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# Two-parameter model for delamination growth under mode I fatigue loading (Part B: Model development)

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ABSTRACT

A two-parameter model for mode I fatigue delamination growth has been developed and is presented in this paper. The model is based on the mechanisms of decohesion that was determined through SEM investigations. The experimental data of fatigue delamination growth under mode I fatigue from the current study and the literature has been used for the validation of the model.

## 1. Introduction

A fatigue load cycle can be described by both a cyclic and monotonic load component, for example maximum stress $S_{max}$ and stress range $\Delta S$, or mean stress $S_{mean}$ and stress amplitude $S_a$, or $\Delta S$ and the stress ratio $R$. The literature indicates that the delamination growth rate $da/dN$ is not a unique function of either the monotonic or cyclic load, but rather it is related to both the range of the load cycle, and the monotonic load level. In general, this could thus be formulated as:

$$\frac{da}{dN} = f(\Delta S, R) \tag{1}$$

Various authors have attempted to formulate the relationship between delamination growth rate and monotonic and cyclic load components using a so called two-parameter model. For example, Hojo et al. [1] used an empirical approach correlating delamination growth to maximum stress intensity factor (SIF) and SIF range. Jia and Davalos [2] extended Hojo's approach by using strain energy release rate range (SERR) and maximum SERR as correlating parameters for delamination growth modelling. Atodaria et al. [3] used an average SERR and SERR range as correlating parameter for delamination growth characterization. Anderson [4] developed a semi empirical model for delamination growth. The model correlated fatigue failure of composites to the damage development ahead of delamination tip. These all studies seem to have one aspect in common; the formulations are empirical and multiply the cyclic and monotonic SERR contributions with each other varying the individual exponents. In general these two-parameter models have been justified by validating that the formulation indeed collapsed all experimental data to a single crack resistance curve, but the fundamental question concerning the contributions using fractography was neither provided nor it was explained what these single curve represents.

The effect of monotonic and cyclic load on delamination growth at macroscopic level should be the consequence of their effects on delamination growth at microscopic level. One may thus assume that microscopic features are affected by cyclic and monotonic load levels.

The objective of this paper is the development of a mechanistic approach for delamination growth modelling. Mode I delamination growth has been experimentally investigated at both macroscopic and microscopic levels. The experimental investigations have been presented and discussed in [5]. The relation of microscopic delamination growth with fatigue load is linked to the macroscopic delamination growth. As a result a mechanistic two-parameter model is developed. In the current paper, the two-parameter model is presented and discussed using the experimental observations presented in [5]. The next section describes the delamination growth mechanism. The hackle and striation formation observed during delamination growth are discussed in this section. Section 3 establishes relations between monotonic and cyclic load

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*Abbreviations:* COD, crack opening displacement; DCB, double cantilever Beam; FBG, fiber bragg grating; LCSM, laser confocal scanning microscope; LEFM, linear elastic fracture mechanics; SEM, scanning electron microscope; SERR, strain energy release rate; SIF, stress intensity factor; UD, unidirectional; WTDCB, width taper double cantilever beam.

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## Nomenclature

| Symbol | description unit |
|---|---|
| $a$ | delamination length (m) |
| $b$ | plate width (m) |
| $C$ | compliance (m/N) |
| $da/dN$ | delamination growth rate (m/cycle) |
| $G_{max}$ | maximum SERR (J/m$^2$) |
| $G_{min}$ | minimum SERR (J/m$^2$) |
| $\Delta G_s$ | SERR range, $(\sqrt{G_{max}} - \sqrt{G_{min}})^2$ (J/m$^2$) |
| $G_{th}$ | threshold SERR(J/m$^2$) |
| $G_c$ | critical SERR (J/m$^2$) |
| $K_{max}$ | maximum SIF (MPa m$^{1/2}$) |
| $K_{th}$ | threshold SIF (MPa m$^{1/2}$) |
| $K_c$ | critical SIF (MPa m$^{1/2}$) |
| $\Delta K$ | SIF range (MPa m$^{1/2}$) |
| $K_{min}$ | minimum SIF (MPa m$^{1/2}$) |
| $k$ | taper of WTDCB specimen (–) |
| $L$ | hackle length (mm) |
| $N$ | number of cycles (–) |
| $P$ | load (N) |
| $R$ | stress ratio (–) |
| $s$ | striation spacing (mm) |

components and hackles and striation spacing using experimental results from [5]. Section 4 presents the development of the two-parameter model principles. The model is based on fractographic observations on the fracture surface. The implementation of the developed model is described in Section 5 using experimental data from the fatigue experiments. The model was subsequently validated using case studies from the literature, which is presented in Section 6. Section 7 discusses the developed model in the context of delamination growth characterization. The conclusions are presented in Section 8.

