A Study of the Dynamic Plane Strain Fracture Toughness on Concrete by SHPB[1]

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Abstract: - Concrete is a kind of engineering composites, which is broadly used in military and civil structures. The static performance on concrete can not be provided to estimate the variation of concrete under high strain rates concerning dynamic loads. by introducing three point bending test under static and dynamic loads, the plane strain fracture toughness K_{IC} and K_{Id} was measured. And with the application of experimental-numerical method, tri-dimensional model has been established by FEM software Ansys/LS-DYNA, to operate transient analysis, and the response curves of stress intensity factor-time can be achieved through opening displacement of fracture. Thus, with obtaining the cracking time by the method of strain-gauge, the dynamic plane strain fracture toughness K_{Id} can be determined. Compared the K_{Ic} and K_{Id} we could conclude a result which meant concrete was more liable to crack under dynamic load.

Key-Words: - concrete; plane strain fracture toughness; strain rate; Hopkinson press bar

1 Introduction

Concrete is a commonly used engineering composite, which is broadly used in military and civil structures such as buildings, defense works and support units of tunnels and underground construction. Like other ceramic products, concrete shows the same sensitivity to strain rate under compression, tension and bending, which means that the static performance obtained in the laboratory cannot be applied to predict the change under high strain rate related to dynamic loads. Common static instrument cannot obtain high loading speed. Therefore, a specific instrument is needed. There is still no detection criterion for concrete impact test in our country.

2 Sample Design and Curing

Concrete is the composite with complex ingredients, which is different from metal and polymer with their good homogeneous property. The size of one ingredient, aggregate, is large and different sizes and shapes of defects, such as fracture and gas cavity, are distributed in and around the aggregate. The size of test sample should be large enough to do the test. Because of the limitation of the instrument, the Hopkinson compression bar with the diameter of 37mm is used in the test.

To do impact test for concretes, on the one side, aggregate sizes should be reduced properly and on the other side, the diameter of SHPB should be as large as possible[1]. Material mixture ratio is shown in the table for the 37mm-diameter bar used in the test.

Table1 Material Mixture Ratio

material	concrete	sand	water
property	Portland cement 425	Maximum particle diameter 5mm	Main-water
Mass ratio	1	1.65	0.35

2.1 Curing Condition

Based on the common concrete mechanical performance testing method (GBJ81—85) established by Concrete Research Center of Chinese Architecture Institute in July, 1985, the surface of the test sample under standard curing should be covered after molded in order to prevent water evaporation and should be under stewing for one or two days in 20±5 . Then, number the sample and remove the mould. Lack of standard curing room, the curing of the test sample is in the stagnant water with PH value under 7 in 20±3 . The test sample should be taken out immediately after 28 days' curing in case of the significant changes of temperature and humidity in the sample.

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2.2 Material Size

Determination of the test sample is commonly by certain geometric and size requirements. Any test sample with K_I calibrated expression and easy to test can be applied to determine K_{IC}. In the present paper, by GB4161-84 national criterion[2], a three-point bending test sample is applied, where W is 70mm, a is the length of precast fracture with a=W/2=35mm. It has to be mentioned that in the present paper, test samples with the same size is used in the determination of stress intensity factor under static and dynamic loads.

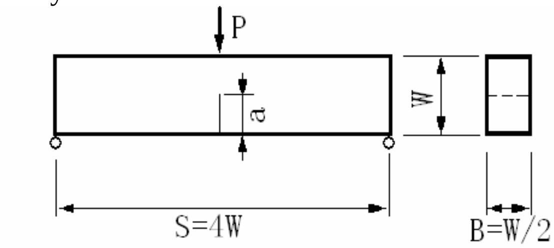

Fig.1 Measurement of pre-crack three-points bending specimen

3 Test of Static Stress Intensity Factor in Plane Strain Problem

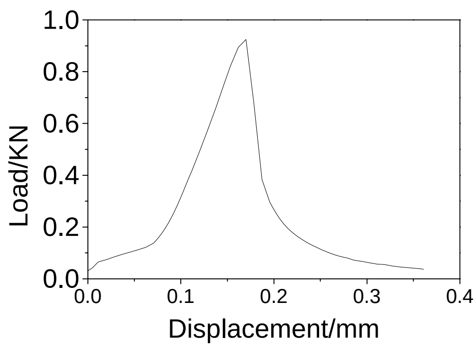

Fig. 2 Load-displacement relationship of three-points bending specimen

Instron4505 universal test machine is applied to do the three-point bending test. The load- displacement curve is shown in Fig.2. From the figure, it can be seen that visible fragile fractural feature appears in concretes.

