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Fatigue damage evolution in GFRP laminates with constrained off-axis plies

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A B S T R A C T

The characterisation of fatigue damage evolution in constrained glass fibre reinforced plastic off-axis laminates is presented. A newly developed imaging technique known as Automatic Crack Counting (ACC) is used to quantify the off-axis crack state in constant amplitude (CA) and variable amplitude (VA) block loading tension-tension fatigue tests and constant amplitude compression-tension tests. The quantified crack states are analysed by combining the newly developed ACC method with a data mining approach and applying these to large data sets obtained during fatigue tests. It is shown that for a constant stress level, the stochastic nature of off-axis crack initiation and crack growth is accurately modelled by the Weibull distribution, with the distribution parameters being efficiently derived using the developed approach. The data-rich characterisation provides new insight in the crack density evolution process for VA and C-T loading, as well as derived Weibull distribution parameters in combination with the classical S-N curves and Paris' Law relationship. Hence, providing an improved approach that includes the stochastic and deterministic information for physically based modelling of crack density evolution for fatigue loading.

1. Introduction

Laminated polymer based composite materials or fibre reinforced polymers (FRP) are being used increasingly in structural components subjected to fatigue loading. Accurate predictions of the material failure are essential for reliable and weight efficient structural design. The fatigue life prediction of FRP has been the subject of significant interest for more than three decades, and the fatigue damage modes observed in FRP laminates are generally well understood in qualitative terms, e.g. [1]. In pristine layered Multi-Directional (MD) laminates, the first damage mode usually takes the form of off-axis cracks tunnelling through the laminate layers, followed by delamination and fibre breakage leading to ultimate structural failure. This failure sequence has been reported by several authors on the coupon scale [2–4] and on the structural scale [5], where it was clear that a predominant failure mode of a wind turbine blade subjected to fatigue loading was off-axis cracks, although not specifically mentioned by the authors. It is particularly important to predict the off-axis crack damage mode, since these cracks promote other damage modes such as delamination and fibre breakage [6,7] and are linked directly to the stiffness degradation observed in composite laminates during fatigue loading [3,4,8,9].

Classically, the rate of fatigue damage development is described on the macroscopic scale in terms of strength by utilising S-N curves and in terms of crack propagation thresholds by utilising Paris' law relationships. S-N curves and Paris' law relationships are established from a set of phenomenological material constants resulting in fatigue limits and threshold limits for crack propagation, i.e. fatigue failure parameters, which are determined using a prescribed fatigue characterisation method. In the very early work [10] a fatigue characterisation method and a failure criterion distinguishing between failure in the matrix and the fibres were proposed, where the matrix failure corresponded to the off-axis crack damage mode. The fatigue failure parameter identification method in [10] consisted of a set of S-N curves, which required extensive testing on Uni-Directional (UD) laminates, to produce needed material input to a stress based phenomenological fatigue model. The ideas presented in [10] have resulted in extensive testing

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campaigns on UD material systems, e.g. [11], to provide a basis for material input to fatigue models. However, a recent detailed review of phenomenological fatigue models [12] concluded that for some load cases the proposed fatigue criteria give non-conservative predictions. The reason for the non-conservative predictions could not be determined, as the models reviewed in [12] did not account for the actual physical damage mechanisms. To model the actual damage mechanisms, a branch of fatigue models known as 'progressive continuum damage models' have been proposed [13–17], where fatigue damage is modelled at the ply thickness scale. The models are based on phenomenological quasi-static failure criteria and as with the fatigue models also involve extensive characterisation of UD materials systems to calibrate the empirical constants. The models show good predictive capabilities on the tested materials, but the empirical nature of such models may question their general applicability and validity. An explanation for the shortcomings of the phenomenological models described in [12], and why progressive continuum damage models require calibration of several empirical constants, is provided in the present paper. Here it is considered that the fatigue failure parameters derived from UD laminates are not representative for the case when the UD plies are combined and constrained to form a MD laminate. This is because, as described in [18], the damage progression in a UD ply embedded in an MD laminate is different to that of a UD ply embedded in a UD laminate. In a laminate consisting entirely of UD plies unstable propagation of a single crack occurs, which is not accompanied by progressive stiffness degradation prior to final failure. When constraining plies are present, as is the case for UD plies embedded in MD laminates, stable crack propagation is observed, resulting in a progressive stiffness degradation of the laminate during the testing. Therefore, fatigue tests on UD laminates cannot provide sufficient fatigue failure parameters to model the progression of actual damage mechanisms in MD laminates. Hence, in the present paper, a new way to inform fatigue models and provide general applicability, whilst limiting the need for empirical constants, is proposed by quantifying the off-axis crack evolution process throughout fatigue tests and derive material parameters from measurements on MD laminates.

