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CHARACTERIZATION, ANALYSIS AND PREDICTION OF DELAMINATION IN COMPOSITES USING FRACTURE MECHANICS

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ABSTRACT

The state-of-the-art for characterizing, analyzing, and predicting delamination growth in composite materials and structures using a fracture mechanics approach will be reviewed. Techniques for measuring delamination fracture toughness and fatigue delamination onset data will be highlighted. The use of these data in finite element analyses utilizing fracture mechanics will be examined. The virtual crack closure technique for calculating strain energy release rates will be highlighted. The importance of capturing the physics of damage formation, accumulation, and growth will be emphasized. Application of this approach to delamination onset and life predictions for stiffener pull-off behavior in skin-stiffened regions and fatigue failure of composite rotor hub flexbeams will be highlighted.

KEYWORDS

composites, delamination, fracture mechanics, strain energy release rate, virtual crack closure technique, fatigue, stiffener pull-off

INTRODUCTION

One of the most commonly observed failure modes in composite materials is delamination, a separation of the fiber reinforced layers that are stacked together to form laminates. The most common sources of delamination are the material and structural discontinuities shown in figure 1. Delaminations occur at stress free edges due to the mismatch in properties of the individual layers, at ply drops where thickness must be reduced, and at regions subjected to out-of-plane loading such as bending of curved beams. Delaminations form due to some combination of three basic fracture modes shown in figure 2. These include the opening mode (mode I), the sliding shear mode (mode II), and the scissoring shear mode (mode III). The interlaminar fracture toughness (IFT) associated with each of the fracture modes must be characterized and the corresponding strain energy release rates for each mode associated with the configuration and loading of interest must be calculated to predict delamination onset and growth.

DELAMINATION CHARACTERIZATION

A mixed-mode I & II delamination failure criterion that is used for 2D problems is shown in figure 3. The IFT is determined as a critical value of the strain energy release rate, G_c, plotted as a function of the mixed-mode ratio, G_{II}/G_c. For the pure mode I opening case, $G_{II}/G_c=0$, whereas for the pure mode II case, $G_{II}/G_c=1$. These properties are determined using test methods that are being evaluated and standardized by the American Society for Testing and Materials (ASTM) and other national standards organizations, as well as the International Standards Organization (ISO) [1]. The pure mode I data are generated using a Double Cantilever Beam (DCB) specimen. The pure mode II data are generated using an End-notched Flexure (ENF) specimen. The mixed mode I&II data are generated using a Mixed-mode Bending (MMB) specimen. As shown in figure 3, the apparent toughness increases monotonically between the pure opening mode I case and the pure shear mode II case. Furthermore, due to the complex micro-mechanisms involved, the scatter is very large for the mode II case [2]. For cases where a mode III fracture toughness is required, the Edge-cracked Torsion (ECT) specimen is preferred.

Because delaminations often form and grow under cyclic loads, a fatigue characterization is also desired. The classical Paris Law for fatigue crack growth has often been generated. However, the exponents in these power laws are quite high compared to similar characterizations for metals. Hence, a no growth threshold approach is often proposed instead [3-6]. Furthermore, for mode I fatigue, fiber bridging typically develops in the unidirectional DCB specimens [1,4]. Fiber bridging can cause a growing crack to arrest artificially early yielding a non-conservative threshold value. Therefore, as shown in figure 4, an alternate G versus N onset curve is typically generated to achieve a threshold characterization for delamination onset [4-7].

DELAMINATION ANALYSIS

The strain energy release rate, G, associated with onset and growth must be determined to predict delamination. Typically, a plot of the G components due to the three unique fracture modes (G_I, G_{II}, G_{III}) and the total $G= G_I+G_{II}+G_{III}$ are calculated as a function of delamination length, a, using the Virtual Crack Closure Technique (VCCT) in a finite element analysis (FEA) [8,9]. The VCCT technique, depicted in figure 5, utilizes the product of nodal forces and the difference in nodal displacements to calculate the G components for each fracture mode. For predicting delamination onset under quasi-static or cyclic loading in 2D problems, the peak value of the G as a function of delamination length is compared to the delamination onset criteria shown in figures 3 and 4, respectively. The VCCT technique has also been extended to three dimensional problems [10,11].