The moving velocity of INSTRON4505 universal test machine is 0.2 mm per minutes constantly. The stress intensity rate obtained from the loading rate is $300\,MPa\sqrt{m}/s$ approximately. Thus, PC=0.92KN. Substituting PC into (1), it can be achieved that the static plane strain SIF K_{IC} is 1.06 $MPa\sqrt{m}$ approximately.

$$K_I = \frac{PS}{BW^{3/2}} f\left(\frac{a}{W}\right) \quad (1)$$

4 Dynamic Fracture Toughness in Plane Strain Problem

4.1 Instruments and Test Principle

The instrument is derived from separated Hopkinson compression bar. The basic principle is that the cylindrical bullet with the length of 1m and the diameter of 37mm is launched by aerodynamic gun and impacts coaxially on incidence bar with the diameter of 2m. When the compression stress impulses transmitted onto the contact surface of incidence bar and the sample, some return to incidence bar and others load on the sample, which exert shock on the sample and make the sample collapse. Load on the sample P(t) is obtained by one-dimensional stress wave theory as

$$P(t) = EA(\varepsilon_i + \varepsilon_r) \quad (2)$$

, where ε_i and ε_r are incidence impulse and reflective impulse recorded by strain gauges on the bar, respectively, E and A are Young's modulus and the cross-sectional area of the compression bar, respectively and c is the velocity of elastic wave.

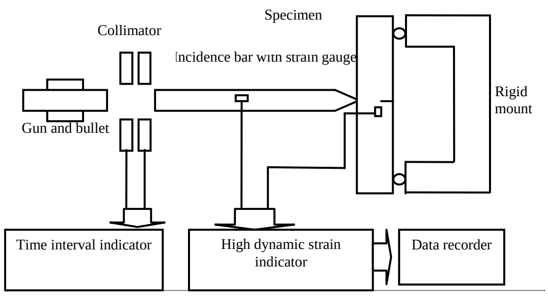

Fig. 3 Device for stress wave loading test

4.2 The Crack Initiating Time

The crack initiating time is determined by electric resistance strain gauge method. The basic principle is that a strain gauge is bended near the crack tip and when the sample is under load, the strain measured by the strain gauge increases with the load. When the crack initiates, unloading wave occurs and makes the strain decrease drastically. Thus, the crack initiating time t_f is that the time corresponding to the maximum strain measured by the strain gauge subtracts the time needed for strain wave transmitted from the crack tip to the strain gauge[3].

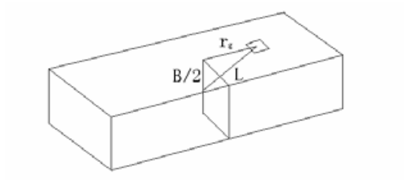

Fig. 4 Pattern for gluing train-gauge

4.3 The Loading Function of the Test Sample

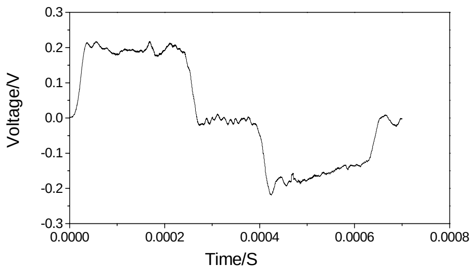

Fig. 5 The original voltage signal from the strain-gauge on the bar

Under shock loads, typical testing results are shown in Fig.5 and Fig.6. The original voltage signal data obtained by the strain gauge bended on the incidence bar are illustrated in Fig.5. Fig.6 shows the load-time curve on the test sample obtained by one-dimensional stress wave theory.

