Engineering Fracture Mechanics 134 (2015) 354–367

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Experimental study on interaction between matrix crack and fiber bundles using optical caustic method

Wenfeng Hao [a,b], Xuefeng Yao [a,*], Yinji Ma [a], Yanan Yuan [a]

[a] Department of Engineering Mechanics, Applied Mechanics Lab, Tsinghua University, Beijing 100084, China
[b] Beijing Key Laboratory of Aeronautical Materials Testing and Evaluation, Beijing Institute of Aeronautical Materials, Beijing 100095, China

ARTICLE INFO

Article history:
Received 6 September 2014
Received in revised form 26 November 2014
Accepted 6 December 2014
Available online 15 December 2014

Keywords:
Matrix crack–fiber bundle interaction
Stress intensity factor
Transformation toughening
Caustics

ABSTRACT

The stress singularity of the matrix crack perpendicular to the fiber bundles was studied by the method of optical caustics. First, the strain fields at the matrix crack tip in the neighbor of the fiber bundles were derived based on transformation toughening theory and Eshelby inclusion method. Then the caustic equation at the matrix crack tip in the neighbor of the fiber bundles was established. Finally, an optical caustic experiment for the interaction between the matrix crack and the fiber bundles was conducted to visualize the stress singularity at the matrix crack tip in the form of caustic spots.

1. Introduction

The interaction between the matrix crack and the fiber bundles is not only an important but also a difficult research problem in evaluating the mechanical behaviors of fiber composites [1,2]. Usually, the matrix is easily damaged, and the matrix crack propagates toward the fiber bundles. Therefore, it is necessary to investigate the stress singularity at the matrix crack tip in the neighbor of the fiber bundles.

In fiber reinforced composites, the matrix crack tip field is strongly affected by the properties and geometry of the fiber bundles, and the elastic properties of the matrix. Kagawa and Goto [3,4] 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. [5] studied the influences of fiber–fiber and fiber–crack interaction on the strength of long fiber composites using finite element method (FEM). Helsing [6] and Atkinson [7] presented a numerical algorithm to calculate the stress intensity factors at the crack tip in front of an inclusion. Li et al. [8,9] investigated the crack–inclusion interaction using Eshelby equivalent inclusion method for mode I crack and mixed mode crack in the isotropic material. Shi and Li [10] derived an approximate solution of the interaction force between an edge dislocation and an inclusion of the arbitrary shape. Caimmi and Pavan [11] studied the crack–fiber interaction for varying fiber orientations and different inclusion-to-matrix stiffness ratio using the numerical analysis method. It is obvious that most of theoretical and analytical works devoted to linear elastic constituent behavior of two dimensional problems and the influences of inclusion on the stress intensity factor at the crack tip.

However, the experimental studies on the stress singularity at the matrix crack tip ahead of the fiber bundles are scarce as yet. Among many experimental techniques, the optical caustic method has been proved to be very effective for determining stress intensity factor at the crack tip in composite and polymer [12,13]. Theocaris et al. [14–16] used the caustic method to

* Corresponding author. Tel./fax: +86 10 62771546.
E-mail address: yxf@mail.tsinghua.edu.cn (X. Yao).

http://dx.doi.org/10.1016/j.engfracmech.2014.12.004
0013-7944/

Nomenclature

$\varepsilon_{11}^T, \varepsilon_{22}^T, \varepsilon_{12}^T$	the unconstrained transformation strain component in the area (dA) located at (r, θ)
E_m, ν	the elasticity modulus and Poisson's ratio of the matrix materials, respectively
$\mathbf{S}$	the Eshelby tensor which is dependent solely upon the inclusion geometry and the Poisson's ratio of the matrix material
$\mathbf{C}_f$ and $\mathbf{C}_m$	the elastic constants of the fiber bundles and the matrix, respectively
$E_1, E_2, G_{12}, \nu_{12}, \nu_{21}$	the elastic constants of the fiber
X, Y	the coordinate system in the reference plane
x_1, x_2	the coordinate system in the specimen plane
λ	a scale factor (parallel light $\lambda = 1$, convergent light $\lambda < 1$ or divergent light $\lambda > 1$)
d	the thickness of the specimen
z_0	the distance from the specimen plane to the reference plane
c	the stress optical-constant of the specimen ($c = -0.97 \times 10^{-10}$ m^2/N for epoxy material)
ε_{33}	the out-of-plane strain component at the crack tip in the specimen

measure the stress intensity factor at the crack tip in isotropic materials. Li et al. [17,18] investigated dynamic fracture problems in orthotropic composites and viscoelastic materials using the optical caustics method. Yao et al. [19–22] studied the crack tip singularity and fracture characterizations using the optical caustic method, including: the stress intensity factor at the crack tip in fiber reinforced composites; the local stress singularities of laminated composite materials under the concentrated loads; the stress intensity factor in graded materials under static and dynamic loadings.

Actually, the main advantage of the caustic method compared with the classical optical interferometry is that the local stress singularity at the crack tip can be reflected by means of the simple caustic spot, which is a sharp and well defined curve [23]. Also, some measurement errors in determining the characterization size of the caustic spot can be minimized by means of precise optical adjustment and fine digital image processing.

In principle, the caustic method is based on the assumption that the state of stress near the crack tip is plane stress. However, experimental and analytical solutions have shown that the state of stress changes from plane strain near the crack tip to plane stress away from the tip through an intermediate region where the stress state is three-dimensional [14]. Rosakis and Ravi-Chandar [24] determined the extent of the region of three-dimensionality of the stress field in the neighborhood of the crack tip using the reflected and the transmitted caustics, which indicate that the stress state approaches that of plane stress at distances away from the crack tip greater than half the specimen thickness. Meletis et al. [25] investigated three dimensional regions around the crack tip in double cantilever beam specimens of aluminum alloy with different thicknesses using the method of caustics. Gdoutos [26,27] indicated that the state of stress in the neighborhood of a crack tip is three-dimensional up to a critical distance which depends on the ratio of crack length to specimen thickness, t, and varies from t to $0.4t$ for plate thicknesses from 3 to 12.5 mm.

In this paper, the stress singularities at mode I matrix crack tip in the neighbor of the fiber bundles were studied by means of the optical caustic method. Also the influences of material constant, the geometrical patterns of the fiber bundles on the stress singularity at the matrix crack tip were investigated. Some typical caustic experiments for the interaction between the matrix crack and the fiber bundles were conducted to verify the theoretical results.

2. Out-of-plane strain field at the matrix crack tip in neighbor of the fiber bundles

2.1. Out-of-plane strain field

In order to establish the strain field at the matrix crack tip in the neighbor of the fiber bundles, some necessary assumptions are considered as follow: (1) The overall volume fractions and distributions of the fiber bundles are not considered because the stress intensity factor at the matrix crack tip is strongly influenced by the fiber bundles in the neighborhood of the matrix crack tip. (2) The fiber bundles may have an arbitrary shape but it is assumed to be symmetrical with respect to the crack plane. (3) The bonding between the matrix and the fiber bundles is perfect.

In fact, the fiber bundles in the neighbor of the matrix crack tip can be considered as the inclusion as shown in Fig. 1, due to the transformation toughening in brittle matrix materials, the enhancement dK_{tip} of the mode I stress intensity factor at the matrix crack tip in the neighbor of the fiber bundles can be expressed as [8,28,29]:

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

Here