International Symposium on Earth Science and Technology, CINEST 2012

Relation between the Velocity Profile at the Free End and Fracture Information of Rock Sample

Shiro Kubota\textsuperscript{a}, Tei Saburi\textsuperscript{a}, Yuji Ogata\textsuperscript{a}, Yuji Wada\textsuperscript{a}, and Ganda M. Simangunsong\textsuperscript{b}\textsuperscript{,}a*

\textsuperscript{a} Research Institute of Science for Safety and Sustainability (RISS), National Institute of Advanced Industrial Science and Technology, 16-1 Onogawa, Tsukuba, Ibaraki, 305-8569 Japan
\textsuperscript{b} Institute of Technology Bandung Jl. Ganesha 10 Bandung 40132, Indonesia

Abstract

To establish the effective method for blasting, the understanding of the dynamic fracture process is important. We have proposed the dynamic fracture test for rock which has employed the underwater shock wave generated by explosion of explosive. This report presents the estimation method for the tensile strength of rock materials using the experimental results obtained by our proposed fracture test.

Keywords:

1. Introduction

Explosive energy has been utilized for blasting, which is necessary in mining and quarrying operations and some civil engineering applications. Since structures that were built during the boom year have a relatively short lifespan, large numbers of these structures will be required to be demolished in the near future in Japan. Because of its low cost and high efficiency, the demolition, which utilizes blasting, may become one of the most powerful methods once the effective technique is perfected in Japan. In order to promote blasting efficiency and to establish effective blasting demolition techniques, it is important to know the mechanism of the dynamic fracture process on rock or construction materials. The fragmentation by blasting is the joint action of gaseous pressure and stress waves (Bhandari 1997). Since the stress wave greatly depends on the fracture conditions near the explosion source, the fragmentation near the free surface by the reflection of the stress wave also depends on it. Therefore, it is necessary to consider the experiments that can simultaneously estimate both the fragmentation conditions near the explosion source and those near the free surface. The experimental and numerical studies were conducted to understand the behavior of the dynamic fracture of the rock under the explosive loading. In the experimental study, a new technique, which include underwater explosion as dynamic loading, was proposed. The explosive material is used as the explosion source, and a pipe filled with water is arranged between the explosive and the cylindrical rock specimen. The strength of the shock loading can be adjusted by changing the length of the pipe.

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: author@institute.xxx.
2. Experiment and Theory

Figure 1 shows the experimental set up for the proposed fracture test (Kubota et al. 2006). During the fracture process of the rock, the free surface velocity and the fracture part near the free surface were observed by a laser vibration meter (OFV-300; made by Polytec) and high speed camera (model 124 framing type camera; made by Cordin). The light source for a high speed camera uses a Xenon flashlight. The precise detonator was used to control the initiation time of the explosive by using an accurately controlled blasting machine, which was made by Nihon Kayaku Co. Ltd.

Figure 2 shows the part of the explosion source for the proposed fracture test. For the explosion source, the emulsion explosive was used. Because the detonation product rapidly expands and obstructs the view of the high speed camera, the explosive is set in the double layer pipe. After the explosion by the precise detonator, the detonation wave interacts with water, and the underwater shock wave generates in the pipe filled with water. Since the underwater shock wave attenuates with its propagation, the impact strength of the shock wave into the rock specimen can be easily adjusted by changing the length of the pipe.

In this experiment the length of the pipe was varied as 30, 50, 70, 100, 150, 200 and 300mm. Kimachi sandstone was used as the rock specimen with 60mm diameter and 300mm length. Arrival time at the free surface of the stress wave from the initiation of emulsion can be roughly estimated in the following for the trigger setting. The transit time of the detonation wave in the explosive pipe is about 18μs estimated by 4000 m/s average detonation velocity and 70mm length of the pipe. The underwater shock wave spends 25μs to pass through the water part estimated by the 2000 m/s average velocity of the underwater shock wave and the 50mm length of the water pipe. By using the average velocity of the 2700m/s longitudinal wave of Kimachi sandstone, it is understood that the stress wave pass through the rock specimen about 110μs.

Under the action of one-dimensional shock loading, the stress that acted on the material is given by:

\[ \sigma = \rho C_p v \]  \hspace{1cm} (1)

Where \( \rho \) is density, \( C_p \) is the velocity of elastic wave and \( v \) is the particle velocity of the material. Hino (Hino 1956a and b) showed that reflection of the shock wave at the free surface causes the fracture of the rock near the free surface, and he proposed the original method for determining the dynamic tensile strength of the rock materials.

Figure 3 shows the conceptual diagram for the estimation method of dynamic tensile strength proposed by Hino. In this figure the upper one corresponds to the stress distribution when one-dimensional shock wave reaches the free surface, and the lower one corresponds when spalling occurs. If there is no free surface, the shock wave travels into the rock material which is shown as a broken line in this figure. However due to the existence of the free surface, the shock wave goes back to the opposite side as a solid line. The tensile stress near the free surface can be estimated by using both compressive and tensile components, \( Pa + (-Pb) \). The sign plus corresponds to tension. Finally when the sum of these components exceeds the dynamic tensile strength \( S_d \), the fracture of the rock material just occurs.

