Polymer Testing 51 (2016) 101–108

Contents lists available at ScienceDirect

Polymer Testing

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

Material Properties

Photoelastic analysis of matrix crack-tilted fiber bundle interaction

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ARTICLE INFO

Article history:
Received 28 January 2016
Accepted 4 March 2016
Available online 9 March 2016

Keywords:
Photoelastic
Crack-fiber interaction
Stress intensity factor
Shielding
Finite element method

ABSTRACT

Matrix crack-tilted fiber bundle interaction was explored using photoelasticity. First, the isochromatic fringe patterns near the matrix crack tip, either shielded by a tilted fiber bundle or crossed by a broken fiber bundle, were observed. Then, the stress intensity factors of cracks at varying distances from the tilted fiber bundle were extracted from the isochromatic fringe patterns. Finally, finite element simulation was conducted in ABAQUS software to verify the experimental results, and the difference between photoelasticity measurement and FEM simulation were discussed. The results show that the mode I stress intensity factor of the crack near a tilted fiber bundle increases with the increase of crack length and decreases with the increase of the Young's modulus of the fiber bundle. However, the mode II stress intensity factor, which clearly increases as crack length increased and, as opposed to mode I, increases as the Young's modulus of the fiber bundle increased.

1. Introduction

Fiber-reinforced composite materials are commonly used in the civil engineering, aviation and aerospace, and automotive fields, favored for their high specific strength, high specific modulus, fatigue behavior and corrosion resistance [1–3]. Interaction between the matrix and fiber bundle is an important feature of such composites, because the matrix cracks more readily than the fiber bundles. To ensure successful application of fiber-reinforced composites, it is necessary to investigate the fracture behavior of matrix cracks shielded by fiber bundles or crossed by broken fiber bundles.

Many previous researchers have applied optical methods, such as digital image correlation [4–6], digital gradient sensing [7,8], coherent gradient sensing [9], photoelasticity [10–12], moiré interferometry [13,14] and caustics [15–17], to solve crack-inclusion interaction problems; these methods do show certain advantages (i.e., non-contact, full-field measurement). Photoelasticity is a practical technique with simple test setup and straightforward post processing that is applicable to a variety of stress analysis problems, and has also been employed by many previous researchers. Shukla et al. [18], for example, conducted photoelastic investigation of interfacial fractures between orthotropic and isotropic materials. Ayatollahi and Safari [19] used photoelasticity to evaluate the crack tip constraint. Guagliano et al. [20] applied photoelastic methods to determine the K_I, K_{II}, and K_{III} values of internal cracks subjected to mixed mode loading. Zakeri et al. [21] studied the lateral load effects on a center-cracked plate using photoelastic methods, and Ayatollahi et al. [22–24] determined stress field parameters in notches using photoelasticity.

Photoelastic stress analysis was employed in this study to evaluate stress distribution around a matrix crack tip. The isochromatic fringe patterns were obtained near the matrix crack tip as either shielded by a tilted fiber bundle, or crossed by a broken fiber bundle. Stress intensity factors were extracted from the isochromatic fringe patterns. A finite element simulation was then conducted in ABAQUS to verify the results, and differences between photoelasticity and FEM simulation were investigated.

2. Experiment

2.1. Photoelastic method

Based on Williams's asymptotic stress field expansion for mixed-mode cracks, the elastic stress field distribution around the crack tip can be expressed as follows [11]:

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http://dx.doi.org/10.1016/j.polymertesting.2016.03.006
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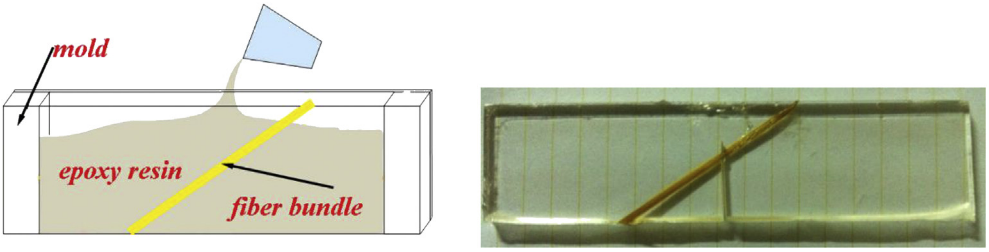
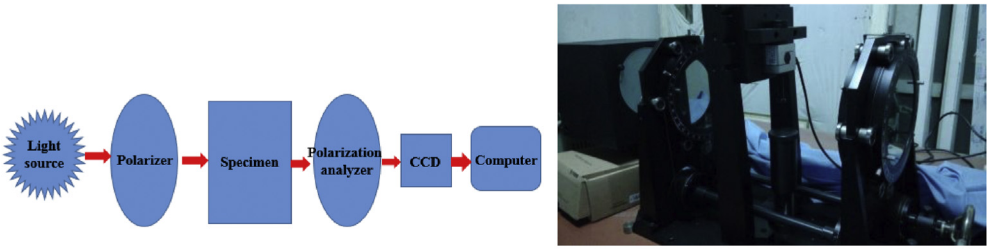


