Crack propagation velocity of granite by impact splitting tests

Vitesse de propagation des fissures du granit par des tests de fissuration par impact

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ABSTRACT

In this study, impact splitting tests were carried out by loading cylindrical granite specimens horizontally and obtaining the crack propagation velocities by an image analysis using a super-high-speed video camera, which has the fastest frame rate in the world. The relationship between the impulse and the crack propagation velocity indicates that there appears to be a critical state at which the crack propagation velocity does not exceed a certain value even if an increased impulse is applied. The critical value obtained for the granite specimens was 2.6 km/sec.

RÉSUMÉ

Dans cette étude, des tests de fissuration par impact ont été effectués par le chargement horizontal d'échantillons de granit cylindriques et l'obtention des vitesses de propagation des fissures en analysant les images réalisées avec une caméra vidéo à super haute vitesse dotée de la vitesse de défilement la plus rapide du monde. Le rapport entre l'impulsion et la vitesse de propagation des fissures indique qu'il semble y avoir un état critique à partir duquel la vitesse de propagation des fissures ne dépasse pas une certaine valeur même si une plus grande impulsion est appliquée. La valeur critique obtenue pour les échantillons de granit a été de 2,6 km/sec.

Keywords : Impact splitting test, image analysis, impulse, crack propagation velocity, granite

1 INTRODUCTION

The propagation velocity of the cracks in a fault plane that cause seismic motion is estimated at about 2.5 km/sec (Geller, 1976). As for this crack propagation velocity, further study is needed to clarify the outbreak mechanism of the seismic motion. However, studies on the crack propagation velocity in brittle materials, like granite, have not yet been experimentally confirmed. Recently, Eto et al. (2003) made advances in a study that clarifies various physical and mechanical phenomena visible due to the development of a super-high-speed video camera which can take digital images at a speed of 1,000,000 frames per second. Moreover, Tamano et al. (2005) developed the impact testing machine which can be used for studying material properties at impact compression and in impact tension tests with high accuracy. In addition, it is experimentally shown that the failure patterns for granite differ greatly due to static and impact loading. Even the impact loading differs greatly depending on the induced impulse.

Based on these studies, impact splitting tests were carried out in the present study on horizontally laid cylindrical granite specimens (hereafter, simply referred to as specimens). Crack propagation patterns and crack propagation velocities were then examined by an image analysis through the use of the super–high-speed video camera.

2 IMPACT SPLITTING TESTS

2.1 *Method of impact splitting tests*

The impact testing machine developed in this study is shown in Figure 1. A heavy weight was dropped

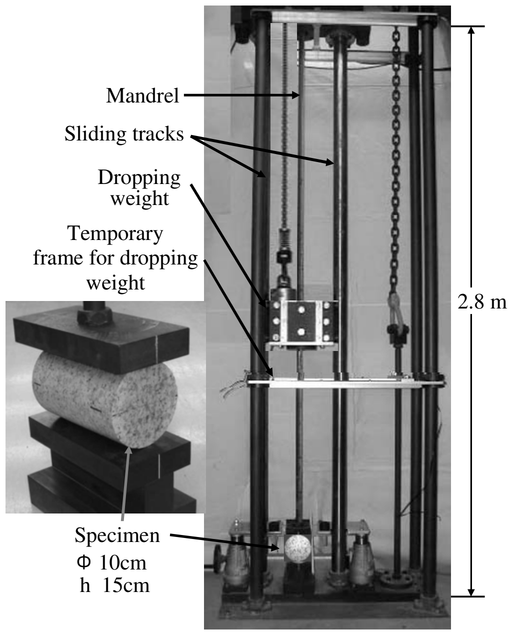

Figure 1. Impact testing machine.

accurately in a vertical direction, and close attention was paid to directing the impulse at the granite specimen. Impact splitting tests were used in this study for two reasons: one was to perform the experimental method that can produce a crack in a vertical direction in each granite specimen, and the second was to guarantee the material homogeneity due to the short size of the granite specimen. Each granite

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specimen was 10 cm in diameter by 15 cm in height. Moreover, half-size granite specimens, namely, 10 cm in diameter by 7.5 cm in height, were also prepared.

