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Laboratory study of wave propagation due to explosion in a jointed medium

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ABSTRACT

A digital laser dynamic caustics experimental system is utilized to study the dynamic characteristics of propagation of main cracks and secondary cracks in PMMA medium with flaws under explosion loads. Prefabricated through-cracks are found to open or close as a result of the explosion stress wave reflection from these flaws, which weakens the dynamic behaviors of the main cracks. These main cracks generally do not pass through prefabricated cracks and continue to propagate. Secondary cracks are generated from the ends of the prefabricated through cracks. The initiation and propagation of secondary cracks are caused by the diffraction effect of the tensile stress concentration at both tips of the flaws. The cracking angles of the secondary cracks are closely related to the prefabricated cracks and the incident angle of the explosion stress wave. The secondary cracks initiate from the direction of the maximum energy release rate, and exhibit the mixed fracture mode. The mechanical characteristic values such as the crack length, propagation velocity, and DSIF of main crack that are not directly affected by prefabricated through-cracks are much greater than the values for secondary cracks. Under explosion load, the initiation toughness is from 0.5 to 0.65 $MN/m^{3/2}$, and the arrest toughness is from 0.25 to 0.35 $MN/m^{3/2}$.

1. Introduction

Geotechnical blast engineering, conventional explosion protection engineering, water conservancy project, earthquakes and rock bursts are closely related to the transmission of stress waves in rock masses such as stone, concrete and brick with bedding or joints. Research concerning the dynamic mechanical properties of joints and stress wave propagation in rock masses is a popular topic in the field of geotechnical engineering.[1–3] Rock masses contain a variety of structural planes, weak planes and soft interludes, exhibiting significant discontinuity, anisotropy and complexity in the crushing process. It is widely accepted that these weak planes play a controlling role in stress wave propagation and in rock crushing.[4–6] Discontinuous planes in rock masses greatly affect the propagation process of a stress wave and the action of an explosive gas, resulting in stress wave attenuation and the reduction of the propagation velocity. Rock crushing is the result of the interaction of explosion stress waves and explosive gas. First, a stress wave acts on a layered rock masses, which causes cracks to open. Next, explosive gas wedges into the open cracks and prompts further fracture of the rock masses.

Due to the complexity of the problem itself, only a few researchers have done theoretical research and experimental explorations on this topic. Shi[7] studied the theoretical transient response for a crack under an impact load and the scatter of stress waves around both static and moving cracks. Bonamy and Ravi-Chandar[8] investigated the phenomenon of disturbance without bifurcation of shear waves at a crack tip. Ravi-Chandar and Knauss[9] researched the interaction between stress waves coming from different directions and advancing cracks, as well as the variation of the stress intensity factor at the tip of the cracks, using a high-speed camera. Dally[10] investigated the explosive stress wave propagation process and its interaction with cracks and holes using dynamic photoelasticity. Rossmanith et al. [11] studied the diffraction of explosive stress waves at the tip of static cracks and the regulation of crack initiations. Rossmanith and Shukla[12] investigated the mechanism of the interaction of explosive stress waves at different incident angles with cracks. Then, they analyzed the reflection, scatter, and diffraction phenomena of different incident waves in moving cracks. Finally, they obtained a series of results about the stress intensity factor, the speed of the cracking process, the positions of the crack bifurcation, and more using theoretical analysis and dynamic photoelasticity methods. Guo[13]

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studied the dynamic response of specimens containing cracks under explosive loading with different kinds of parameters using dynamic photoelasticity. Wang et al.[14] analyzed the theoretical attenuation of explosive stress waves going through cracks. Li[15] studied the stress wave propagation process in weak structural surfaces, and found the corresponding reflection coefficient and criterion. Zhu,[16–18] using dynamic photoelasticity, observed the interaction between explosive stress waves and running cracks that were produced by blasting, the post-explosion static cracks, and waves reflected by free boundaries with advancing cracks.

Although researchers[19,20] have analyzed the explosive stress wave propagation in the layers of a jointed rock masses and crack propagation regulation at different angles, because of the complexity of the rock masses structure and instantaneity of the explosion load, blasting theory research of jointed rock masses is quite limited and requires the effective support of experimental research, with a host of problems that remain to be solved and be perfected. In this work, a digital laser dynamic caustics experimental system was utilized to perform the following tasks: (1) explore the interaction of stress waves with prefabricated through cracks, (2) analyze the dynamic response of prefabricated through cracks and stress field around the running crack, and (3) obtain the regular pattern of crack propagation in the medium containing flaws. Such work not only has crucial theoretical significance but also has a practical guiding value in the optimization of blasting parameters, due to the improvement of the utilization ratio of explosives and the explosion effect.

