Research Article

Dynamic Tensile Test of Granite and Its Tensile Sensitivity

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Through the dynamic splitting tensile test under various loading rates, different mechanical parameters have been analyzed; not only the dynamic peak stress but also the dynamic peak strain has a good linear relationship with the strain rate. The tensile sensitivity obtained from the dynamic tensile test increases with strain rate gradually, and it shows a nearly linear relation, which fully indicates that the granite specimen is a strain rate sensitive material. Moreover, with the numerical simulation, the damage area of the specimen is consistent with the actual failure mode of the specimen. Furthermore, the influenced factor on the dynamic tensile strength is discussed, which illuminates that the most fundamental reason of the rate effect is that the stress wave velocity is faster than the crack propagation velocity in the specimen during the impact process.

1. Introduction

Dynamic mechanics of rock materials are widely used in rock engineering, such as tunnel excavation, blasting mining, and other civil engineering projects. Loading on the rock not only includes static load, such as in situ stress, but also includes dynamic load, which ranges from low strain rate to high strain rate, such as blasting excavation or mechanical disturbance [1]. Meanwhile, as the rock tensile strength is far less than the compressive strength, the rock is more prone to tensile failure [2, 3]. Therefore, one of the main mechanical factors charging of rock failure is the tensile. Under the dynamic load, the mechanical response of rock is significantly different from that under static conditions, with an obvious strain rate effect. Many scholars have studied the dynamic mechanical properties of rocks, especially the dynamic compressive mechanics [4, 5].

Stress wave propagation can not be ignored in the dynamic mechanical properties of rock and other materials [2]. For rock breaking or blasting excavation, dynamic load with a strain rate generally ranges from 10^1 to $10^3 s^{-1}$ [6]. And the Split Hopkinson Pressure Bar (SHPB) is mainly used to study the dynamic mechanical properties of rock. Due to the difficulty of direct tensile testing of rock materials, indirect tensile method is used to measure tensile property, and the most commonly used method is Brazilian disc test, i.e., split tensile test [7]. Therefore, the SHPB experimental device with Brazilian disc specimen has become an efficient and simple experimental method to study the dynamic tensile properties of rocks. The experiment technology and application progress of Hopkinson pressure bar has been summarized [7]. Gong [8] put forward the analytical algorithm of tensile modulus in Brazilian disc splitting experiment through relevant experimental research on Brazilian disc specimen. Furthermore, using INSTRON hydraulic servo testing machine and SHPB impact device, a unified dynamic enhancement factor model based on rate effect is proposed [9, 10], and the dynamic compressive strength and tangent modulus could be well described. However, there are few researches on dynamic tensile mechanical properties of rock.

As is known, the static loading test with Brazilian disc specimen shows that the failure pattern is split along the middle of the specimen [11, 12]. For the conventional SHPB impact tensile test, the failure is also split from the specimen center [13–15]. Nonetheless, the failure characteristics of rocks under complicated tensile stress states are still not well understood, and the effects of the dynamic loading rates on

the tensile strength of brittle rocks have not been comprehensively investigated.

In this paper, the homogeneous granite samples are focused. By the SHPB experimental device, the dynamic splitting tensile tests of granite samples under different impact speeds are carried out. And the dynamic tensile mechanics of granite are analyzed, so the efficient excavation and support scheme design of rock engineering could be provided and referenced.

2. Dynamic Tensile Experiment

SHPB device with a 50 mm diameter was used as the loading equipment. The dynamic tensile test was carried out on granite specimens with different loading rates. The failure modes were analyzed, and then the dynamic tensile mechanics of granite under impact load were studied.

2.1. Experimental Device and Principle. SHPB device is the main equipment for rock dynamic tensile testing. The device system is with bar diameter of 50 mm. The system is mainly composed of impact device, incident bar, transmission bar, and damping device. During the experiment, the specimen should be placed between the incident bar and the transmission bar along its radial direction.

