Polymer Testing 55 (2016) 230–237

Contents lists available at ScienceDirect

Polymer Testing

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

Test Method

Mixed mode dynamic crack-fiber bundle interaction using caustics

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ARTICLE INFO

Article history:
Received 17 July 2016
Received in revised form
22 August 2016
Accepted 4 September 2016
Available online 7 September 2016

Keywords:
Mixed mode crack
Dynamic caustics
Crack-fiber bundle interaction
Stress intensity factor
Shielding effect

ABSTRACT

Caustic method was extended to study the interaction between the mixed mode dynamic matrix crack and the fiber bundle in fiber reinforced composites. First, the dynamic caustic experiments were conducted using transparent specimens with different thicknesses of fiber bundles under dynamic three point bending load. Then, the evolutions of dynamic shadow spots at the crack tip shielded by different thicknesses of fiber bundles were obtained. Moreover, the dynamic stress intensity factors were extracted from the shadow spots. Finally, the crack propagation and bifurcation behaviors were analyzed. It was shown that the stress intensity factors and crack propagation velocities were shielded by the fiber bundles, and the shielding effect increased with the increase of fiber bundle thickness.

1. Introduction

Due to the excellent mechanical properties and corrosion resistance, fiber reinforced composites are widely used in engineering, such as in aviation and aerospace fields, automotive field, civil engineering field [1–7]. The problem of crack initiation and propagation in fiber reinforced composites is of great importance. The crack usually initiates in the matrix and propagates to the fiber bundle. The mechanism of interaction between the matrix crack and the fiber bundle is not only an important but also a difficult problem.

Generally, the fiber bundles can be considered as inclusions in matrix material. Some researchers pay attention on the crack-inclusion interaction using theoretical and numerical methods. Li et al. [8,9] investigated the crack-inclusion interaction for mode I crack using Eshelby equivalent inclusion method. They predicted the variations of stress intensity factors induced by the stiffness and geometry of the near crack-tip inclusion. They extended this method to the crack-inclusion interaction for mode II crack [10,11] and mixed mode crack [12]. Furthermore, Peng et al. extended this method to crack–inclusion interaction in orthotropic medium [13] and crack–inclusion interaction with coupled mechanical and thermal strains [14,15]. Caimmi and Pavan [16] and Savalia et al. [17] investigated the crack–inclusion interaction using finite element method, and the effects of inclusion proximity, inclusion size, and the Young's modulus mismatch between the matrix and the inclusion on crack tip parameters were analyzed. Their simulation results show that for inclusions stiffer than the matrix a transition between two distinct behaviors, shielding and anti-shielding of the crack front, could be recognized on varying orientation. Kitey et al. [18] and Dong et al. [19] investigated the crack–inclusion interaction using boundary element method, and extracted the stress intensity factors from the simulation. Recently, experimental studies also conducted on the crack-inclusion interaction. Hao et al. investigated the interaction between matrix crack and fiber bundles using optical caustic method [20] and photoelasticity method [21]. They extracted the stress intensity factors, and valid the simulation results by Savalia et al. [17]. Lei et al. [22,23] investigated the crack–fiber interaction using micro-Raman spectroscopy. They found that the stress on the bridging fiber distributed uniformly and a fiber bridging zone was isolated from the fiber debonded zone. O'Toole et al. [24] and Hao et al. [25] investigated the crack–inclusion interaction using photoelasticity method. Hao et al. [26,27] investigated the crack–inclusion interaction using digital gradient sensing method. Savalia and Tippur [28] investigated the crack–inclusion interaction using Moiré Interferometry. They all measured the stress intensity factors, and analyzed the shielding effect of the inclusions.

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http://dx.doi.org/10.1016/j.polymertesting.2016.09.006
0142-9418/

Actually the researches of crack–inclusion interaction are mainly concentrated on the static crack, and only small numbers of researches pay attention on the interaction between the dynamic crack and inclusions. Tang [29,30] investigated the dynamic crack–fiber interaction using caustics, and extracted the dynamic stress intensity factors from the caustic spots. Kitey and Tippur [31] investigated the dynamic crack growth past a stiff inclusion using reflection mode Coherent Gradient Sensing (CGS) and digital image correlation [32,33]. They observed the crack path and extracted the stress intensity factors. To the author's knowledge, the process of the stress intensity factor extracting of coherent gradient sensing and digital image correlation is sophisticated. Moreover, the optical setups for coherent gradient sensing are complicated, and the speckle preparation of digital image correlation may influence the specimen. The main advantage of caustic method is that the local stress singularity at the crack tip can be reflected by means of the simple caustic spot [34–36]. Among many experimental techniques, the optical caustic method has been proved to be very effective for determining stress intensity factor at the crack tip [37–39].

In this study, the optical caustic method was extended to study the interaction between the mixed mode dynamic matrix crack and the fiber bundle in fiber reinforced composites. The dynamic shadow spots evolution at the crack tip shielded by different thicknesses of fiber bundles were obtained. The dynamic stress intensity factors were extracted from the shadow spots. Finally, the crack propagation and bifurcation behaviors were analyzed.

