Microcracking of Pressure Vessel with Fiberite 934/T300 Laminates under Fatigue Loads

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Abstract

The goal is to assess the effect of fatigue loading on mechanical properties of Fiberite 934/T300 laminates of pressure vessel using the recent variational mechanics analysis. This analysis has been useful in providing fracture mechanics interpretation of matrix microcracking in cross-ply laminates. This paper describes using the new energy release rate analysis for a fracture mechanics based interpretation of microcrack formation during fatigue loading. The master plot by modified Paris-law gives a complete characterization of a material system's resistance to microcrack formation.

1. Introduction

Some pressure vessels are made by composite laminates. In operation, they get damages from fatigue loads. The initiation of damage in multidirectional laminates was often observed to be caused by microcracks in the off-axis plies that run parallel to the fibers in those plies [1-8]. These microcracks have typically been studied in cross-ply laminates in which the cracks form in the 90° plies [1-8]. Microcracks form during static testing, during fatigue testing [3,9,10]. Because microcracks cause a reduction in stiffness [3], a change in the thermal expansion coefficient [12,13], and provide sites for the initiation of delaminations, it is important to gain a quantitative understanding of the formation and propagation of microcracks during both monotonic loading (static tests) and during cyclic loading (fatigue tests).

Ply strength theories were attempted to analyze microcracking [2,14]. As pointed out by Flaggs and Kural [5], however, strength based theories are fundamentally inappropriate and most recent work has been based on energy release rate calculations. A more recent energy release rate analysis uses the improved stress analysis technique developed by Hashin. The improved stress analysis is based on variational mechanics principles and has been shown to accurately predict stiffness reduction [18,19]. The variational approach was modified to include thermal stresses and used to calculate the energy release rate due to the formation of microcracks [17].

Some investigators have measured the longitudinal stiffness of cross-ply laminates as a function of cycle number during constant load-amplitude fatigue. The goal is to assess the effect of fatigue loading on mechanical properties. Analyzing such fatigue data requires the simultaneous solution of two problems, which are the microcrack density as a function of cycle number and the effect of microcracks on mechanical properties. If attempts to fit experimental results fail, it may not be clear which problem introduces error. Even though data can be fit, it still may not be clear whether the physics of the problem is understood or there is nothing but a fortunate cancellation of errors. The preferred approach is to separate the two problems. The effect of microcrack density on mechanical properties is a micromechanics problem that was discussed in Ref. [17]. The new problem discussed in this paper is the prediction of the microcrack density as a function of cycle number during fatigue loading.

2. Fatigue analysis

Figure 1 shows the process of forming a new microcrack at some location between two existing microcracks. A recent thermoelastic variational mechanics analysis gives the total energy released due to the formation of the microcrack illustrated in Figure 1.

Consider a laminate loaded by a tensile stress of σ_o in the x direction. In $[(S)/90_n]_s$ laminates, the energy release rate is

$$G_m = \sigma_{x0}^{(1)^2} C_3 t_1 Y(D) \tag{1}$$

where

$$\sigma_{x0}^{(1)} = k_m^{(1)} \sigma_o + k_{th}^{(1)} T \tag{2}$$

is the stress in the 90° plies before damage, σ_o is the total applied axial stress, T is the effective residual stress term, C_3 is a constant, t_1 is the semi-thickness of the 90° plies, and C is a function and D is microcrack density which is the number of microcracks divided by sample length. An extended variational analysis gives an analogous expression for energy release rate for the formation of microcracking in $[90_n/(S)]_s$ laminates [10]:

$$G_m = \sigma_{xo}^{(1)^2} C_{3a} t_1 Y_a(D) \tag{3}$$

where C_{3a} and $Y_a(D)$ are analogs of C_3 and Y(D). They account for the antisymmetric damage state in $[90_n/(S)]_s$

