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Mixed-mode translaminar fracture of plain-weave composites

Dhatreyi Boyina [a], Anuradha Banerjee [a,*], R. Velmurugan [b]

[a] Department of Applied Mechanics, IIT Madras, Chennai 600036, India
[b] Department of Aerospace Engineering, IIT Madras, Chennai 600036, India

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ABSTRACT

The present study characterizes translaminar fracture in plain-weave, fabric-reinforced composite under mixed-mode loads. From fractography of the fracture specimen, the effect of mixity on the failure mechanisms and crack paths is established. Finite element analysis is performed using effective elastic properties of the composite material obtained from meso-scopic analysis. The fracture properties are characterized based on modified compliance method assuming quasi-brittle behavior of the composite. Higher mixity is shown to encourage fiber–matrix debonding which while lowers the fracture toughness for initiation of an effective crack, results in significantly higher energy dissipation for continued stable growth of the effective crack.

1. Introduction

Fiber-reinforced composites are widely used in a large number of engineering applications as they have high specific strength, high specific stiffness and therefore are effective as light weight structural material. To enhance their functionality, the properties of a composite material can be designed to have the desired mechanical behavior. Based on the type of fiber reinforcement, composites can be broadly classified as non-woven and woven composites [1,2]. Plain-weave composites are the simplest form of woven composites, where the fibers are interlaced with each other in orthogonal directions. The fibers being oriented in two orthogonal directions in the plane results in balanced properties in the plane of the lamina. In addition, these composites exhibit good impact strength and fracture resistance [1,3]. To ensure the structural integrity of these composites it is of importance to evaluate the factors that control their mechanical as well as fracture behavior under realistic conditions.

The dominant fracture modes in composite laminates are intra-laminar and inter-laminar fracture. The inter-laminar fracture, i.e. delamination, occurs mainly due to the failure of matrix and therefore involves insignificant fiber breakage [4–6]. Intra-laminar/translaminar fracture, on the other hand, involves growth of a nominal crack-like defect across the thickness which has both matrix failure as well as significant fiber-breakage [7–9]. A comprehensive review of the numerous studies focusing on characterization of translaminar fracture in composites is presented by Laffan et al. [10]. Across the studies, CT specimen finds maximum popularity as not only it exhibits significant stable crack growth which is essential in characterization of resistance curves but it also has efficient use of the material.

To characterize the mode-I fracture behavior of woven fabric composites Rokbi et al. [2] studied a glass/epoxy twill weave laminate using Digital Image Correlation and compliance method. Both techniques were found to give similar predictions for the fracture toughness. They also identified various stages of composite damage: prior to peak load the primary mechanisms were attributed to matrix cracking, fiber–matrix debonding while post peak the dominant mechanism was fiber breakage along with matrix cracking [11,12]. Liu and Hughes [13] found mode-I fracture behavior of woven flax fiber rein composites to be strongly dependent on the volume fraction of the yarns and the direction of crack propagation with respect to orientation of the fabric rather than the weave architecture. Laffan et al. [14] in their study on characterization of mode-I fracture toughness of cross-ply laminates evaluated the comparative effectiveness of different methods for data reduction. Based on the fracture data from CT specimens, they argue that the modified compliance calibration method gave most consistent results and it is simpler as it does not require optically measured crack length.

In the earlier studies on mixed-mode fracture, the mode-mixity in the load was introduced by changing the orientation angle of the crack in center notch specimens, but these specimens experienced unstable crack growth [15,16]. Therefore, these studies could only characterize the toughness for fracture initiation. Laffan et al. [8] by using a mixed-mode CT specimen were able to generate resistance curves and establish the damage mechanisms

* Corresponding author. Tel.: +91 44 22574075; fax.: +91 44 22574052.
E-mail address: anuban@iitm.ac.in (A. Banerjee).

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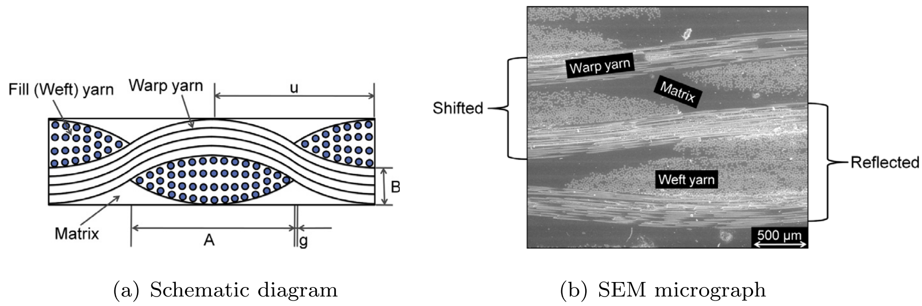

Fig. 1. Cross-section of the plain-weave fabric glass/epoxy composite. (a) Schematic diagram. (b) SEM micrograph.