2.2 *Material properties of granite*

The values for the strength and the elastic modulus of the granite specimens were derived from static compression tests, pure tension tests, and static splitting tests, as shown in Table 1. Moreover, dynamic elastic modulus E_d, primary wave velocity V_p, secondary wave velocity V_s, dynamic Poisson's ratio v_d, and rigidity modulus G are shown in Table 2.

3 EXPERIMENTAL RESULTS OF STATIC SPLITTING TESTS

First of all, static splitting tests were conducted in order to further understand the results of the impact splitting tests. The static splitting tests were carried out with four sets of loading speeds, namely, 70 kN/min, 210 kN/min, 600 kN/min, and 800 kN/min. The tensile strength in the static splitting tests, in which the granite specimen is laid horizontally with the load applied in a vertical direction, could be calculated according to the mechanical assumption of static splitting failure. In other words, the same tensile stress was produced uniformly in the vertical direction from the elasticity theory. As the dispersion of cracks could not be clearly observed by the naked eye, even in the static splitting tests, the super-high-speed video camera was used. Moreover, a method to change the impact sound into voltage as a trigger technique was applied during this image analysis.

Table 1. Strength and elastic modulus of the granite specimens.

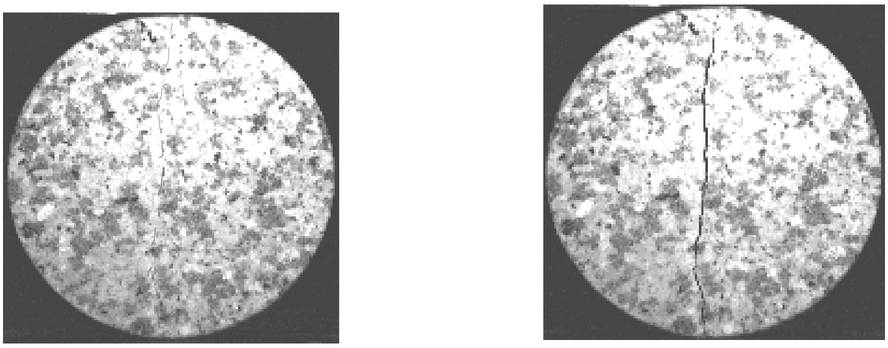
Test	Strength (MPa)	Elastic modulus (GN/m^2)
Compression	150.6	51.7
Pure tension	5.0	27.5
Splitting tension	5.9	25.5

Each value is the average of five tests.

Table 2. Dynamic properties of the granite specimens.

P wave velocity (km/sec)	S wave velocity (km/sec)	Dynamic elastic modulus (GN/m^2)	Dynamic poison ratio	Modulus of rigidity (GN/m^2)
4.0	2.1	29.3	0.31	11.2

Each value is the average of ten tests.



at 300 µsec   at 360 µsec

Figure 2. Failure pattern for the static splitting tests captured by the image analysis.

