Experimental and numerical study on crack-propagation control in blasting

SangHo Cho (Chonbuk National University)
Yuichi Nakamura (Yatsushiro National College of Technology, Japan)
Katsuhiko Kaneko (Hokkaido University, Japan)

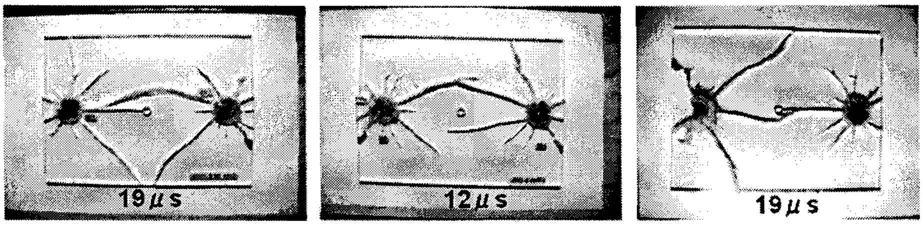
1. INTRODUCTION

Mechanical excavation techniques employing tunnel boring machines (TBM) and rock splitters have been proposed to minimize rock damage. These then can serve as underground repository sites for nuclear waste disposal with the rock forming a natural barrier against possible seepage or leak. Such mechanical excavations, however, are extremely expensive and not applicable in all cases. One way of achieving controlled crack growth along specific directions and inhibit growth along other directions is to generate stress concentrations along those preferred directions[1]. The most direct way of achieving this is to introduce notches along the prescribed directions on the surface of the bore-hole wall. This results in a very high stress concentration at the notch tips when the gas pressure acts on the bore hole wall, or a stress wave reaches a guided hole.

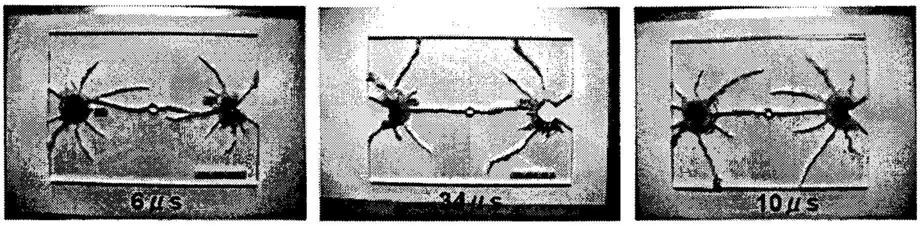
In this study, fracture properties for analyzing blasting-induced fracture processes in PMMA specimens were estimated by comparing the blast induced fracture patterns generated from experimental tests and numerical blast models. The model experiments, which employ a guide hole between the charge holes, are analyzed by the dynamic fracture process analysis (DFPA) code [2] to examine the effect of the notched guide hole on crack-propagation control in blasting. The effect of the guide hole, distance between the charge holes, and the initiation time error on crack-propagation in blasting are investigated in this paper.

2. PMMA LABORATORY BLAST TESTS

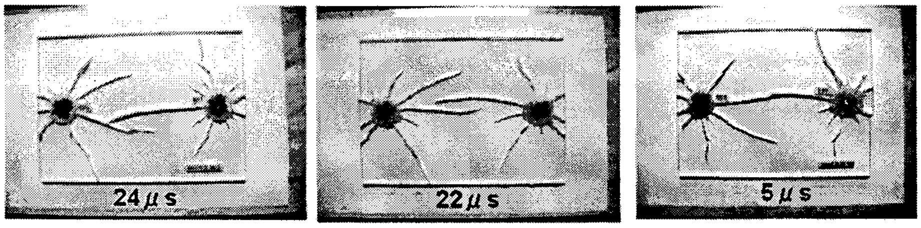
Nakamura and Cho et al. [3] carried out model experiments using PMMA specimens and electric detonators to observe the dynamic fracture process by means of high-speed video graph. A high accuracy firing circuit is used to control firing time of two charges. The dimension of PMMA specimens (length×width×thickness) was $400\times300\times20\mathrm{mm}^2$ for Model I and $300\times300\times20\mathrm{mm}^2$ for Model II experiments. Figure 1 shows examples of fracture patterns produced by blasting in PMMA specimens. These studies revealed that in the case of simultaneous firing of two charges with very small inter-hole delay, the resulting fracture was co-linear along the line connecting the charge holes. The circular guide hole between two charge holes was found to be not effective in fracture plane control. The circular guide hole with two notches, on the other hands, was toward to be effective in driving the cracks along the line connecting two charge holes.



(a) With a regular guide hole



(b) With a guide hole having notches toward side the charge holes



(c) Without a guide hole

Fig. 1 Fracture patterns in the PMMA specimens having a guide hole between two charged holes (after Nakamura and Cho [3]). The times shown on each picture are firing-time error between two charge holes.

