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A refined cohesive zone model that accounts for inertia of cohesive zone of a moving crack

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ABSTRACT

Existing cohesive zone models assume that actual fracture zone of non-zero mass can be modeled by a line segment (cohesive zone) with no mass and inertia. In the present work, a simplified mass-spring model is presented to study inertia effect of cohesive zone on a mode-I steady-state moving crack. It is showed that fracture energy predicted by the present model increases dramatically when a finite limiting crack speed is approached. Reasonable agreement with known experiments indicates that the present model has the potential to catch the inertia effect of cohesive zone which has been ignored in existing cohesive zone models and better simulate dynamic fracture at high crack speed.

1. Introduction

The cohesive zone models, first proposed by Barenblatt [1] and Dugdale [2] for a static crack, have successfully been employed in analytical and numerical studies of crack propagation in nonlinear or ductile materials [3–9]. In all existing cohesive zone models, the cohesive zone, which represents actual fracture zone of non-zero volume and mass, is simplified as a line segment with no volume and mass. The constitutive law in cohesive zone is modeled by linear or nonlinear springs distributed along the cohesive zone [10,11] and the surrounding bulk materials are often assumed to be linearly elastic [5,6]. Apparently, all of the above-mentioned existing cohesive zone models have completely ignored the mass and inertia of the cohesive zone. Since the cohesive zone actually represents fracture region ahead of the crack tip in which complex plastic or nonlinear deformation dominates [12,13], the mass of this fracture region, which has been ignored in the existing cohesive zone models, could have a significant effect on dynamic fracture of a high-speed moving crack. Therefore, it is of great interest to study the inertia effect of cohesive zone ignored in existing cohesive zone models. To the best of our knowledge, this issue has not been well addressed in the literature.

On the other hand, from experimental observations, a limiting crack propagation speed is found for many materials [14–16]. Sharon et al. [15] attributed this physical phenomenon to micro-cracks formed at higher crack speed; while Gao [14] proposed a wavy crack model in which the energy release rate reaches maximum at limiting crack speed. For cohesive zone models, Roy and Dodds [16] proposed that the materials in cohesive zone should be weaker than bulk materials. However, the mass and inertia of cohesive zone, as well as its effect on dynamic fracture have not been considered in above-mentioned researches.

The present paper aims to study the inertia effect of the cohesive zone on a mode-I Yoffe-type steady-state moving crack of constant length. The cohesive zone of mass and inertia is modeled as distributed springs with concentrated mass attached at the two ends of each spring, as shown in Fig. 1. The present new cohesive zone model for a steady-state moving crack of Yoffe-type is described in Section 2. Determination of the mass distribution function in cohesive zone is discussed in Section 3. In particular, the mass distribution along cohesive zone is defined by a simple function which vanishes at the two ends of the cohesive zone so that traction remains finite at both crack tips and cohesive zone tips. Iteration method and an alternative numerical method are described and tested in Section 4. Traction distribution surrounding the cohesive zone and speed-dependent fracture energy are then solved numerically and discussed in Section 5. Finally, main conclusions are summarized in Section 6.

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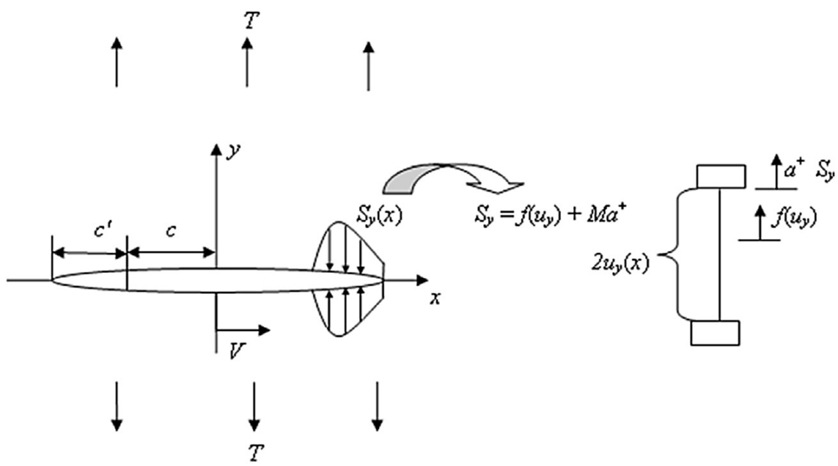

Fig. 1. A crack of constant length $2c$ moving along the x-axis at speed V in the moving coordinate system (x, y) with a cohesive zone characterized by distributed mass-springs, where T is the remote mode-I loading, c' is the cohesive zone length, S_y is the outer traction surrounding the cohesive zone, M is the distributed mass attached on the two ends of each spring, $f(u_y)$ is the inner traction, u_y is the half of cohesive zone separation and a^+ is the y-directional acceleration of the upper end of the spring.

