Loading rate effect on fracture process in Brazilian splitting tests of Beishan granites

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Abstract. In the present study, to reveal the loading rate effect on fracture process in Beishan granite, a series of Brazilian splitting tests under conventionally monotonic loading and stepwise loading conditions were performed to observe the crack propagation process of granites, with the aid of a digital image correlation (DIC) technique. The fracture process zone (FPZ) length and opening displacement ahead of notch tips, and so on were measured, and the loading-rate dependence was acquired correspondingly. The experimental results show that the peak load, axial and lateral deformation of granite gradually increased with the increasing loading rate. With the increase in the loading rate, the stress level for fracture initiation decreased, while the critical opening displacement and FPZ length gradually increased. The granite underwent insignificant deformation during the constant stress loading period when a lower stress was applied. When a larger stress was applied, obvious three-stage creep deformation was observed. The opening displacement ahead of notch tips increased slowly at a constant rate during the primary and secondary creep stages, then exhibited an approximately exponential increase with increasing time during the tertiary creep. Moreover, the FPZ length of granite at the critical state under conventional loading was higher than that under stepwise loading. The inner mechanism is analyzed to explain the rate-dependent fracturing behavior.

1. Introduction
Understanding the effects of loading rate or strain rate on rock mechanical behavior is essential in solving various rock engineering problems. Different brittle rocks exhibit different mechanical characteristics with the change of loading rate [1-3]. It has been found that loading rate during test can affect the strength, fracture toughness and microscopic characteristic of the fracture surface of brittle rock [1-12]. In particular, the compressive strength and static or dynamic tensile strength increase significantly with an increase in the loading rate [4-8]. The rate-sensitivity of dynamic propagation toughness is more evident than that of the dynamic crack initiation toughness, and static fracture toughness remains constant at any loading rate in a certain range [9-11]. The fracture surface of rock observed by SEM reveals that the micro failure mechanism in quasi-static tests mainly consisted of mostly intergranular fracture under a low loading rate, which forms a rougher surface, and results in a higher fractal dimension value. With the increase in the loading rate, the transgranular fractures become dominant over the intergranular fractures, which in turn leads to a lower value of fractal dimension [4, 9, 12]. However, these studies mainly cover the loading rate effect on rock mechanical characteristics from the macroscopic and microscopic perspective, while few have fully reflected the whole process of
crack propagation from a mesoscopic perspective. At the same time, the inner mechanism of crack propagation has not been explained extensively.

In the present study, a series of Brazilian splitting tests under conventional loading and stepwise loading conditions were performed by applying the digital image correlation (DIC) technique, aiming to reveal the loading rate effect on the fracture process of Beishan granite.

2. Specimen preparation and testing

2.1. Specimen preparation

Granite from the Jijicao quarry in Beishan, Gansu Province in China, is used in this study. It contains 35% quartz, 30% k-feldspar, 20% plagioclase, 5% biotite and 10% muscovite. The grain sizes range from 0.2 to 4mm [13]. The granite is white grey and dark brown in color, and has an average density of 2,620 kg/m³. To prepare the CCBD specimen, cylinders 50 mm in diameter were cored from the same block of granite materials. Next, these cylinders were sliced into circular discs 15 mm in height using a high-precision diamond tool. Finally, a notch with a length of 20 mm and width of 1 mm was prefabricated at the center of the granite specimen.

2.2. Procedure of Brazilian splitting tests under quasi-static loading conditions with different loading rates and step loading conditions

Two types of Brazilian splitting tests were performed, as shown in Fig. 1. The specimens were deformed either under conventionally monotonic loading with three different constant displacement loading rates (0.001 mm/s, 0.002 mm/s and 0.005 mm/s) or under stepwise loading conditions (i.e. extremely slow displacement loading rate). In the latter case, the specimens were initially loaded with a constant displacement loading rate (0.002 mm/s) to a target load. Then, the target load was held constant for a period of time. Three target loads (i.e. 1 kN, 2 kN and 3 kN) were set during the stepwise loading process in this study. Two different holding periods were considered (i.e. 5 minutes and 10 minutes). In this study, 13 rock specimens were prepared for splitting tests under conventionally monotonic loading, and two rock specimens for splitting tests under stepwise loading.

