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Material behaviour

Experimental investigation of the fiber bundle shielding effect on the dynamic matrix crack using optical caustic method

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ABSTRACT

The fiber bundle shielding effect on the dynamic matrix cracking in fiber reinforced composite under dynamic loading was investigated using an optical caustics method. First, edge cracked epoxy beams, with a symmetrically positioned fiber bundle ahead of the crack tip, were preformed to simulate matrix crack shielding by the fiber bundle in fiber reinforced composites. Then, the effect of fiber bundle width on the dynamic matrix crack propagation behavior was analyzed using the caustics method, where the caustic spot shape, the dynamic stress intensity factor and crack propagation velocity were obtained to characterize the shielding effect of the fiber bundle. Finally, the shielding effect of a tilted fiber bundle with an angle of 30°on the dynamic matrix crack was analyzed using the optical caustics method, where the different fiber bundle width would cause different failure modes and failure mechanisms.

1. Introduction

It is well known that brittle polymers can be toughened by the addition of fibers. The most common technique usually followed for the production of fiber-reinforced plastics is to resolve the fiber as a separate phase which may incorporate inclusions of the polymer. The addition of fibers to a polymer matrix results in a composite material, which may possess a very complex mechanical property profile. In particular, matrix crack propagation and fracture toughness of the material strongly depend on (1) how the fibers are oriented with respect to the initial crack, (2) what kind of fibers and matrix are used, (3) the volume fraction of fibers, and (4) the bond quality of the fiber/matrix interface. 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 behavior of fiber composites [1]. Therefore, it is necessary to investigate the fiber bundle shielding effect on the dynamic matrix crack in fiber reinforced composites.

The main advantage of the caustics method compared with the classical interferometry or holographic interferometry is that the local stress singularity at the crack tip can be reflected by means of the simple caustics spot, which is a sharp and well defined curve [2]. Some measurement errors in determining the characterization size of the caustics spot can be minimized by means of precise optical adjustment and fine digital image processing. On the contrary, some full field optical methods such as coherent gradient sensing and photoelastic show a density fringe distribution surrounding the crack tip, and it is difficult to evaluate the stress intensity factor at the crack tip from these fringe patterns. As to moiré interferometry and electronic speckle pattern interferometry, it is difficult to obtain the local crack tip stress information due to the inherent limits.

The caustics method is an effective optical method to experimentally obtain the stress intensity factor. This method has been applied to various problems, due partly to its simple measurement system. In recent years, research has been conducted on the application of the caustics method for measurement of a wide range of stress intensity

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factors including those of new materials and those under mixed-mode loading. Theocaris and Papadopoulos [3] studied the dynamic stress intensity factor and the evaluation of the velocity of propagation of a transverse crack under mode I in specimens made of optically inert materials using optical caustics. Theocaris et al. [4] studied the effect of filler-volume fraction on stress intensity factor and crack propagation velocity in iron-epoxy particulate composites using a caustics method. Rosakis and Ravi-Chandar [5] examined measurement accuracy of caustics under mode I loading and clarified the effect of an initial curve on the measurement accuracy. Theocaris et al. [6,7] investigated the problem of a moving crack passing through rectangular hard inclusions embedded in the soft matrix material. Li et al. [8,9] investigated dynamic fracture problems in orthotropic composites and viscoelastic materials using the optical caustics method. Yao et al. [10–13] studied the crack tip singularity and fracture characterizations using the optical caustics method, including: the stress intensity factor at the crack tip in fiber reinforced composites, the local stress singularities of laminated composite materials under concentrated loads and the stress intensity factor in graded materials under static and dynamic loading. Tomlinson and Patterson [14] extended the method of caustics by considering the residual caustics and its formation, then to consider the effect on the measured stress intensity factor over a fatigue cycle of the residual caustics for different crack lengths and loads. Tomlinson and Patterson [15] performed an investigation to assess the effects of curvature on the stress intensity factor determined from caustics, to study the equations that were presented by Theocaris and develop a generalized version of this theory to include all possible cases of curvature and optical arrangement, and to quantify any limits there may be on the surface topography and on the experimental procedure required to obtain accurate results. Carazo-Alvarez and Patterson [16] provided a general method for automated analysis of caustics. Patterson and Whelan [17] expanded the caustics method for tracking the location and movement of nanoparticles with an optical microscope. Gdoutos and Raftopoulos [18] combined the method of caustics with the stress frozen technique for the investigation of three-dimensional crack problems. Gdoutos [19–21] studied the effect of the changing state of stress around the crack tip on the determination of stress intensity factors by the method of caustics. Papadopoulos [22] proposed a new formula of experimental calculation stress intensity factor that depended to the area of the caustics.

