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Investigation of dynamic mode I matrix crack-fiber bundle interaction in composites using caustics

Wenfeng Hao [a, b, *], Can Tang [a], Yanan Yuan [b], Yinji Ma [b]

[a] Faculty of Civil Engineering and Mechanics, Jiangsu University, Zhenjiang, Jiangsu, 212013, China
[b] Department of Engineering Mechanics, Applied Mechanics Lab, Tsinghua University, Beijing, 100084, China

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ABSTRACT

In this work, the dynamic mode I matrix crack-fiber bundle interaction was studied using caustics. First, the strain fields at the dynamic mode I matrix crack tip ahead of the fiber bundles were deduced using transformation toughening theory. Subsequently, the caustic equation at mode I dynamic matrix crack tip ahead of the fiber bundles was established to investigate the influences of the fiber bundle and the crack propagating velocity on the initial curves and caustic curves at the dynamic matrix crack tip. Finally, a series of dynamic caustic spots surrounding the propagating crack tip were recorded using optical caustic experiment, and dynamic stress intensity factor were extracted from the shadow spots.

1. Introduction

The moving matrix crack interaction with the fiber bundles in fiber reinforced composites have gained increasing attention owing to the widely used of composites in engineering fields [1–5], which depended on the orientation of fiber bundles related to the matrix crack, the elastic properties of fiber bundles and matrix, the interface properties between the fiber bundles and the matrix [6–8]. Therefore, it is necessary to study dynamic matrix crack-fiber bundle interaction in composites.

Most studies about the interaction between the matrix crack and the fiber bundles in composites are concentrated on theoretical and numerical investigation. Kagawa and Goto [9,10] investigated the effects of the matrix-fiber interface bonding and debonding condition on the crack growth behaviors in fiber reinforced ceramic matrix composite. Masud et al. [11] studied the influences of interaction between fiber and crack on the strength of long fiber composites using finite element method (FEM). Caimmi and Pavan [12] studied the crack-fiber interaction for varying fiber orientations and different inclusion-to-matrix stiffness ratio using the numerical analysis method. Bouhala et al. [13] modelled the failure in long fibers reinforced composites by X-FEM and cohesive zone model. Wang et al. [14] carried out a finite element simulation of the failure process of single fiber composites considering interface properties. Tosun-Felekoglu and Felekoglu [15] analyzed the effects of fiber–matrix interaction on multiple cracking performance of polymeric fiber reinforced cementitious composites. It is obvious that most of theoretical and analytic works devoted to linear elastic constituent behavior of two dimensional problems and the influences of inclusion on the fracture parameters of the crack.

The method of caustics is a valid experimental techniques for measuring the stress intensity factor at the crack tip thanks to its simple experimental equipment [16,17]. Theocaris et al. [18,19] studied the fracture parameters in composites influenced by the filler-volume fraction and the inclusion shapes using optical method of caustics. Hao et al. [20] experimentally studied the matrix crack-fiber bundles interaction by means of caustics and derived the strain fields and caustic equation surrounding the matrix crack tip ahead of the fiber bundles. Therefore, the caustic method was employed to study the dynamic matrix crack interacting with the fiber bundle in this work.

In this paper, the dynamic fracture performance of mode I matrix crack ahead of the fiber bundles was studied by means of the optical caustic method. Also the influences of the fiber bundles and the crack velocity on initial curves and caustic curves at the matrix crack tip were investigated. Caustic experiments were conducted

* Corresponding author. Faculty of Civil Engineering and Mechanics, Jiangsu University, Zhenjiang, Jiangsu, 212013, China.
E-mail address: haowenfeng2007@163.com (W. Hao).

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for the dynamic mode I matrix crack-fiber bundles interaction to confirm the theoretical analysis.

2. Dynamic strain field near the matrix crack tip ahead of the fiber bundle

In this work, the plane stress assumption was adopted, and the effect of fiber shape and modulus on the stress intensity factor at the matrix crack tip are investigated. There are three assumptions: 1) The distribution and volume fraction of the fiber bundles are not considered, this is due to that only the fiber bundle near the crack tip can affect the stress intensity factor obviously; 2) The fiber bundle is symmetrical with the crack plane, which may have an arbitrary shape; 3) The matrix-fiber bundle interface is perfect.

In the plane stress mechanical mode shown in Fig. 1, the externally applied stress field to the fiber bundle is the unperturbed stress field of the dynamic mode I crack problem [21]:

$$\sigma_{11}^{A}=\frac{K_1}{r^{\frac{1}{2}}R(v)}\left[\left(1+\beta_2^2\right)\left(2\beta_1^2-\beta_2^2+1\right)F_1-4\beta_1\beta_2F_2\right] \tag{1}$$

$$\sigma_{22}^{A}=\frac{K_1}{r^{\frac{1}{2}}R(v)}\left[4\beta_1\beta_2F_2-\left(1+\beta_2^2\right)^2F_1\right] \tag{2}$$

$$\sigma_{12}^{A}=\frac{2K_1\beta_1\left(1+\beta_2^2\right)}{r^{\frac{1}{2}}R(v)}[G_2-G_1] \tag{3}$$

where K_1 is the mode I stress intensity factor at the crack tip; v is the velocity of the crack and

