Polymer Testing 68 (2018) 287–293

Contents lists available at ScienceDirect

Polymer Testing

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

Test method

Caustic investigation of dynamic interactions between propagating matrix crack and modified fibre bundles

Yanan Yuan, Xuefeng Yao*, Bin Liu

Department of Engineering Mechanics, Applied Mechanics Lab, Tsinghua University, Beijing, 100084, PR China

ARTICLE INFO

Keywords:
Polymer
Dynamic caustic analysis
Dynamic stress intensity factor
Fibre/matrix bond
Carbon nanotube

ABSTRACT

The dynamic interactions between a propagating crack in a matrix and fibre bundles coated with multi-wall carbon nanotubes (MWCNTs) are investigated. First, the dynamic stress intensity factor at the propagating crack tip in front of the fibre bundles was derived. Second, dynamic caustic experiments were performed to characterise the dynamic interactions for three different modified fibre/epoxy specimens with MWCNTs. Finally, important fracture parameters of these specimens are evaluated. The modified MWCNT fibre bundles perform better than untreated fibre/epoxy specimens in reducing the dynamic stress intensity factor and the crack propagation velocity at the propagating crack tip in front of the fibre bundles. The modified MWCNT-coated fibre bundles can also realise equilibrium partitioning of the fibre fracture energy and interfacial bonding energy, thus preventing massive interfacial debonding and matrix failure. These results can be used to evaluate the toughening effect of carbon nanotubes on polymer composites.

1. Introduction

In the study of the mechanics of composite materials, the dynamic interaction between a propagating crack in a matrix and a fibre bundle is not only an important research subject but also a difficult one. Nowadays, fibre bundle surfaces are being modified for strengthening the resistance of fibre composites. Therefore, the investigation of the dynamic interactions between a propagating crack in a matrix and modified fibre bundles is an interesting academic problem.

The method usually used for investigating experimental fracture mechanics [1] is the optical caustic method, which has some merits such as the production of simple optical patterns [2] and the visualisation of the crack tip singularity [3,4]. Arakawa et al. [5] studied the unsteady dynamic crack propagation in a brittle polymer using the caustic method in combination with a high-speed camera. Yao et al. [6–8] investigated the applications of the optical caustic method for studying the fracture behaviour of composite materials. Theocaris et al. [9,10] measured the stress intensity factor (SIF) at the crack tip in soft–hard phase materials using the caustic method. Hao et al. [11,12] investigated the static interactions between the matrix crack and fibre bundles in a plane strain problem using the optical caustic method.

On the other hand, the theoretical investigation of the crack–-inclusion interaction has received considerable attention. With regard to the study of isotropic inclusion, the Eshelby equivalent inclusion theory was developed to predict the variation in the SIF at matrix crack tips such as a mode I crack tip [13,14], mode II crack tip [15], and mixed mode crack tip in plane strain problems [16]. With regard to anisotropic inclusion, Peng et al. [17] studied the effect of orthotropic inclusion on the SIF at a mode I crack tip subjected to remote stress; the results indicated that a hard (or soft) inclusion may have a shielding effect (or an amplification effect) on the SIF at the crack tip. In addition, numerical methods have been used to study the crack–inclusion interaction. Caimmi et al. [18] simulated the effect of orthotropic inclusion on the crack–fibre interaction by varying fibre orientations and inclusion-to-matrix stiffness ratios. Salivia et al. [19] studied the crack–-inclusion interaction and matrix–inclusion debonding using a finite element method.

With regard to fibre/polymer composites based on nano-modification, only a few studies have characterised the toughness effect on the interfacial property between the fibre and matrix using the caustic method. In this paper, the dynamic caustic method is used to investigate the interactions between the propagating crack in epoxy specimens and fibre bundles modified by multi-wall carbon nanotubes (MWCNTs). In addition, a modified dynamic caustic equation is established based on the Eshelby equivalent inclusion theory to evaluate the dynamic SIF at the propagating crack tip in front of the fibre bundles. Finally, some fracture mechanisms are discussed with regard to the shielding effects of the modified fibre bundles on matrix crack propagation, i.e., the equilibrium partitioning of the fibre fracture energy and interfacial bonding energy.

* Corresponding author.
E-mail address: yxf@mail.tsinghua.edu.cn (X. Yao).

https://doi.org/10.1016/j.polymertesting.2018.04.028
Received 14 March 2018; Accepted 17 April 2018
Available online 18 April 2018

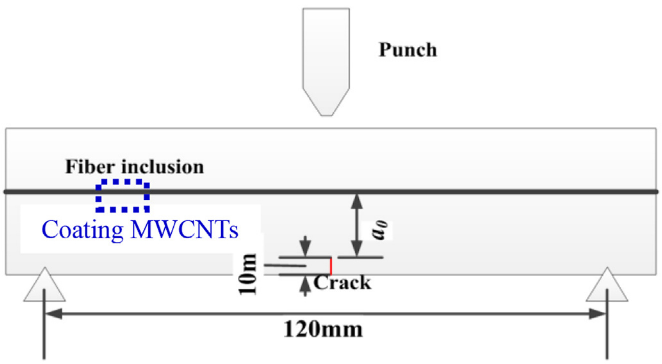

Fig. 1. The specimen and low-velocity experimental system.