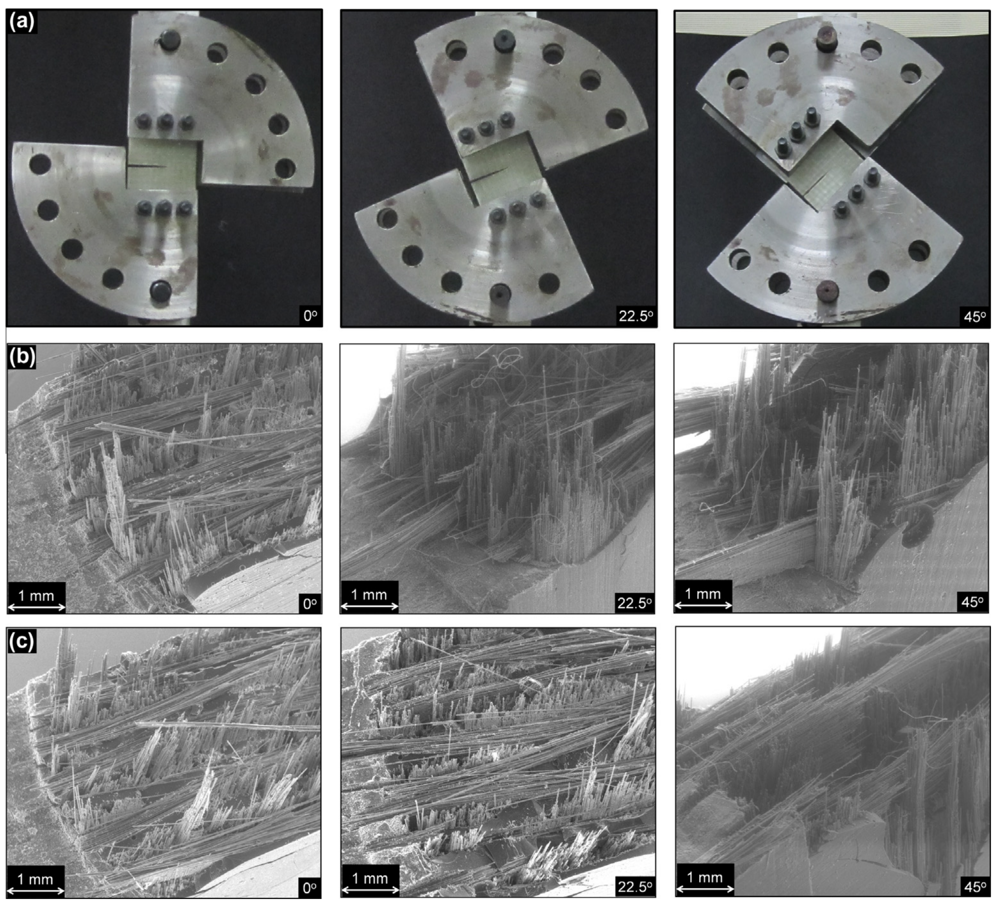

Fig. 2. (a) Experimental loading arrangement for different loading angles. (b) SEM images of fractured surface of the upper half of the specimen. (c) SEM images of fractured surface of the lower half of the specimen.

specifically caused by the mixity in the load for unidirectional carbon/epoxy laminates. To the best of authors knowledge, characterization of resistance curves for mixed-mode fracture has not been reported for woven composites.

In the present study, mixed-mode translaminar fracture studies are carried out on plain-weave glass fabric-reinforced composite laminates by performing experiments on modified CT specimen. As the material properties of the plain-weave composites depend on the curvature of the yarns, the yarn curvature is measured from the Scanning Electron Microscope (SEM) image and the effective elastic properties of the composite laminate are obtained from the finite element analysis of a unit cell model of the material. These effective/homogenized properties are used in the numerical simulations of the modified CT specimen to establish the compliance calibration curves. Assuming quasi-brittle nature for the material, the effective crack length is estimated using the experimental macroscopic response and calibration curves for the compliance. The failure mechanisms and complex crack path are identified and a discussion is developed to understand the significantly nonlinear behavior exhibited by the fracture specimens having higher mode-mixity in spite of the brittle nature of the constituents of the composite.

2. Material and experiments

The material used in this study is plain-weave glass fabric-reinforced epoxy composite. A schematic diagram representing the cross-section of a single layered plain-weave composite is shown in Fig. 1(a). The key geometric parameters that control its