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Short communication: test method

Experimental study on the fiber pull-out of composites using digital gradient sensing technique

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ABSTRACT

A method to measure the stress field at the fiber tip in the fiber pull out test was proposed by using a digital gradient sensing technique. First, the principle of digital gradient sensing is introduced, and the non-contact optical system of digital gradient sensing developed. Then, a fiber reinforced composite model specimen, where a nail was inserted in epoxy resin to act as a fiber, was performed, and a pull out test was conducted on the specimen using the digital gradient sensing technique. Finally, the angular deflections contour at the fiber tip was obtained, and the stress intensity factor was extracted from the angular deflections. The results show that the stress intensity factor at the fiber tip extracted from the angular deflections agreed with the results calculated by the finite element method.

1. Introduction

Composite materials have been widely used in light aircraft with advantages of high strength-density ratio and high stiffness-density ratio, good corrosion resistance and high fatigue life compared to steel [1,2]. It is widely known that the fiber/matrix interface influences the properties of fiber-reinforced composite materials [3]. In general, fiber-reinforced composites should possess good interfacial shear strength that is dependent on the fiber surface properties and the mechanical properties of the fiber and matrix. Several test methods have been developed for the evaluation of interfacial shear strength including fiber fragmentation, push-out or indentation, and the single-fiber pull-out test. The different techniques yield different results and correlations between them are often poor. The single-fiber pull-out test is, however, a method commonly employed for the determination of the interfacial parameters because of its simplicity and versatility.

Although the single-fiber pull-out test has been commonly used for assessing the fiber-matrix interfacial shear strength, a survey of published literature reveals a number of observations which have yet to be accounted for. DiFrancia et al. [4,5] reviewed and interpreted the single-fiber pull-out test, and carried out a quantitative evaluation of an uncatalysed TGDDM/DDS epoxy. Banholzer et al. [6,7] studied the single-fiber pull-out test in view of a direct problem and an inverse problem. Yue et al. [8] assessed fiber-matrix adhesion using a technique based on the fiber pull-out test. Zhandarov et al. [9] proposed an alternative method of determining the local interfacial shear strength from force-displacement curves in the pull-out and microbond tests. Graupner et al. [10] studied fibre/matrix adhesion of cellulose fibers in PLA, PP and MAPP using a pull-out test, microbond test and single fiber fragmentation. Koyanagi et al. [11] made a comparison of glass–epoxy interface strengths examined by cruciform specimen and single-fiber pull-out tests under combined stress state. Fu

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et al. [12] analyzed the micromechanics of stress transfer in single- and multi-fiber pull-out tests.

Optical full-field measurement techniques such as photoelasticity [13,14], moiré interferometry [15,16] and digital image correlation (DIC) [17,18] are found very promising for the experimental stress/strain analysis of fiber pull-out tests. Recently, as an extension of the DIC based method, Periasamy and Tippur proposed a full field optical technique called Digital Gradient Sensing (DGS) [19] which can quantify elasto-optic effects using the digital image correlation method for mechanical characterization of optically transparent planar solids. The method can link angular deflections of light rays quantified using digital image correlation to two orthogonal stress gradients under plane stress conditions.

In this article, the fiber pull out of fiber-reinforced composites was studied using the digital gradient sensing method. The stress intensity factor at the fiber tip was extracted from the stress gradient calculated by digital gradient sensing. Moreover, a numerical simulation was carried out to verify the experimental results.

2. Experimental details

2.1. DGS method

A schematic representation of the experimental setup for the DGS method is shown in Fig. 1 [19,20]. It consists of a uniformly illuminated speckle target, a planar transparent test object and a digital camera. The target is a planar surface coated with a random speckle pattern produced by spraying it with fine mists of black and white paint. The transparent specimen to be tested is placed in front of and parallel to the target plane at a known distance Δ (= distance between the mid-plane of the specimen and the target plane). A camera fitted with a relatively long focal length lens is placed behind the specimen at a large distance *L*, L > D, and focused on the target plane through the specimen in the region of interest.