2.3. Experimental set-up

Fig. 2 shows the experimental set-up, which is composed of a loading system and digital image acquisition system. The loading system is the servo-controlled rock mechanics testing system RMT-150C, which has a maximum loading capacity of 1,000 kN and maximum vertical stroke of 50 mm. Digital image correlation (DIC) is an efficient non-contact technique for measuring deformations of solids, which can provide the full-field displacement and strain of a target surface in real time during the loading process. The digital image acquisition system contains a charged coupled device camera (CCD) with a resolution of 3,376 × 2,704 pixels, two white lights, and a computer with image acquisition software program [14, 15].

3. Results
The formation of the fracture process zone (FPZ) is a result of the generation and propagation of microcracks, thus the FPZ length is used to characterize the length of crack induced during the loading process described below, and the opening displacement ahead of the notch tips is used to characterize the crack opening.

3.1. Loading rate effect on fracture process

3.1.1 Loading rate-dependent peak load and deformation characteristics

Fig. 3 shows the load-displacement curves of Brazilian splitting tests under three different displacement loading rates. Note that the axial and lateral deformation of granite specimens during the tests were obtained by DIC, as it is difficult to measure them with a linear variable differential transformer or strain gauge in the Brazilian splitting tests. The set of the axial and lateral virtual extensometers is shown in Figs. 4(b)-(c). The peak load, peak axial deformation and peak lateral deformation of granite specimens are portrayed in Fig. 4. It can be seen that peak load of granite gradually increases with the increase in the loading rate, thus indicating that the fracture resistances of granite is strengthened with the increasing loading rate, which is consistent with the results of previous studies [16]. Moreover, the axial and lateral deformation at the peak load also increase with the increase of loading rate, thereby indicating that additional microcracks may be generated in rocks.

Figure 3 Load-displacement curves under three displacement loading rates: (a) 0.001 mm/s, (b) 0.002 mm/s and (c) 0.005 mm/s

3.1.2 Fracture initiation and FPZ development at three different loading rates

The fracture initiation and FPZ length of granite were identified based on the displacement gradient-based method [14]. Previous studies indicate that a fully-developed FPZ occurs at the peak load of rocks under mode I loading [16]. Therefore, the peak load in this study is assumed to be the critical point between the FPZ unfully-developed and unstable propagation of mode I fractures [16].

Figure 4 Peak load and peak deformation of granite specimens under three different displacement loading rates: (a) peak load, (b) peak axial displacement and (c) peak lateral displacement

Fig. 5 presents the development of FPZ in granite at a loading rate of 0.001 mm/s. Note that the fracture initiation direction is defined as $y_1$, while the direction perpendicular to the fracture initiation is defined as $x_1$. The $v_1$ is the displacement along $y_1$, and $u_1$ represents displacements along $x_1$. In addition, $w_1$ is the opening displacement of the upper notch tip, and $w_2$ is the opening displacement of the lower notch.
tip. $L_1$ is the FPZ length of the upper notch tip, and $L_2$ is the FPZ length of the lower notch tip. It can be observed that the displacement contours of $u_1$ presents remarkable discontinuity ahead of the notch tip, and the size of displacement discontinuous zone gradually grows with the increasing loading stress. However, the displacement contours ahead of notch tips in the $v_1$ direction are generally continuous during tests. The notch opening and fracture initiation occurs when the loading stress reaches a certain level.

![Development of FPZ above the notch tips in granite at a loading rate of 0.001 mm/s](image)

The load for fracture initiation, critical opening displacement, and FPZ length of granite specimens under three different loading rates are shown in Fig. 6. Note that the average value of $w$ and $L$ corresponds to the average value of critical opening displacement and FPZ length at a given loading rate. It can be seen that, with the increase in the loading rate, the load stress level for fracture initiation decreases and the critical opening displacement and FPZ length gradually increase. This indicates that rock is more prone to fracture, and the microcracks are more likely to generate and propagate under a larger loading rate.