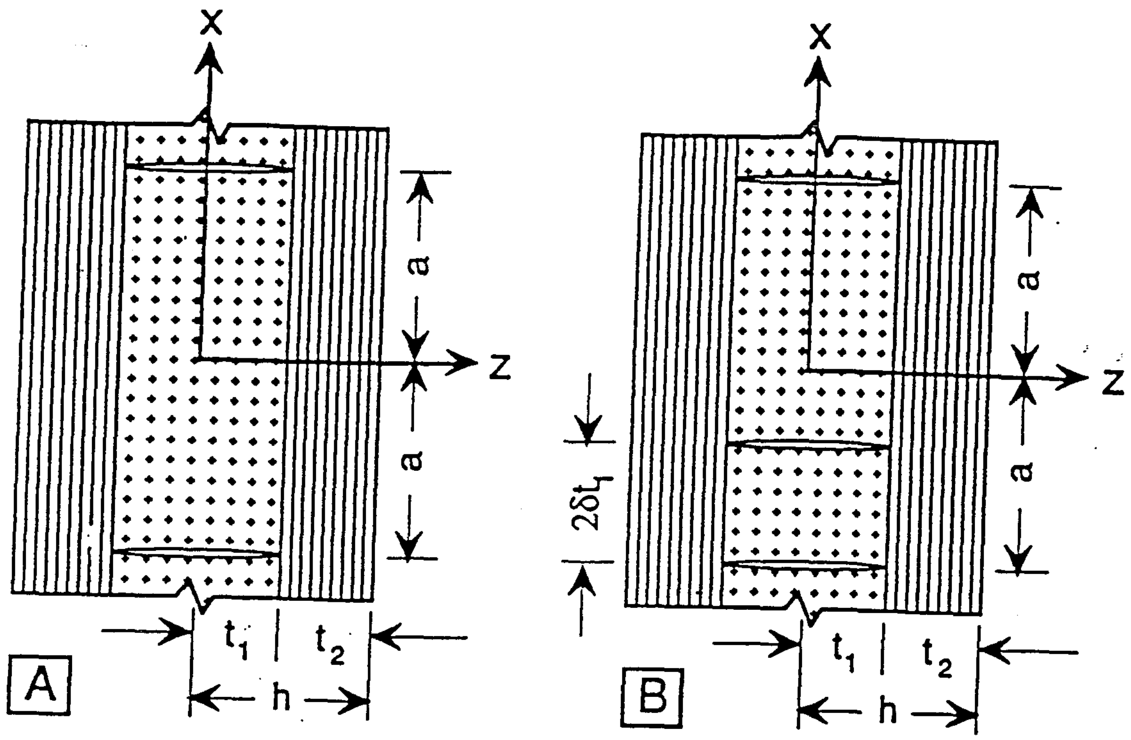

Figure 1 : Edge view of a cross-ply laminate with microcracks.

A: Two microcracks in the 90° plies.

B: The formation of a new microcrack at a distance $2\delta t_1$ above the bottom microcrack.

laminates [10].

Equations (1) and (3) give microcracking energy release rate as a function of applied thermal and mechanical load. In this paper, I describe some preliminary results of applying equation (1) to the analysis of fatigue experiments. A rational procedure for analyzing microcracking damage during fatigue is to use a modified Paris law in which the microcrack density increase per cycle is given by

$$\frac{dD}{dN} = A\Delta G_m^n \tag{4}$$

where A and n are two power-law fitting parameters. From any laminate having 90° plies, it is a simple matter to calculate ΔG_m using equation (1) or equation (3). If equation (4) is valid, plotting dD/dN as a function of ΔG on a log-log plot should yield a linear relation. All cross-ply layups of a single material system should fall on the master Paris-law plot.

3. Materials and Methods

Fatigue experiments were run on cross ply laminates of generic lay-up $[0_m/90_n]_s$ laminates. The material is Fiberite 934 epoxy/T300 graphite fiber laminates. Specimens were nominally 12mm wide and 150 mm long with thickness determined by the stacking sequences (about 0.125 mm per ply). All specimens had 29 mm x 12 mm aluminum end-tabs. End-tab attachment to the specimens was important, because high load is required to get high microcrack density and the specimen is reloaded repeatedly.

The fatigue tests were run on a Minnesota Testing Systems (MTS) 25 kN servohydraulic testing frame using load control. The load span was set to cycle between a maximum stress, and small stress; in other words, the stress span was approximately equal to the maximum stress. The cycling rate was usually 5 Hz. A few experiments were done using a lower rate of 1 Hz and the results were identical to the results at 5 Hz. During the fatigue tests, the load cycling was periodically stopped and the microcrack density was measured by examining the sample edges under an optical microscope and counting the cracks. To facilitate microcrack observation, the edges of the samples were polished prior to testing. The measurement was done on both edges of the flat specimens and the results were averaged.

4. Results and Discussion

With a given $\Delta\sigma_o$ at a given crack density, it is a simple matter to calculate ΔG using equation (1). If equation (4) is valid, plotting dD/dN as a function of ΔG on a log-log plot should yield a linear relation. The problem with most crack propagation experiments is that during the experiments, both the dependent variable (crack length) and the independent variable (ΔK) change. A fortunate feature of microcracking fatigue experiments, however, is that the dependent variable (ΔG) remains constant up to reasonably high crack densities. Figure 2 plots ΔG as a function of crack density for a typical fatigue experiments on a $[0_2/90_4]_2$ Fiberite 934 epoxy/T300 composite. ΔG is constant up to a crack density of about 0.20-0.25 mm^{-1} and then drops rapidly to a low value.

