Article

Model experiments on crack propagation between two charge holes in blasting

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Abstract

Model experiments using PMMA plates and electric detonators were carried out to observe the dynamic fracture process between two charge holes in blasting by means of high-speed videography. The experiments are related with control of fracture planes along the line connecting the charge holes in smooth blasting. In this paper, firstly, the influence of the initiation time lag on the fracture formation between two charge holes was discussed. Secondary, the effect of a guide hole on fracture control was examined. The experimental results showed that the effect of stress reinforcement exists by simultaneously firing two charges. Applicability of the guide hole method using the circular hole having two notches for fracture plane control between two charge holes was demonstrated. The fracture process near the guide hole with two notches was also analyzed by numerical calculations using the dynamic finite element method.

1. Introduction

Fracture control in blasting is very important in underground excavation and demolition of concrete structures. In underground excavation, the strength and stability of the rock walls must be maintained and smoothness of the rock wall must be achieved. The smooth blasting, such as the cushion blasting is one of the most commonly employed procedures for achieving some degree of fracture control. In demolition, the controlled blasting works must be done without damaging the remaining part of the structure. It is required to produce a maximum of blasting effects with the use of a minimum of explosives. The conversion and transmission of explosive energy to the surroundings constitute a very complicated process in blasting. Therefore, it is valuable to obtain an understanding of the dynamic behavior of stress waves, gases and cracks in the blasting process for the development of fracture control methods.

In smooth blasting, it is important to clarify the dynamic behavior of cracks between the rows of charge holes. Several researchers studied the mechanism of fracture formation and the guide hole effects on fracture plane control[1)–6)]. Numerical calculations of the problems have been made with the progress of computer machine. Y. Ogata et al. analyzed the dynamic effects of stress wave interaction with the circular hole[7)]. K. Kaneko et al. analyzed the fracture process in smooth blasting by the finite element method with a re-meshing algorithm[8)].

In this study, model experiments using PMMA specimens and electric detonators were carried out to observe the dynamic fracture process between two charge holes by means of high-speed videography. A schlieren system using an Ar-ion laser was set up for visualization of the stress waves and cracks in the blasting process[9)]. A high-speed digital video camera was used to record the dynamic fracture process. Firstly, the influence of initiation time lag of the electric detonator on fracture formation between two charge holes was discussed. Secondly, the effect of the guide hole on controlling fracture formation along the line connecting the charge holes was examined. Applicability of the guide hole method using the circular hole having two notches for fracture plane control in smooth blasting was also presented based on the experimental results and the numerical simulation.

2. Experimental methods

It is desirable to obtain a time sequence of visualization images during a blasting event. In the schlieren system, an Ar-ion laser was used as a light source. The optical arrangement of the schlieren system is shown in Fig. 1. The system consists of a set of concave schlieren mirrors of 200mm in diameter and 1500mm in focal length. A filter with high transmittance at the desired wavelengths (514nm, bandwidth 18nm) was placed in the front of the knife-edge to prevent the optical noise arisen from explosion of explosives. The high-speed video camera system of the digital storage type was used to record the visualization images. The maximum framing rate is the 40500 frames per second. The system is capable of recording 49152 frames of dynamic events.

Figure 2 shows the experimental setup using the video camera system. A pulse generator and a firing circuit to initiate an electric detonator as a charge were used to synchronize the video camera system with a blasting event. The firing circuit is capable of controlling the delay time for the initiation of the electric detonator with accuracy of the order of 1 us. The detonator has the lower 10 mm filled with the main charge, 0.4 g of PETN (penta-erythritote-tranitrate). Model experiments were performed with PMMA specimens as a transparent material. PMMA has been shown by earlier workers to be a suitable material for laboratory experiments on rock blasting process[10]. Crack patterns in PMMA are easily visible. Mechanical properties of the specimen materials are listed in Table 1. The modulus of elasticity and the Poisson's ratio were evaluated from measurements of elastic wave velocities by means of an ultrasonic pulse method, where well-known relationships between the wave velocities and the elastic constant were used. Dimensions of PMMA specimens (length×width×thickness) are 400×300×20mm^3 (Type 1) and 300×300×20mm^3 (Type 2). These were fabricated from a large sheet of PMMA (Acrylite S). Figure 3 shows the geometry of the specimen of Type 1 used in the guide hole experiment. As shown in Fig. 3, the guide hole with two notches is placed between two charges. It is necessary to identify the initiation of the detonator in order to analyze the dynamic behavior of the stress waves in the blasting process. In this experiment, a double pin ionization gauge was used to detect the initiation of the explosive charge. The ionization gauge was inserted through a hole of 1mm in diameter at the base of the charge hole. These signals were recorded in a digital storage-type oscilloscope. Two metal haloid lights were used in a reflection mode to observe crack propagation and white paper was attached to the back of the specimen to make the cracks more clearly visible.