The measurement principle of DGS as shown in Fig. 2 is as follow:

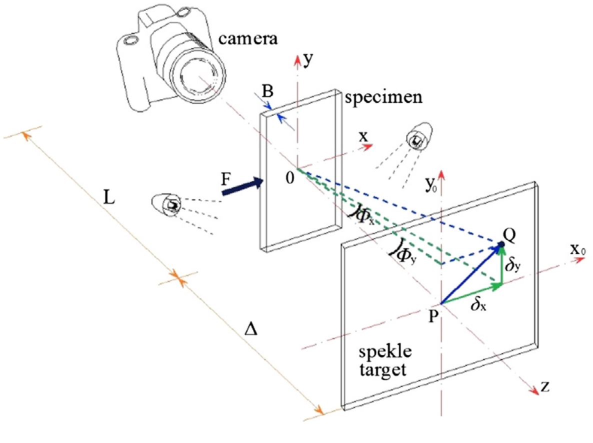

Fig. 1. Schematic of the experimental setup for DGS.

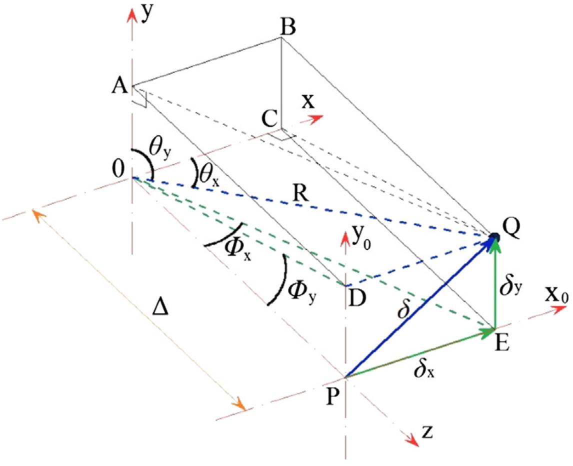

Fig. 2. Schematic of the working principle of DGS.

Thickness of a transparent specimen is *B* and refractive index is *n*0 in the no-load state. Cartesian systems, (*x, y, z*) and (*x*0, *y*0, *z*0) are chosen on the specimen and target plane, respectively, so that the z axis is perpendicular to the specimen (or target plane). When the target plane surface is imaged through the transparent specimen, a point P on the target plane corresponding to O on the specimen is imaged in the reference state. When imposing load, thickness and refractive index of specimen are all changed due to local stress, a neighbor point Q corresponding to O is imaged in the deformed state. That is, light rays $\overline{OP}$ in the reference state corresponding to $\overline{OQ}$ in the deformed state. The spatial vector $\overline{PQ}$ with known Δ can be related to angular deflections of light rays. The governing equations of the DGS method are expressed as [19]

$$\phi_x = \frac{\delta_x}{\Delta} = C_\sigma B \frac{\partial(\sigma_{xx} + \sigma_{yy})}{\partial x} \tag{1}$$

$$\phi_y = \frac{\delta_y}{\Delta} = C_\sigma B \frac{\partial(\sigma_{xx} + \sigma_{yy})}{\partial y} \tag{2}$$

From this, δ_x and δ_y can be derived from digital image correlation, C_σ is the elasto-optic constant of the transparent material. Hence, angular deflections as well as stress gradients are obtained.

2.2. Specimens and loading

In order to study the fiber pull out test using the digital gradient sensing technique, a transparent epoxy specimen with a 3 mm diameter nail acting as a fiber is shown in Fig. 3(a). First, a standard DGEBA (diglycidyl ether of bisphenol-A) epoxy cured with a bifunctional polyamide was employed so that partial curing at room temperature would occur, enabling the positioning of the nail in the desired locations within the specimens prior to full hardening. Then, a resin-rich composition with the resin and the curing agent (3:1 in weight percentage) was used to create an epoxy solid. In the initial fabrication step, both the resin