Because ΔG is constant over a fairly wide range, I can do relatively simple fatigue microcrack propagation experiments. I measure the crack density as a function of cycle number for various values of $\Delta\sigma_o$. Up to values of the crack density of about 0.20-0.25 mm^{-1} , ΔG is constant and I expect by equation (4) that the crack density will increase linearly with cycle number. Typical experimental results are given in Figure 2. For this sample there is a region of linear density increase between crack densities of 0.13 mm^{-1} and 0.23 mm^{-1}. In agreement with Paris-law behavior, the crack density

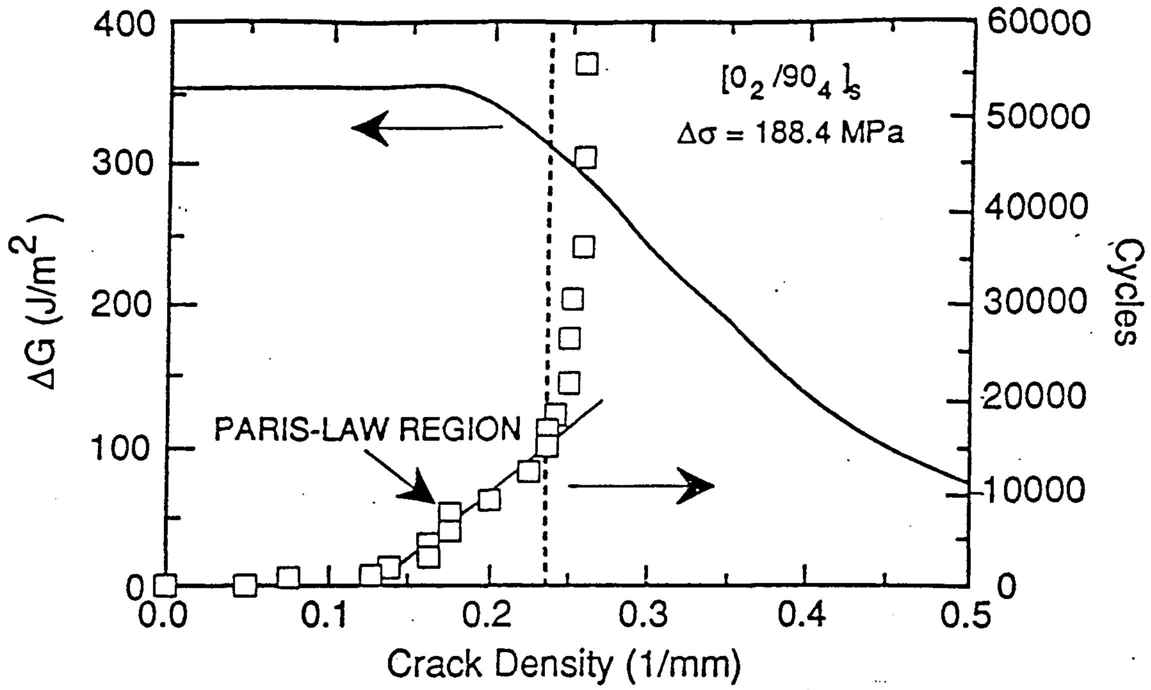

Figure 2 : Microcracking fatigue data for a $[0_2/90_4]_2$ Fiberite 934 epoxy/T300 composite. The solid line shows ΔG as a function of crack density. The symbols show the crack density as a function of cycle number. The straight line through the crack density data shows the Paris-law region of constant crack density growth rate.

stops increasing after it reaches $0.25mm^{-1}$ which corresponds to the density at which ΔG begins its rapid decline.

Contrary to Paris-law behavior, however, there is rapid increase in crack density up to 0.13 mm^{-1} that occurs before the linear Paris-law growth region. I suggest that these cracks are a result of inherent flaws in the laminate. Similar observations were made during static experiments in which some cracks typically form at loads well below the loads predicted by the fracture toughness of the material system. In those experiments, the early cracks were observed using microscopy and were normally found to be located near obvious flaws. With the above comments, I divide the crack density vs. cycle number data into three regions:

1. **Flaw Dominated Region:** The first few microcracks form during the first few cycles and form at flaws. The formation of these microcracks are controlled by laminate quality. The energy release rate in equation (1) does not account for macroscopic flaws and can not be used to predict the behavior in this region.
2. **Constant Growth Region:** After the inherent flaws are used up, the crack density increases according to the Paris-law in equation (4). Up to a crack density of about 0.25 mm^{-1} (depending on laminates properties and the thickness of the 0° and 90° plies), ΔG remains relatively constant and therefore the crack density increase at a constant rate. The crack formation in this region is controlled by the inherent toughness of the material system.
3. **Slow Growth Region:** At high crack densities, ΔG decreases. According to the Paris-law in equation (4), this decrease will cause a dramatic reduction in the crack formation rate.

