Effect of loading rate on dynamic mixed mode I/II fracture behavior in rock

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ABSTRACT: Dynamic mixed mode I/II fracture of rock is quite common in rock engineering due to various dynamic disturbances. However, the understanding of rate effect of mixed mode I/II fracture behavior in rock is still at its infancy. To investigate mixed-mode fracture under different loading rates, the split Hopkinson pressure bar tests were conducted on cracked straight through Brazilian disc sandstone specimens. The results show that the crack propagation velocity, mode I and mode II stress intensity factors, dissipated energy increase with increasing loading rate. The effect of loading rate on crack propagation path is slight. The changes in micromorphology of rock may be the main reason for the rate effect of fracture. Findings in this work can help understand the dynamic mixed mode I/II fracture in rock engineering subjected to high loading rates.

Keywords: Mixed mode I/II fracture, Stress intensity factor, Rate effect, Rock material.

1 INTRODUCTION

Dynamic mixed mode I/II (opening-sliding) fracture in rock could easily lead to the violent destruction and large-scale collapse of rock structures due to various engineering disturbances (Xie et al. 2020 and Zhou et al. 2020). The dynamic mixed mode I/II fracture toughness of rock has a pivotal role in the design of rock structures (Li et al. 2020). However, the rate effect of mixed-mode fracture behavior is still poorly understood. Therefore, it is of great significance to study the dynamic mixed mode I/II fracture of rock for assessing safety and stability in rock engineering.

In recent decades, extensive research has been carried out in investigating the mixed-mode fracture behavior of rock under quasi-static loading. Al-Shayea et al. (2020) studied the influence of confining pressure on mixed mode I/II fracture toughness of limestone using the cracked straight through Brazilian disc (CSTBD) specimen. Ayatollahi & Aliha (2007) used the generalized maximum tangential stress (GMTS) criterion to estimate modes I and mode II stress intensity factors (SIFs) of rock under different loading angles. In addition, some work has been devoted to investigating the effect of wetting-drying cycles, rock anisotropy and temperature on the mixed-mode fracture properties of rock (Hua et al. 2017; Aminzadeh et al. 2019; Yin et al. 2020). Recently, the rate effect of dynamic mode I fracture toughness has also been studied by many researchers (Dai et al. 2011 and Zhang & Zhao 2013). Nevertheless, few attention has been paid to study the mixed mode I/II fracture behavior under dynamic loading.

In this study, the split Hopkinson pressure bar (SHPB) tests were conducted on CSTBD sandstone specimens, aiming to investigate the rate effect of dynamic mixed mode I/II fracture behavior in rock. The dynamic SIFs, cracking behavior, dissipated energy and micrographs of the sandstone fracture surface were analyzed. The findings would contribute to a deeper understanding of dynamic fracture for mixed-mode I/II under various loading rates in rock engineering.

2 EXPERIMENTAL METHODOLOGY

2.1 *Specimen preparation*

The tested sandstone specimens were cored from Wuding, China. The thickness and diameter of the CSTBD specimen are 30 mm and 75 mm, respectively. The length and width of pre-existing crack are 15 mm and 1 mm respectively. To obtain the dynamic mode I, mixed mode I/II and mode II crack, the loading angle (β) is set to 0°, 15° and 30°, respectively (Ayatollahi & Aliha 2007).

2.2 *Experimental setup and method*

The detailed configuration parameters of the SHPB system were described in Li et al. (2022). The CSTBD specimen is sandwiched between the incident and transmitted bars (see Fig. 1). The high-speed camera with 100,000 frames per second and the resolution of 640 × 280 pixels was used to capture the cracking process.

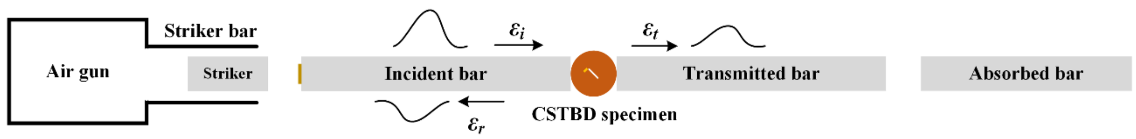

Figure 1. The SHPB system.

When the stress equilibrium in the specimen is achieved, the dynamic critical mode I (K_I^d) and II (K_{II}^d) SIFs are expressed as (Atkinson et al. 1982 and Cao et al. 2023):

$$K_I^d = \frac{P_d\sqrt{a}N_I(\alpha,\beta)}{\sqrt{\pi}tR} \tag{1}$$

$$K_{II}^d = \frac{P_d\sqrt{a}N_{II}(\alpha,\beta)}{\sqrt{\pi}tR} \tag{2}$$

where P_d is the peak dynamic load a is the half of crack length, t and R are the thickness and radius of disc, respectively, $\alpha = a/R$ is the relative crack length.

