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Composite Structures 69 (2005) 1–9
COMPOSITE STRUCTURES
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Effect of stitching on Mode I strain energy release rate

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Abstract

Stitching advanced graphite/epoxy composites in the through-thickness direction improves the interlaminar fracture toughness. The Mode I energy release rate of a graphite/epoxy composite, with and without stitching fibers, was experimentally determined using double cantilever beam specimens. The fibers employed in this research are not densely stitched. Three different fibers, namely Para-Aramid fiber, Glass fiber, and PAN-based carbon tow fiber, were used to study the effect of fiber stiffness on the strain energy release rate. The 3-D finite element model combined with the crack closure integral method is employed to obtain the G_I and G_{IC} values. Experimental results were compared with finite element analytical calculations and good agreement was found. The first mode of strain energy release rate of stitched specimens is about three to six times that of unstitched specimens depending on the stiffness of the stitched fibers.

Keywords: Stitching; Finite element method; Delamination; Mode I energy release rate

1. Introduction

Graphite/epoxy composite laminates have very high in-plane strength and stiffness, but they usually exhibit poor interlaminar strength and energy release rate, and hence are vulnerable to delamination. Various techniques have been considered to improve the out-of-plane properties by increasing the resistance to delamination. Some researches had focused on materials improvements, i.e. on the use of tougher matrices, better fiber/matrix interface or interleaving concepts [1–3]. Alternative approaches to bringing about substantial improvements in interlaminar fracture toughness of composite structures require modifications of the fiber architecture. Weaving, knitting, and braiding have shown to achieve considerable enhancement in fracture toughness and impact properties, but these methods reduce the proportion of fibers along the in-plane directions and create large resin pockets throughout the structure, which tends to deteriorate the in-plane properties. The biggest advantage of stitching compared with other methods of through-thickness reinforcement is its versatility. Stitching utilizes traditional materials and fabrication process using components that can be manufactured from either a prepreg or perform layup.

To improve the Mode I critical strain energy release rate, Dransfield, et al. [4] proposed two micro-mechanics-based models for studying the effect of through-thickness stitching fibers in improving the delamination crack growth resistance of double cantilever beam (DCB) specimens. They found that the reinforcement achieved by through-thickness stitching fibers improves significantly the crack growth resistance, and hence inhibits or delays extension of delamination. In their first model, they assumed that the stitching fibers are not interconnected; while in their second model, they considered the effect of interconnected stitches. They found that a large interfacial shear stress and higher stitching density together with a small stitching thread diameter are desirable and can maximize the crack growth resistance. Mouritz et al. [10] studied the flexural strength and inter-laminar shear strength of stitched glass-reinforced plastic (GRP) laminates. The GRP laminates were stitched through the thickness with Kevlar thread in two orientations with a low or high stitching density. They found that the Mode I inter-laminar fracture toughness, G_{IC}, increased with Kevlar thread in two orientations, whereas the Mode II toughness, G_{IIC}, was not affected by the stitching fibers. The three-point flexural strength and short beam inter-laminar shear strength of the GRP laminates before impact loading

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0263-8223/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruct.2004.02.009

were reduced as a result of damage incurred by stitching fibers. Subsequently they concluded that stitching fibers did not enhance the impact damage resistance, the post-impact flexural strength or the inter-laminar shear strength of the GRP laminates. They also found that the extent of delamination arising from single or repeated impacts was slightly higher in stitched laminates. However, these findings may not be applicable to other types of fiber–reinforced polymer composites. Generally, the DCB specimen [4–10] was used to determine the Mode I inter-laminar fracture toughness of lightly stitched composites. Owing to the higher bending moment at the crack tip [11], laminates with medium- and high-density stitches will fail under compressive stresses before delamination can propagate. The Mode I fracture toughness of graphite/epoxy laminates containing Kevlar stitches with a density of 64 stitches per square inch obtained by a novel DCB test [12] was about 45 times that of unstitched specimens.

Most of the abovementioned studies focused on investigating the effect of stitching fiber density on fracture toughness and no effort has yet been made on exploring the effect of fiber stiffness on fracture toughness. In this paper, fibers of different stiffness are employed to examine their effect on the energy release rate of the stitched composite material. In addition, this study is the first attempt to calculate the fracture toughness of stitched and delaminated composite laminates using the finite element method.

The critical strain energy release rate plays an important role in determining the initiation and growth of delamination in composite laminates. Linear elastic fracture mechanics (LEFM) available at the sharp crack of the structure can help predict the failure behavior. LEFM is only applicable for smaller plastic area at the crack tip and becomes unavailable when the plastic zone at the crack tip is bigger than that of the crack length. The Mode I strain energy release rate (G_{I}) would be calculated using theoretical analysis, experimental method and finite element analysis (FEA) [13–15]. Theoretical analysis involves the use of the linear elastic beam model proposed by Gilman [16]. He employed the DCB to calculate the G_{I} value without considering the shear stress at the crack tip. Berry [17] proposed the compliance calibration method for evaluating the relationship between the critical loading and displacement observed from the experimental data and for calculating the critical strain energy release rate. The FEA calculation can be direct or indirect [18]. Indirect FEA calculation obtains the energy release rate by increasing the small crack length (Δa) twice. In other words, FEA is first performed with crack length of a, then it is performed again with crack length of $a + (\Delta a)$. The results of both calculations yield the GI. Nevertheless, this method is more time-consuming. On the other hand, direct FEA calculation of energy release rate yields the nodal forces and displacements at the crack tip without the need of performing the analysis twice. Another approach is the crack closure integral method proposed by Irwin [19]. It calculates the energy release rate using the stress and opening displacement at the crack tip. The 3-D eight-node non-singular element used by Roeck and Wahab [14] is adopted in this study to examine the strain energy release rate.

2. Strain energy release rate of composite laminate

The evaluation of failure behavior using fracture mechanics can be described by the following parameters: (1) stress intensity factor, K; (2) strain energy release rate, G; (3) J-integral, J; and (4) crack tip opening displacement, CTOD. K and G are available in the linear elastic area of very small plastic zone at the crack tip, whereas J-integral and CTOD are available in the elastic–plastic area of bigger plastic zone. The failure behavior of isotropic material is evaluated using K values; while the delamination behavior of composite materials is generally examined by obtaining the G values.

The failure strength of the composite laminate, the interface strength between the fiber and matrix as well as the strength of the matrix are affected by many factors such as the sliding and breakage of fibers, the crack of the matrix and the extent of delamination. There are three major types of failure of composite materials: (1) inter-laminar fracture; (2) intra-laminar fracture; and (3) trans-laminar fracture, as shown in Fig. 1. Delamination propagation is generally thought to be the result of inter-laminar fracture, therefore the strain energy release rate and critical energy release rate would be used to evaluate the initiation and propagation of delamination.

3. Compliance calibration method

Griffith [19] proposed using the strain energy release rate to evaluate the failure behavior, and developed the

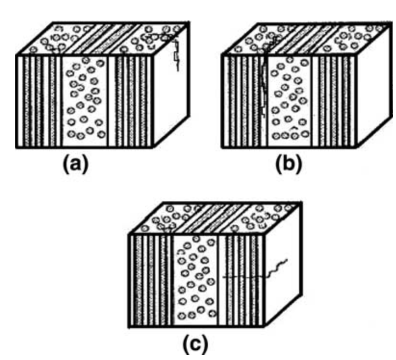

Fig. 1. (a) Intra-laminar fracture; (b) inter-laminar fracture and (c) trans-laminar fracture.