks near the center of the specimen and the fracture propagation direction are bilateral to the loading ends and

some cracks also appeared at the contact side of rock and bars. The result indicates that the failure patterns of dynamic Brazil test under SHPB loading approximately include tensile failure and shear failure. Accordingly, the cracks near the center of rocks are mainly caused by the tensile failure which is the main axial crack parallel to the loading direction, and other cracks are caused by the shear failure that is a result of secondary fractures due to the further compression.

FIGURE 10: Relationship between V , V_{Ap} , and V_D in the SHPB experiment.

FIGURE 11: An illustration of crack morphological features. (a), (c), and (e) are original images represent crack initiation, propagation, and coalescence, respectively; (b), (d), and (f) are extracted cracks from corresponded images.

4.2. Dynamic Mechanical Properties. Figure 14 illustrates the incident $\varepsilon_i(t)$, reflected $\varepsilon_r(t)$, and transmitted $\varepsilon_t(t)$ strain signals of rock specimens under different impact velocities during SHPB dynamic loading test. According

to the three-wave analysis method, the mechanical properties of rocks under SHPB loading are determined. In this study, the absorbed energy and stress-strain parameters are calculated and further compared with crack

FIGURE 12: (a) Relationship between V_{Comp} and V_D ; (b) relationship between V_{Anis} and V .

FIGURE 13: Crack distribution for rocks under different impact velocities.

propagation features to explore the relationship between them.

4.2.1. Dynamic Fracture Energy. It has been generally recognized that the fracture of rock under loading rates is the process of accumulation and dissipation of energy [57]. In specific, the consumed energy under SHPB dynamic loading can be well quantified based on the first law of thermodynamics [34]. During the SHPB dynamic loading test, the energy of the incident wave W_I , the energy of the reflected wave W_R , and the energy of the transmitted wave W_T can be computed as

$$\begin{aligned} W_I &= \frac{A \cdot C}{E} \int \varepsilon_i(t)^2 dt, \\ W_R &= \frac{A \cdot C}{E} \int \varepsilon_r(t)^2 dt, \\ W_T &= \frac{A \cdot C}{E} \int \varepsilon_t(t)^2 dt, \end{aligned} \quad (11)$$

where A is the cross-sectional area, C is the longitudinal wave speed, and E is Young's modulus of the bars.

Assuming that all the energy loss at the specimen and bar interfaces can be negligible, the energy absorbed by the rock specimen W_S can be expressed as

FIGURE 14: Incident, reflected, and transmitted signals of rocks under different impact velocities.

FIGURE 15: Relationship between v and W_s .

$$W_s = W_I - W_R - W_T. \quad (12)$$

Figure 15 shows the total energy absorbed versus the impact velocity for the rock specimens. It indicates that the

energy absorbed by the rock specimen increases with increasing impact velocity.

Moreover, substantial efforts have been devoted to performing quantitative measurements on fracture surface, and it

FIGURE 16: (a) Relationship between W_S and V_D ; (b) relationship between W_S and V_{Anis} .

FIGURE 17: Curves of strain parameters with crack propagation velocity V and associated results after linear fitting. (a) $\bar{\epsilon}$ as a function of V ; (b) ϵ_{max} as a function of V .

has been well recognized that surface roughness in rock-like materials exhibits self-similarity properties at least over a given range of length scales. In other words, the fracture surface topography of rock-like materials reveals inherent details associated with energy dissipation mechanisms that govern the fracturing process. Therefore, the relationship between fractal dimension and absorbed energy was first calculated, and the result is shown in Figure 16(a). However, it can be found that there is no obvious relationship between the two variables.

On the other hand, Figure 16(b) presents the total energy absorbed W_S versus the crack feature V_{Anis} for the rock specimens. It can be seen that there is a linearly negative correlation between the two variables, the greater the W_S , the smaller the V_{Anis} .

4.2.2. Strain-Stress Parameters. According to the incident $\epsilon_i(t)$, reflected $\epsilon_r(t)$, and transmitted $\epsilon_t(t)$ strain signals illustrated in Figure 14 and formulas (1)–(3), the max stress, max strain, and mean strain rate of rocks under different impact velocities were calculated. Combining with the crack characteristic parameters in the above section, the relationship between the crack propagation process and dynamic mechanical properties was analyzed.

Figure 17 shows the max strain and mean strain rate versus the crack propagation velocity V , while Figure 18 shows the max strain and mean strain rate versus the crack propagation velocity V_{Ap} . It can be seen that, with the increase of the V , both the max strain and mean strain rate are gradually decreased and mean strain rate basically

FIGURE 18: Curves of strain parameters with crack propagation velocity V_{Ap} and associated results after linear fitting. (a) $\dot{\epsilon}$ as a function of V_{Ap} ; (b) $\epsilon_{\max}$ as a function of V_{Ap} .

remains the same when V ranges from 350 m/s to 650 m/s. Similarly, the max strain and mean strain rate also linearly decrease with the increase of crack propagation velocity V_{Ap} .

5. Conclusion

In this study, the Brazil test of rock specimens was performed under different impact velocities using the SHPB system to explore fracture characterizations of rocks under dynamic loads. Based on image processing technique, crack propagation process was quantitatively described from three perspectives: the crack propagation velocity, crack fractal characteristic, and crack morphological features. According to the recorded strain wave signals, the dynamic mechanical properties of rocks were also calculated, and the relationship between impact velocity and crack propagation process was explored and analyzed. The main conclusions are listed as follows:

- (1) Crack propagation velocities V and V_{Ap} both increase with increase of the crack fractals velocity V_D
- (2) The proposed two crack features, Compactness and Anisometry, have a capacity of describing the fracture process of rock. In specific, V_{Anis} linearly decreases with the increase of impact velocity v while V_{Comp} exhibits a negative relationship with crack fractals velocity V_D
- (3) The energy absorbed by the rocks increases with the increase of impact velocity v but shows a linear negative trend with V_{Anis}
- (4) The mean strain rate and max strain both decrease with increase of crack propagation velocity, which shows that there is a certain relationship between the crack propagation process and dynamic mechanical properties of rocks under dynamic loading

In the future work, we will conduct the static tensile tests using the BD specimen on the same rock material and compare the static and dynamic results in terms of mechanical properties and crack propagation process.

Nomenclature

$\dot{\epsilon}$:	Mean strain rate (s^{-1})
$\sigma_{\max}$:	Max stress (MPa)
$\epsilon_{\max}$:	Max strain (10^{-3})
A :	Cross-sectional area of the bar (mm^2)
A :	Crack length (mm)
A_p :	Crack quantification area (pixels)
A_s :	Cross-sectional area of the specimen (mm^2)
$Anis$:	Crack feature descriptor—anisometry
C :	Longitudinal stress wave speed of the bar (m/s)
$Comp$:	Crack feature descriptor—compactness
D :	Fractal dimension
E :	Young's modulus of the bar (GPa)
L_s :	Length of rock specimen (mm)
P_1, P_2 :	Dynamic forces on incident and transmitted ends (N)
r_{xy} :	Pearson's correlation coefficient
V :	Crack propagation velocity (m/s)
v :	Impact velocity (m/s)
V_D :	Fractal dimension velocity ($D/frame$)
V_{Ap} :	Crack propagation velocity (pixels/s)
V_{Anis} :	Anisometry velocity (anis/frame)
V_{Comp} :	Compactness velocity (comp/frame)
W_s :	Absorbed energy (J).

Data Availability

The data utilized in this 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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