The optical method of caustics is adopted here to investigate the fiber bundle shielding effect on the dynamic matrix crack in the fiber reinforced composites. Edge cracked epoxy beams, with a symmetrically positioned fiber bundle ahead of the crack tip, were preformed to simulate a matrix crack shielding by the fiber bundle in fiber reinforced composites, and some typical caustic experiments for the shielding effect were conducted. The effect of fiber bundle width and tilt angle of the fiber bundle on the caustic spot shape, the dynamic stress intensity and the crack propagation velocity were investigated.

2. Experiment details

2.1. Specimens fabrication

The caustics experiments reported here were performed with three point bending fracture specimens, having a square cross section of 140mm × 40mm and a thickness of 5mm, cast from a transparent epoxy, and with an aramid fiber bundle to act as inclusion, which is shown in Fig. 1. The aramid fiber used in this study was Kevlar 49 manufactured by DuPont, USA. The density of Kevlar 49 is $1.47g/cm^3$, and the longitudinal and transversely elastic modulus of the aramid fiber is $165GPa15GPa$, respectively. A transparent epoxy was chosen for the matrix material because it lacks other distracting damage mechanisms, such as crazing or microcracking, and can be formulated to a very brittle state. 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 fiber bundle in the desired location within the specimens prior to full hardening. A resin-rich composition of three parts resin to one part curing agent was used to create an epoxy solid which was as brittle as possible using this particular curing agent.

In the initial fabrication step, the resin and curing agent were heated to approximately 65°C, mixed for at least five minutes, and then evacuated until most degassing activity ceased. The liquid was then poured into PMMA molds which had been coated with a release agent, which is shown in Fig. 1(a). In the finished specimens, the center plane was visually indiscernible and mechanically sound after crosslinking was completed by the post-curing process. Following a room temperature cure of at least 24 hours, the filled molds were post-cured for one hour at 135°C and cooled at a rate of approximately 10°C/hour in a programmable oven. Specimens were then milled to the dimensions indicated previously, which is shown in Fig. 1(b).

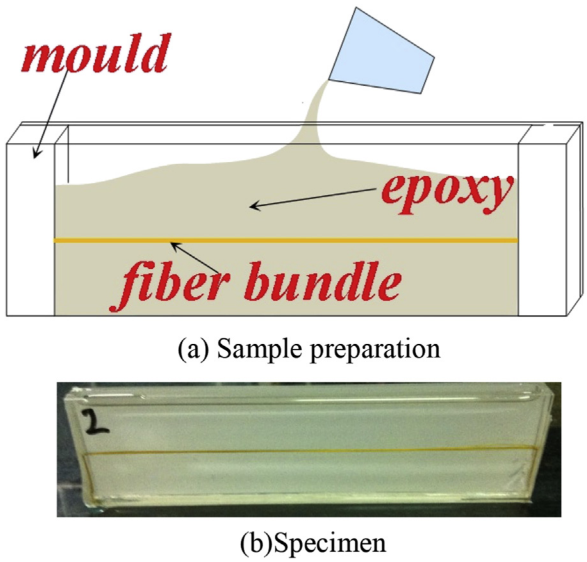

Fig. 1. Specimen details.