3. DYNAMIC FRACTURE PROCESS ANALYSES OF PMMA BLAST TESTS

3.1 Fracture properties for simulating laboratory blasting

The dynamic fracture process analysis (DFPA) code which employs the microscopic strength inhomogeneity and the FPZ model was used to simulate the laboratory blast experiments of PMMA specimens. In the DFPA code incremental displacement form of a dynamic finite element method is used to describe large-scale displacement behavior. A re-meshing algorithm is used to model crack propagation, assuming that tensile fractures, i.e., crack initiation, propagation, and coalescence, occur at element boundaries. A no free-surface model was used, consisting of a charge hole. The outer boundary is considered as a continuous boundary. The analysis model was divided into

Table 1 Input parameters for analyzing the dynamic fracture processes of PMMA in blasting

Parameter	Value
P-wave velocity V_p (m/s) [1]	2620
S-wave velocity V_s (m/s) [1]	1300
Density (kg/m^3) [1]	1188
Elastic modulus (GPa) [1]	5.39
Poisson's ratio [1]	0.28
Fracture energy (Pa·m or N/m)	10, 50, 100, 300
Mean microscopic yield strength S_t(MPa)	50,75,90,105,120
Mean microscopic tensile strength S_y(MPa)	10,20,30,40

triangular elements. The parameters for the analysis model are listed in Table 1. The minimum size of elements around the borehole is 1mm. In order to avoid mesh-dependency on dynamic fracture process analysis, the mesh size should be as small and uniform as possible. Because there are limitations on computational capability due to the complex geometries and dynamic analysis for simulating the laboratory test blasts having several holes, fine meshes were used around only the borehole as shown in Fig. 6. Note that the length of cracks generated through the boundaries of elements should be smaller than the characteristic lengths of the FPZ. This characteristic length l_{FPZ} can be estimated as $G_f{\times}E/(S_t^2(1\text{-}v^2))$ and equals 3.2 mm referring the values in Table 1.

To apply a blast pressure to the hole boundary, the following pressure function $P(t)$ with respect to time 't' was used:

$$P(t)=P_{jwl}(V(t))P_s(t) \qquad (1)$$

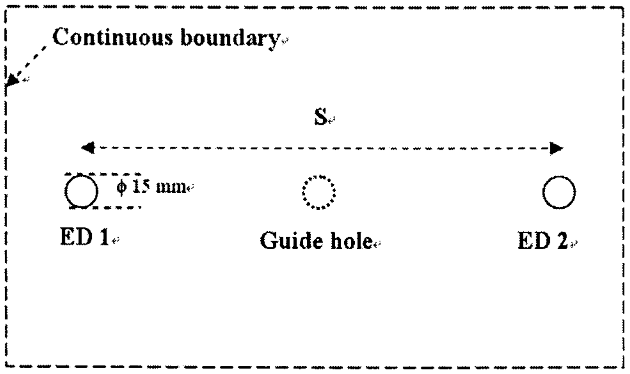
where, $P_{jwl}(V(t))$ is the JWL pressure, which has been extensively used to describe the isentropic expansion of detonation products, and is called the JWL equation of state, and $P_s(t)$ denotes a trapezoidal function with 1μs rise time. $V(t)$ is the relative volume, $V_e(t)/V_o$. Here, $V_e(t)$ is the volume of gas produced and V_o is the volume of the explosive. In this study $V_e(t)$ is calculated from the expanded volume of charge hole.

The parameters used and calculation conditions are listed in Table 1. However, fracture energy and strengths of PMMA subjected to the detonation of explosive are unknown. We tried to evaluate the fracture properties by comparing resulting fracture patterns obtained from the laboratory blast tests [3] with patterns calculated in the analysis models considering the calculation conditions listed in Table 1. The analysis models which consider 50, 75, 90, 105 and 120MPa for the mean microscopic yield strengths were simulated respectively and the yield strength S_y and yield zone r_y were plotted with peak pressure P_{max} and radius of the charge hole a. Considering the ratio $r_y/\,a$ and the peak value, the mean microscopic yield strength S_y was estimated as 66 MPa. Note that we considered glassy and densely crack zone around the charge hole as yield zone. Using the estimated

N_c*l_c/a of 105.17, the mean microscopic tensile strength S_t was estimated to be 20 MPa when G_f is 240 Pa•m.

3.2 Dynamic fracture process in PMMA laboratory blast tests using a guide hole

The laboratory blast experiments explained in section 2, which have a notched guide hole between the charge holes, were analyzed by the DFPA code to study the effect of the guide hole on crack-propagation control in laboratory scale blasting of PMMA. The fracture parameters estimated in section 3.1 were used in the analysis model.