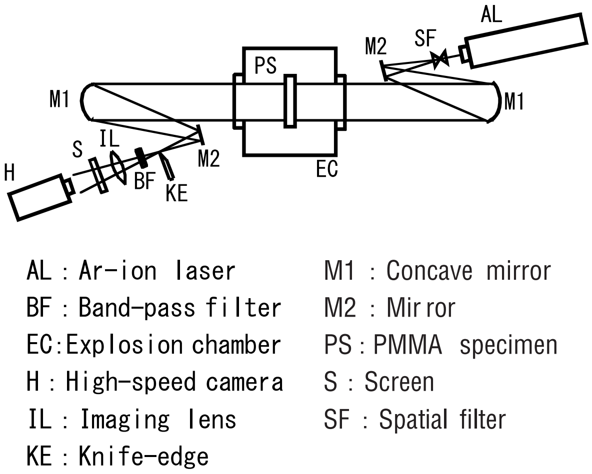


Fig. 1 Optical arrangements for visualization.

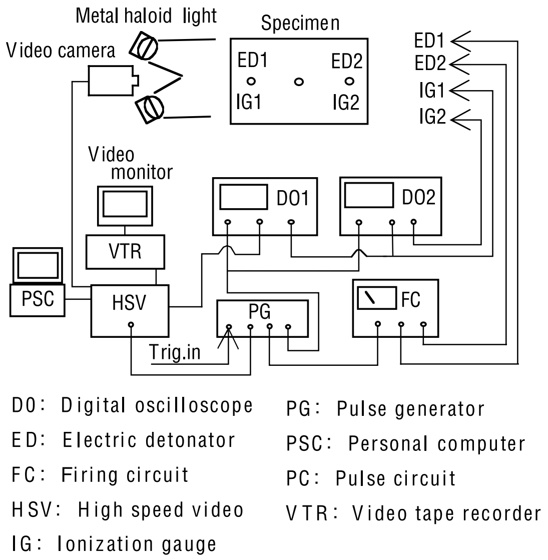


Fig. 2 Experimental set up using a high-speed video camera.

3. Results and discussion

3.1 Influences of the initiation time lag of the charge on the fracture formation

The following results have been extracted from the numerical simulation for fracture formations in smooth blasting by K. Kaneko et al[8]. The stress waves arising from the adjacent charge holes interact with each other on the line connecting the two holes so that the tensile stress in the zone between the charge holes increases and com-

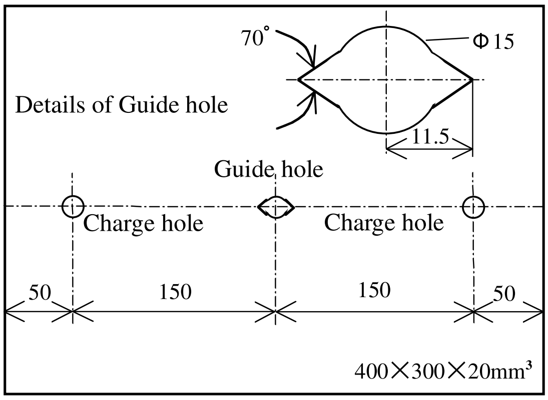


Fig. 3 Geometries of the PMMA specimen (Type 1) and the guide hole with notches.

Table 1 Mechanical properties of the PMMA specimen.