Therefore \( S_d \) can be expressed as follows:

\[ S_d = 2Pa\delta /L_1 \]  \hspace{1cm} (2)

Where \( \delta \) is the distance from the free surface to the fracture surface and \( L_1 \) is the pulse width of the stress wave. In the above concept, there are three important assumptions, 1) the phenomena is one-dimensional, 2) the stress wave is a triangle pulse and a shock wave and 3) the stress wave, which travels in the materials by free surface, is steady near the free surface. From these assumptions, \( L_1 \) can be obtained by the number of slabs \( N \) as in the following equation.

\[ N = L_1 / (2\delta) = Pa / Sd \]  \hspace{1cm} (3)

Ma et al (Ma et al 1998) also indicated the prediction method for dynamic tensile strength of rock materials.
History of the free surface velocity $v(t)$ is continually measured by using a laser vibration meter, and is converted to stress history at an inner point of the material. Figure 4 shows the conceptual diagram for determining the dynamic tensile strength. In this case the assumption 2) has not been considered, because the history of the stress wave is obtained directly from the experiment. Instead, one assumption is added, which is that the fracture occurs when the peak of the stress wave for the tensile component arrives at the fracture surface. From the free surface approximation, the peak stress of the tensile component is $\rho C_p v(tp)/2$. The dynamic tensile strength is given by

$$S_d = \rho C_p \left(-v(tp + 2\Delta t)\right)/2 + \rho C_p v(tp)/2 \tag{4}$$

The first term corresponds to the compressive component, and $\Delta t = \delta/C_p$. One of the purposes of this fracture test is to estimate the dynamic tensile strength of the rock according to above estimation methods, and we will discuss the relation between the results of the test and the assumptions in the methods.

3. Results and Discussion

Figure 5 shows the relationship between pipe length and the distance from the free end to the fracture position where a crack first appeared near the free end. These distances are measured at the eight equal points that divided the circumference of the ejected specimen. The average of these distances is defined as the distance from the free end to the fracture position. In this paper, this average distance is merely called measured fracture distance. The velocity profiles at the free end of the rock specimen are shown in Fig. 6. The data for two different shots are plotted. The velocity profiles show excellent reproducibility of the measured velocity at the free end under the same shock loading.

After the maximum velocity appears, if the crack does not grow, the velocity profile decreases...
continuously without disturbance. However, a small disturbance appears which may be an effect of crack initiation or growth.

Figure 3. Conceptual diagram for the estimation method of dynamic tensile strength proposed by Hino

Figure 4. Conceptual diagram for the estimation method of dynamic tensile strength (Ma et al. 1998)
At about 70 μs, an inflection point, i.e., the local minimum value, appears. It is plausible that this change is caused by a decrease in the strength of the specimen due to sufficient crack growth. Finally, the completely grown crack was confirmed by high speed photography. After fragmentation, ejected part moves with nearly uniform velocity. It can be suggested that, the velocity profile at the free end is affected by crack initiation or growth. After that point, the velocity profiles cannot be used to estimate stress. The inflection point at about 70 μs is an arrival time of information to the free end from the damage zone in which the specimen loses its strength. By using this point, a certain point in damage zone can be specified.

Even if the length of the pipe was the same, the measured fracture distance varied. These results are inconsistent with the excellent reproducibility of the velocity profile. The velocity profile reflects the degradation of strength in the whole damage zone containing the fracture cross section rather than that from a fracture cross section. It can be considered that since sandstone has a comparatively homogeneous characteristic macroscopically, there is reproducibility in the formation and growth of a damage zone. The concept of the formulation of the tensile strength does not consider the formation of the damage zone. To acquire the effect of the damage zone to the formulation of dynamic tensile strength, the local minimum point at the velocity profile has been selected to determine the representative point of information on the fracture instead of the fracture cross section. We will define such representative point as average fracture point.
4. Estimation Method

For estimation of the dynamic tensile strength, the average fracture point which is obtained by velocity profile is employed instead of the measured fracture distance estimated by recovered specimen (Kubota et al. 2008). The conceptual diagram for the proposed estimation method of dynamic tensile strength is shown in Fig.7. We defined the $t_B$ as the time from the arrival time of the stress wave to the first inflectional point. The arrival time of the peak stress is $t_p$. The $\Delta t_d$ denotes $t_B - t_p$. The length from the free end to the fracture activation point, $L_g$, can be calculated as follows.

$$L_g = \left( \Delta t_d - t_p \right) / 2 \times C_p .$$  \hfill (5)

The improved formulation to estimate the dynamic tensile strength can be written,

$$\sigma_d = \frac{\rho C_0}{2} \left[ -V_f(t_p + 2\Delta t_g) + V_f(t_p) \right] ,$$  \hfill (6)

Where $\Delta t_g$ is:

$$\Delta t_g = L_g / C_0 .$$  \hfill (7)

![Figure 7. The conceptual diagram for the damage zone and the fracture activation point](image)

The proposed method is effective for the evaluation of tensile strength when there is reproducibility in the velocity profile like sandstone.

References

1. Bhandari, S., Engineering rock blasting operations”, A.A.Balkema, Rotterdam, Brookfield, (1997).
2. Hino, K., Fragmentation of rock through blasting, Journal of the industrial explosives society, Japan 17, 1, pp.2-11, (1956a).
3. Hino, K., Velocity of rock fragments and shape of shock wave, Journal of the industrial explosives society, Japan 17, 4, pp.236-241, (1956b).
4. Kubota, S., Ogata, Y., Wada, Y., Simangunsong, G. Shimada, H., Matsui, K., Behaviors of cylindrical rock specimen under dynamic load, Science and Technology of Energetic Materials vol.67 pp124-128, (2006).
5. Kubota, S., Ogata, Y., Wada, Y., Simangunsong, G., Shimada, H., Matsui, K., Estimation of dynamic tensile strength of sandstone, International Journal of Rock Mechanics & Mining Sciences 45 pp 397-406, (2008).
6. Ma G., Miyake A., Ogawa T., Wada Y., Ogata Y., Seto M. and Katsuyama K., Study on the Numerical Investigation on breakage behavior of reinforced concrete by blasting demolition, Journal of the Japan explosives society 59,2, pp.49-56, (1998).