Advances in Computational & Experimental Engineering & Science

A Total Fatigue Life Model for Composite Laminates

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Summary

Proposed and developed a total fatigue life prediction model for laminated composite structures subjected to mode-I fracture loading. The model includes the delamination growth in subcritical, linear, and final fracture domains. 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 where included through normalization of the equation by the instantaneous resistance value (G_{IR}). The proposed method was applied to woven roving glass/vinyl ester laminated composite. The ASTM standard mode I fracture test was conducted to determine the G_{IR} as a function of delamination extension and 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 (da/dN) equation as a function of maximum cyclic energy release rate (G_{Imax}). The total life delamination growth rate was found to be $\frac{da}{dN} = 0.004\left(\frac{G_{Imax}}{G_{IR}}\right)^{5.4}\left(1-\left(\frac{G_{Ith}}{G_{Imax}}\right)^{8}\right)\Big/\left(1-\left(\frac{G_{Imax}}{G_{IR}}\right)^{2}\right)$. This equation was verified for a block loading case and found to accurately predict the delamination length.

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 exceed 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] 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

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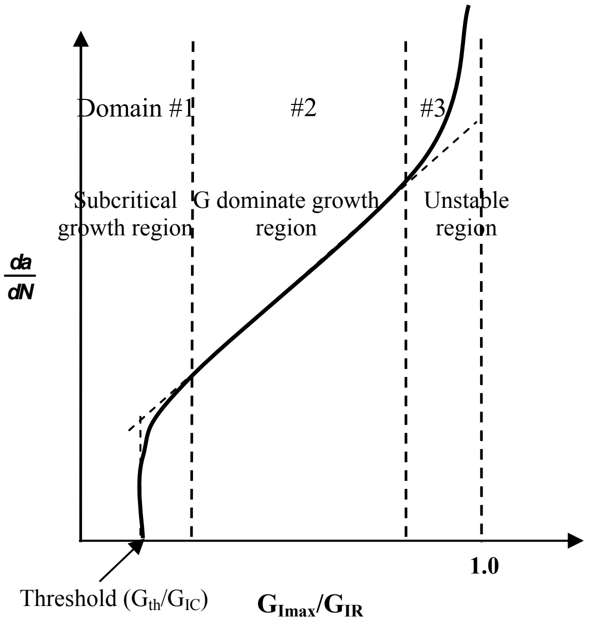

Fig. 1 Hypothetical plot of da/dN vs G_{Imax}/G_{IR}

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 the fracture characteristics in the unstable domain 3. In composite laminates substantial research 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 the effect of stress ratio, matrix toughness, and pure and mixed mode stress states. But none of these studies tried to model the all three domains. 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 under estimate the life of a component. A complete summary of the literature is presented in reference 1.

Poursartip[2] was the first to recognize the importance of resistance curve and proposed G_R normalization *da/dN* equation for edge delaminated composite specimens. His results showed that the G_R normalization increased the exponent in the *da/dN* equation. Recently, Paris and O'Brien[3] 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 loadings.

Methodology

The methodology proposed is more general and is applicable to both pure and mixed mode loading. However, the description presented here is for mode-I loading condition 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*.

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.

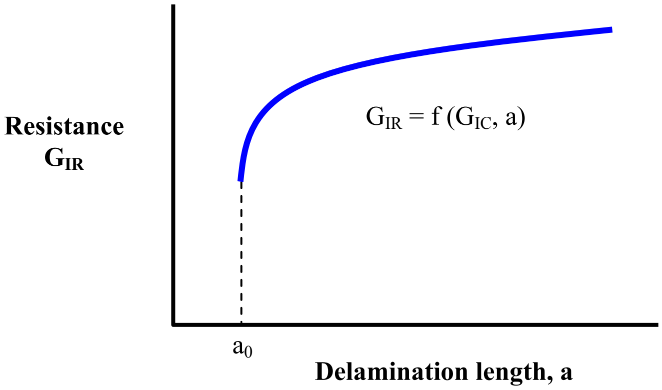

Fig. 2 Typical delamination growth resistance curve

2. The *da/dN* is proportional to the driving force G_{Imax} and inversely proportional to the resistance G_{IR} at the current delamination front 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 zero and the G_{IR} at which *da/dN* is infinite (unstable).
4. The value of G_{Ith} can be determined by fatigue delamination onset test as per ASTM D6115 or by displacement controlled fatigue delamination growth

rate test. The G_{Ith}=G_{Imax} when *da/dN* ≈ 0 (or <10^{-7} in/cycle). In the ASTM D6115, G_{Ith}=G_{Imax} when the compliance change is less than or equal to 2% in one million load cycles.

