A MICROSCOPIC APPROACH TO RATE EFFECT ON CONCRETE STRENGTH UNDER COMBINE LOAD

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ABSTRACT

The enhancement of concrete strength under combined dynamic load is investigated in this paper. As we know, concrete structures in engineering often suffer dynamic loading, so that the research on the dynamic mechanical properties of concrete has great significance. It has been shown by the current available publications that the rate effect of concrete is affected by two effects, the free water viscosity dominating under lower loading rate, and the inertia effect under higher loading rate. In this paper, a crack in an infinite solid subjected to linear loading normal to the crack surface is considered accounting for these two effects. Based on linear elastic dynamic fracture mechanics, the influence of free water viscosity is concerned by means of viscous cohesive force on the crack surface known as Stefan effect, in which the magnitude of viscous cohesive force is assumed to be in proportion to loading rate. Based on the sliding crack model, the compressive strength is obtained by considering the interaction between microcracks with Kachanov method. The reason why rate effect of concrete under compression is much smaller than under tension is presented and failure model difference between dynamic loading and static loading under compression is indicated. The relationship between the dynamic strength increase factor and the strain rate both under tension and under compression is obtained. With the help of the analysis of rate effect of concrete under linear increasing load, different kinds of load functions and load combination is considered. A comparison between the theoretical result and the experimental data published in the literature has been made and shown that a good agreement is achieved.

1 INTRODUCTION

Many concrete structures may be subjected to high rate dynamic loadings (earthquake, impacts, explosions, etc.). It is therefore necessary to know the behavior of this material in order to predict the response of the structure. The mechanical properties of cement-based material are sensitive to strain rate. Under dynamic loading, the increases of strength and fracture toughness are observed; this phenomenon is called as “rate effect” (Malvar [1], Bischoff [2]).

Recently, many experimental results show that the free water in concrete plays an important role in concrete property under dynamic loading. The strength of concrete after drying is not sensitive to lower loading rate ($< 1s^{-1}$) (Rossi [3, 4]). Furthermore, the effect of loading rate on concrete increase with the water/cement ratio of the material. The rate effect is less for high-strength concrete than that for normal concrete (Rossi [5], Ross [6]).On the other hand, under higher loading rate ($>1s^{-1}$), both dry and wet samples exhibit significant strain rate sensitivity. The inertial effect should also be included to analyze the rate effect.

Many experiments have been done, yet no physical mechanism can clearly explain the rate effect for concrete. Accordingly, the objective of the present paper is to propose a dynamic fracture model, which can quantitatively explain the rate effect for concrete both under tension and compression.

2 RATE EFFECT OF CONCRETE IN TENSION

A crack with length 2a (Fig.1) located in an infinite medium is employed to analyze the loading rate effect of a single crack. The cracks surfaces are subjected to linearly increasing tensile load. While the crack surfaces begin to separate from each other, the cohesive force σ_c known as Stefan effect (Cotterll [7]) delays the movement of the crack surface, and then delays the initiation of the crack.

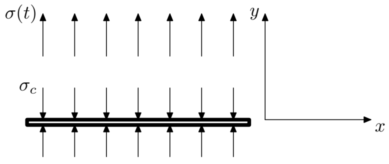

Fig. 1 Single crack subjected to dynamic loading

Freund [8] have discussed the response of an elastic solid containing a crack and subjected to impact loading normal to the crack surface. The solution for stress intensity factor of the model can be achieved by some simple transformations (Zheng [9]). With the presence of external loading $\sigma(t)$ and the viscous force of free water σ_c, the applied loading is

$$\sigma(t) = \dot{\sigma}t - \sigma_c = \dot{\sigma}(t - T_0) \tag{1}$$

This can be regarded as linear increasing loading added at time T_0. The variation of dynamic stress intensity factor with the normalized time is plotted in Fig.2.

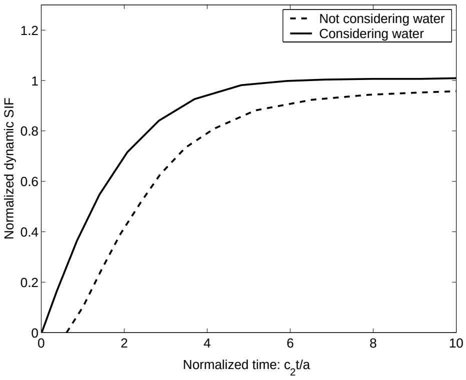

Fig. 2: Dynamic SIF variation with normalized time of linear increasing loading

Assume that the real (or micro) fracture toughness of the medium does not vary with loading rate, then a higher corresponding stress under dynamic loading is needed than that under static loading to reach the same critical fracture intensity factor. Then the dynamic enhancement factor can be deduced as

$$\frac{D}{f^{-1}(1/D)} = \frac{a\dot{\sigma}}{c_2\sigma_0} \tag{2}$$

3 RATE EFFECT OF CONCRETE IN COMPRESSION

The sliding crack model (wing crack model) has been broadly applied to describe the properties of brittle materials under compressive loading (Fanella [10], Horri [11]).

Not like that in tension, the SIF at the crack tip decreases while the crack propagates in compression after the microcrack kinks into the cement matrix. Because $\partial K_{\rm I}/\partial a_l < 0$, the crack propagation is stable. It follows that the compressive strength of concrete cannot be obtained with this kind of model. This drawback can be circumvented through considering the interaction between the microcracks. The microcracks grow in a stable way until they start to interact. The crack interaction increases the SIF dramatically and leads to an instability till the final failure.

