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Modeling delamination growth in composites under fatigue loadings of varying amplitudes

Benoit Landry, Gabriel LaPlante *

Département de génie mécanique, Université de Moncton, Moncton, New Brunswick, Canada E1A 3E9

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ABSTRACT

A numerical model was developed to simulate the progressive delamination of a composite subjected to mode I fatigue loading regimes of varying amplitude. The model employs a cohesive zone approach, which combines damage mechanics and fracture mechanics, and requires only standard material data as input, namely the delamination toughness and the fatigue delamination growth curve. The proposed model was validated against delamination growth data obtained from a fatigue test conducted on a DCB specimen. The model predictions agree very well with the experimental results. This model is an initial step toward life prediction of composite structures subjected to complex fatigue regimes.

1. Introduction

Advanced laminated composites, such as those found in aerospace applications, are prone to delamination initiation and growth. To maximize the potential benefits of composites in large structures while preventing catastrophic failures, a damage tolerance design philosophy akin to the one for metal structures needs to be developed and implemented in composite design. In this methodology, the delamination growth rate in predefined critical areas is estimated, and structural inspections and/or maintenance are scheduled accordingly. Due to the complexity of the geometry and loading involved, finite element modeling (FEM) currently appears to be the best tool to simulate delamination growth in real composite structures. Two approaches have mostly been employed with FEM: fracture mechanics and cohesive zone models. In the former, the delamination driving force is evaluated by a numerical technique such as the virtual crack closure technique (VCCT) [1] and compared to the delamination toughness. This scheme requires constant remeshing as delamination progresses. On the other hand, the cohesive zone models have the advantage of not requiring any remeshing of the geometry.

In a cohesive zone model, cohesive finite elements are placed at the interface of structural elements along a potential crack path and they obey a prescribed traction-separation law to simulate delamination. Cohesive elements have been successfully employed to simulate delamination under quasi-static loading in mode I [2–14], mode II [2,4–6,8,9,11,12,14] and mixed modes [2,4–6,8,9,11,12,14]. These simulations were performed on double cantilever beam (DCB), end-notched flexure (ENF), end-loaded split (ELS), mixed-mode bending (MMB) and/or fixed-ratio mixed-mode (FRMM) test configurations.

Following a damage mechanics philosophy, damage parameters have been integrated into cohesive laws to simulate progressive delamination during fatigue loadings. These models can be divided in two categories: low-cycle and high-cycle fatigue [15]. Models designed for low-cycle fatigue are based on a cycle-by-cycle analysis from which the evolution of a damage variable is determined. Several low-cycle models are presented in the literature. Yang et al. [16] proposed a cohesive zone model for fatigue crack initiation and growth in quasi-brittle materials. The fatigue life of a center-crack panel was evaluated by Nguyen et al. [17] using a cohesive law with unloading–reloading hysteresis. Roe and Siegmund [18] successfully modeled fatigue delamination growth across the adhesive of bonded metallic substrates. Yang et al. [19] also presented a cohesive zone model capable of predicting the fatigue life of solder joints.

In high-cycle fatigue models, a 'cycle jump' strategy is implemented to reduce the computational effort. Peerlings et al. [20] developed a damage evolution law relating the rate of damage to an equivalent strain that is function of several parameters obtained by curve fitting with experimental data. Their model was used to simulate high-cycle fatigue in a blunt notched metal plate. Robinson et al. [21] adapted Peerlings' law to a cohesive zone model to simulate high-cycle fatigue in a composite laminate in DCB, four-point bend end-notched flexure (4ENF) and asymmetric double

* Corresponding author. Fax: +1 506 858 4082.
E-mail address: gabriel.laplante@umoncton.ca (G. LaPlante).

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cantilever beam (ADCB) test configurations. Muñoz et al. [22] studied the influence of the number of cycles per increment and the element size and also presented a stress ratio dependent formulation.

To overcome calibration needs in the numerical models, Turon et al. [23] proposed a model that linked linear elastic fracture mechanics (LEFM) and damage mechanics. A similar formulation was developed by Harper and Hallet [24], where the cohesive zone has been divided in two distinct regions: a quasi-static and a fatigue damage zone. These two models included stress ratio effects and were validated against mode I (DCB), mode II (4ENF) and mixed mode (MMB) loadings. These models were intended for high-cycle fatigue applications, where the delamination driving force can be assumed constant during a delamination length increment of the analysis, and they were validated for applied loadings producing a constant delamination driving force.

This paper presents a cohesive zone-based composite delamination growth model designed to deal with fatigue loadings of varying amplitude. The behavior of the cohesive elements is governed by a damage evolution scheme linked to LEFM. The cohesive element formulation was implemented through a user-written element subroutine in commercial finite element code ANSYS® Mechanical. A model validation test was performed under mode I loading with the DCB test configuration. Numerical results were compared to experimental data obtained for an aerospace grade carbon/epoxy composite.