(a) Specimen preparation process (b) Specimen

Fig. 1. Specimen preparation.



(a) Schematic diagram (b) Photograph

Fig. 2. Experimental setup.

$$\sigma_r = \frac{K_I}{\sqrt{2\pi r}}\frac{1}{4}\left(5\cos\frac{\theta}{2} - \cos\frac{3\theta}{2}\right) + \frac{K_{II}}{\sqrt{2\pi r}}\frac{1}{4}\left(-5\sin\frac{\theta}{2} + 3\sin\frac{3\theta}{2}\right) \tag{1}$$

$$\sigma_\theta = \frac{K_I}{\sqrt{2\pi r}}\frac{1}{4}\left(3\cos\frac{\theta}{2} + \cos\frac{3\theta}{2}\right) + \frac{K_{II}}{\sqrt{2\pi r}}\frac{1}{4}\left(-3\sin\frac{\theta}{2} - 3\sin\frac{3\theta}{2}\right) \tag{2}$$

$$\tau_{r\theta} = \frac{K_I}{\sqrt{2\pi r}}\frac{1}{4}\left(\sin\frac{\theta}{2} - \sin\frac{3\theta}{2}\right) + \frac{K_{II}}{\sqrt{2\pi r}}\frac{1}{4}\left(\cos\frac{\theta}{2} + 3\cos\frac{3\theta}{2}\right) \tag{3}$$

where r and θ are polar coordinates of any point in front of the crack, which are measured relative to a local coordinate system located at the crack tip. K_I and K_{II} are the mode I and mode II stress intensity factors, respectively.

According to the classical concepts of photoelasticity, the mathematical equation for an isochromatic fringe is generally written as follows:

$$\tau_{\max} = \frac{Kf_\sigma}{2t} \tag{4}$$

where K is the relative retardation in terms of a complete cycle of retardation (number of isochromatic fringe patterns), f_σ is the fringe value, and t is the plate thickness. The maximum shear stress is calculated as follows:

$$(\tau_{\max})^2 = (\sigma_r - \sigma_\theta)^2 + 4(\tau_{r\theta})^2 \tag{5}$$

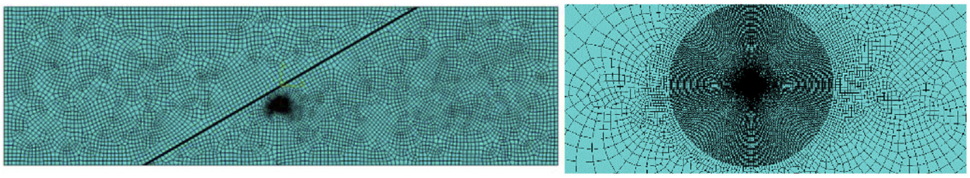
Combining Eqs. (4) and (5) yields the following:

$$\left(\frac{Kf_\sigma}{2t}\right)^2 = (\sigma_r - \sigma_\theta)^2 + 4(\tau_{r\theta})^2 \tag{6}$$

In order to calculate SIFs, at least two points in the vicinity of the crack tip and their fringe orders (K) are required.

2.2. Specimen preparation

In order to examine the interaction between matrix cracks and tilted fiber bundles (30°) using the photoelastic method, a transparent epoxy specimen with an aramid fiber bundle reinforcement



(a) FE mesh of the model (b) FE mesh near the crack tip

Fig. 3. FE mesh.