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A review of dynamic fracture mechanics in China

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Abstract. This paper summarizes the recent development of dynamic fracture in China. The review covers analytical and numerical results on elastodynamic crack fields in 3D and layered media; experimental and theoretical research on dynamic mechanical properties of rocks and advanced materials; transient effects on ideally plastic crack-tip fields when the inertia forces are not negligible.

Key words: dynamic fracture, 3D-fundamental solution, transient effects, rocks, advanced materials

1. Analytical and numerical results on elastodynamic crack fields

The elastodynamic transient response of a body containing a crack or cracks is a difficult analytical problem. Its solution is important to the understanding of the dynamic fracture properties of cracked solids, especially for nondestructive ultrasonic measurement.

The layered model of the earth crust has been widely applied to seismology and to geophysics. Shen et al. [1], investigated the dynamic behaviour of a finite interface crack in a layered medium irradiated by a normally incident harmonic longitudinal wave. Wang et al. [2, 3], considered the scattering of steady elastic waves in a layered medium with circular arc-shaped cracks at the interface. Using the similar approach of Chen and Sih [5], Zhong et al. [4], studied the dynamic mode II stress intensity factor of a crack embedded in an infinite medium subjected to an arbitrarily oriented transient concentrated line force. Yang et al. [6], investigated the crack-tip field for transonic debonding under anti-plane and in-plane loads. They presented the complete solution for an interfacial crack advancing at velocity regimes below the longitudinal wave speed of the stiff material component. Liu et al. [7], considered the interaction between a plane SH-wave and a finite crack in anisotropic media and discussed the condition of fracture.

In recent years, little progress has been made in three-dimensional dynamic fracture because of mathematical difficulty. Recently the authors obtained the exact solution for the problem having a pair of opposed collinear concentrated loads acting on the crack faces at a fixed distance from the crack edge. Due to the existence of the characteristic length in loading, the details of the analysis are complicated. The full details are given in [8] and [9].

The key results are shown in Figures 1–3. The results show not only the arrival of the first direct wave, but also the second reflection wave produced by the first wave interacting with the crack edge. Because the solution includes all waves arriving at a fixed position for a given time, the result is very complex. At a fixed $z(=L), K_1(z,T)$ decays gradually toward its equilibrium $K_1(z,\infty)$ after $C_d t/L \geqslant 10$. On the other hand $k_r(z,T)(r=2,3)$ decays much slower toward their equilibrium $K_r(z,\infty), (r=2,3)$. These solutions could have a significant impact on the future study of 3D electrodynamics.

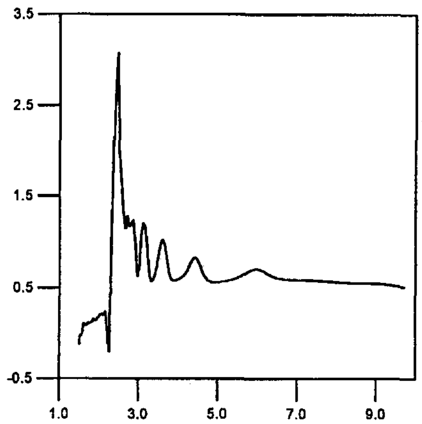

Figure 1. Normalized stress intensity factor k_1 versus normalized time t/aL. Here L and a denote the characteristic lengths in loading and the dilatational slowness, respectively.

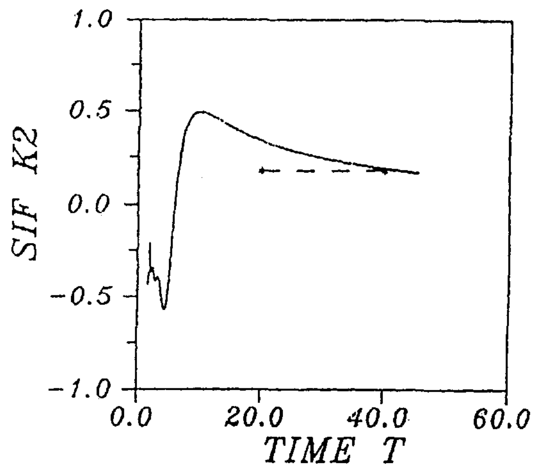

Figure 2. Normalized stress intensity factor k_2 versus normalized time t/bL. When $P_1 = 0.0, P_2 = -1.0, z = L$ and $T_0 = \sqrt{2}$ – –– static SIF; – dynamic SIF. Here time T_0 corresponds to the arrival of the shear wave at the observation position z along the crack front, and L and b denote the characteristic lengths in loading and the shear slowness, respectively.

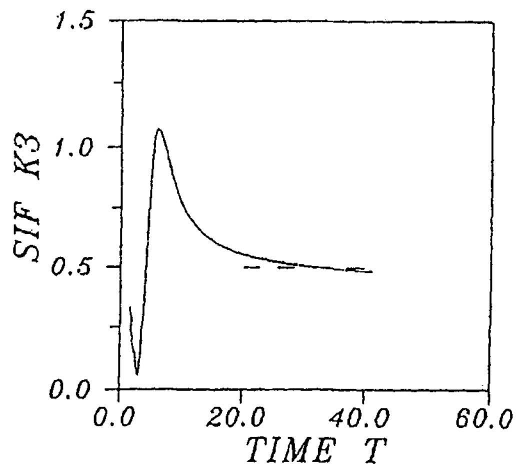

Figure 3. Normalized stress intensity factor k_3 versus normalized time t/bL. When $P_1 = 0.0, P_3 = -1.0, z = L$ and $T_0 = \sqrt{2}$ – –– static SIF; – dynamic SIF. Here time T_0 corresponds to the arrival of the shear wave at the observation position z along the crack front, and L and b denote the characteristic lengths in loading and the shear slowness, respectively.