2. Fatigue delamination overview

The fatigue delamination growth curve of composite materials can be subdivided in three regions (Fig. 1): subcritical growth, stable growth and unstable growth. The subcritical growth region is characterized by the delamination driving force threshold of the material, G_{Ith}, below which delamination does not propagate. In the stable growth region, the delamination growth rate increases linearly with G_{Imax} when plotted on a log–log scale. This relationship can be represented by a modified Paris law in the form:

$$\frac{\partial a}{\partial N} = A(G_{Imax})^m \quad (1)$$

where G_{Imax} is the maximum delamination driving force during fatigue cycles, and A and m are material properties determined by curve fitting Eq. (1) to experimental data. Finally, in the unstable growth region, the delamination growth rate increases sharply as G_{Imax} approaches G_{Ic}, the delamination toughness of the material.

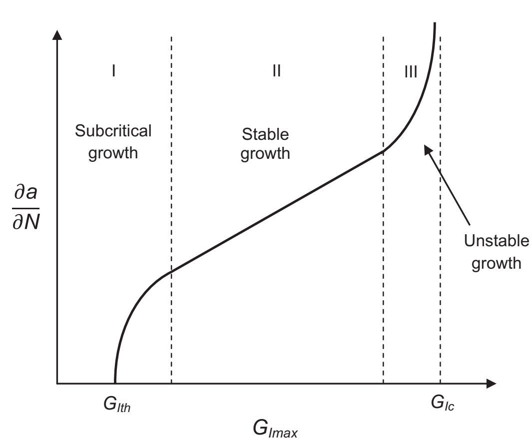

Fig. 1. Typical fatigue delamination growth curve showing three regions corresponding to subcritical, stable and unstable growth.

3. Cohesive zone model

3.1. Traction-separation relationship

The cohesive zone model (CZM) is a numerical scheme employed to simulate the effects of a process zone ahead of the crack tip during delamination growth. It is easily implemented in finite element formulation. In a composite delamination FEM, cohesive elements are inserted between structural elements along a potential delamination path and follow a specified traction-separation relationship. A large number of traction-separation curves have been proposed in the literature [25], among which the bilinear relationship (Fig. 2) appears the most used and numerically simplest formulation. It consists of a linear elastic region of stiffness K followed by a linear softening region. The interfacial strength, σ_o, is attained when the interface separation, λ, reaches the irreversible interface damage initiation point, Δ_o. With further loading, the traction decreases linearly with λ until it returns to zero at Δ_f. Further separation of the interface occurs without traction. For mode I loading, the area under the traction-separation curve is equal to delamination toughness G_{Ic}. Note that the model described here is for pure mode I loading, but a similar formulation can be presented for mode II.

The loss of stiffness of the interface is tracked by a stiffness damage parameter, d, defined as:

$$d(\lambda_{\max}) = \begin{cases} 0, & \text{if } \lambda_{\max} \leqslant \Delta_o \\ \frac{\Delta_f}{\lambda_{\max}}\left(\frac{\lambda_{\max}-\Delta_o}{\Delta_f-\Delta_o}\right), & \text{if } \Delta_o < \lambda_{\max} < \Delta_f \\ 1, & \text{if } \lambda_{\max} \geqslant \Delta_f \end{cases} \quad (2)$$

where $\lambda_{\max}$ is the local maximum interfacial separation that occurred at the point of interest. After a maximum loading corresponding to $\lambda_{\max}$, the local traction during subsequent unloading and reloading follows the dashed line shown in Fig. 2.

The local loss of strength (maximum traction) is tracked by a static damage parameter, d_s, which is related to the stiffness damage parameter, d, by:

$$d_s = \begin{cases} 0, & \text{if } \lambda_{\max} \leqslant \Delta_o \\ 1 - \frac{\lambda_{\max}}{\Delta_o}(1-d), & \text{if } \lambda_{\max} > \Delta_o \end{cases} \quad (3)$$

At any given time, the traction in the damaged interface is given by:

$$\sigma = (1-d)K\lambda \quad (4)$$

where

$$K = \frac{\sigma_o}{\Delta_o} \quad (5)$$

is the undamaged interface stiffness.

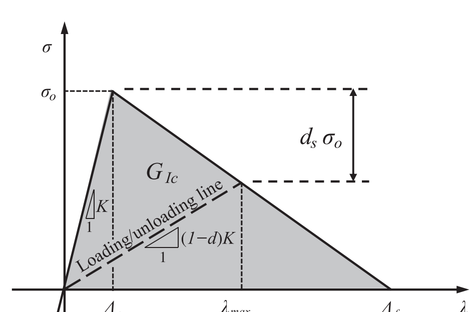

Fig. 2. Bilinear traction-separation relationship. The undamaged interface is characterized by the stiffness K. An interface that previously suffered damage corresponding to d_s will have its stiffness reduced by a factor d, as shown by the new loading/unloading line. The shaded area corresponds to the delamination toughness G_{Ic}.