QUANTIFYING THE EFFECT OF FIBER BRIDGING ON MODE I QUASI-STATIC AND FATIGUE TESTING

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Abstract
This investigation focuses on mode I delamination propagation in a unidirectional (UD) carbon fiber reinforced polymer (CFRP) composite laminate. Delamination propagation in this type of material may be accompanied by fiber bridging, a phenomenon where fibers from one face of the delamination cross over to the other face, such that the fibers are simultaneously pulled from both faces, thus, bridging the delamination. This increases the material's apparent resistance to further propagation of the delamination. This phenomenon occurs mostly in beam-type test specimens commonly used to characterize failure of composite materials, but does not generally occur in structures with the exception a few structures such as rotor blades. The aim of this investigation is to quantify the effect of fiber bridging for quasi-static and fatigue testing of DCB specimens so as to eliminate it from the fracture and fatigue delamination propagation properties.

1. Introduction

Composite materials are widely used in aerospace applications in order to increase strength-to-weight ratios as compared to metals, thus decreasing the weight of structures and consuming less fuel. A common type of composite is a polymer matrix reinforced with fibers arranged in one direction. Beam-type specimens are commonly used to determine the fracture toughness of this type of material, and in mode I, double cantilever beam (DCB) specimens are usually tested. DCB specimens of unidirectional laminates exhibit fiber bridging (FB), a phenomenon that occurs when a delamination, the most common failure mode in laminate composites, propagates as a result of an external load. While propagating, reinforcement fibers from one face of the delamination cross over to the other face, such that fibers are simultaneously pulled from both faces, increasing the apparent resistance of the material to delamination propagation. However, in most applications fiber bridging is not observed in components containing a delamination, and in such cases fiber bridging may be considered an artifact of fracture toughness laboratory testing performed on DCB specimens. Hence, it is necessary to eliminate the influence of fiber bridging from the fracture toughness and fatigue delamination propagation properties.

2. Results

Analytical and numerical models are developed that describe the material behavior of delamination propagation. These models are based on mode I laboratory tests conducted by means of quasi-static and fatigue loading on coupons of a carbon/epoxy composite AS4/8552, and may be used to predict failure of composite laminate structures. The experimental work for quasi-static delamination propagation consists of standard testing, adjusted to enable the determination of fiber bridging parameters. The results of these tests allow determination of the fracture toughness of the material, as well as the fiber bridging parameters required to model the material response. For determination of fatigue delamination propagation parameters, two test protocols are used. The first protocol consists of testing a specimen containing a delamination in fatigue for about three million cycles with no intervention during the testing procedure. The second protocol consists of a series of fatigue test sequences applied consecutively to a single specimen. The results of the quasi-static and fatigue tests are used in the calibration of the respective numerical models.

In order to construct a numerical tool to predict delamination propagation, the cohesive zone approach is used to model the behavior of the material. A cohesive zone model is used in both quasi-static and fatigue loading. Each of the two cohesive zone models is implemented in finite element analyses via a user element (UEL) subroutine coded for that purpose. The results of the laboratory tests are used to calibrate the models.

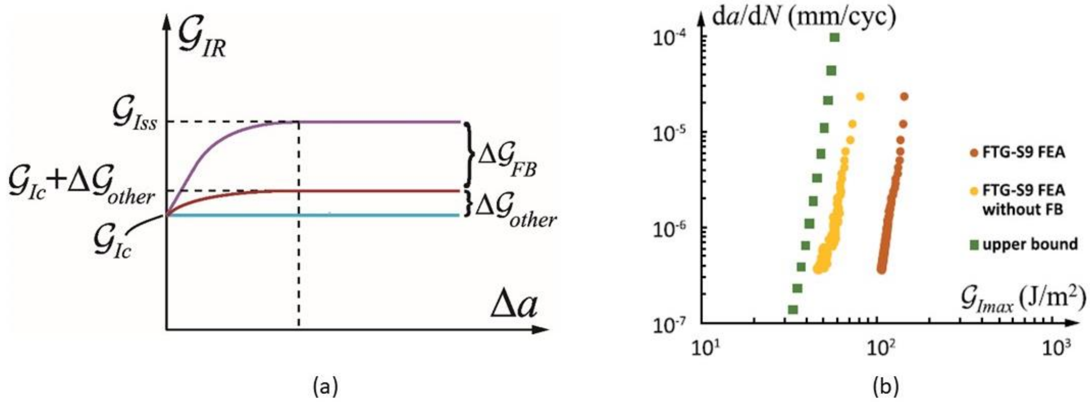

Fig. 1 – (a) Fracture resitance curve with fiber bridging contribution shown. (b) Fatigue delamination propagation rate with fiber bridging contribution eliminated.

Good correlations are obtained for both the quasi-static and fatigue tests. The cohesive zone models enable determination of the contribution of fiber bridging to the energy release rate of the material in both quasi-static and fatigue loading.

For the quasi-static loading, a fracture resistance curve of $\mathcal{G}_{IR}$ vs. the delamination length increment Δa is obtained as shown in Fig. 1a. The delamination initiates for $\mathcal{G}_{IR} = \mathcal{G}_{Ic} = 224.0$ J/m^2, the initiation fracture toughness. The curve rises up to the steady state fracture toughness value $\mathcal{G}_{Iss} = 331.8$ J/m^2. The value of the contribution of the fiber bridging to the energy release rate is calculated by means of a cohesive zone model with $\Delta\mathcal{G}_{FB} = 75.4$ J/m^2. For other dissipative mechanisms such as matrix cracking, $\Delta\mathcal{G}_{other} = 32.5$ J/m^2. Thus, fiber bridging contributes 22.7% to the steady state value of the fracture resistance. The red curve in Fig. 1a is the fracture resistance curve with the effect of fiber bridging eliminated.

For fatigue, the delamination propagation rate da/dN is plotted vs. the maximum mode I energy release rate in a cycle $\mathcal{G}_{Imax}$ in Fig. 1b for specimen FTG-S9 where FTG represents fatigue and S9 is the number of the specimen in the series. The red curve respresents the delamination propagation rate including all contributions to the energy release rate; the yellow curve represents the delamination propagation rate when the contribution from fiber bridging is eliminated using the cohesive zone model. In fatigue, the fiber bridging energy release rate accounts for 95% of the dissipative energy release rate. The green curve is obtained by another method suggested in the literature in which both the square-root of the energy release rate threshold value $\sqrt{\mathcal{G}_{Ithr}}$ and the cyclic fracture toughnes A are decreased by three standard deviations. It is seen that the latter is more conservative than the method presented here.

3. Conclusions

A cohesive zone model was developed here to evaluate the contribution of fiber bridging to the quasi-static energy release rate, as well as to the fatigue delamination propagation rate for a UD laminate composite. It was found that fiber bridging accounted for 22.7% of the quasi-static fracture resistance. In fatigue, the fiber bridging energy release rate accounted for 95% of the dissipative energy release rate. The methods developed here may be applied to other materials to evaluate the contribution of fiber bridging in quasi-static and fatigue testing of composite laminates.