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Two-parameter model for delamination growth under mode I fatigue loading (Part A: Experimental study)

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Mode I delamination growth under fatigue loading has been experimentally investigated in carbon/epoxy laminates. The experimental results are used in Part B of this paper for the development of a two-parameter mechanistic model for delamination growth. Fatigue tests are performed using double cantilever beam and width tapered double cantilever beam specimens. Delamination growth has been characterized using strain energy release rate approach. Fracture surfaces have been investigated for the effect of stress ratio and monotonic and cyclic load using scanning electron microscopy. The results show that microscopic features depend on monotonic and cyclic load.

1. Introduction

Fibre reinforced polymer composites are attractive for aerospace applications because of their exceptional strength and stiffness-to-density ratios. Aerospace industries use composites to lower the weight of aircraft structures, and to increase their fuel efficiency. Composite components used in military and commercial aircraft are (among others) horizontal and vertical stabilizers, wing skins, fin boxes, flaps, spoilers, doors, elevator elements, rudders and other parts [1].

Initially, composites were used only in secondary aircraft structures and its use was limited to about 2% by aircraft weight [2]. However, with improved material and knowledge, composites are now being adopted in primary aircraft structures. Modern aircraft like the Boeing 787 and the Airbus A350 have wing and fuselage skins made of composites. The weight percentage of composites in these aircrafts is 50–53% respectively with an increased fuel efficiency of 20–23% compared to similar sized aircraft utilizing aluminium [3].

The use of composites in primary aerospace structures has to comply with the need for high reliable design. Composites are inherent to various damage types including fibre breakage, ply delamination and micro cracking in the matrix. The occurrence of damage in composite structures can never be entirely avoided. The structures should be designed to function safely despite the presence of damage, a concept known as damage tolerance [4]. The damage tolerance analysis of a composite structure is based on the initial damage size, damage growth and residual strength of the structure after damage growth [5,6].

Delamination is the most severe type of all damage types. The strength and stiffness of composite structures reduce due to delamination, potentially leading to structural failure [7]. The causes of delamination are bad layups of plies during manufacturing, low velocity impact of tools during assembling and service, overstressing or fatigue [7]. Fatigue is a major cause of delamination growth in composite structures, making it a primary design concern. For the adoption of damage tolerance design approaches in primary composite structures in aerospace applications, the development of accurate fatigue delamination growth assessment tools is therefore necessary.

A fatigue load cycle can be described by both a cyclic and monotonic load component. For example the maximum stress S_{max} and stress range ΔS describe the cycle, or the mean stress S_{mean} and stress amplitude S_a, or ΔS and the stress ratio R. This implies that in order to attribute delamination growth to fatigue loading, two components of the load cycle are to be considered.

In the case fatigue loading comprises a fully arbitrary load spectrum, one may assume that for each load cycle the combination of monotonic and cyclic load is different, i.e. the stress ratio is different, see the illustration in Fig. 1. To be able to describe delamination growth under these arbitrary load spectra, two aspects should be understood:

– The relation between the delamination growth rate and both the monotonic and cyclic load component.
– The potential interaction between subsequent load cycles.

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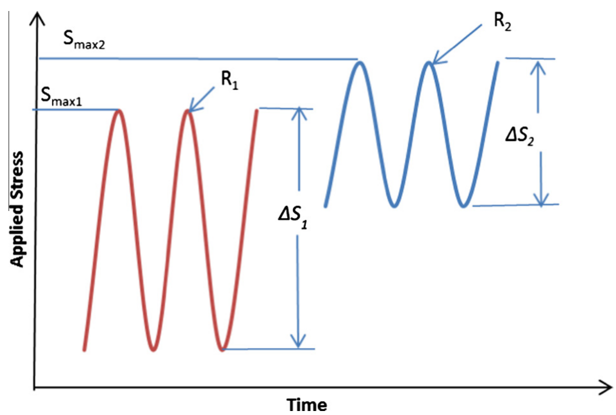

Fig. 1. Illustration of two load cycles with different stress amplitudes and different maximum stresses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The literature contains evidence of studies that correlated the delamination growth rate to two loading parameters i.e. monotonic and cyclic load. For example, Hojo et al. [8,9] correlated the delamination growth rate to the maximum stress intensity factor (SIF) K_{max} and SIF range ΔK. Similarly, Jia and Davalos [9] correlated delamination growth to the strain energy release rate (SERR) range ΔG and maximum SERR G_{max}. Atodaria et al. [10] used an average SERR and SERR range as correlating parameter for delamination growth characterization. Despite the commonality in linking to linear elastic fracture mechanics (LEFM) parameters, the approaches of these studies were however empirical.