![Load for fracture initiation, critical opening displacement, and FPZ length of granite specimens under three different loading rates: (a) 0.001 mm/s, (b) 0.002 mm/s and (c) 0.005 mm/s.](image)

### 3.2. Loading scheme effect on fracture process

#### 3.2.1 Time-dependent fracture evolution characteristics under stepwise loading conditions

Fig. 7 shows the load-displacement curves of Brazilian splitting tests under stepwise loading conditions. The axial and lateral deformation of granite specimens during test are also measured using the DIC technique. It can be seen that granite specimen undergoes insignificant deformation during the constant stress loading period when a lower constant stress is applied, which indicates that almost no microcracks are generated and propagated during that period. However, obvious three-stage creep characteristics are shown when a greater constant stress is applied, which indicates that greater numbers of microcracks...
are induced during the constant stress loading period. This can be verified through the measurement of
the opening displacement ahead of the notch tips (Fig. 8). Moreover, the lateral deformation is more
significant than the axial deformation for rocks during the constant stress loading period.

![Figure 7 Displacement-time curves under stepwise loading: (a) CCBD-4-1 and (b) CCBD-4-2.](image)

The deformation-time curves present three-stage creep characteristics during the constant stress loading
period when the applied constant loading stress is equal to 3 kN (Fig. 8). It can be seen that the
deformation of granite during the primary and secondary creep stages tends to be stable, and exhibits a
rapid rise during the tertiary creep. The opening displacement ahead of the notch tips increases slowly
at a constant rate during the primary and secondary creep stages. However, it exhibits an approximately
exponential increases with increasing time during the tertiary creep. In addition, the strain fields ahead
of the notch tips change slowly during the primary and secondary creep stages, yet the strain
concentration zone ahead of the notch tips increases significantly with time during the tertiary creep, as
observed from the strain contours along the x axis. This indicates that greater numbers of microcracks
are generated during the tertiary creep, while fewer microcracks are induced in the primary and
secondary creep stages.

![Figure 8 Three-stage creep curves (CCBD-4-1)](image)

3.2.2 Characteristics of FPZ in granite under two loading schemes
The rock is considered to be in a critical state when the loading stress reaches the peak stress, or when
the rock enters the tertiary creep stage. That is to say, more microcracks are converged in this critical
state. Therefore, the FPZ of mode I fractures under stepwise loading conditions are fully developed when the rock enters the tertiary creep stage. The start point of the tertiary creep stage is generally determined by minimum creep strain rate. However, the minimum creep strain is difficult to determine directly from the strain rate curve. Based on the above analysis, the opening ahead of notch tips is determined to be closely related to the generation and propagation of microcracks. Therefore, the opening displacement rate ahead of the notch tips under stepwise loading conditions is used to determine the start point of the tertiary creep stage. It is assumed that the rock enters the tertiary creep stage when the opening displacement rate ahead of the notch tips transforms from a stable stage to an accelerated stage. Fig. 9 presents the opening displacement and its rate when the applied constant stress is equal to 3 kN.

Table 1 presents the FPZ length and opening displacement of granite in the critical state under two loading schemes. It can be seen that the average FPZ length of the granite under conventionally monotonic loading is greater than that under stepwise loading, while the average opening displacement ahead of the notch tips of the granite under monotonic loading is approximately uniform with that under stepwise loading. This observation indicates that the crack opening within the granite at the critical state under monotonic loading is same as that under stepwise loading.

4. Concluding remarks
(1) With the increase in the loading rate, the load stress level for the fracture initiation decreases, while the critical opening displacement and FPZ length increase gradually. The average FPZ length of the granite at the critical state under monotonic loading is greater than that under stepwise loading. The granite specimen exhibits obvious three-stage creep characteristics during the constant stress loading period under stepwise loading when a constant stress is sufficiently high. In addition, the opening displacement ahead of the notch tips increases slowly at a constant rate during the primary and secondary creep stages, while it exhibits an approximately exponential increases with time during the tertiary creep.
(2) The plastic strain has sufficient time to fully develop before the following incremental load when a slow loading rate is used. However, the plastic strain component may not have sufficient time to develop fully at each load increment when a high strain rate is used, thereby causing the material to stiffen.

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5. References

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