During the dynamic tensile test, the stress wave is reflected and transmitted many times in the granite specimen, and the impact simulation process is shown in Figure 1.

According to the one-dimensional stress wave assumption and the uniform distribution of internal stress assumption [16–18], through the dynamic force balance verification of the experimental data, the data obtained are effective and reliable, that is, $\varepsilon_i + \varepsilon_r = \varepsilon_t$. The equation of two waves method can be used to process the data, and it is considered that the forces on the end face of the specimen are approximately equal. Based on the two basic assumptions of Hopkinson bar test technique and Brazilian disc splitting principle, the dynamic tensile strain, strain rate, and tensile stress of granite samples could be calculated as follows:

$$\varepsilon_s = -\frac{2C_0}{l_s} \int_0^{t_0} \varepsilon_r dt, \tag{1}$$

$$\dot{\varepsilon}_s = \frac{d\varepsilon_s}{dt} = -\frac{2C_0}{l_s} \varepsilon_r, \tag{2}$$

$$\sigma = EA\varepsilon_t \tag{3}$$

where E is the elastic modulus of the impact bar and A is the sectional area of the impact bar.

Through finite element calculation and photoelastic experiment [19, 20], the stress and deformation of the specimen in the dynamic Brazilian disc experiment have been analyzed. It is considered that the dynamic stress distribution is basically consistent with the static stress distribution after the internal stress of the sample reaches an equilibrium state, while small stress differences only exist at the loading end of the specimen. Therefore, the dynamic

tensile stress formula at the center point of rock specimen can be obtained by combining the tensile stress formula of static Brazilian disc splitting with formula (3):

$$\sigma_s = -\frac{2EA\varepsilon_t(t)}{\pi DB}, \tag{4}$$

where D and B are the diameter and thickness of the specimen, respectively.

2.2. Preparation of Granite Sample. According to the experiment regulations of rock mechanics by International Society for Rock Mechanics (ISRM), granite samples are processed and prepared. It means that the nonparallelism and nonvertical straightness of the samples are less than 0.02 mm, the height and diameter errors of the samples should be less than 0.3 mm, and the specification is Φ 25 mm × 50 mm, as shown in Figure 2.

The collected rock is gray and has a medium-grained porphyritic texture. To evaluate the geological nature of the rock, an analysis was conducted using an optical microscope and a scanning electron microscope (SEM). The dominant minerals in the rock are exposed to cross-polarized light to identify. A microscopic view of a thin section of the rock is presented in Figure 3. It was found that quartz, alkaline feldspar, plagioclase, and biotite are the major rock constituent minerals. In addition, SEM observations show that the rock has a dense texture.

2.3. Experimental Result. It is necessary to verify whether the specimen is clamped well between the incident bar and transmission bar. In the meantime, it should be confirmed that the radial direction of the specimen is coaxial with the impact bar. Moreover, in order to reduce the friction force between the specimen and the impact bar and to decrease the influence of the loading constraint on the stress distribution of the specimen, Vaseline should also be applied between specimen and the two-end face of the impact bar.

Use a C11000 copper disc to shape the incident wave. In addition, a rubber disc is placed in front of the copper shaper to reduce the rising slope of the incident pulse. This combined pulse shaping technique was also used. Forces on both ends of the specimen in a typical test are shown in Figure 4.

The dynamic force on one side of the specimen P1 is proportional to the sum of the incident (In) and reflected (Re) stress waves, and the dynamic force on the other side P2 is proportional to the transmitted (Tr) stress wave. It can be seen from Figure 3 that the dynamic forces on both sides of the specimens are almost identical during the whole dynamic loading period. The inertial effects are thus eliminated because there is no global force difference in the specimen to induce inertial force.