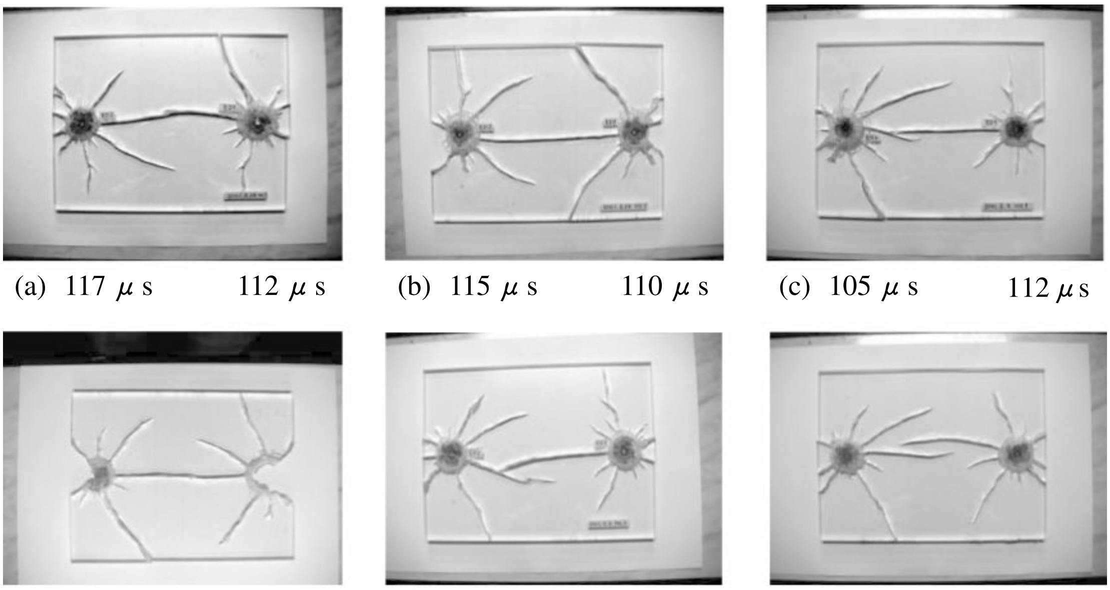
	PMMA
P-wave velocity (km/s)	2.62
S-wave velocity (km/s)	1.30
Modulus of elasticity (GPa)	5.39
Poisson's ratio	0.33
Density (kg/m^3)	1188

pression zones are formed over and under the charge holes. Thus, a fracture surface along the line connecting the charge holes is formed and the damage in the remaining parts of the zones is reduced.

Figure 4 shows fracture patterns in the PMMA specimens (Type 1) associated with firing two charges. The time indicated under each photograph is the initiation time of the electric detonator after the firing system was operated. The difference of two times is the initiation time lag of the charges. Although many cracks are formed in the specimen as a result of two explosions, only cracks located in the region between two charge holes are of primary concern. It is shown from Figs. 4 (a)~(d) that the fracture surface is formed along the line connecting the two charge holes in the cases that the initiation time lag is within about 10 μ s. The fracture surface along the line connecting two charge holes was formed by a head-on collision of the two cracks emitted from the charge holes. In the case shown in Fig. 4 (f), two cracks along the line connecting two charge holes approach each other. J. W. Dally et al. indicated the followings based on the dynamic photo-elastic experiments on smooth blasting5). When two charges are initiated simultaneously, it is possible to produce a crack connecting two adjacent charge holes. The beneficial effects of stress reinforcement in the region between two holes are minimal, since the crack extension during the passage of each of the stress waves is quite small. Figure 5 shows the fracture patterns in PMMA specimens (Type 2) associated with firing two charges. In these cases, it may be considered that the effect of stress reinforcement increases due to the shorter distance between two charge holes than that of the specimen (Type 1). It can be seen from Fig. 5 that the fracture surface is formed along the line connecting two charge holes and the other cracks progressing into the region between two holes doesn't arise.

3.2 Guide hole effects on the fracture formation connecting the two charge holes

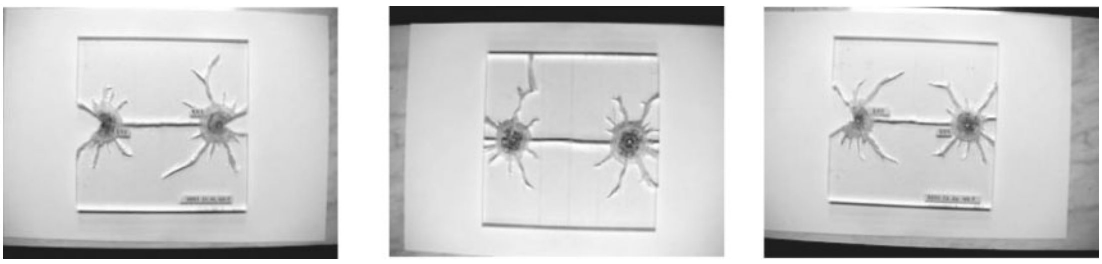
Previous experiments by J. W. Dally et al. showed that circular holes placed near the charge hole as a guide hole are not effective in fracture control unless a crack is initiated at the circular hole5). Utilization of the guide hole with