Because the concrete failure begins from a local crack, the influence of the nearest crack to the dominant crack is most remarkable while other cracks are not so significant. Accordingly, in the present model, only two cracks in a RVE (Representative Volume Element) are considered and the interaction of other remote cracks is neglected (Fig. 3). The interaction between cracks under splitting force is evaluated with Kachanov method (Zheng [12]).

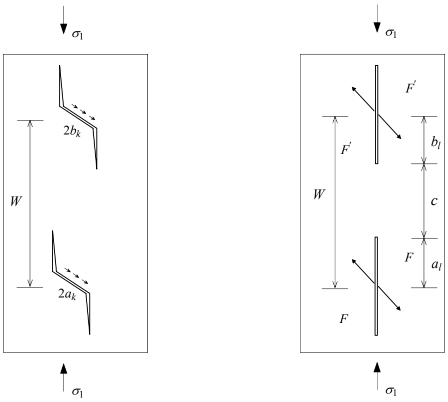

Fig. 3 (a) RVE of 2 kinked cracks with distance W, (b) Corresponding equivalent cracks

With consideration of viscous force between the crack surfaces which is proportional to the loading rate (Frank [13]), the splitting forces on the equivalent cracks under dynamic compression loading are

$$F^{\rm d} = 2a_k(\sin\theta\cos\theta - \mu\cos^2\theta)\dot{\sigma}(t-A) \tag{3}$$

which can be regarded as linear increasing load added at time $T_0 = A$. While under dynamic load, the model I dynamic SIF of the equivalent crack was determined as

$$K_{\rm I}^{\rm d}(a_l, t, \dot{a}_l) = k(\dot{a}_l)K_{\rm I}(a_l, t, 0) \tag{4}$$

where $K_{\rm I}$ (a_l, t, 0) is the stress intensity factor resulted from the applied loading if the crack tip had always been at its instantaneous position represented by a_l. The function $k(\dot{a}_l)$ represents the inertial effect of crack tip speed and is given as

$$k(\dot{a}_l) = \frac{1 - \dot{a}_l / C_R}{1 - 0.5\dot{a}_l / C_R} \tag{5}$$

where C_R is the Rayleigh wave speed which can be derived by material parameters, E Young's modulus, ρ mass density and v Poisson's ratio. For normal strength concrete, $C_R \approx 3000$m/s, at loading rate $\dot{\varepsilon} < 10^4/s$, the stable crack growing speed $\dot{a}_l < 10^{-2}$m/s, then

$k(\dot{a}_l) \approx 1$. It means that the influence of crack tip growing speed can be neglected under moderate loading rate

Consequently, only the inertia effects and water viscosity are considered in this analysis. The dynamic SIF can be derived as

$$K_I^{\mathrm{d}}(a_l, t, \dot{a}_l) = K_I(a_l, t, 0) = f\left[c_2(t-A)/a_l\right] I(W-2a_l)\frac{\sigma_1 T(\theta) a_k}{\sqrt{\pi a_l}} \quad (6)$$

where, I is the cracks interaction factor, $T(\theta) = 2\sin^2\theta(\cos\theta - \mu\sin\theta)$, f is the normal dynamic SIF subjected to linear increasing load with consideration of water viscosity (See Fig.2).

The effect of loading rate on the concrete strength subjected to compressive loading at lower and moderate strain rate ($<10^4$ /s) is investigated. The material parameters are: a_k= 4.9mm, c_2 = 500m/s, σ_0 = 30MPa, E=2.7×10^4 MPa.

In Fig. 4 a comparison of the strength increase is shown between the proposed model and the experimental results under uniaxial compression (Bischoff [2]). As can be seen from this figure, the results of the model correlate well with the experimental data.

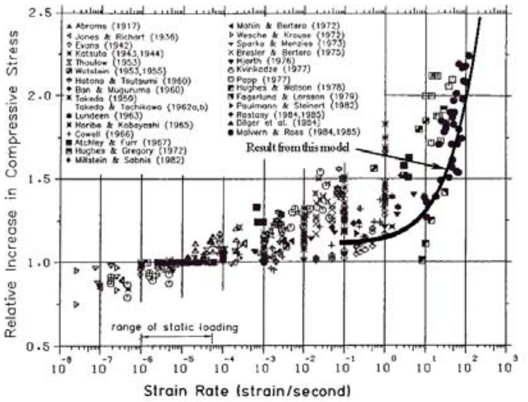

Fig. 4 Variation of dynamic enhancement factor with strain rate in compression

4 RATE EFFECT OF CONCRETE UNDER COMBINE LOAD

From the above analysis, the rate effect of concrete is affected by two effects, the free water viscosity dominating under lower loading rate, and the inertia effect under higher loading rate.

In fact, the microscopic fracture toughness of concrete doesn't change with loading rate, the macroscopic strength enhancement of concrete is because of the energy dissipation by viscous force and inertial effect. Consequently, under different combine load, the static load doesn't influence the dynamic properties of concrete. Under a certain load history

$$f(t) = f_s + f^{\mathrm{d}}(t) \quad (7)$$

the dynamic strength of concrete can be obtained as:

$$\sigma^{\mathrm{d}} = \sigma + \Delta\sigma \quad (8)$$

where f_s is the static load, $f^{\mathrm{d}}(t)$ is the dynamic load,; σ is the static strength of concrete, $\Delta\sigma$ is the strength enhancement generated by the dynamic load, which can be obtained by the method in the above sections.

5 CONCLUSIONS

A model for predicting the dynamic strength increase of concrete under combine load has been formulated based on dynamic fracture mechanics with both inertia and free water viscosity included. The concrete compressive strength is obtained by considering crack interaction until unstable crack growth. The predicted results by this model appear reasonable comparing with the current available experimental ones.

6 REFERENCES

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