A total of 70 granite specimens were tested. According to the step size of impact velocity, i.e., the interval is 0.5 m/s, all the testing data have been adapted based on the dynamic force balance, while the average values of impact velocity, strain rate, and stress peak value of all specimens within the step size range are calculated, respectively. Mechanical
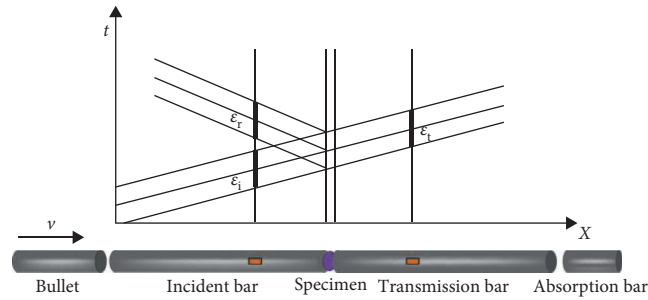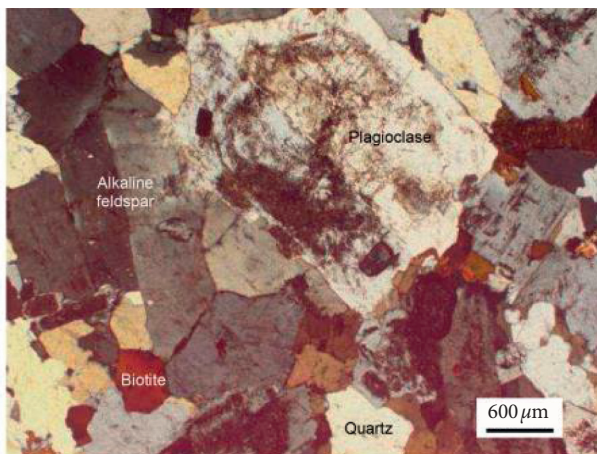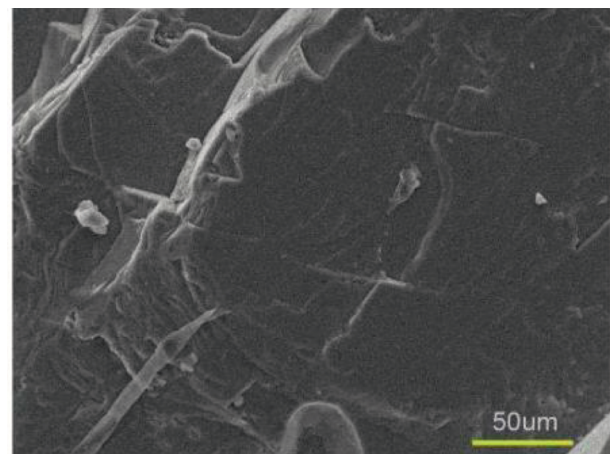
FIGURE 1: Dynamic Brazilian disc splitting test.

FIGURE 2: Processed granite samples.

(a)   (b)

FIGURE 3: Observations of medium-grained monzogranite at different scales.

parameters of splitting tensile test of granite specimens are shown in Table 1.

3. Failure Modes and Mechanical Properties of Granite Samples

3.1. Failure Mode. After SHPB splitting tensile test under different impact velocity, the typical fracture morphology of granite specimens is shown in Figure 5.

It can be seen that different failure modes under different impact velocities have been shown, which are intact, slight crack, fracture, and smashed state separately. When the impact velocity is less than 6 m/s, the specimen is intact, while the specimen shows a small crack when the impact velocity ranges from 6 m/s to 8 m/s. In the meantime, the specimen is broken when the impact velocity is 9 m/s~10 m/

s, and the specimen is crushed totally when the impact velocity is greater than 11 m/s. The results show that, with the increase of loading rate, the incident kinetic energy increases, and the internal fracture surface of rock specimen becomes more, and then the fragmentation degree increases obviously. It should be noticed that all the specimens under a high impact velocity have been broken with the crack initiated from the center of the specimen, as the same phenomenon during the static Brazilian testing.