3 TESTING RESULTS AND ANALYSIS

3.1 *Dynamic critical mode I and II SIFs*

Fig. 2 shows the dynamic critical mode I and II SIFs of specimens versus loading rate for different β. It can be found that mode I and II SIFs increase with increasing loading rates. When β = 0°, corresponding K_{II}^d = 0, the dynamic mode I fracture toughness (K_{IC}^d) of sandstone increases from 0.828 to 3.048 MPa·m$^{0.5}$. Additionally, the effect of β on dynamic SIFs for mixed mode I/II is also remarkable. K_I^d decreases while K_{II}^d increases with increasing β.

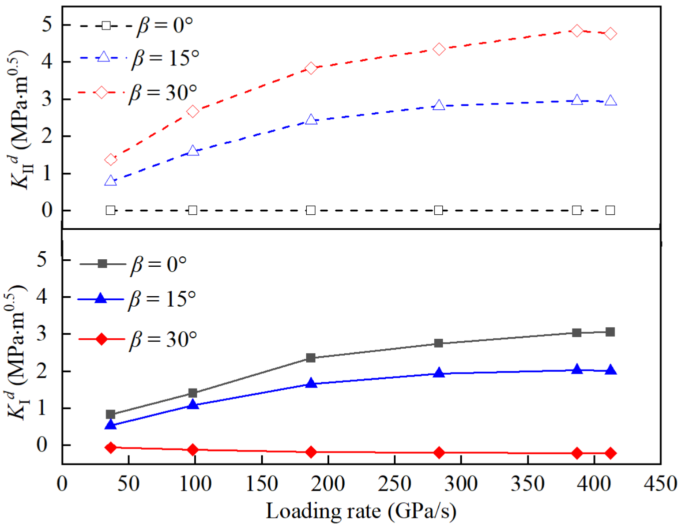

Figure 2. The dynamic critical SIFs of specimens versus loading rate for different β.

3.2 *Dynamic mixed mode I/II cracking behavior*

Fig. 3(a) depicts the mixed-mode fracture characteristics under different loading rates. Results show that the influence of loading rate on mixed mode I/II crack extension is slight. The mixed mode I/II crack initiates at the notch tip and propagates towards the incident and transmitted loading points, respectively. It should be noted that when the loading rate is greater than 387 GPa/s, the crushing zone was generated near the impact loading point due to instantaneous large compressive-shear stress induced at the specimen end (Li et al. 2022 and Zhao et al. 2023).

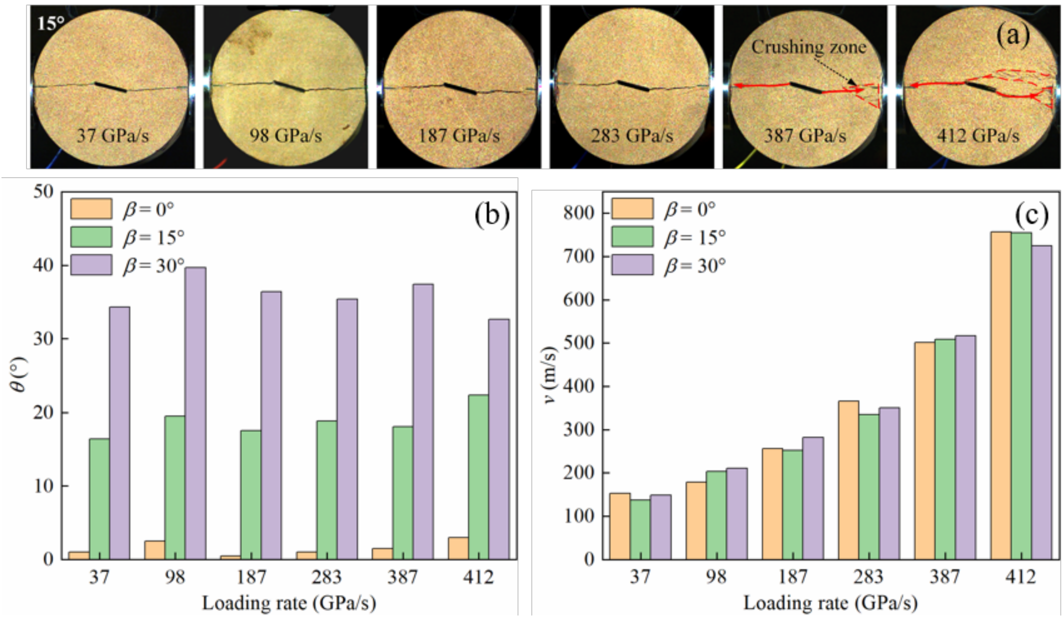

Figure 3. The dynamic mixed mode I/II cracking behavior in sandstone under different loading rates: (a) Fracture characteristics; (b) crack initiation angle; (c) crack propagation velocity.