2. Experimental details

2.1. Specimen

A transparent epoxy resin specimen was embedded in fibre bundles modified by MWCNTs, as shown in Fig. 1. The specimen was used to investigate the crack resistance of the fibre bundles modified by MWCNTs and the interactions between the matrix crack and fibre bundles. Three different fibre/epoxy specimens were prepared by coating 0, 1.7, and 3.3 wt% MWCNTs on the surface of Kevlar fibre bundles. MWCNTs with 97% purity were purchased from Shenzhen Nanotech Port Corporation, China. The MWCNTs with a diameter of approximately 10 ~ 20 nm and a length less than 2 μm were uniformly distributed on the surface of Kevlar fibre bundles (3K, Kevlar-49). Eventually, the Kevlar fibre bundles with 0, 1.7 and 3.3 wt% MWCNTs coating were fixed in the middle of a rectangular polymethyl methacrylate mould. The 508# transparent epoxy resin was mainly composed of a low-molecular-weight bisphenol-A epoxy resin, an active diluent, a toughening agent, and a modified amine curing agent, which were purchased from Beijing Oak Company, China. The epoxy resin and amine curing agent were mixed in the proportion of 3:1. After mechanical mixing for 10 min, the mixture was spun in a centrifuge for 20 min to remove excess bubbles, and then the transparent epoxy resin was slowly poured into the mould. Demoulding was performed after the resin was fully cured for 24 h; thus, rectangular specimens (length: 160 mm, width: 40 mm, thickness: 5 mm) were prepared. The curing ensured that light was suitably transmitted through the specimen during the optical experiment. Meanwhile, specimens with untreated Kevlar fibre bundles were also prepared for comparison. The mechanical properties of the Kevlar fibre and epoxy resin are listed in Table 1. In addition, an initial crack (length: 10 mm, width: 0.8 mm) was introduced using a polytetrafluoroethylene (PTFE) film, as illustrated in Fig. 1. To create the initial crack, the PTFE film was inserted into the non-cured epoxy resin, and the position and length of the initial crack were determined by adjusting the position of the PTFE film. The thickness of the PTFE film was fixed and, accordingly, the width of the initial crack could be determined. After curing was completed, the initial crack (length: 10 mm, width: 0.8 mm) was formed. Here, a_0 (= 15 mm) is the distance between the initial crack tip and the middle plane of the fibre bundles. The surface topographies of the fabric inclusion for 0, 1.7, and 3.3 wt% MWCNTs coating are illustrated in Fig. 2, including the cross section of the Kevlar fabric coated with MWCNTs having different contents (0, 1.7, and 3.3 wt%).

Table 1
Mechanical properties of epoxy resin and inclusion [23].

Elastic modulus/GPa	3.2
Poisson's ratio	0.3
Elastic modulus longitudinal E_L/GPa	165
Elastic modulus perpendicular E_T/GPaE_m	15

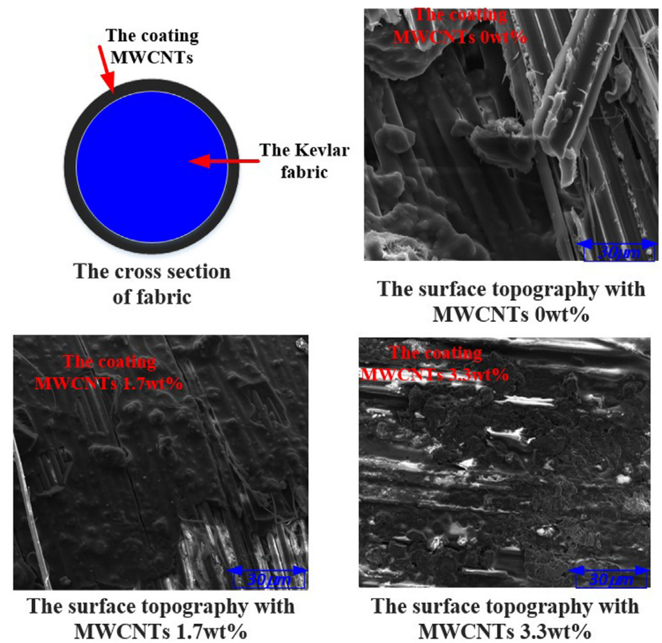

Fig. 2. The surface topography with MWCNT coating.

2.2. Experimental setup

The digital laser dynamic experimental system [12,20] shown in Fig. 3 was used to record the dynamic fracture characteristics of the specimens. The system consisted of a low-velocity impact system, a green-pump laser light source with 50 mW power, an optical lens and a high-speed camera. First, parallel light rays are formed after the laser light passes through the first lens and then through the transparent specimen. Because of the stress concentration effect at the crack tip zone under an external applied load using a free drop hammer, the parallel light rays are deflected. Consequently, caustic spots are formed surrounding the crack tip on the reference plane behind the specimen at a distance Z_0.

In this study, the high-speed camera could capture dynamic crack propagation and transmit the image signals to a computer. Therefore, both crack propagation and the dynamic caustic spots could be observed. In addition, the high-speed camera could adjust the photograph resolution and exposure time. In the present experiment, the frame rate of the high-speed camera with a photograph resolution of 128 × 64 pixels was 3×10^5 frames per second, and the exposure time of the camera was 3 μs. The initial height used for the drop hammer with a 1 kg weight was 500 mm. Once the drop hammer impacted the specimen, the initial crack was initiated, and the crack propagated under the impact load. Simultaneously, the high-speed camera recorded the dynamic caustic spot surrounding the propagating crack tip, and the recorded images were used to extract the characteristic size of the caustic spots, crack velocity, and dynamic SIF.

3. Dynamic SIF

3.1. Dynamic SIF in homogeneous material

Based on the dynamic caustic analysis of a crack propagating in a homogeneous material, the dynamic SIF (K_{I-dyn}^{hom}) surrounding the running mode I crack tip [9,10] can be expressed as

$$K_{I-dyn}^{hom} = \frac{2}{3}\frac{\sqrt{2\pi}F(\nu)}{Z_0 cd}\left(\frac{D}{3.17}\right)^{\frac{5}{2}} \tag{1}$$