2. On dynamic properties of rocks and advanced materials

Most underground geophysical cracks in rocks are partially-through ones. Yin et al. [10], carried out a series of experiments on the extension of non-through cracks in marble, glass and Plexiglass under compression. The experimental results showed that a non-through crack is essentially a combination of modes II and III. It has the following character:

(1) When the load increases to a certain level, a great number of nearly equally spaced subcracks initiate almost simultaneously in the middle segment of a crack front. A limited number of these subcracks grow as load increases.

(2) The subcracks do not initiate along the pre-crack plane. The kinking angle and the twisting angle keep changing during the course of crack growth. The crack system consists of a family of curved surfaces. They intersect the back surface of the specimen forming echelon fissures that are similar to the characteristics of ground fissures after an earthquake.

(3) The interaction of the two flanks of a pre-existing crack has a strong influence on the subcrack development. The dimension of the overall fracture surfaces in the specimen is a fractal which relates to the magnitude-frequency of earthquakes and acoustic emission of rock-bursts.

Xie [11], analysed the crack-tip motion along a fractal crack trace. Using the fractal kinking model of crack propagation on dynamic stress intensity factor and on crack velocity, Xie showed that the reason for the apparent (or measured) crack velocity, v_0, being significantly lower than the Rayleigh wave speed, C_r in dynamic fracture experiments, could be explained by the effects of fractal crack propagation.

Using the Palmer–Rice model and the Rice–Simons model, Fan [12], considered a dynamic shear fault in a fluid-infiltrated elastic medium. Considering the inertia effect caused by high-speed propagation of a shear fault, Fan established the size of the so-called breakdown zone of dynamic slippage and the critical shear stress checking instability of the fault. Fan also tried to establish the possible link between the fault propagation and an earthquake.

Yang et al. [13], developed the velocity-stress finite difference method to simulate the elastic wave propagation in azimuthal anisotropic media. To reduce the computational effort, the absorbing boundary conditions filled with anisotropic media were introduced and the corner points were specially treated. The numerical results could have practical application to composite materials.

Sheng et al. [14], made uniaxial compression experiments upon domestic Comp. B and TNT at different strain rates and temperatures. The experimental results show a close correlation between temperature and strain rate. Young's modulus and the compression strength of Comp. B are larger than those of TNT. The dynamic experimental curves are smoothed with a method of introducing a factor of flexibility. Means to determine the dynamic mechanical properties of domestic Comp. B and TNT at low temperatures were provided.

Most of the estimates of fracture toughness were based on Charpy impact and Hopkinson pressure bar tests. Xia et al. [15], gave a simplified dynamic analysis of the pendulum impact tensile test apparatus of a block bar. They proposed a new method for measuring the plane stress dynamic fracture toughness J_{id}. Liu et al. [16], used the Hopkinson pressure bar technique to determine the dynamic fracture initiation toughness of 40Cr material K_{id}.

The authors obtained the dynamic J_{id} of 09MnNiDR steel using a Charpy specimen precracked by fatigue. In this approach, the deflection at the crack initiation point in the load-deflection curve must be known. In the experiment, the crack initiation point is detected by the 'whole extent and small angle initiation correct method' [17]. This method is a 'multi-specimens method' [18]. We can then measure the J_{id} value based on the Rice procedure. We further simulated the dynamic response of a three-point-bend specimen ($10 \times 10 \times 55\ \mathrm{mm}^3$) using MARC finite element code. The dynamic fracture toughness of seven steels was determined experimentally and compared with finite element solutions. The results show that the deep crack formula for the J integral overestimates the actual value by about 25 percent if the relative crack depth is about 0.4–0.6. The result verifies the transition time concept proposed by Shih et al. [19]. We concluded that fracture toughness may be obtained from a Charpy specimen test if the time to fracture initiation is larger than twice the transient time.

3. Transient effect on ideally-plastic crack-tip fields

During the past decade, significant advances have been made in establishing asymptotic solutions at a crack tip. A systematic review was given by Hwang et al. [20]. Past work often neglected the transient effect. Therefore, the evolution rule crack-tip field in rate-sensitive materials under dynamic loads is not clear. The evolution rule is crucial for establishing fracture criteria pertinent to crack growth [21]. Recently the authors determined the first-order perturbation solution for ideally-plastic stationary and advancing crack-tip fields [17, 22]. The solution shows the general feature of the motion of the plastic crack-tip field as a function of time. The solution for an advancing crack-tip field gives two discontinuous interface lines for stresses.

In ideal elastic-plastic solids, the particle velocity jumps along the radial line at $\theta = \pi/4$ and an elastic unloading zone exists near $\theta = 3\pi/4$. We speculated that the transition from the dynamic to quasi-static result may occur rapidly, especially in the interface zones between the fan section and other sectors. The transition pattern could be that, before the crack advances, the plastic zone embraces the whole crack-tip area and the elastic deformation is a small fraction of the plastic deformation. The velocity and stress fields are continuous in all regions. As the tip moves, the stress field near the tip changes rapidly due to the inertia effects. The stress components across the two interface lines appear to be discontinuous. In conclusion, the dynamic crack-tip field may have multi-scales; different physical quantities compete with each other to reach a dynamic balance process.

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