Approach

As in metallic material, *da/dN* data for composite laminates also falls into three domains, namely, subcritical or slow crack growth domain, G_{Imax} controlled domain, and the unstable fracture domain (see a typical Fig.1). From the assumptions 1 and 2, the *da/dN* in the domain 2 is written in a power law form as

$$\frac{da}{dN} = A\left[\frac{G_{Imax}(a)}{G_{IR}(a)}\right]^m \tag{1}$$

Where *A* and *m* are material constants to be determined from the curve fit to the experimental data.

In the subcritical domain, the *da/dN* (assumption 3) varies between zero (when $G_{Imax} \le G_{Ith}$) and a value that matches with the 2nd domain. The form of the *da/dN* equation can be written as:

$$\frac{da}{dN} = A\left(\frac{G_{Imax}}{G_{IR}}\right)^m \left[1-\left(G_{Ith}/G_{Imax}\right)^{D_1}\right] \tag{2}$$

The exponent D_1 is determined from curve fit to the test data.

In the unstable domain, *da/dN* varies between ∞ (when G_{Imax}=G_{IR}) and the transition value that matches with Eq. 1 in the 2nd domain. The form of the *da/dN* equation can be written as:

$$\frac{da}{dN} = A\left(\frac{G_{Imax}}{G_{IR}}\right)^m \frac{1}{\left[1-\left(G_{Imax}/G_{IR}\right)^{D_2}\right]} \tag{3}$$

The exponent D_2 is a material parameter determined from the curve fit to the test data.

Finally, the combined *da/dN* equation that covers all three domains is

$$\frac{da}{dN} = A\left(\frac{G_{I\max}}{G_{IR}}\right)^{m} \frac{\left(1-\left(\frac{G_{Ith}}{G_{I\max}}\right)^{D_1}\right)}{\left(1-\left(\frac{G_{I\max}}{G_{IR}}\right)^{D_2}\right)} \qquad (4)$$

The values of A, m, D_1 and D_2 have to be determined by curve fit to the fatigue test data.

Test Procedure for Establishing the Parameters

a. Conduct mode-I fracture test using the DCB specimen and establish resistance curve $G_{IR}(a)$ as per ASTM D5528. Fit a G_{IR} versus a equation. Many times a power law equation fits the data very well.
b. Conduct ASTM D-6115 fatigue onset life test and establish the G_{Ith} by a curve fit and a chosen onset life criteria.
c. Conduct a fatigue test on a virgin DCB specimen with G_{Imax} value about 0.3 G_{IC} till the compliance change is about 2% for unidirectional and 5% for textile preform composites. This ensures a natural delamination to initiate yet the resistance change from G_{IC} is very little and $G_{IR}=G_{IC}$ can be assumed.
d. Conduct constant amplitude displacement controlled fatigue tests starting with G_{Imax} value that is slightly lower than G_{IC}. A good starting value is about $G_{Imax}=0.8G_{IC}$. Continue the test till the delamination growth rate becomes very small (for example, $da/dN \leq 10^{-7}$ in/cycle).
e. Repeat the test at least for three specimens and plot the data as da/dN versus (G_{Imax}/G_{IR}) on a *log*-*log* graph.
f. Divide the plot into three domains by visual inspection (see Fig. 1). The middle linear region and the two ends, namely subcritical and unstable regions.
g. Perform least square *log*-*log* fit to the 2nd domain data and determine the constants A and m.
h. Determine D_1 of Eq. 2, using already determined A and m by fitting the equation to domains 1 and 2 data. A trial and error approach works well.
i. Finally determine D_2 of Eq. 3 by fitting the equation to domains 2 and 3 data as in step 'h'.
j. Using the constants determined above plot the Eq. 4 and compare it with the test data. If the fit is not satisfactory repeat steps 'f' through 'j'.

Material System and Specimen Configuration

The material system chosen was woven roving E-glass fiber supplied by fiber Glass Industries (FGI) with FGI's super 317 sizing for ease of handling, fast wet out, and compatibility with vinyl ester resins. The fabric designation was FGI

1854 with 18 Oz/square yard areal weight and unbalanced construction. About 59% of fibers in warp (0-deg) direction and the remaining in fill (90-deg) direction. The matrix used was Dow Chemicals Derakane 510A-40 brominated for fire resistance property. The vinyl ester has 350 cps viscosity at room temperature, which is ideally suited for vacuum assisted resin transfer molding (VARTM). The 510A-40 matrix has specific gravity of 1.23, tensile modulus and strength of about 0.5 Msi (3.4 GPa) and 10.5 ksi (73 MPa) respectively, flexural modulus and strength of about 0.53 Msi (3.6 GPa) and 18 ksi (125 MPa), and heat distortion temperature of 225 ^{o}F.