When the loading rate increases, the crack initiation angle (θ) changes slightly, whilst θ greatly increases with increasing β, as shown in Fig. 3(b). The average crack initiation angles for mode I, mode II and mixed mode I/II fracturing are 1.4°, 18.7° and 36° respectively. In addition, Fig. 3(c) shows the effect of loading rate on crack propagation velocity (v). The effect of β on v could be neglected. v increases with increasing loading rates. It rises from approximately 146 to 746 m/s as loading rate varies from 37 to 412 GPa/s.

4 DISCUSSION

The rate effect of mixed mode I/II fracture behavior of rock results from the energy dissipation and accumulation in rock. According to the law of energy conservation, the dissipated energy (W) of the CSTBD sandstone specimen is determined by the elastic strain energy in incident and transmitted bars for SHPB system induced by corresponding stress waves. The detailed calculation method of dissipated energy can be referred to Li et al. (2022).

Fig. 4(a) illustrates the dissipated energy of specimens under different loading rates and loading angles. The dissipated energy increases significantly with increasing loading rate while almost remains constant when β increases. When the loading rate increases, the increase in transgranular (TG) fracture and the development of microcracks (MC) are the main reason for the rise in dissipated energy (see Fig. 4(b)) (Zhang & Zhao 2013). Based on the dynamic energy release rate criterion (Freund 1998), the fracture toughness for mixed mode I/II increases due to more energy absorption by specimen fracture. Therefore, microstructural changes may be the root of the rate effect of fracture in rock.

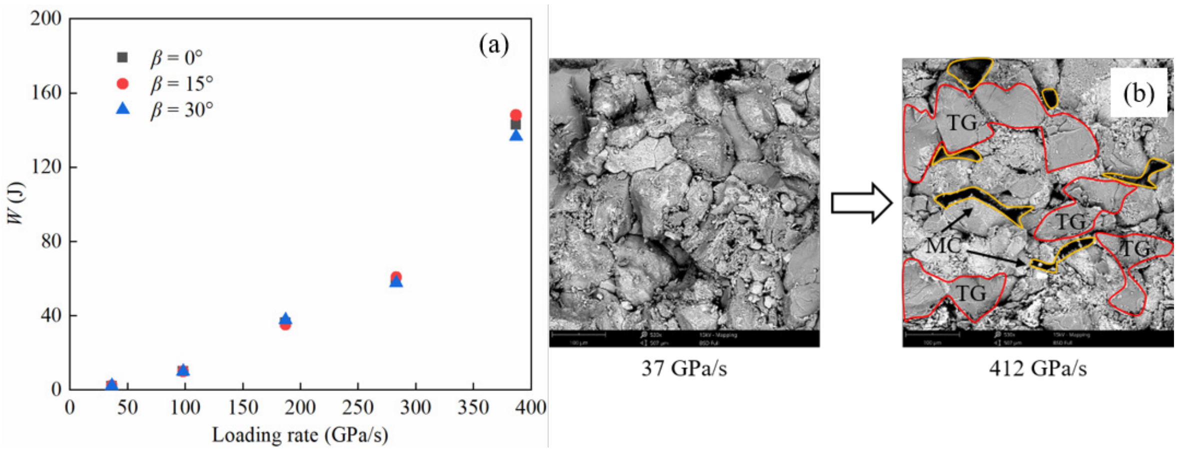

Figure 4. The dissipated energy and microscopic morphological features of rock: (a) The effect of loading rate and loading angle on W; (b) The typical micrographs of the fracture surface when β = 15° (× 530).

5 CONCLUSIONS

The main conclusions of this paper are as follows:

1. The SIFs for mixed mode I/II fracture increase with increasing loading rate. The mode I SIFs decrease while mode II SIFs increase with increasing β.
2. The crushing zone was generated at high loading rates. The influence of loading rate on crack propagation path is slight. v increases as loading rate increases, and θ increases with increasing β.
3. The dissipated energy increases significantly with increasing loading rate while changes slightly when β increases. The changes in microstructure of rock may be the main reason for the rate effect of fracture.

ACKNOWLEDGEMENTS

This work is funded by Shandong Energy Group (No. SNKJ2022A01-R26), National Key R&D Program of China (No. 2022YFC3004602), Program for Guangdong Introducing Innovative and Entrepreneurial Teams (No. 2019ZT08G315) and Shenzhen Fundamental Research Program (No. JCYJ20220818095605012; No. JCYJ20210324093402006).

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