## 2. Mechanism of delamination growth

In general, one may observe loose or broken fibres, partially imbedded fibres, fibre imprints in the matrix, and matrix cracking on the fracture surfaces delaminated under mode I fatigue loading. Several of these features for example matrix cracking and fibre imprints are specifically related to the progression of the delamination or crack tip during application of load cycles.

In a formed delamination at a given interface between or within fibre-reinforced plies, one may observe a few dominant failure modes, i.e. adhesive failure between fibre and matrix that creates (feature often identified as fibre imprint), or a cohesive failure in the matrix. In the particular case of crack tip extension, it is assumed that fibre failure (and related observations of loose fibres) is not occurring at the crack tip, but further away behind the crack tip.

The fibre bridging and fibre failure both happen behind the crack tip. This implies that these phenomenons could be excluded when considering the mechanism at the crack tip. In other words, when describing the crack growth in relation to both cyclic and monotonic loading, only fibre disbonding (may still be cohesive or adhesive failure) and matrix cracking is to be considered.

For both mechanisms, the progression of damage growth should be formulated in relation to the cyclic and monotonic loading components. For this purpose, specific fractographic features were evaluated in order to develop such relations. For the cohesive failure of the matrix (in-between fibres), the formation of so-called hackles has been investigated, while for the fibre–matrix decohesion, the formation of striations in the fibre imprint have been analyzed.

### 2.1. Hackle formation during matrix decohesion

Hackles have been observed on the fracture surfaces in the matrix between two adjacent fibre imprints. Hackles are formed due to local shear stress field and microcracks formation perpendicular to the tensile principle stress ahead of the crack tip. In delamination growth under mode I, the fibre disbands from the matrix earlier than the matrix decohesion due to which the matrix between the fibres is under the influence of both mode I (global) and mode III (transverse/out of plane shear). The decohesion lags the fibre disband and the delamination fronts are locally different in fibre imprint and matrix. The circular shapes of fibre and matrix blank generate in plane shear mode II. The microcracks are thus formed under mix mode I, II and III. The coalescence of these microcracks into macrocracks results in the formation of hackles.

Hackles are formed in opposite directions on both mating fracture surfaces. In this study no comparison was made to verify formation of hackles on opposite fracture surfaces, however several studies in the literature [6,7] have reported evidence of hackles with opposite angles on mating fracture surfaces. These literature hypotheses for the shape of microcracks further dictate that hackles are formed under the influence of two-dimensional stress. The crack tip is straight throughout the width of the matrix between adjacent fibres. In the current study, the shape of hackles suggests that microcracks have been formed under three-dimensional stress states. Fig. 1 shows hackles on fracture surface of DCB 3. In Fig. 1(b), the edges of the top hackle flank are inclined to the

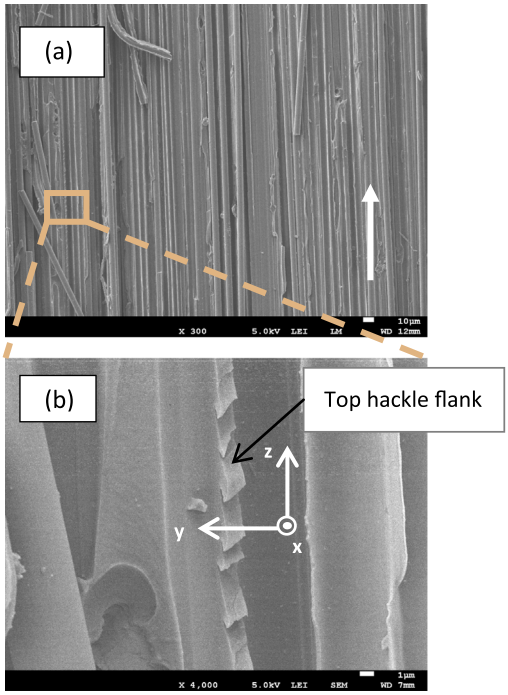

**Fig. 1.** SEM images of fracture surface of DCB 3 at magnification of 300× (a) and 4000× (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)