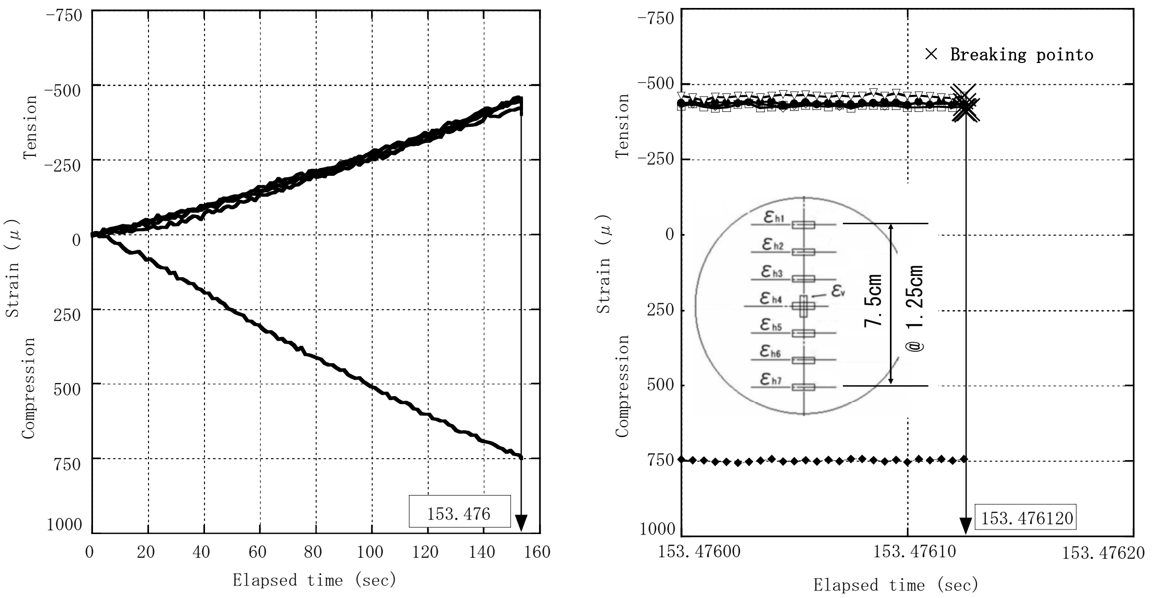
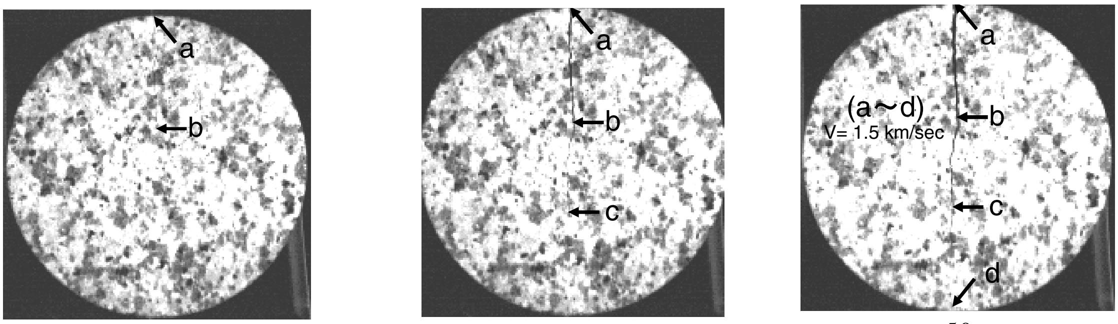


Figure 3. Measuring results for static strain: loading speed of 70 kN/min.



at 15 μsec at 30 μsec at 50 μsec

Figure 4. Crack propagation pattern for the impact splitting tests: impulse of 97.0 N·sec.

The purpose of the trigger technique was to establish the starting point in time for the super-high-speed video camera and to grasp the failure process precisely. Figure 2 shows the failure pattern that was captured by the image analysis in the static splitting tests with a loading speed of 70 kN/min. The appearance of cracks was observed at the same time in many locations in the vertical direction at the time of 300 μsec from the start of the procurement, and finally a crack occurred vertically separating the granite specimen into right and left pieces at a time of 360 μsec.

Next, the measurements of strain in horizontal and perpendicular directions along the cracks were carried out. Strain measurements were performed 200,000 times per second. The strain measurement results for the specimen with a loading speed of 70 kN/min are illustrated in Figure 3. Seven sets of strain gauges, ε_{h1}-ε_{h7}, were attached in the horizontal direction at a pitch of 1.25 cm, and one strain gauge,ε_v, was attached in a perpendicular direction at the center point of the granite specimen, as shown in Figure 3. During the static loading, from uppermost strain gaugeε_{h1} to lowermost strain gaugeε_{h7}, the tensile failure at every strain gage was broken due to a tensile strain of 405 μ to 458 μ occurring at the same time of 153.476120 sec from the start of the failure pattern procurement. Similar results were obtained in the static splitting tests with four loading speed levels. Compressive strain was generated in a perpendicular direction.