$$R(v)=4\beta_1\beta_2-\left(1+\beta_2^2\right)^2 \tag{4}$$

$$F_j=\left\{\frac{1}{2}\frac{\left(\cos^2\theta+\beta_j^2\sin^2\theta\right)^{\frac{1}{2}}+\cos\theta}{\cos^2\theta+\beta_j^2\sin^2\theta}\right\}^{\frac{1}{2}} \tag{5}$$

$$G_j=\left\{\frac{1}{2}\frac{\left(\cos^2\theta+\beta_j^2\sin^2\theta\right)^{\frac{1}{2}}-\cos\theta}{\cos^2\theta+\beta_j^2\sin^2\theta}\right\}^{\frac{1}{2}} \tag{6}$$

$$\beta_j=\left(1-v^2/c_j^2\right)^{\frac{1}{2}},j=1,2 \tag{7}$$

In these relations c_1,c_2 are the velocities of the longitudinal and the shear wave respectively, which are given by:

$$c_1=\left[\frac{E_m}{\rho\left(1-\mu^2\right)}\right]^{\frac{1}{2}}=\left(\frac{2}{1-\mu}\right)^{\frac{1}{2}}c_2 \tag{8}$$

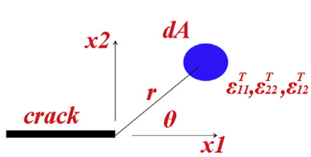

Fig. 1. Transformation differential elements located with respect to the crack plane.

$$c_2=\left[\frac{E_m}{2\rho(1+\mu)}\right]^{\frac{1}{2}} \tag{9}$$

where E_m is elasticity modulus of the matrix material, μ is the Possion's ratio of the matrix material, andρ is the density of the matrix material.

Therefore, the strain fields surrounding the crack are obtained by using the constitutive relation between stress and strain:

$$\varepsilon_{11}^{A}=\frac{K_1}{E_m r^{\frac{1}{2}}R(v)}\left[\left(1+\beta_2^2\right)\left(2\beta_1^2-\beta_2^2+1\right)F_1-4\beta_1\beta_2F_2\right] \tag{10}$$

$$\varepsilon_{22}^{A}=\frac{K_1}{E_m r^{\frac{1}{2}}R(v)}\left[4\beta_1\beta_2F_2-\left(1+\beta_2^2\right)^2F_1\right] \tag{11}$$

$$\varepsilon_{12}^{A}=\frac{2K_1\beta_1\left(1+\beta_2^2\right)}{E_m r^{\frac{1}{2}}R(v)}[G_2-G_1] \tag{12}$$

According to transformation toughening, the enhancement of mode I stress intensity factor in brittle materials owing to two differential materials of area dA (Fig. 1) is defined as [22–24].

$$dK_{tip}=\frac{1}{2\sqrt{2\pi}}\frac{E_m}{1-\mu^2}r^{-\frac{3}{2}}f\left(\varepsilon_{\alpha\gamma}^{T},\theta\right)dA \tag{13}$$

where

$$f\left(\varepsilon_{\alpha\gamma}^{T},\theta\right)=\left(\varepsilon_{11}^{T}+\varepsilon_{22}^{T}\right)\cos\frac{3\theta}{2}+3\varepsilon_{12}^{T}\cos\frac{5\theta}{2}\sin\theta+\frac{3}{2}\left(\varepsilon_{22}^{T}-\varepsilon_{11}^{T}\right)\sin\theta\sin\frac{5\theta}{2} \tag{14}$$

In the expressions above, $\varepsilon_{11}^{T},\varepsilon_{22}^{T},\varepsilon_{12}^{T}$ are the transformation strains at(r,θ).

On account of Eshelby equivalent inclusion theory, the equivalent transformation strain $\boldsymbol{\varepsilon}^{\mathbf{T}}$ is defined as

$$\boldsymbol{\varepsilon}^{\mathbf{T}}=\left[\left(\mathbf{C}_f-\mathbf{C}_m\right)\mathbf{S}+\mathbf{C}_m\right]^{-1}\left(\mathbf{C}_m-\mathbf{C}_f\right)\varepsilon^{A} \tag{15}$$

where$\boldsymbol{\varepsilon}^{\mathbf{A}}$ is the applied elastic strain. $\mathbf{C}_f$ and $\mathbf{C}_m$ are the elastic parameters of the fiber and matrix, respectively, and$\mathbf{S}$ is the Eshelby tensor. In fiber reinforced composites, it assumes that the matrix is isotropic and the fiber bundle is anisotropic. It is evident from Eq. (15) that $\boldsymbol{\varepsilon}^{\mathbf{T}}$ varies with $\boldsymbol{\varepsilon}^{\mathbf{A}}$.

Assuming

$$\mathbf{L}=\left[\left(\mathbf{C}_f-\mathbf{C}_m\right)\mathbf{S}+\mathbf{C}_m\right]^{-1}\left(\mathbf{C}_m-\mathbf{C}_f\right)=\begin{bmatrix}L_{11}&L_{12}&L_{13}\\L_{21}&L_{22}&L_{23}\\L_{31}&L_{32}&L_{33}\end{bmatrix} \tag{16}$$

where