DELAMINATION PREDICTION

Skin/stiffener debonding

In reference 12, the pull-off loads associated with separation of a hat stiffener from the skin of a composite part by delamination were predicted by comparing G's calculated from FEA using VCCT to mixed-mode delamination failure criterion. Subsequent studies led to the development of a simple specimen consisting of a skin bonded to a tapered flange laminate [13]. By applying various types of loads in a finite element analysis of the specimen, VCCT may be used to calculate G's and predict the onset of delamination from the matrix cracks. From this prediction, a failure criterion for combinations of bending and membrane loads may be generated.

Flexbeam Fatigue Life Prediction

Composite rotor hubs contain tapered flexbeams with large numbers of ply terminations, or ply drops, to taper the beam thickness. These ply drops act as initiation sites for delamination in the flexbeam under high combined tension and cyclic bending loads. In reference 14, flexbeams were tested and analyzed to determine the fatigue life. Fatigue delamination onset data were compared to G distributions determined from FEA and VCCT to predict the onset of unstable delaminations in these complex tapered laminates (figure 6).

CONCLUSIONS

Delamination fracture toughness and fatigue onset have been characterized using fracture mechanics. The virtual crack closure technique (VCCT) is commonly used in finite element analyses (FEA) to calculate strain energy release rates. Characterization data were used with VCCT in FEA to predict delamination onset and life in composite rotor hub flexbeams and stiffener pull-off behavior in skin-stiffener reinforced composites.

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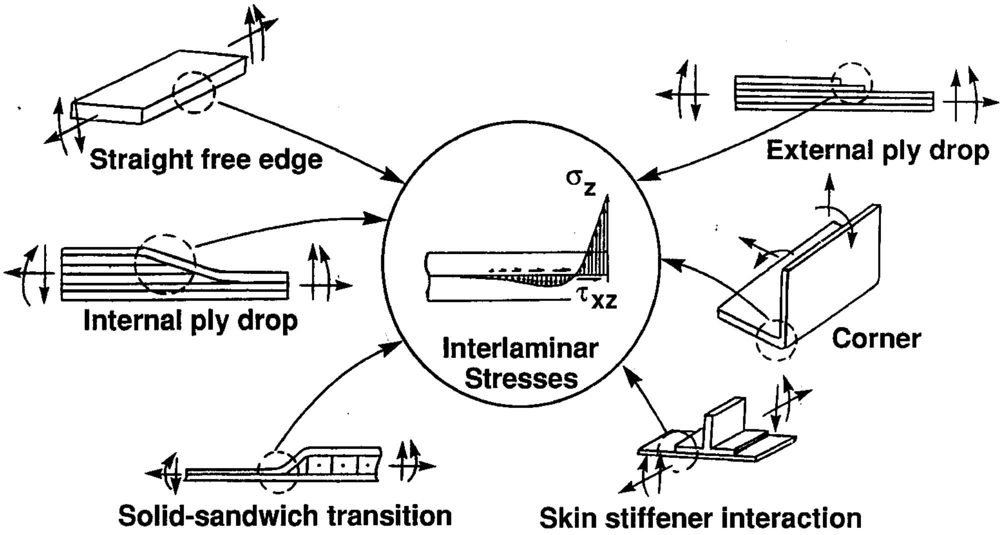