(a) 117 μ s 112 μ s (b) 115 μ s 110 μ s (c) 105 μ s 112 μ s

(d) 111 μ s 100 μ s (e) 101 μ s 125 μ s (f) 105 μ s 127 μ s

Fig. 4 Fracture patterns in the PMMA specimens (Type 1) associated with firing two charges.



(a) 110 μ s 107 μ s (b) 122 μ s 116 μ s (c) 107 μ s 129 μ s

Fig. 5 Fracture patterns in the PMMA specimens (Type 2) associated with firing two charges.

notches for fracture control was suggested by Y. Nakamura et al. on the basis of experimental results obtained from visualization of the stress waves interacting with the circular hole11)12). Figure 6 is the high-speed video images showing crack propagation in the vicinity of the circular hole without notches in the PMMA specimen (Type 1) produced by the single charge. The circular hole didn't capture the crack emitted from the charge hole. It was also seen from another experimental results that the circular hole acts to arrest the crack limiting the length along the control fracture plane.

High-speed video images showing crack propagation in the PMMA specimen (Type 1) with the circular hole between two charge holes are shown in Fig. 7. The crack propagating towards the right charge hole stopped at the guide hole and the crack emitted from the right charge hole intersected the crack from the left charge hole after passing the guide hole. High-speed video images of crack propagation in the PMMA specimen (Type 1) produced by the stress wave interaction with the circular hole having two notches between two charge holes are shown in Fig. 8. It can be seen that two cracks originating from the apexes of the notches propagate in the direction opposite to each other and the fracture plane connecting two charge holes are produced.

The fracture patterns in PMMA specimens (Type 1) with the circular hole after blasting are shown in Fig. 9. It indicates that utilization of the circular guide hole is not effective for achieving the controlled fracture formation connecting two charge holes in the present experiments. In Fig. 9 (b), the initiation time lag is small, however, the controlled fracture formation was not achieved. Thus, it appears that better control of the fracture process is necessary to achieve smoothness and precision of the fracture plane connecting two charge holes. The fracture patterns in the PMMA specimens (Type 1) with the circular hole having two notches are shown in Fig. 10. These results show that it is possible to produce the controlled fracture plane by utilizing the guide hole with two notches. Especially, it should be noted from Fig. 10 (c) that controlled fracture formation connecting two charge holes is also obtained in the case of relative large initiation time lag. On the applicability of the present method to field usage, this result is important in the following point.

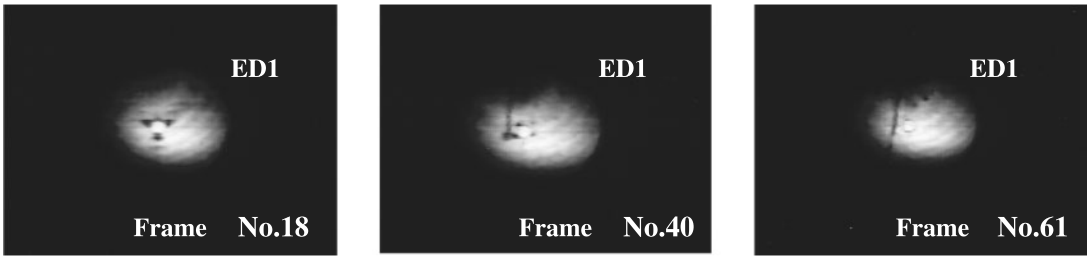


Fig. 6 High-speed video images showing crack propagation produced by the single charge in the specimen (Type 1), framing rates; 40500 $f \cdot s^{-1}$.