A 10 ply 0-deg laminate with a 0.5 mil Kaptan insert at the mid-plane was fabricated using woven-roving glass fiber and vinyl ester resin by the VARTM process. The Kapton insert was to create a delamination. One-half mil thickness is best suited for the study. The panel was about 32 in (813mm) wide, 12.5 in (318 mm) length with a delamination length of 2.5 in (64mm). Edges of the panel were trimmed about 1 in (25 mm) all around to make sure that the edges were parallel and perpendicular to the weft (0-deg) direction of the fibers. The specimens were machined using the diamond tipped wheel and finished with surface grinder. The specimen length (L), width (b) and delamination length (a_0) were about 10 in (25.4 cm), 1.5 in (38 cm) and 1.5 in (38 cm).

After the specimen were machined, the loading hinges were mounted on the outer faces of the specimen at the debond end. The hinges were located 1.0 in (25 mm) from the debond end to achieve delamination length (a_0) of about 1.5 in (38 mm) that is same as specimen width (b). The aluminum hinges were mounted using 3M DP-460 two-part epoxy adhesive. The adhesive was cured at 60°C for 2 hours. The specimen configuration and loading are shown in Fig. 3.

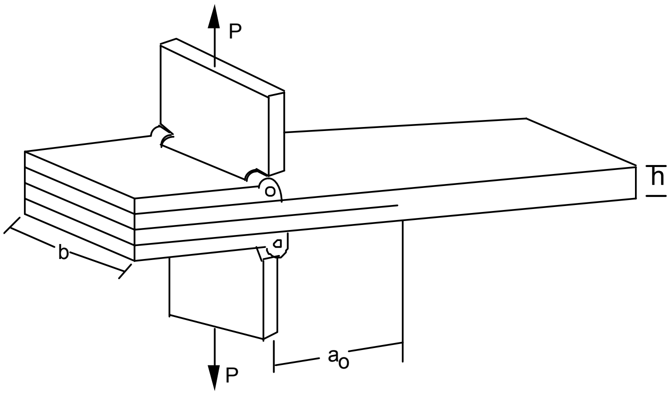

Fig. 3 Specimen configuration

Test

As Stated in the methodology section, three types of tests were conducted. Fracture test as per the ASTM D5528 from that data G_{IR} equation $G_{IR} = 1.97 + 2.25(a - a_0)^{0.31}$ was determined. Onset life test as per ASTM D6115 and determined the threshold energy release rate G_{Ith}=0.15G_{IC}. Finally conducted the constant displacement amplitude fatigue test (R=0.1) and generated *da/dN* data. Test data is plotted as *da/dN* versus G_{Imax}/G_{IR} in Fig. 4.

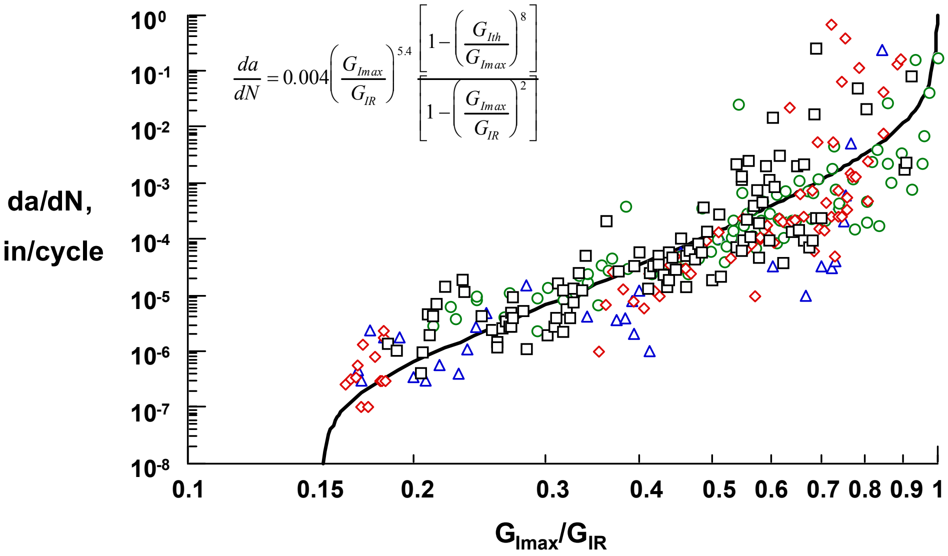

Fig. 4 Comparison of total delamination growth rate equation with test data

Fatigue Delamination Growth Rate Equation

The fatigue test data and the equation are bounded by the limits G_{Imax}=G_{Ith} and G_{Imax}/G_{IR}=1. The G_{Ith} from the onset life test was 0.15 G_{IC} and the upper limit G_{Imax}/G_{IR}=1 is from the condition that when G_{Imax}=G_{IR} the delamination growth rate is infinite.