2. Experimental details

2.1. Specimen and loading

Polymethyl methacrylate (PMMA) was chosen for this study because it is optically isotropic and has a high optical constant c, making it easy to analyze the caustics images and improve the accuracy of results. The dynamic mechanical parameters of PMMA[21] are as follows: the propagation speed of expansion waves (P-wave) and shear waves (S-wave) in PMMA are 2320 m/s and 1260 m/s, respectively; the elastic modulus E_d is 6.1 GPa; and the Poisson's ratio υ_d is 0.31. The dimensions of the specimen model are as follows: 6 mm in thickness and dimensions of 400 mm $\times$ 300 mm. The prefabricated crack through the entire thickness of the plate was machined using the modern laser cutting method, with its width controlled to within 0.3 mm. To ensure the accuracy of the test, the cutting surface should be absolutely smooth. Angles of 90°, 60°, 45°, 30°, and 0° between the prefabricated through crack axis and the explosion incident stress wave radial direction and multiple cracks were considered in this study. Geometrical form of model M (1) to M (7) is shown in Fig. 1. Specially for M (6) and M (7), they stand for multi-joints and filled joints. A prefabricated borehole with a diameter of 6 mm was located at the center of the plate. A small groove with a 60° angle, and a length of 1 mm was cut at the borehole's surface to control the direction of the initial crack. One hundred forty milligrams of a lead azide elemental explosive was placed into each hole. The signal probes of the initiating explosive were plugged from the holes, and the specimen was fixed on the loading frame. A high-speed camera was set to obtain pictures at a time interval of 10 μs.

2.2. Optical test system

The new digital laser dynamic caustics experimental system[22] includes a laser, a beam expander, a combination of field lenses, and a high-speed digital camera. The laser produces a steady optical beam. Through the beam expander and field lens 1, a parallel beam of light is incident onto the surface of the loaded specimen. After transmission through the sample, the beam is focused by field lens 2 and then passes through a high-speed camera lens to be imaged by the camera.

Changing the camera's capture speed enables the monitoring of the light intensity changing process on the reference plane using digital photos of the caustics spots. This device is easy to operate and convenient for examining the optical results of dynamic fracture testing, such as the processes of explosion and impact. Fig. 2 shows a schematic of the transmission caustics experimental system.

3. Evaluation of the dynamic behavior parameters

3.1. Crack path and velocity

The crack tip position during crack propagation can be precisely determined using the speckle-focus. Thus, the propagation crack length at each time instant is measured. The crack length difference of two subsequent photographs divided by the time interval of 10 μs is equal to the average velocity during the period.

3.2. Dynamic stress intensity factor (DSIF)

Light deflection in a plate containing cracks under tensile stress is caused by the change of both the thickness of the plate near the tip of the cracks and the refractive index of the material. A beam of parallel light that is vertically incident to the surface of the plate will vertically penetrate the plate. However, near the crack tips, the light will be deflected. Therefore, at an arbitrary plane (such as an image or a reference plane) that is not far away from the specimen on the other side, the light intensity distribution is no longer uniform. Some areas darken, while other areas become much brighter because the light intensity is doubled. The light intensity distribution is intuitively shown on the reference screen, and the stress distribution is described quantitatively by captured images. Through these various methods, the distribution of caustics can be observed in the form of real or virtual images.

The above physical process is represented by a mathematical mapping equation using the coordinate system shown in Fig. 3:

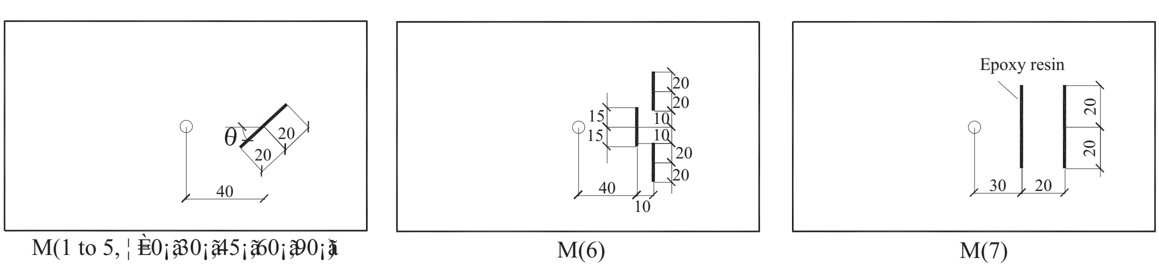

Fig. 1. The dimensions of the model specimens (units: mm).