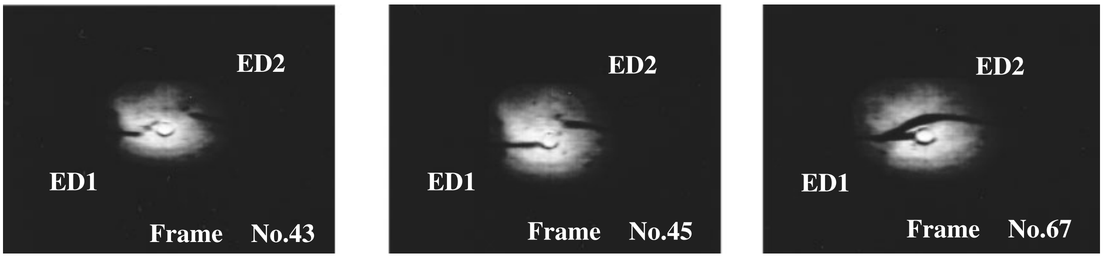


Fig. 7 High-speed video images showing crack propagation in the specimen (Type 1) with the circular hole between two charge holes, framing rates; 40500 $f \cdot s^{-1}$.

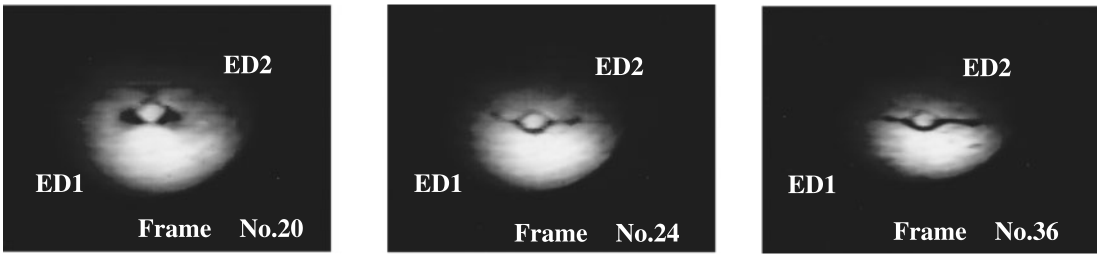


Fig. 8 High-speed video images showing crack propagation in the specimen (Type 1) produced by the stress wave interaction with the guide hole having two notches between two charge holes, framing rates; 40500 $f \cdot s^{-1}$.

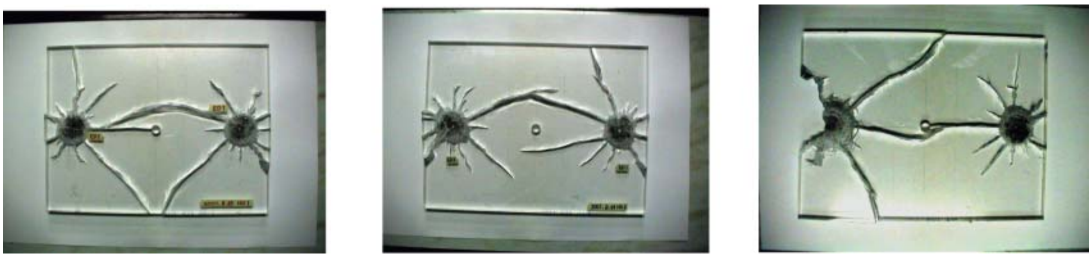


Fig. 9 Fracture patterns in the PMMA specimens (Type 1) with the circular holes between two charge holes.

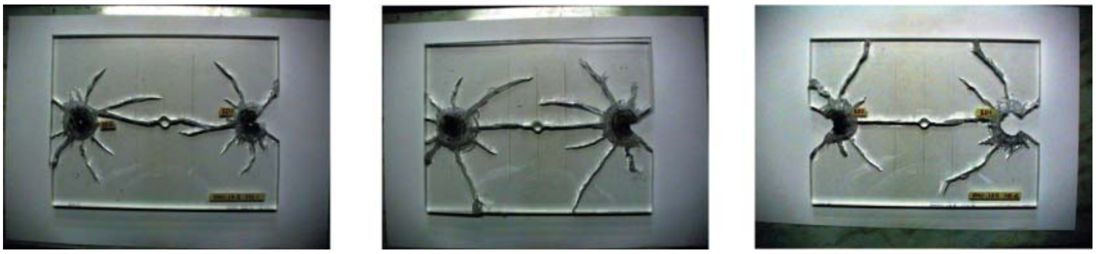


Fig. 10 Fracture patterns in the PMMA specimens (Type 1) with the circular holes having two notches between two charge holes.

M.Yamamoto et al. suggested that ground vibration in blasting can be reduced by using the electric detonator with high accuracy delay intervals (EDD) 13).