3.2. Mechanical Analysis. According to formulas (1)–(4) shown above, for granite samples collected under different impact velocities, the reflected and transmitted wave signals are processed by two-wave method, and the stress obtained is the tensile stress, while the strain obtained is somewhat a compressive strain, as the impact on the two bars and the
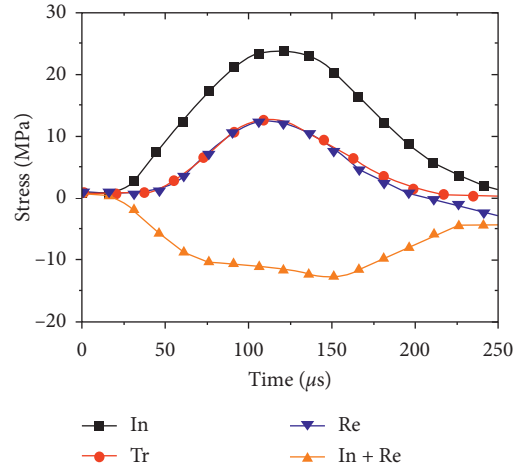
Figure 4: Dynamic balance for the original data.

Table 1: Impact test results of granite specimens.

V (m/s)	$\dot{\varepsilon}$(s)	$\varepsilon_{\max}$	$\sigma_{\max}$(MPa)
5.5	92.12	0.00825	22.76
6	96.75	0.00817	23.13
6.5	95.14	0.00821	22.84
7	110.71	0.00796	23.61
7.5	105.11	0.00809	23.37
8	120.56	0.00786	23.93
8.5	116.11	0.00785	23.86
9	138.64	0.00754	25.23
9.5	122.47	0.00778	24.02
10	139.31	0.00752	25.31
10.5	143.3	0.00745	25.57
11	152.3	0.00728	26.29
11.5	153.7	0.00724	26.45
12	165.7	0.00715	26.82
12.5	165.7	0.00715	26.82
13	183.0	0.0069	27.49
13.5	155.8	0.00718	26.69
14	190.8	0.0067	27.43
14.5	194.8	0.0066	28.52
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specimen. Therefore, there is no stress-strain relationship corresponding to the strain under a certain stress condition.

The mechanical meaning of the strain-stress relationship is that it reflects the basic dynamic response of the granite under those strain rate tested.

It should be noticed that the strain here is compressive strain, while the stress calculated by formulas (3) and (4) is tensile stress. Therefore, the stress and strain by the compressive strain and tensile stress just mean the loading situation of the sample corresponding to a certain displacement during its impact progress. Furthermore, the rate effect of the granite sample could be well reflected using the compressive strain, as it is an intrinsic index, which can fully represent the physical meaning of the rock.

It could be observed from Figure 6 that the dynamic peak stress gradually increases with the increase of strain rate. Especially, the peak stress has a good linear relationship with the strain rate, and the specific expression is as follows:

$$\sigma = 0.055\dot{\varepsilon} + 17.65, \tag{5}$$

in which $\dot{\varepsilon}$ is the strain rate, and σ is the dynamic peak stress. The correlation coefficient of the fitted lines is $R^2 = 0.96$.

Furthermore, in addition to the peak stress varies with the strain rate, the peak strain vs. strain rate also should be studied in deep.

It can be seen from Figure 7 that the dynamic peak strain increases gradually with the strain rate, and the peak strain decreases gradually. The peak strain and strain rate have a good linear relationship. The fitting formula is as follows:

$$\varepsilon = -0.157\dot{\varepsilon} + 97.04, \tag{6}$$

in which $\dot{\varepsilon}$ is the strain rate, and ε is the peak strain. The correlation coefficient of the fitted lines is $R^2 = 0.98$.

The peak strain is inversely proportional to the strain rate; that is, the peak strain decreases gradually with the increase of strain rate, which indicates that the deformation capacity becomes worse with the strain rate increases.

