Composites Part A 107 (2018) 421–431

Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

A damage-based model for mixed-mode crack propagation in composite laminates

J.A. Glud[a,*], P.A. Carraro[b], M. Quaresimin[b], J.M. Dulieu-Barton[c,a], O.T. Thomsen[c,a], L.C.T. Overgaard[a]

[a] Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstraede 16, 9220 Aalborg Oest, Denmark
[b] Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, 36100 Vicenza, Italy
[c] Faculty of Engineering and the Environment, University of Southampton, Highfield, SO17 1BJ, Southampton, United Kingdom

ARTICLE INFO

Keywords:
Laminates
Fatigue
Transverse cracking
Mixed-mode
Damage mechanics
Multi-scale

ABSTRACT

A model for the off-axis crack propagation in laminated fibre reinforced polymer composites subjected to multiaxial fatigue loadings is presented. On the basis of several observations reported in the literature, the crack propagation phenomenon can be seen as the result of a series of micro-scale events occurring ahead of the crack tip within a process zone. The mixed mode loading condition defines the type of the micro-scale events which occur in the process zone and lead to fatigue crack propagation. Based on this evidence and by using a multiscale approach to determine the micro-scale stress fields in the matrix, two simple parameters are defined for predicting the crack growth rate through a Paris-like law. By extracting the proposed parameters from experimental data obtained from the literature, it is demonstrated that the crack propagation data are all included into two Paris-like scatter bands covering the whole mode-mixity range.

1. Introduction

Laminated Fibre Reinforced Polymer (FRP) composites are used extensively for weight critical structural applications, which are often subjected to severe fatigue loading conditions over their service life. The fatigue loading conditions are typically non-proportional and multiaxial, making predictions of fatigue life difficult because of the influence of multiple factors that need to be combined. Therefore, many researchers have resorted to phenomenological models to make fatigue life predictions, which have been shown to be sometimes deficient when seeking safe design guidelines [1]. Therefore, physically based models that incorporate a better understanding of material behaviour are required to establish more consistent and generally applicable fatigue models, as well as more reliable design guidelines.

The sequence of damage modes for multidirectional laminates usually consists of off-axis cracking followed by delamination and fibre breakage leading to the ultimate structural failure [2–5]. Off-axis cracks are through-the-thickness cracks in the laminate layers, which propagate along the longitudinal direction in the matrix between the fibres. Off-axis cracking represents a very important progressive damage mode, because it usually occurs first, thus promoting other damage modes, such as delaminations and fibre failures; in addition, off-axis cracking is directly linked to the stiffness degradation observed in composite laminates [6]. Another important consideration is that the damage evolution in composite laminates is a multi-scale and hierarchical process, involving several length scales [7]. In fact, the initiation of an off-axis crack (or macro-crack) results from the damage accumulation in the matrix material at the micro-scale, i.e. at the length scale of the inter-fibre spacing [7]. A damage-based model for the initiation of off-axis cracks must therefore consider this evidence through a multi-scale approach.

A damage-based crack initiation criterion for multiaxial fatigue loading was presented in [8] where two micro-scale stress parameters controlling the initiation process were identified from experimental observations of damage modes occurring at the fibre-matrix level. Depending on the multiaxial stress state, either the Local Hydrostatic Stress (LHS) or the Local Maximum Principal Stress (LMPS) were found to promote the initiation of off-axis cracks. To use this model, two S-N curves for crack initiation must be derived from fatigue experiments. One curve should be derived for a stress state where the LHS is governing the crack initiation and the other should be derived when the initiation is driven by the LMPS.

---

* Corresponding author.
E-mail addresses: jag@m-tech.aau.dk (J.A. Glud), marino.quaresimin@unipd.it (M. Quaresimin), janice@soton.ac.uk (J.M. Dulieu-Barton), ott@m-tech.aau.dk, o.thomsen@soton.ac.uk (O.T. Thomsen), lcto@m-tech.aau.dk (L.C.T. Overgaard).
URLS: http://www.m-tech.aau.dk (J.A. Glud), http://www.gest.unipd.it/en (M. Quaresimin), http://www.southampton.ac.uk/engineering (J.M. Dulieu-Barton).

https://doi.org/10.1016/j.compositesa.2018.01.016
Received 13 May 2017; Received in revised form 30 October 2017; Accepted 16 January 2018
1359-835X/

When an off-axis crack has initiated within a ply of a laminate it will grow in a steady state manner along the fibre direction. The resistance to the crack propagation has been found to depend on the local mode-mixity in the off-axis crack front [5]. Typical results found in literature show that in terms of the total Energy Release Rate (ERR or G_{tot}), the resistance to fatigue crack growth in Mode I is less than in Mode II and the trend between the pure mode conditions is not necessarily monotonic. In spite of the importance of this phenomenon, physically based models targeted specifically at mixed-mode off-axis tunnelling crack propagation do not exist at present. However, a wide range of literature is available regarding the propagation of interface cracks in bonded joints and delaminations in laminates (e.g. [9–17]). In these cases, a macro-crack grows within a thin adhesive or matrix layer between the fibres. Therefore, in both these cases and in that of an off-axis crack, the problem can be regarded as that of a crack growing under mixed-mode conditions in a soft interlayer between two stiffer adherends. Because of the analogy with adhesive bonds, a literature review of the modelling efforts related to the mixed-mode growth of delaminations and bondline cracks is pertinent and may provide inspiration for the development of a new propagation criterion for off-axis tunnelling cracks. Several empirical relationships have been proposed to predict the critical ERR and the crack growth rate in fatigue as a function of the mode-mixity for inter-laminar cracks. Benzeggagh and Kenane [9] studied mixed-mode delamination propagation in glass/epoxy under quasi-static loading using the Mixed-Mode Bending (MMB) test fixture. Based on the experimental results, the authors computed the critical ERR for any mode-mixity using results for at least three different conditions to obtain the empirical constants of their proposed power law relationship. The same authors, later, proposed power law relationships for the proportional scaling coefficient and the slope of the Paris-like law to predict the crack growth rate (CGR) for varying mode-mixity [10], which required fatigue tests with at least three different mode-mixities to obtain the empirical constants. Liu et al. [11] used an MMB fixture to test bonded metal joints subjected to mixed-mode conditions and found that a linear interpolation between G_{Ic} and G_{IIc} was sufficient to predict the critical ERR for the mode-mixity range under consideration. Adhesively bonded double-lap joints were tested in [12], where a similar linear interpolation of the critical ERR was used to compute an equivalent ERR as input to a Paris-like law to predict the CGR. Adhesively bonded metallic joints were tested under quasi-static loading in [13] and under fatigue in [14] and purely empirical parabolic fits were used to provide the measured proportional scaling and the exponent of the Paris-like law. Even though the proposed empirical relationships have been reported to fit the reported experimental results, it is clear that, due to the empirical nature of the approach, several tests are required to derive the empirical constants. Moreover, it is not clear whether the derived empirical constants are valid for material systems other than those specifically studied.