2. Experimental details

2.1. Dynamic caustics

The governing equations of the transmitted caustics under dynamic stress field are given by Refs. [40,41]:

$$\Xi/\lambda_m = \left(\frac{3}{2}\mu_t\right)^{2/5}\left[R^{2/5}\cos\theta_1 + \frac{2}{3}R^{-3/5}\cos\frac{3\theta_1}{2}\right] \quad (1)$$

$$H_t/\lambda_m = \left(\frac{3}{2}\mu_t\right)^{2/5}\left[\frac{1}{\beta_1}R^{2/5}\sin\theta_1 + \frac{2}{3}\beta_1 R^{-3/5}\cos\frac{3\theta_1}{2}\right] \quad (2)$$

where

$$\mu_t = \frac{z_0 d c_t K_I^d}{\lambda_m (2\pi)^{1/2}} \quad (3)$$

$$R = \frac{1}{2}\left(1-\beta_1^2\right)\cos\frac{5\theta_1}{2} + \frac{1}{2}\left[\left(1-\beta_1^2\right)^2\cos^2\frac{5\theta_1}{2} + 4\beta_1^2\right]^{1/2} \quad (4)$$

$$\beta_1 = \left[1-\left(c/c_1\right)^2\right]^{1/2}, c_1 = \left[\frac{E_m}{\rho_m\left(1-\upsilon_m^2\right)}\right]^{1/2}, c_2 = \left[\frac{E_m}{2\rho_m\left(1+\upsilon_m\right)}\right]^{1/2} \quad (5)$$

In the above relations, K_I^d is the dynamic stress intensity factor, d is the thickness of the specimens, c_t is the optical constant of the material, z_0 is the distance between specimen and reference plane of the optical set-up, λ_m is the magnification ratio of the optical set-up, υ_m is Poisson's ratio, E_m is the elastic modulus, ρ_m is the density of the matrix material, c is the instantaneous velocity of the crack, c_1, c_2 are the velocities of the longitudinal and shear waves.

The dynamic stress intensity factors K_I^d and K_{II}^d are given [42]:

$$K_I^d = \frac{2\sqrt{2\pi}}{3z_0 d\lambda_m^{3/2} c_t}\left(\frac{D_t^{max}}{\delta_t^{max}}\right)^{5/2} \quad (6)$$

$$K_{II}^d = K_I^d \tan\frac{\varphi}{2} \quad (7)$$

where D_t^{max} is the maximum transverse diameter of the caustics, δ_t^{max} is the correction factor of the diameter, which depends on the relative velocity c/c_2 of the crack, and φ is the angular displacement of the caustics.

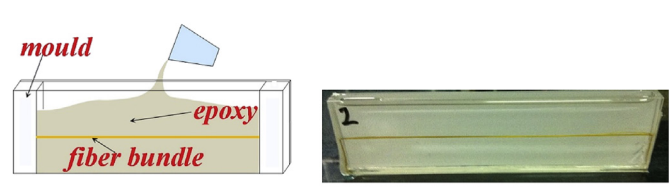
2.2. Specimens preparation

In order to examine the interaction between the dynamic matrix cracks and the fiber bundles using the caustics, a transparent epoxy specimen with aramid fiber bundle reinforcement was fabricated as shown in Fig. 1. The aramid fiber used in this study was Kevlar 49 (DuPont, USA). First, a standard DGEBA (diglycidyl ether of bisphenol-A) epoxy cured with a bifunctional polyamide was employed for partial curing at room temperature, enabling us to position the fiber bundles at the desired locations prior to full hardening. Next, a resin and curing agent composition (3:1 wt percentage) was used to create an epoxy solid. Both the resin and the curing agent were heated to approximately 65 °C, mixed for at least five minutes, and then evacuated until most degassing activity had ceased. The liquid was poured into PMMA (polymethylmethacrylate) molds that had been coated with a release agent. After curing and demolding, the resulting 140 mm × 40 mm × 5 mm (length × width × thickness) specimens were milled, then subjected to caustic experiments using three-point-bending load. An initial single-edge crack, (5 mm length, 0.2 mm width) was made on the down edge of the specimen using a thin diamond saw.

As shown in Fig. 2, three kinds of models were fabricated to investigate the effect of fiber bundle thickness and the distance from crack tip to the fiber bundle (a_0) on the dynamic matrix crack propagation behavior. In model 1, the thickness of the Kevlar 49 fiber bundle is 6 K with a distance of 15 mm from the crack tip. The thicknesses of fiber bundle in model 2 and model 3 are 9 K and 12 K, respectively; the distances from the fiber bundles to the crack tips in model 2 and model 3 are 5 mm and 10 mm, respectively.

2.3. Experimental setup

Fig. 3 is the experimental setup of the dynamic caustics, including a laser (70 mW), beam expanders, two convex lenses, a high speed camera, a computer and a loading system. The light from the laser first penetrated from the convex lens and the transparent specimen, and then entered into the camera where the specimen off-focused images are obtained. In this setup, the



(a) Specimen preparation (b)Specimen

Fig. 1. Specimen details.