3.3. Tensile Sensitivity and Rate Effect Analysis. The tensile sensitivity is defined as the ratio of dynamic tensile strength to static tensile strength. The tensile sensitivity represents the sensitivity of rock dynamic tensile strength to strain rate. The tensile sensitivity is expressed by S_t, which is defined as

$$S_t = \frac{\sigma_{t\,d}}{\sigma_t}, \tag{7}$$

where $\sigma_{t\,d}$ is the dynamic tensile strength and σ_t is the quasi-static uniaxial tensile strength. The static uniaxial tensile strength is calculated as 12.59 MPa.

It can be observed from Figure 8 that, in the dynamic splitting experiment, the tensile sensitivity increases with strain rate gradually, and it is close to the linear relationship, which fully indicates that granite is a strain rate sensitive material.

Figure 9 shows that the dynamic elastic modulus gradually increases with the increase of strain rate. Especially, the changing amplitude increases with the increase of strain rate.

$V = 5.53 \, \text{m/s}$

(a)

$V = 6.51 \, \text{m/s}$

(b)

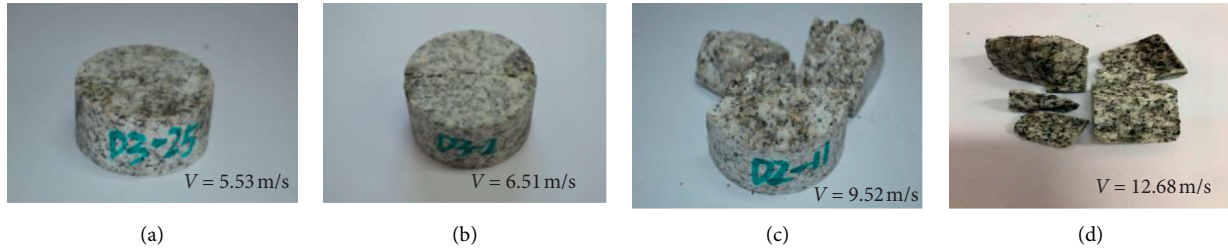$V = 9.52 \, \text{m/s}$

(c)

$V = 12.68 \, \text{m/s}$

(d)

FIGURE 5: Failure mode of different impact velocity. (a) Intact. (b) Fractured. (c) Cracked. (d) Broken.
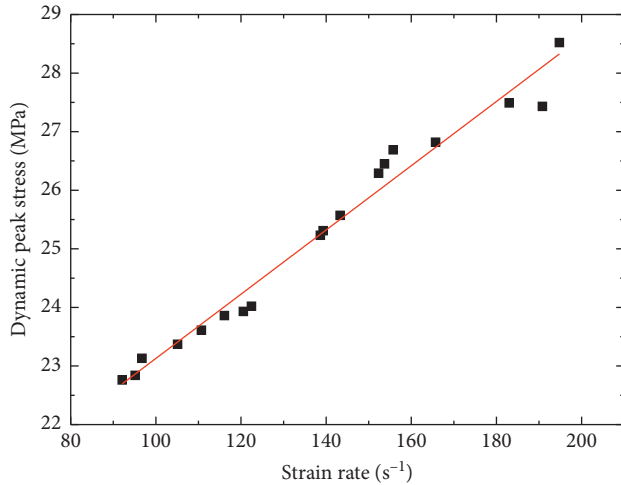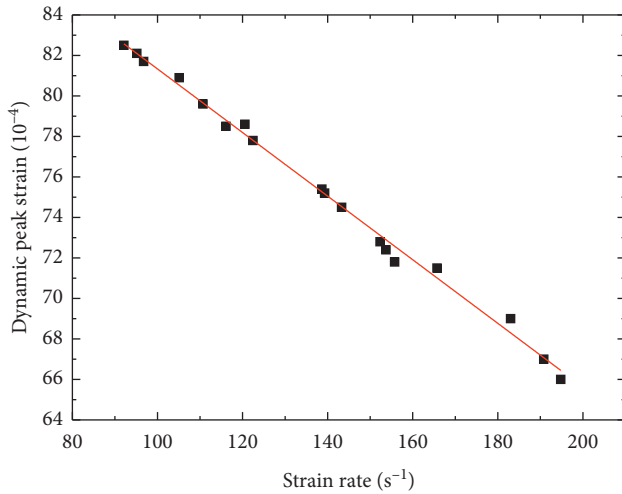