According to two close observations, viz., the image analysis and the measuring of the tensile strain, the failure pattern of the static splitting tests was clearly confirmed and the cause of this failure pattern was simply forecasted by the mechanical assumption of the aforementioned static splitting failure.

4 EXPERIMENTAL RESULTS OF IMPACT SPLITTING TESTS

4.1 *Relationship between impulse and crack propagation velocity*

Impact splitting tests were carried out by changing the weight and the dropping height of a heavy weight which subjected the granite specimens to four sets of impulses, i.e., 97.0 N·sec, 313.2 N·sec, 594.3 N·sec,and 693.0 N·sec. From the image analysis during this experiment, the crack development pattern was generally recognized as the one in which a crack propagates from the upper part and advances to the lower part. As shown in Figure 4, the crack propagation pattern for the impulse of 97.0 N·sec is illustrated at 15 μsec, 30 μsec, and 50 μsec from the start of the pattern procurement. The crack propagation velocity, advancing from the top part to the bottom part (a ~ b ~ c ~ d), is 1.5 km/sec (a ~ d in the figure).

It is evident that the results of the image analysis, obtained from such impact splitting tests, differ from those of previous mechanical assumptions of static splitting failure. That is,the failure mechanism differs greatly in its failure patterns between static splitting tests and impact splitting tests. The failure mechanism predicted by the impact splitting tests can be recognized as the crack propagation phenomenon. The relationship between the crack propagation velocity obtained by the image analysis and the applied impulse is shown in Figure 5. The regression curve, derived from the mean values of the experimental values, leads to the following discussion.

The rate of increase for the crack propagation velocity in the specimen was seen to increase for impulses ranging from 97.0 N·sec to 313.2 N·sec. Then, it was not seen to increase at the same rate for impulses ranging from 594.3 N·sec to 693.0 N·sec. The rate of increase dropped to a small amount. In addition, the increase was not seen above a crack propagation velocity of 2.6 km/sec for the applied impulses ranging from 594.3 N·sec to 693.0 N·sec, which was an extremely interesting result.

It is clear that there appears to be a critical state at which the propagation velocity does not increase, even if the impact force is increased over it. The maximum impulse used in this experiment was 693.0 N·sec as this is the maximum value that can be applied in the existing impact testing machine. As such, an experiment with the maximum impulse of 693.0 N·sec with the half-size granite specimens, 10 cm in diameter by 7.5 cm in height, was also carried out. The results showed that the mean value of the crack propagation velocity is 2.6 km/sec in this case as well. It can be recognized, therefore, that the crack propagation velocity does not increase even if the impulse is increased to 693.0 N·sec or higher. When the impulse is lower than 97.0 N·sec, no impact failure is observed for the granite specimens.

5 DYNAMIC STRAIN MEASUREMENTS DURING CRACK PROPAGATION

Dynamic strain measurements were performed as in the case of the static splitting tests. The dynamic

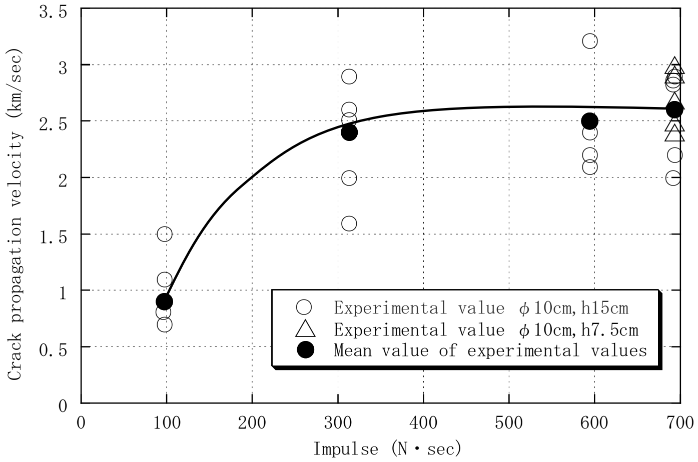


Figure 5. Relationship between the impulse and the crack propagation velocity.

strain measurement results for the granite specimen with the impulse of 97.0 N・sec are illustrated in Figure 6. And the failure condition of the granite specimen after testing is shown in Figure 7. During the impact loading, uppermost strain gauge ε_{h1} broke first due to the tensile strain of 334μ, the strain gauges in the bottom direction then broke sequentially one by one, and after 0.7×10^{-5} sec, lowermost strain gauge ε_{h7} finally broke due to the tensile strain of 205μ. These values were small in comparison to the measuring results of the static strain shown in Figure 3. On the other hand, compressive strain was generated in a perpendicular direction, and strain gaugeε_{v} broke in the bottom immediately after the crack appeared.