Figure 11 shows the fracture process in simultaneously firing two charges of the PMMA specimen (Type 1) obtained from the numerical simulation using the dynamic finite element method with the re-meshing algorism8)14). The PMMA specimen was considered to be the fracture energy of 300 Pa·m, the average micro tensile strength of 5.0MPa and the coefficient of uniformity of 5.0. The stress is positive in tension and negative in compression at all times. It can be seen from Fig. 11 (c) that the tensile stress fields are produced in the vicinity of the notches of the guide hole at time,110 μs. The dynamic behavior of cracks initiated from the guide hole is similar to that obtained from the video images, Figs. 8 (b)(c). Although the two dimensional condition of the problem is satisfied in simulation, it must be recognized that the tested PMMA specimen is a plate and the two dimensional conditions is not satisfied in the experiment. Therefore, the fracture process in Fig. 11 includes the mechanism for crack growth by the stress field due to the residual explosion gas.

The borehole having two notches is made with a mechanical broaching tool. Mukugi et al. developed a drilling system with grooving tools applicable to hard rocks like granite. The system enables us to easily create a borehole with notches in a single pass 15).

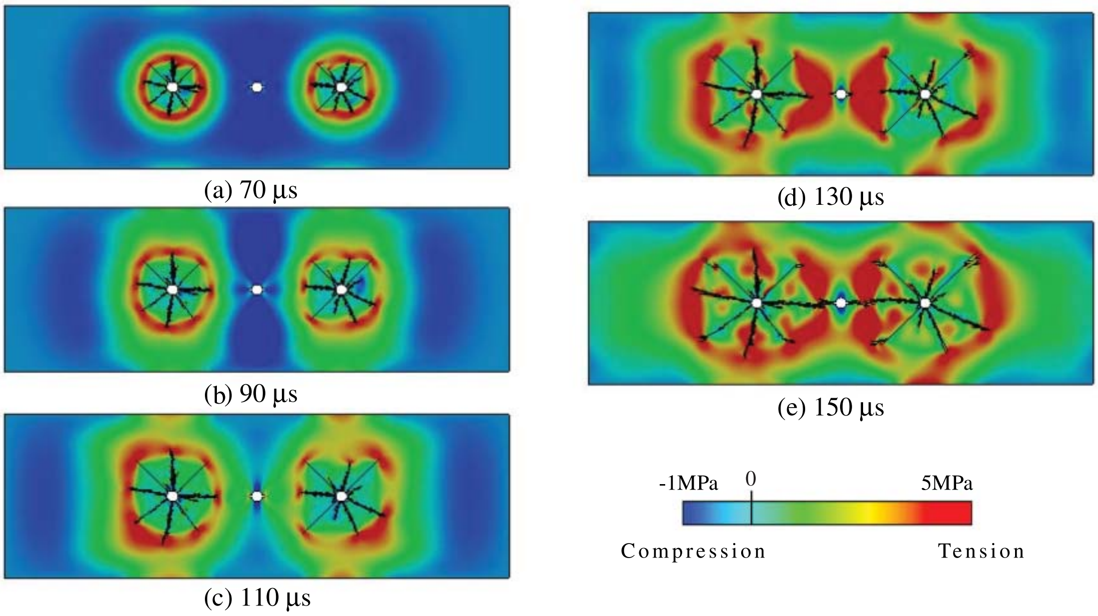


Fig. 11 Distributions of the maximum principal stress and crack propagation associated with firing two charges in the PMMA specimen (Type 1) with the guide hole having two notches obtained from the numerical calculations.

4. Conclusion

Model experiments using PMMA specimens and electric detonators were made to examine to the dynamic behavior of cracks between two charge holes in smooth blasting. Crack propagation was observed by the high-speed video camera. In the case of simultaneously firing two charges with small time lag, the fracture surface was formed along the line connecting the charge holes. It can be considered that stress waves reinforce each other in the region between two charge holes. The circular guide hole between two charge holes is not effective in fracture plane control. The hole acted to arrest the crack and did not control the propagation direction of the crack emitted from the charge hole. The circular guide hole with two notches is effective in driving the cracks along the line connecting two charge holes. The dynamic behaviors of cracks in the vicinity of the guide hole with two notches obtained from the experiment could be demonstrated in the numerical simulation. The presented guide hole method is applicable in field usage.

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