The data between the above limits in Fig. 4 was divided into three parts by visual inspection, middle linear region (Domain #2) and two ends, namely subcritical (Domain #1) and unstable regions (Domain #3). The least square *log-log* equation fit was performed for the middle region 0.2≤G_{Imax}/G_{IR}≤0.7. The constants A and m were found to be 0.004 and 5.4, respectively.

The exponent D_1 in Eq. 2 was determined by trial and error approach to best fit the data in domains 1 and 2. The D_1 was found to be 8. A similar approach was used to determine D_2 in the domain 2 and 3 and it was found to be 2.

The final equation of *da/dN* that covers all three domains is:

$$\frac{da}{dN} = 0.004\left(\frac{G_{Imax}}{G_{IR}}\right)^{5.4} \frac{\left(1-\left(\frac{G_{Ith}}{G_{Imax}}\right)^{8}\right)}{\left(1-\left(\frac{G_{Imax}}{G_{IR}}\right)^{2}\right)} \tag{5}$$

Figure 4 compares the Eq. 5 with the test data. It shows that the equation fits the test data very well.

Verification of Equation 5 for a Block Loading

Equation 5 was verified for the block fatigue loading. The block loading chosen has three segments of 100k cycles each with all tests conducted under constant amplitude displacement loading with R =0.1. The first segment is increasing G_{Imax} (0.3 to 0.5 G_{IC}), the 2nd is constant G_{Imax}, (0.5 G_{IC}), the 3rd segment is decreasing G_{Imax} (0.5 to 0.3 G_{IC}). Since this loading can not be applied directly, a stepped (step of 10k cycles) constant amplitude cyclic displacement approach was used.

Prediction was performed starting with initial crack length of a_0=1.463 in and the average linear variation of G_{Imax} with N. The delamination lengths were calculated for every 1, 10, and 100 load cycle intervals. The results were nearly same for all these cases analyzed. Figure 8 compares the prediction with the test data. The final crack lengths from the experiment and the Eq. 5 were 2.131 in and 2.078 in, respectively. The difference between the two is about 2.5%.

A more aggressive block loading test was also conducted. The predicted delamination growth was about twice that of the test data. This large difference was due to large fatigue data scatter.

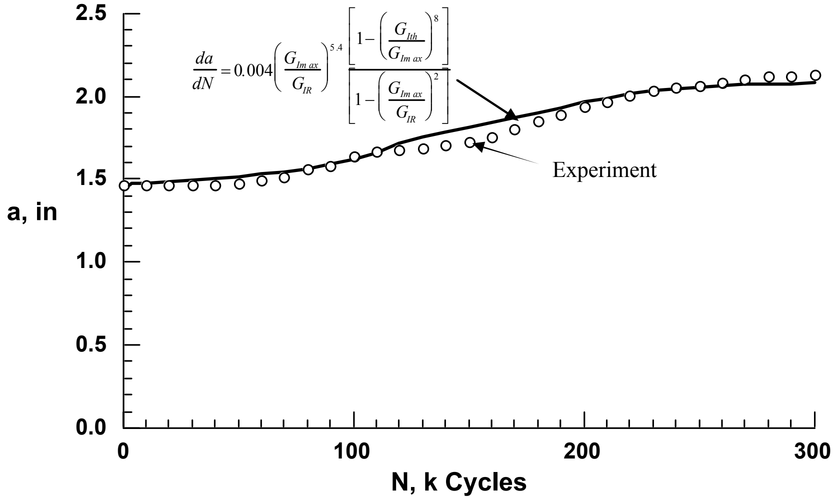

Fig. 5 Comparison of predicted delamination growth with measured values

Conclusions

Proposed and developed a total fatigue life prediction model for laminated composite structures subjected to mode-I fracture loading. The equation is $\frac{da}{dN} = 0.004\left(\frac{G_{I\max}}{G_{IR}}\right)^{5.4}\left(1-\left(\frac{G_{Ith}}{G_{I\max}}\right)^{8}\right)\Big/\left(1-\left(\frac{G_{I\max}}{G_{IR}}\right)^{2}\right)$. It was verified for typical and high cyclic block loading cases.

Reference

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