FIGURE 6: Dynamic peak stress-strain rate.

FIGURE 7: Dynamic peak strain-strain rate.

It can be seen from Figure 10 that, with the increase of impact velocity, the strain rate gradually increases. The impact velocity forced on the granite specimen has a good linear relationship with the strain rate, which indicates that granite is a strain rate sensitive material. And the specific relationship between strain rate and impact velocity is as follows,

$$\dot{\varepsilon} = 27.50 + 11.16 \, v, \tag{8}$$

while the correlation coefficient of the fitted lines is $R^2 = 0.92$.

4. Numerical Simulation of Dynamic Tensile Process

4.1. Dynamic Splitting Model Setup. ABAQUS finite element program is used to simulate the impact splitting process. The finite element model and its mesh generation are shown in Figure 11.

4.2. Numerical Simulation of Failure Process. The simulation process of dynamic splitting could be clearly divided into the following stages.

(1) The bullet impact could produce the incident pulse stress wave in the input bar.

(2) The dynamic force balance would be established in the specimen after several reflections.

(3) The stress wave would be reflected and transmitted into the input bar and output bar, respectively. The whole stress wave propagation process is shown in Figure 12.

Figure 13 shows the impact splitting failure of granite measured here. It can be seen that the stress concentration occurs firstly at the two contact surfaces of the specimen under the impact stress wave. With the stress concentration increases, the specimen is cracked under the concentrated stress. The crack fractures from the middle of the sample and propagates to the contact surface until the crack penetrates through the sample, and then the specimen totally cracked. When the crack is generated, the stress at both ends of the crack propagates to both sides in a fan-shaped pattern.

Furthermore, the experimental results are compared with the simulation. It can be concluded that the cracks are basically straight under different impact velocities, and the fractured areas are all near the horizontal diameter of the specimen.

5. Discussion

Based on Reinhart and Weerheijm [21], the decreased crack velocity at higher loading rates could increase the rock strength. As is known, according to the Griffith's theory, the crack propagation velocity during stable crack growth is often estimated to be $0.38 \, c$, in which c is the propagation velocity of the stress wave. Usually, c was approximately 4000 m/s, then the crack propagation velocity was roughly 1500 m/s.
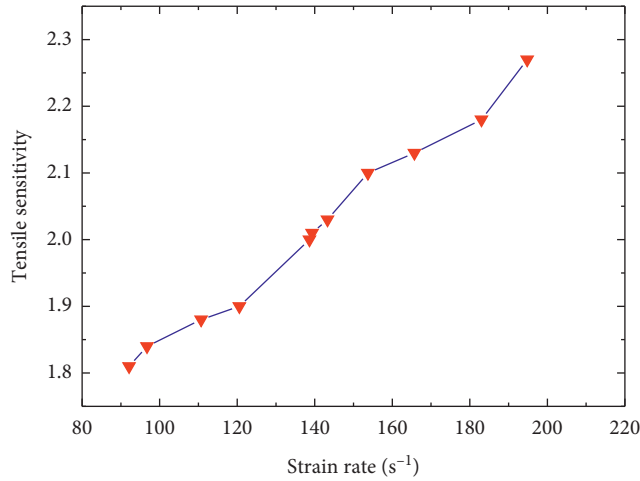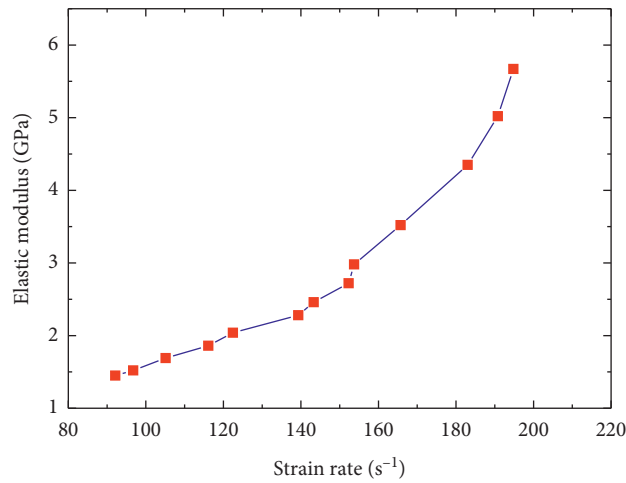
Figure 8: Tensile sensitivity-strain rate.