S: Distance between the charge holes

ED: Charge hole

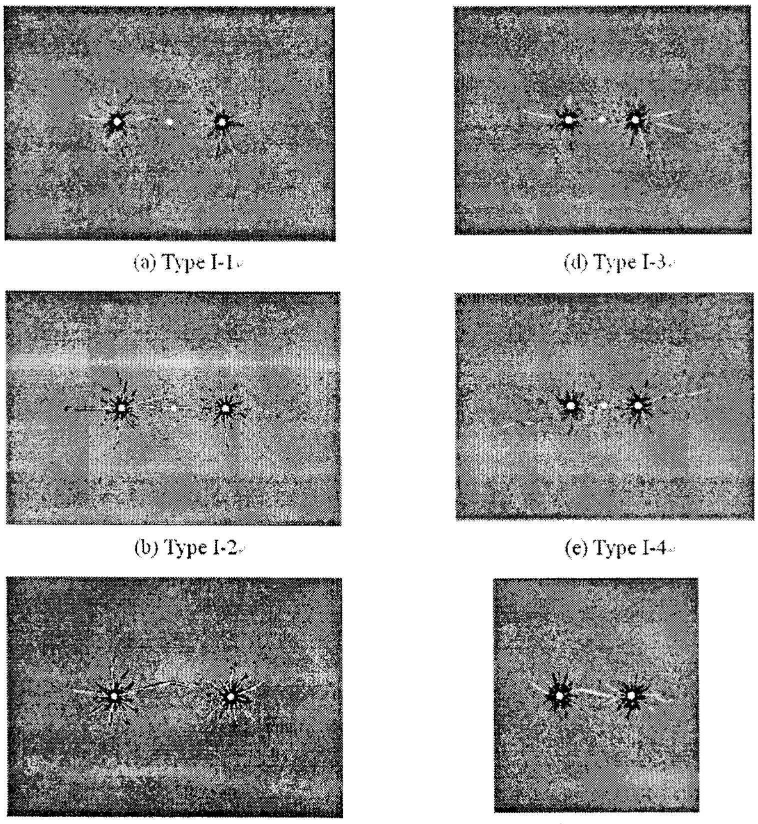
Fig. 2 Schematic geometry for the analysis model

Figure 2 show the schematic geometry for simulating laboratory scale blasts of PMMA specimen, consisting of two charge holes and a guide hole between two charge holes. A no free-surface model was used to avoid the effect of reflected tensile waves from the model boundaries on the formation of a fracture plane. In order to investigate the effects of guide hole and drill-hole pattern, six blast geometries were modeled as shown in Table 2.

Table 4 Blast patterns for simulating the laboratory blast tests of PMMA

Laboratory Blast Model	Spacing S (cm)	Type of the guide hole
Type I-1	30	Notched
Type I-2	30	Regular
Type II-1	30	None
Type I-3	20	Notched
Type I-4	20	Regular
Type II-2	20	None

Figures 3 show the resulting fracture patterns for all the models. Compressive yield zones appear around the charge holes and radial cracks (as lines) are generated from near compressive yield zone. Here, white line and black line indicates the opening crack and micro-cracks within the fracture process zone respectively. Note that Model I-3, Model I-4 and Model II-2 have 20 cm spacing between the charge holes. Contrary to the types that have 30cm spacing, cracks connect between the charge holes for all cases. It is most likely that stress concentration increment caused by decreasing of the distance between the charge holes led to the generation and propagation of the cracks between the holes. The results show that both the notched guide hole and circular guide hole are effective on control of crack propagation control in blasting. Furthermore, introduction of notched guide holes results in a smoother fracture plane. These results agree well with the findings from the model analysis.



(a) Type I-1

(d) Type I-3

(b) Type I-2

(e) Type I-4

(c) Type II-1

(f) Type II-2

Fig. 3 Resultant fracture patterns for different specimen types (white and black line indicates opening crack and micro-cracks respectively)

4. CONCLUSIONS

In this study, fracture process in laboratory-scale blasting of PMMA has been analyzed. The mean microscopic yield strength S_y and mean microscopic tensile strength S_t for a PMMA blast model were estimated as 66 MPa and 20 MPa respectively. Six blast geometries, which constitute the model experiments, were analyzed numerically. This study showed that both the notched guide hole and circular guide hole are effective in controlling crack propagation in blasting. Furthermore, introduction of notched holes leads to earlier crack generation and smoother fracture plane.

REFERENCES

1. Fourney WL, Holloway DC, Dally JW, Fracture initiation and propagation from a center of dilatation. Int J Fracture 1975;11: 1011-1029
2. Cho SH, Kaneko K., Influence of the applied pressure waveform on the dynamic fracture processes in rock, Int. J. Rock Mech. Min. Sci. 2004;41: 771-784
3. Nakamura Y, Cho SH, Yoneoka M, Yamamoto M, Kaneko K. Model experiments on crack propagation between two charge holes in blasting, Science and Technology of Energetic Materials, 2004;65:34-39