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A total fatigue life model for mode I delaminated composite laminates

Kunigal Shivakumar[a,*], Huanchun Chen[a], Felix Abali[b], Dy Le[b], Curtis Davis[b]

[a]Center for Composite Materials Research, NC A and T State University, 1601 E. Market Street, Greensboro, NC 27411, USA
[b]William J. Hughes Technical Center, FAA, Atlantic City, NJ 08405, USA

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Abstract

Fracture mechanics based total fatigue life model for delaminated composite structures is presented. The model includes the delamination growth in three domains, namely subcritical, linear, and final fracture. The resistance increases due to matrix cracking and fiber bridging in the case of unidirectional composites; and tow splitting, separation, bridging and breaking in the case of woven/braided fiber composites were included through normalization of the applied load (G_{Imax}) by the instantaneous resistance value (G_{IR}). The proposed method was applied to mode I loaded woven roving glass/vinyl ester delaminated composite. The ASTM standard mode I fracture test was conducted to determine the resistance (G_{IR}) as a function of delamination extension. The fatigue onset life test was conducted to determine the threshold energy release rate, G_{Ith}. Constant amplitude cyclic opening displacement fatigue test was conducted to establish the delamination growth rate ($\mathrm{d}a/\mathrm{d}N$) as a function of maximum cyclic energy release rate (G_{Imax}). The total life delamination growth rate was found to be $\mathrm{d}a/\mathrm{d}N = A(G_{\text{Imax}}/G_{\text{IR}})^m(1-(G_{\text{Ith}}/G_{\text{Imax}}))^{D_1}/(1-(G_{\text{Imax}}/G_{\text{IR}}))^{D_2}$ where the material constants A, m, D_1, and D_2 were 0.1, 5.4, 8 and 2, respectively. This equation was verified for a block loading and found to accurately predict the delamination length.

Keywords: Delamination; Composite laminate; Mode I; Total life

1. Introduction

Susceptibility to delamination is a major weakness of composite laminates. Knowledge of material's resistance to interlaminar fracture and fatigue is essential to establish design allowable and damage tolerance guidelines for structures. Fracture mechanics based delamination growth models are required to predict fatigue life and establish suitable inspection intervals so that a delamination can be found and repaired long before it becomes critical or exceeds the residual strength of the component. Fatigue delamination growth laws that cover the threshold, the stable growth and the unstable fracture domains are needed for total life estimation. Such growth laws were proposed in the past for metallic materials [1,2] and are now becoming accepted in damage tolerant designs. Similar methodology is needed for composite laminates. Hypothetically, we can assume that the delamination growth rate has three domains, namely subcritical (slow), linear, and unstable growth rate domains (see Fig. 1). The growth rate depends on microscope details of fiber architecture and resin properties in domain 1; on crack driving force (energy release rate G or ΔG) in domain 2; and on interlaminar fracture characteristics of the laminate in the unstable domain 3. In composite laminates substantial research [3–15] has been done on delamination growth laws in domain 2. The data has been expressed by power law equation in G_{Imax} or ΔG_{Imax} by curve fits. Research efforts also focused on studying the effect of stress ratio [3,4], matrix toughness [5,6], and pure and mixed mode stress states [4,6,7]. But none of these studies tried to model the all three domains of delamination growth rates. Furthermore, these studies ignored the effect of increased fracture resistance as the delamination grows. Increased fracture resistance with delamination growth is commonly observed in fracture tests of composite laminates because of fiber bridging and matrix cracking. Ignoring the resistance increase with delamination growth can severely underestimate the life of a component.

Poursartip [14] was the first to recognize the importance of resistance curve and proposed G_{R} normalized $\mathrm{d}a/\mathrm{d}N$ equation for edge delaminated composite specimens.

* Corresponding author. Tel.: +1 336 334 7411; fax: +1 336 256 0873.
E-mail address: kunigal@ncat.edu (K. Shivakumar).