Fig. 1 Delamination Sources at Geometric and Material Discontinuities

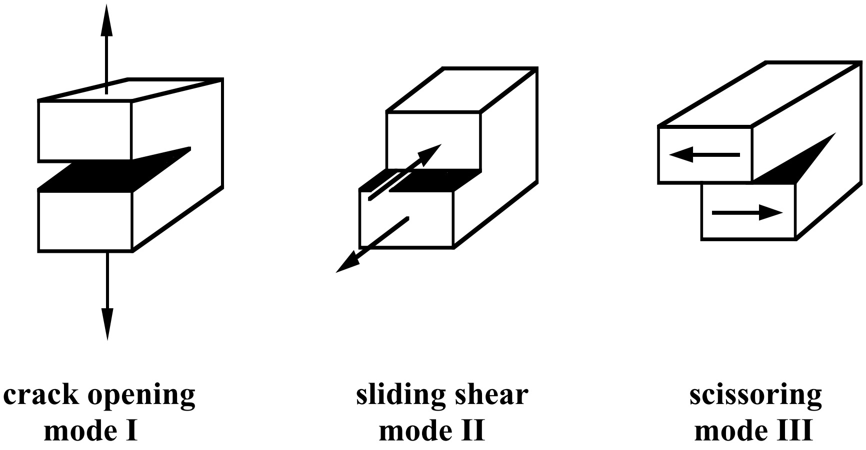


Fig. 2 Three modes of delamination fracture

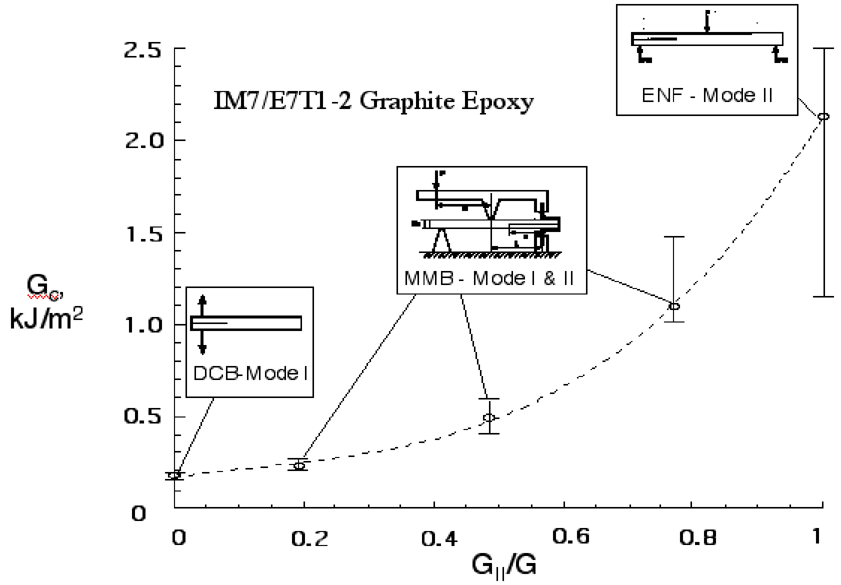


Fig.3 Mixed-Mode I & II Delamination Criterion

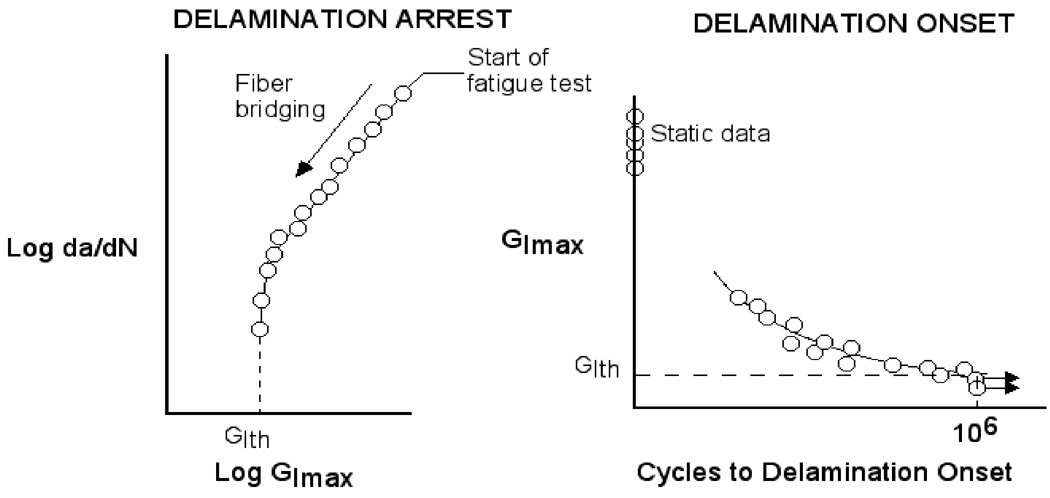


Fig.4 Experimental Technique to obtain a G Threshold for Delamination Onset

- **Eight-noded quadrilateral element**

$$G_I = \frac{1}{2\Delta a}\cdot\left(Y_i\cdot\Delta v_m + Y_j\cdot\Delta v_l\right)$$

$$G_{II} = \frac{1}{2\Delta a}\cdot\left(X_i\cdot\Delta u_m + X_j\cdot\Delta u_l\right)$$

- **Nonlinear Analysis**

$$G_I = \frac{1}{2\Delta a}\cdot\left(Y'_i\cdot\Delta v'_m + Y'_j\cdot\Delta v'_l\right)$$

$$G_{II} = \frac{1}{2\Delta a}\cdot\left(X'_i\cdot\Delta u'_m + X'_j\cdot\Delta u'_l\right)$$