To map out the resistance of a composite material system to fatigue induced microcracking involves measuring the crack density growth rate as a function of applied ΔG. These experiments are most conveniently done in the constant growth region. In brief, I subject various cross-ply laminates to various levels of $\Delta\sigma_0$ and measure the crack density as a function of cycle number. Before starting the experiment, I can use equation (1) to calculate the crack density at which ΔG begins to decrease. I run my experiments up to this crack density and look for the constant growth region. I always observe a constant crack growth region and the slope in this region gives the crack density growth rate. Finally, I plot this growth rate vs. ΔG to obtain a fatigue resistance plot.

The results of the microcrack fatigue resistance done on Fiberite 934 epoxy/T300 laminates are in Figure 3.

1. Over a fairly wide range in ΔG, the log-log plot is linear indicating that equation (4) holds. The power law exponent in the linear region is n=2.34.
2. At very high ΔG the microcracks propagate very fast. This upper limit occurs at a ΔG =650 J/m^2 which is very near to the static microcracking fracture toughness of these laminates which has been measured 690 J/m^2.
3. The lowest ΔG data point falls below the Paris-law line. This may be an indication of a threshold limit to fatigue induced microcracking occurring at about

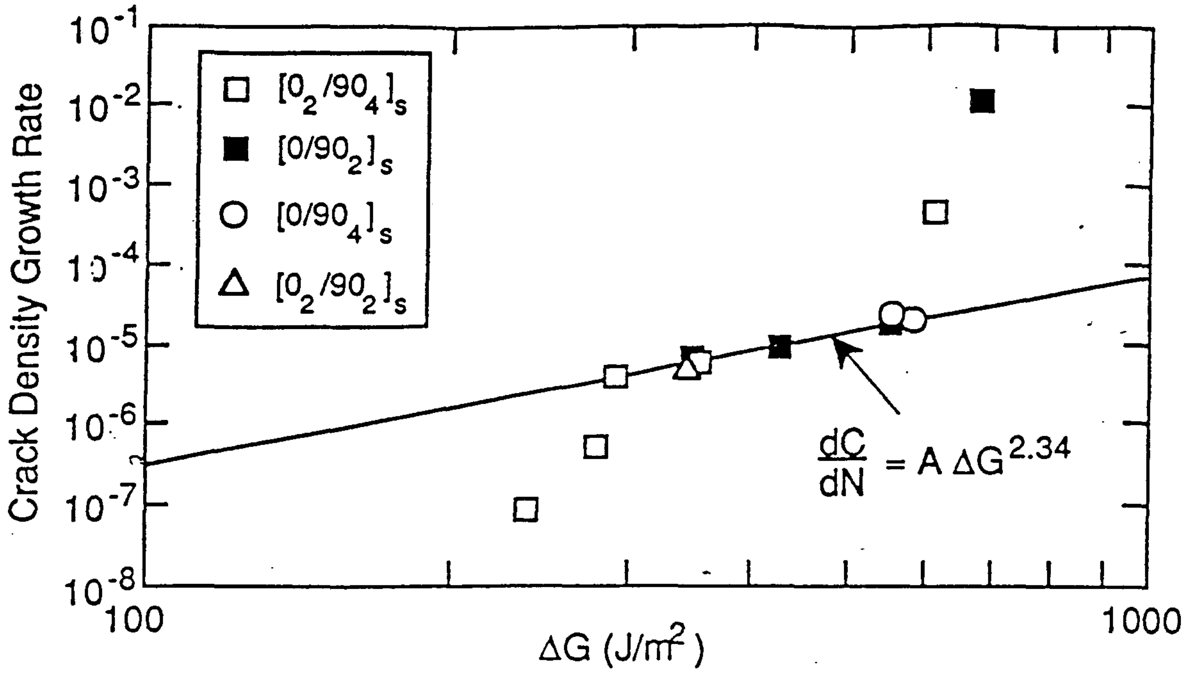

Figure 3 : The crack density growth rate (in cracks per mm per cycle) as a function of applied ΔG for Fiberite 934/T300 laminates. As indicated on the figure, the results are from four different cross-ply lay-ups.

250 J/m^2 . Finally, as indicated in Figure 3, the data came from four different lay-ups - $[0_2/90_4]_s$, $[0_2/90_2]_s$,$[0/90_2]_s$,and $[0/90_4]_s$ laminates. The fact that all this data falls on a single Paris-law plot supports my hypothesis that equation (1) gives a useful fracture mechanics interpretation of composite microcracking.

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