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Nomenclature

a	delamination length
da/dN	delamination growth rate
G_{IC}	opening mode I interlaminar fracture toughness
G_{Imax}	maximum cyclic mode I energy release rate
G_{IR}	opening mode I interlaminar fracture toughness resistance
G_{Ith}	threshold value of mode I energy release rate
P_{Imax}	mode I load at δ_{Imax}
R	ratio of minimum to maximum cyclic displacement
δ_{Imin}	minimum value of cyclic displacement
δ_{Imax}	maximum value of cyclic displacement
Δ	delamination length correction factor for modified beam theory

His results showed that the G_R normalization increased the exponent in the da/dN equation. Recently, Paris and O'Brien [15] proposed an approach for total da/dN equation that also included the resistance effect and hypothesized the total life concept but no data was presented. This paper explains the total life model including the resistance, presents a step by step approach of testing and data reduction results for woven-roving glass fiber/vinyl ester composite laminate subjected to mode I loading. Then the total life equation, and its verification for a cyclic block loading.

2. Methodology

The methodology proposed is general and is applicable to both pure and mixed mode loading. However, the description presented here is for mode-I loaded case for simplicity and clarity. The delamination driving force is expressed by energy release rate G_I, the material resistance by G_{IR}, and the delamination growth rate by da/dN.

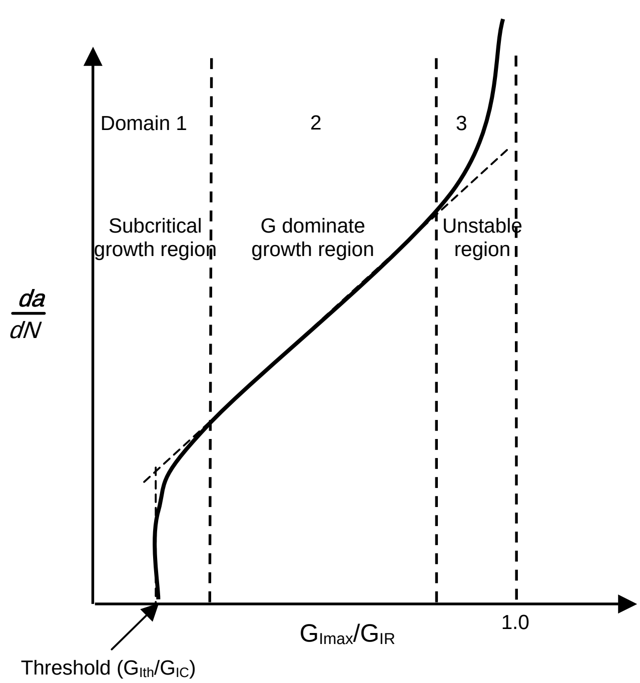

Fig. 1. Hypothetical plot of da/dN versus G_{Imax}/G_{IR}.

2.1. Assumptions

The following assumptions are made in developing the da/dN equation.

1. Interlaminar fracture resistance (G_{IR}) increases with delamination length (a) because of matrix cracking and fiber bridging in the case of unidirectional composites; tow cracking, multiple delaminations, tow bridging and tow breaking in the case of woven/braided fiber composites. The resistance curve G_{IR} (a) can be expressed as a function of initiation fracture toughness G_{IC} and the delamination extension (a–a_0) as shown in Fig. 2. The initial delamination length is a_0.
2. The da/dN is proportional to the driving force G_{Imax} and inversely proportional to the delamination resistance G_{IR} at the current delamination location.
3. The da/dN is bounded by two extreme values of G_{Imax}; the threshold energy release rate G_{Ith} at or below which da/dN is nearly zero (no growth) and the G_{IR} at which da/dN is very large or unstable (infinite). Note that G_{IR} is a function of delamination growth.
4. The value of G_{Ith} can be determined by fatigue delamination onset test as per ASTM D6115.

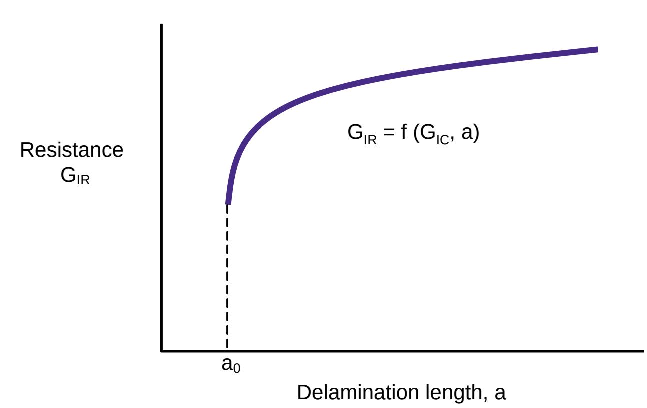

Fig. 2. Typical delamination growth resistance curve.