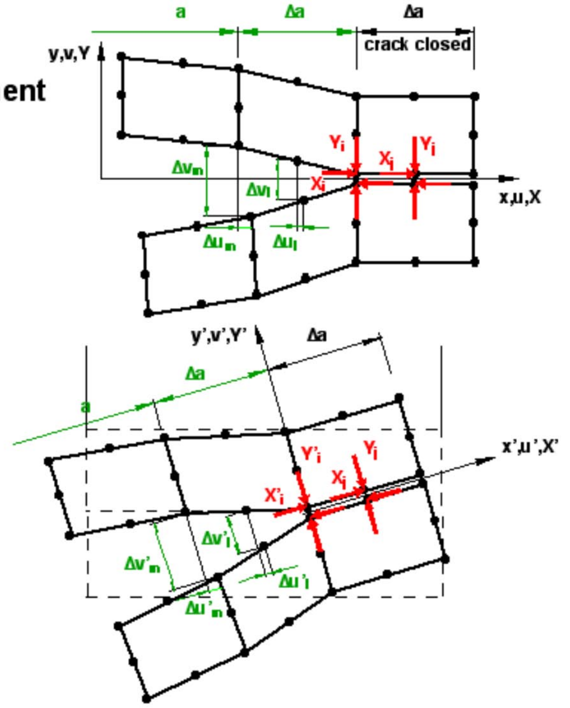
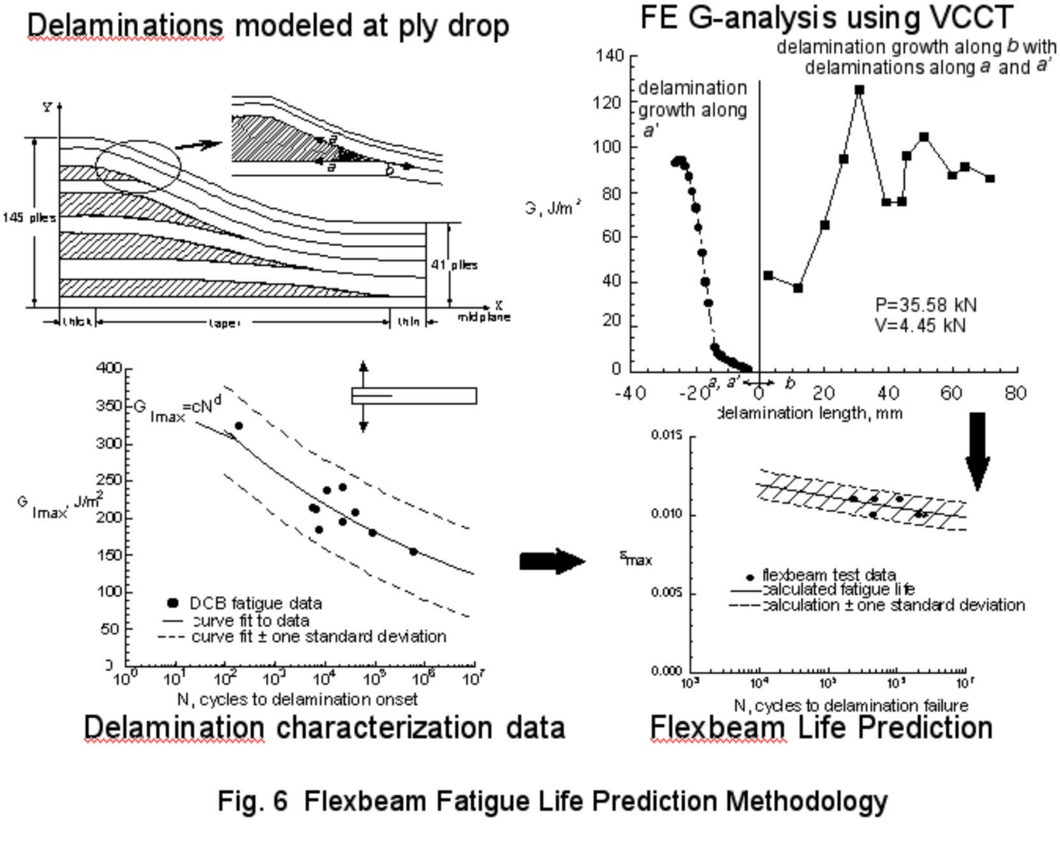


Fig. 5 Virtual Crack Closure Technique (VCCT)



Delaminations modeled at ply drop

FE G-analysis using VCCT

Delamination characterization data

Flexbeam Life Prediction

Fig. 6 Flexbeam Fatigue Life Prediction Methodology