From the strain measurement results, it is seen that cracks propagate between top part strain gaugeε_{h1} and bottom part strain gaugeε_{h7} (7.5×10^{-5} km) over the time of 0.70×10^{-4} sec and at a velocity of 1.07 km/sec. This crack propagation velocity corresponds well to the crack propagation velocity obtained from the image analysis shown in Figure 5. Moreover, it can be estimated that a horizontal tensile strain from 196 μ to 360 μ is being generated at the crack tip.

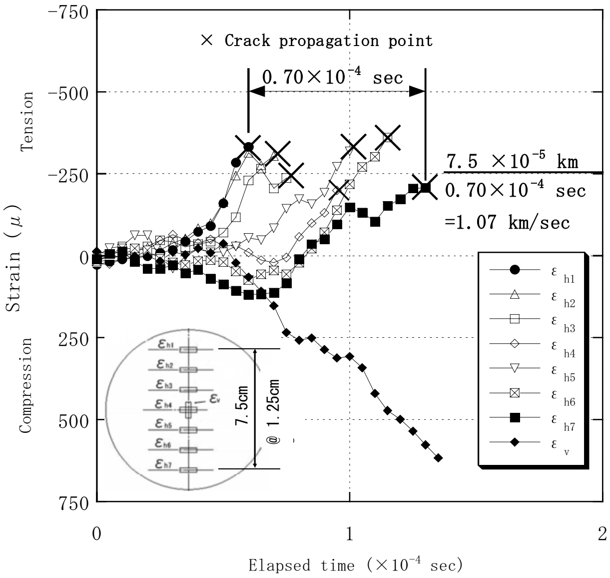


Figure 6. Measuring results of dynamic strain: impulse of 97.0 N·sec.

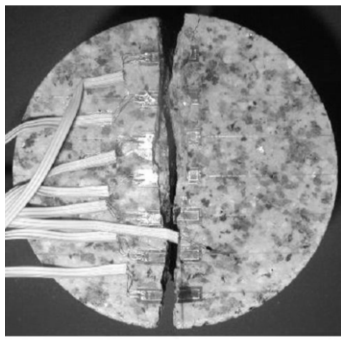


Figure 7. Test specimen after impact splitting tests.

6 CONCLUSIONS

Summarizing the results leads to the following conclusions:

1. There exists a critical state at which crack propagation velocity does not increase, even if the impulse applied to the granite specimen is further increased. The crack propagation velocity is found to converge at 2.6 km/sec.
2. It is concluded from the dynamic strain measurement results that a horizontal tensile strain of 196μto 360μ is generated at the crack tip of the granite specimen subjected to the impulse of 97.0 N・sec in the impact splitting tests. Moreover, the crack propagation velocity was 1.07 km/sec; this value corresponds well to the crack propagation velocity derived from the image analysis.

REFERENCES

Geller, Robert J.1976. Scaling relations for earthquakes source parameters and magnitude, Bulletin of the Seismological Society of America, Vol. 66, No. 5, pp. 1501-1523.

Etoh, G. et al. 2003. An image sensor which captures 100 consecutive frames at 1,000,000 frames/s, IEEE Transactions on Electron Devices, Vol. 50, No. 1, pp. 144-151.

Tamano, T. et al. 2005. Fundamental impact tests on mortar specimens for failure patterns of foundation piles due to up-down vibration in earthquakes, Journal of the Society of Materials Science Japan, Vol. 54, No. 11, pp. 1135-1140,(in Japanese).