Physically based models could potentially circumvent the need for multiple fatigue tests on a range of materials and provide more reliable predictions. However, there is little published on the observed damage mechanisms for interfacial fatigue crack propagation in the literature, so only few physically based models are available. For static loading, Liu et al. [11] reported two distinct types of fracture behaviour, which were found to depend on the mode-mixity. For Mode I dominated loading, a coplanar crack growth was observed, whereas for Mode II dominated loading shear cusps were observed ahead of the crack tip. This region of damage ahead of the crack tip is commonly referred to as the process zone [18]. The same characteristics of the crack path have been reported in [16,17,19] for fatigue loading as well. Based on the reported damage mechanisms for interfacial cracks, Wang [20] proposed a quasi-static fracture criterion that uses the Mode I ERR and a Drucker-Prager type parameter for predicting the critical ERR in the near Mode I and Mode II conditions, respectively. The two models for each type of fracture proposed by Wang [20] were shown to successfully predict the critical fracture toughness for a wide range of mixed-mode quasi-static load cases.

During static and fatigue loading, the damage evolution ahead of the crack tip does not appear to be a point phenomenon, and therefore the idea of a failure process zone model has received considerable attention. Several cohesive zone models and numerical approaches have been developed to create a unified approach for the initiation and propagation and to model the softening behaviour in the process zone through traction-separation laws. However, current methods for predicting the effect of mixed-mode loading rely on empirical relationships [15]. Inspired by the model presented in [20] and the experimental evidence indicating a finite region of damage for Mode II dominated loading reported in [16], Carraro et al. [18], proposed that the average Maximum Principal Stress in a finite region of the adhesive ahead of the crack tip governs the crack propagation in bonded joints for both static and fatigue loading. Finite Element (FE) analyses were adopted to compute the average Maximum Principal Stress in a control volume representative of the process zone, with the adhesive modelled as an undamaged continuum. It was shown that the model allows the fatigue CGR data for Mode II dominated loading to be represented in a single scatter band, when a fixed size of the finite failure process zone was chosen (three times the adhesive thickness). The Mode I ERR contribution was shown to collapse the CGR data for Mode I dominated loading in a single scatter band, hence enabling the CGR in the full mode-mixity range to be described by two Paris-like master curves. The result is a model that, though requiring some computational effort, only requires experimental data for two different mode-mixities (i.e. pure Mode I and Mode II) to derive the coefficients of the two Paris-like master curves.

As mentioned above, off-axis tunnelling cracks have not been widely covered in the literature, meaning that an off-axis crack propagation model suitable for structural scale analysis is highly desirable. To achieve this ambitious target, an efficient multi-scale strategy along with a damage-based mixed-mode model is required. In this work, a new damage-based model is developed and it is shown that two Paris-like master curves and scatter bands can be adopted to predict the CGR for the entire range of mode-mixities. As a consequence, data from fatigue tests on only two different laminate configurations are required as input. Furthermore, a novel multiscale approach is devised, where the model calculates the micro-scale parameters adopted for the predictions using information obtained from the larger scales, resulting in computationally efficient predictions suitable for structural scale analysis.

2. Crack propagation mechanisms

As already mentioned, when a crack propagates in a soft matrix layer between stiffer adherends, as in the case of inter-laminar and also tunnelling cracks, two main mechanisms can be observed at the micro-scale, depending whether the loading condition is Mode I or II dominated. As reported in [11,16–19], the propagation of an inter-laminar crack under near mode I conditions occurs in a co-planar manner at the interface or within the matrix inter-layer, as shown in Fig. 1a). In particular, if the interface is weaker than the matrix, a self-similar propagation will occur at the interface. This scenario is typical of pure Mode I conditions, but it was observed also in the presence of small Mode II contributions [5,16,18]. Therefore, the Mode I ERR (G_I) is responsible for the co-planar crack growth propagation, when the Mode II ERR (G_{II}) contribution is sufficiently low, as discussed extensively in [11,18]. Consequently, predictions of the CGR for the co-planar propagation condition can be done based on G_I only. For the case where the interface is tougher than the matrix, scarps and ribbons are the most commonly observed fractographic features in FRP materials [19,21]. Fig. 1a) illustrates the series of events that cause these features. Micro-voids develop in the process zone and are initially separated from the macro-crack. It is reasonable to postulate that the micro-voids occur where weak spots are located in the process zone. Weak spots could be pre-existing micro or nano voids or flaws, or regions with a lower