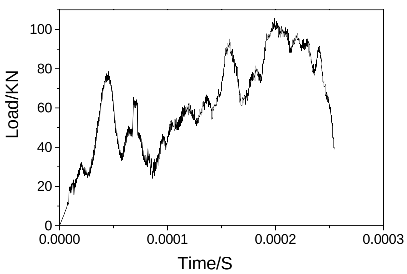

Fig. 6 Load-time curve obtained by the theory of one-dimension stress wave on the test sample

4.4 Analysis by FEM

LS-DYNA integrated package in universal FEM analysis software ANSYS is applied to calculate the COD in the crack front under stress wave loading. When the inertia force is considered and the damping force is omitted, the basic dynamic FEM equation is

$$[M]\{\ddot{u}\}+[K]\{u\}=\{R\} \tag{3}$$

Because of the symmetry of the sample structure, one half of the sample is selected to establish full-scale model and divide the mesh. With the step size of 2×10-6S, instantaneous FEM analysis proceeds. The total steps are 100 in computation.

Similar to static FEM methods[4], polar coordinates is established on the crack tip and by the displacement equation near the Mode I crack tip, we have

$$Ui(r,0)=\frac{K_I}{\mu}\sqrt{\frac{r}{2\pi}}f_i(\theta) \quad i=x,y \tag{4}$$

, where Ux is COD, Uy is the displacement in the load direction, μ is the shear modulus. The right-handed coordinates is established with the origin of Cartesian coordinates as the center point of the loading surface and the x direction parallel to the normal direction of the fracture surface, seen in Fig.4.6. In the equation above,

$$fx(\theta)=\frac{1}{4}\left[(2k+1)\sin\frac{\theta}{2}-\sin\frac{3\theta}{2}\right] \tag{5}$$

$$fy(\theta)=\frac{1}{4}\left[(2k+1)\cos\frac{\theta}{2}-\cos\frac{3\theta}{2}\right] \tag{6}$$

In the plane strain condition

$$k=\frac{3-\upsilon}{1+\upsilon}$$

K_I can be obtained when substituting the displacement by FEM into (5). Because the displacement change at crack opening is significant, a relative accurate approximate solution can be achieved. Thus,

$$K_I=\frac{2\mu}{k+1}\sqrt{\frac{2\pi}{r}}Ux(r,\pi) \tag{7}$$

The equation above is accurate near the crack tip $(r\to 0)$. Therefore, displacement can be calculated by different r on the fracture surface. Substituting it into (7), the corresponding K_I can be obtained. $K_I \sim \frac{r}{W}$ curve is an approximate straight line when r is in a very small scale. By epitaxial method, the crossing point of this line and the longitudinal coordinate is the K_I needed.

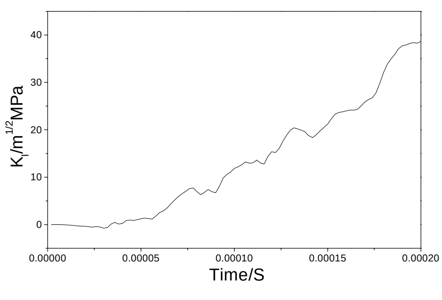

Fig. 7 curve of stress intensity factor-time through the method of opening displacement of fracture

By method of extrapolation, the concrete SIF-time curve can be obtained. Namely, elongate $K_I \sim \frac{r}{W}$ line and make it intersect with longitudinal coordinate, the value of the longitudinal coordinate at the cross point is selected as the corresponding K_I, seen in Fig.7. Thus, the SIF rate of shock three-point bending can be derived from the differentiation with time. Then, the plane strain fracture toughness of the given test sample is $K_{Id} = 0.88MPa\sqrt{m}$ and the SIF rate is $\dot{K}_{Id} = 2\times10^5 MPa\sqrt{m}/s$ approximately.

5 Conclusions

During the testing of concrete three-point bending, fracture toughness is different under dynamic and static loads in contrast test samples. Moreover, the dynamic plane strain fracture toughness is lower than the static value. There are great differences between dynamic and static property. Thus, the influence of dynamic load on the structure should be considered in structural design. The investigation on concrete dynamic fracture toughness has significant importance to military bunkers and directional blasting.

References:

[1] HU Shi-sheng, WANG Dao-rong, Dynamic Constitutive Relation of Concrete under Impact, *EXPL0SI0N AND SHOCK WAVES*, Vol.22, No.3, 2002, pp. 242-246.

[2] B4161-84 national standards experiment method about the plane strain fracture toughness K_{IC} of metal

[3]J.W.Dalley,R.J.Sanford.Strain-gauge methods for measuring the opening-mode stress intensity factor. *Experimental Mechanics*. 1987,pp.381-388.

[4] WANG DUO *Fracture Mechanics*.Harbin Harbin institute of technology press,1989.