In literature, there are several approaches towards controlling the fracture mechanics parameter for delamination growth. Some researchers [8,11] have used the SIF range as fracture mechanics parameter. However, due to the complex stress field at the delamination front, its evaluation is difficult for orthotropic composite laminates making it inconvenient for such materials. Using the SERR as controlling fracture mechanics parameter is an effective alternative for delamination growth analysis and widely adopted by researchers [12,13].

The problem with the SERR approach is the lack of consensus on the formulation of the SERR to characterize fatigue delamination growth. Two commonly adopted formulations for the SERR are the use of maximum SERR G_{max} [14] and the SERR range defined as $\Delta G = G_{max} - G_{min}$ [15,16]. The prevalent use of G_{max} stems from its importance in assessing the limits for static delamination propagation. For delamination growth related to cyclic loading, however, this parameter fails to consider the effect of the minimum energy release rate, G_{min}, related to the minimum load in the applied load cycle. Ignoring G_{min} has several drawbacks, the crack closure effect cannot be captured as it is only active in the lower part of the fatigue cycle. In addition, fibre bridging affects both G_{max} and G_{min}. By ignoring G_{min}, corrections for fibre bridging will be misleading. In fatigue, the fracture surface is affected by both monotonic and cyclic load. Based upon the current observations, G_{min} is considered an essential component of cyclic load and by neglecting it, the variation of fractographic features could not be explained.

The use of $\Delta G = G_{max} - G_{min}$, attempts to remove this shortcoming in a manner analogous to the SIF range, ΔK, used for crack growth in metals. The simple arithmetic difference in maximum and minimum SERRs, however, fails to adhere to the rules of superposition for SERR, thus violating the similitude principle central to linear elastic fracture mechanics. The consequence of using this arithmetic definition is that the effects of monotonic and cyclic loading on delamination growth are inter-related, which can lead to misinterpretation of the results [17].

The above shortcomings of ΔK, G_{max} and ΔG are fulfilled by the use of SERR range ΔG_s, defined as $\Delta G_s = (\Delta\sqrt{G_s})^2 = (\sqrt{G_{max}} - \sqrt{G_{min}})^2$. This formulation is the correct similitude with the applied cyclic load, and corresponding to the formulation of the SIF range.

Although fatigue cycles are determined by two load parameters, most work in the literature seems to utilize single parameter models for delamination growth. In these models, the delamination growth rate is related to a single LEFM parameter, using so called Paris equations. Consequently, these single parameter models are corrected for the stress ratio effect, often using a concept of crack closure. Crack closure increases the effective stress ratio at crack tip due to crack tip closure before minimum load is reached. For example, Hojo et al. [8] used crack closure to correct for the effect of stress ratio. However, Hojo observed crack closure only at lower stress ratios. Crack closure is often the cause of the stress ratio dependency for metallic materials. On the other hand, the authors of Ref. [8] found that the crack closure effect is rather small and the cause of stress ratio dependency is different from metallic materials.

Although numerous papers report qualitative evaluations of typical fracture features such as striation and hackles [8,18–20], the literature however lacks a quantitative analysis of these micro-features originated from fatigue delamination growth.

The effect of monotonic and cyclic load on delamination growth at macroscopic level should be a consequence of the effect at microscopic level. This implies that microscopic features are affected by cyclic and monotonic loading. Literature supports this hypothesis. Bathias and Laksimi [18] for example, compared fracture surfaces to study the stress ratio effect, and reported striations for the lowest stress ratio only. The striation formation in polymers is attributed to the molecular chain fracture (chain scission) [21] as compared to the striations in metallic materials where plastic deformation in each cycle creates a ridge/step. Striation formation is dependent on loading conditions [21]. At low load levels striations are not formed. At intermediate load levels ($0.4 < G < 0.65G_c$), striations form as small steps in the matrix. At very high load levels, i.e. $G > 0.65$, striations form as deep cracks. Thus the variation of microscopic features with load components can be used to correlate macroscopic level delamination growth with monotonic and cyclic load parameters.

The objective of this paper is to develop a mechanistic approach for the delamination growth modelling. Mode I delamination growth has been experimentally investigated at both macroscopic and microscopic levels. The relation of microscopic delamination growth with fatigue loading is correlated to macroscopic delamination growth. As a result, a mechanistic two-parameter model has been developed. The advantage of this paper is to investigate the details of the fracture surfaces, and try to correlate these features with fracture mechanics parameters. The research is divided into two parts, Part A and B. The current paper presents the experimental investigation. The two-parameter model development is described in Part B [22].

2. Experimental program

To characterize the mode I delamination growth, fatigue tests were performed using two specimen types: double cantilever beam (DCB) and width tapered double cantilever beam (WTDCB). The test specimens, test procedure and measurements for these two types are described in the following subsections. Section 2.2 describes the tests for fractographic analysis of the specimens using scanning electron microscopy (SEM).