2. Mass-spring cohesive zone model

Let us consider a Yoffe-type steady-state moving crack. The crack of constant length $2c$ in an infinite elastic sheet or plane, subjected to the mode-I remote tensile loading T, is moving at a constant speed V along the x-axis in a moving coordinates system (x, y). The cohesive zone is defined as a line segment and have a length c' ahead of each crack tip (see the left figure in Fig. 1). However, different than the traditional cohesive zone models in which the mass of the cohesive zone is ignored [3–9], in the present paper, the cohesive zone is modeled by a mass-spring system in which a distributed mass $M(x)$ (per unit length along the cohesive zone, whose specific form is to be determined below) is attached to the two ends of the distributed spring in the cohesive zone (see the right figure in Fig. 1). During fracture process, the cohesive zone face becomes a part of crack faces, so the mass of particular point of cohesive zone changes. However, for a steady-state moving crack problem, since the cohesive zone length remains unchanged, the mass and kinetic energy of the cohesive zone and the whole system including cohesive zone and bulk materials are conserved.

The outer traction S_y surrounding the cohesive zone is given by

$$S_y(x) = f(u_y) + M(x)a^+(x), \quad c \le |x| \le c + c' \tag{1}$$

where, a^+ is y-directional acceleration of the upper cohesive zone face (at the upper end of the spring), u_y is the half of cohesive zone separation, and $f(u_y)$ is the inner traction inside the cohesive zone which defines the Tracion-Seperation (T-S) law in the cohesive zone [10,11]. In the present paper, we consider the T-S law inside the cohesive zone can be described by a bilinear model with 2 adjustable parameter S_{max} and u_0 (see Fig. 2).

$$f(u_y) = \begin{cases} (S_{max} - S_0)u_y(x)/u_0 + S_0, & u_y(x) \le u_0 \\ S_{max}\left[u_y(c) - u_y(x)\right] / \left[u_y(c) - u_0\right], & u_y(x) \ge u_0 \end{cases} \tag{2}$$

In Fig. 2, S_0 is the initial yielding traction at the end of cohesive zone which is related with crack speed and influenced by the inertia effect of bulk materials [17], and S_{max} is the maximum inner traction inside cohesive zone, u_0 is the half of cohesive zone separation at the location of maximum traction, and $u_y(c)$ is the half of cohesive zone separation at the crack tip. In the present paper, the value of S_{max}/S_0 and $u_0/u_y(c)$ are assumed independent of crack speed. When $u_0 = 0$, from the second Eq. in (2), the traction-separation law in cohesive zone reduces to a linear strain softening model [5]: $f(u_y) = S_{max}[1 - u_y(x)/u_y(c)]$.

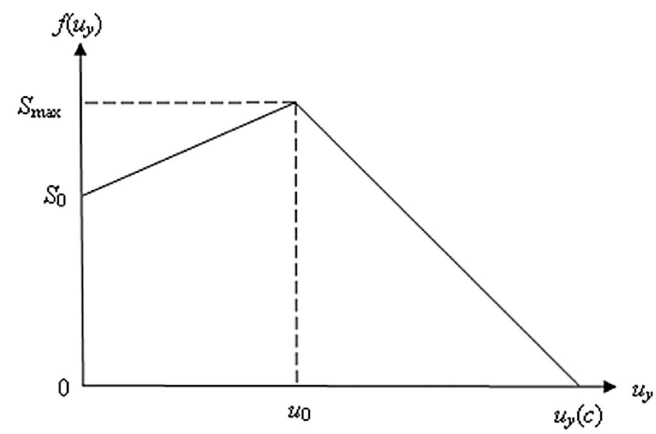

Fig. 2. A bilinear T-S law $f(u_y)$ employed in the present paper, where S_0 is the initial yielding traction at the end of the cohesive zone, S_{max} is the maximum traction in cohesive zone, and u_0 is the half of cohesive zone separation at the location of maximum traction.

To solve Eq. (1), one needs a relation between the outer traction $S_y(x)$ and the cohesive zone separation $2u_y(x)$. For this end, we consider that the traction $S_y(x)$, surrounding the cohesive zone, can be given in the form of symmetric polynomial $P(x)$ with n real coefficients

$$S_y(x) = P(x) = A_n x^{2n-2} + A_{n-1}x^{2n-4} + \cdots + A_2x^2 + A_1 \tag{3}$$

where, $A_1, A_2, \ldots, A_n$ are real constants and will be determined by Eq. (1). From [17], the half of cohesive zone separation can be given by

$$u_y(x) = \int_{c+c'}^{x} \frac{A(V)}{\pi\mu}\left[-P(t)\ln\frac{t\sqrt{(c+c')^2 - c^2} + c\sqrt{(c+c')^2 - t^2}}{t\sqrt{(c+c')^2 - c^2} - c\sqrt{(c+c')^2 - t^2}} + \frac{Q(t)}{\sqrt{(c+c')^2 - t^2}} - \frac{\pi T t}{\sqrt{(c+c')^2 - t^2}}\right]dt \tag{4}$$

where, μ is the elastic shear modulus and

$$A(V) = \frac{\beta_1(1-\beta_2{}^2)}{4\beta_1\beta_2 - (1+\beta_2{}^2)^2} \tag{5}$$