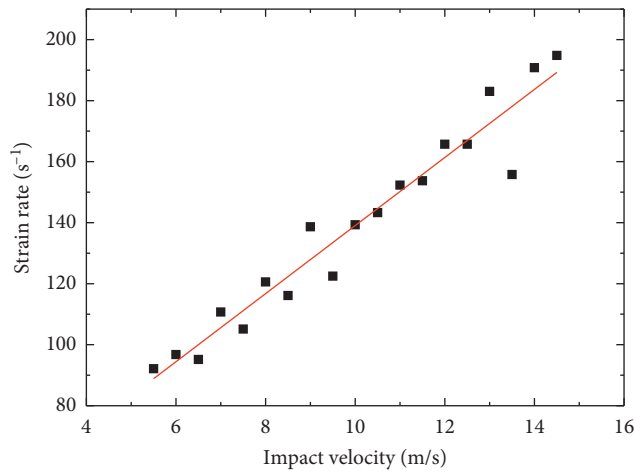Figure 9: Elasticity modulus-strain rate.

Figure 10: Impact velocity-strain rate.

The crack propagation velocity decreased at higher strain rates, leading to a higher dynamic tensile strength. This agrees well with Reinhart's findings and implies that the dynamic tensile strengths obtained in this study include the mechanisms related to the crack propagation velocity. Indeed, the stress wave velocity is faster than the crack propagation velocity.
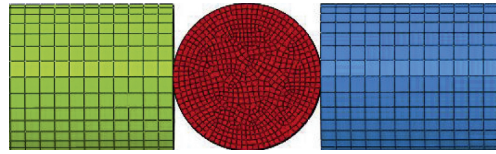
FIGURE 11: Dynamic split finite element model.

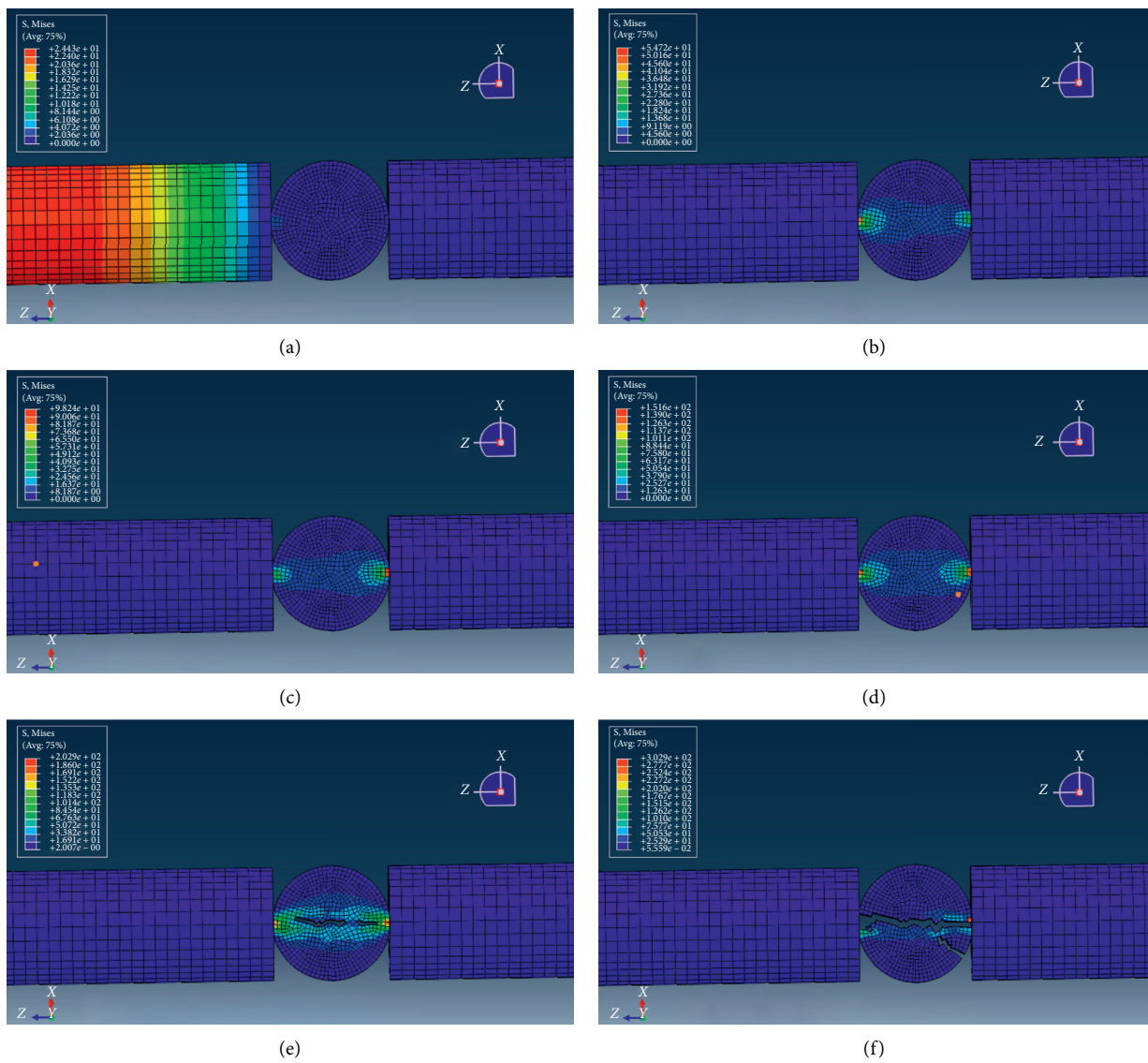FIGURE 12: Three stages of the dynamic splitting process.

FIGURE 13: Failure mode of specimen under high speed impact.

Therefore, the dynamic tensile strength based on Hopkinson's effect combined with the spalling phenomena is influenced by the inhomogeneity of the rock, the stress rate, and the crack propagation velocity, as well as other factors.

6. Conclusions

Through the dynamic splitting tensile test under various loading rate, different mechanical parameters have been analyzed, and the following conclusions are obtained.

(1) Both the dynamic peak stress and the dynamic peak strain have a good linear relationship with the strain rate.

(2) The tensile sensitivity increases with strain rate gradually, and it is close to the linear relationship, which fully indicates that granite is a strain rate sensitive material.

(3) Using the numerical simulation, the damage area of the specimen is consistent with the actual failure mode of the specimen.

(4) The dynamic tensile strength is influenced by the inhomogeneity of the rock, the stress rate, and the crack propagation velocity, as well as other factors. The most fundamental reason of the rate effect is that the stress wave velocity is faster than the crack propagation velocity.

Data Availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflicts of Interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

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