Alongside fatigue models, micro-mechanical modelling represents a promising tool to describe the influence of the current damage state of an MD laminate on the overall structural performance. In [19] an overview and classification of available micro-mechanical damage models was provided. From the findings in [19] it is clear that micro-mechanical models generally predict the degraded constitutive properties of arbitrary laminates solely from information on the volume density of off-axis cracks in each layer. However, the models do not include a means of predicting the off-axis crack evolution, which renders them less useful for design of real layered composite structures. In [20–22] attempts have been made to extend micro-mechanical models to describe fatigue damage, but studies have been limited because of the material data found in literature generally focuses on characterisation of UD plies and laminates.

Several fatigue test campaigns have been devoted to the study of off-axis crack density evolution in GFRP MD laminates for CA loading with constant load ratio [2–4,6,9,23,24]. Based on results from literature it is clear that the crack density evolution rate and saturation value increases when the load amplitude is increased. Further on, the evolution rate and saturation value is reduced when the off-axis angle of the constrained ply decreases. It should be noted that, there is a lack of data in the open literature where the influence of the load ratio and VA block loading on the crack density evolution in GFRP is reported.

The process of off-axis crack initiation has been quantified for CA loading and constant load ratio for different multiaxial stress states [3,6,9,18]. Measurements on the number of cycles to initiation of the first few cracks are obtained by manual and visual assessment of the damage state. Reported results show that the number of cycles to initiation of the first few off-axis cracks is well described by the classical S-N power law curve.

Crack growth rates (CGR) for the stable propagation of off-axis cracks under CA loading with constant load ratio have been reported in [8,9,18,25]. In [8,25] the CGR of off-axis cracks throughout the fatigue test were manually measured and it was found that the CGR were independent of crack length but dependent on stress level and crack density. The CGR increased with increasing stress level and decreased with increasing crack density, where the latter is known as the 'shielding effect' of off-axis cracks [9]. In [9,18] CGR results for the first few non-interacting cracks were reported and it was shown that the CGR for off-axis cracks can be described by a Paris' Law like relationship.

Based on the experimental results reported in literature described above, it is evident that there is a general agreement that the off-axis crack evolution can be described by initiation and the stable growth of cracks until a certain saturation point is reached. However, it is also clear that there is no general agreement on which fatigue properties should be derived or how they should be determined. The result is that fatigue studies cited in literature focus on either crack growth or crack initiation. Consequently there is little reported work that covers both crack growth and initiation [9,18], or work that accounts for the interaction of the cracks. Furthermore, a major consideration is that in all previous work reported in literature [2–4,6,8,9,18,23–25], the crack state quantification procedures were carried out by manually and visually counting cracks. The crack state generally consists of many cracks which are unevenly distributed in the region of interest, so the crack counting task is labour intensive and difficult, essentially because the images are difficult to analyse by eye e.g. [9,26]. This limits the scope and size of studies and leads to a relatively poor temporal resolution of the crack state. Moreover, as a result of the complex images of the crack state, the manual counting procedure is prone to human errors where cracks are not counted in a consistent manner for all tests.

There is a clear need to devise a new approach to derive statistically representative fatigue failure parameters from MD laminate tests. With this aim in mind, an approach has been devised known as the Automatic Crack Counting (ACC) procedure [26], which quantifies the crack state for each ply in terms of the length and location for each individual crack for every processed image. The ACC procedure has allowed the collection of the necessary data sets without human errors at sufficient temporal resolution to obtain the parameters that define off-axis crack initiation and growth. The availability of the high fidelity crack state quantification enables the benchmarking of existing damage models. Moreover the ACC methodology is a prerequisite for the development of improved off-axis crack evolution models. The automated experimental approach combined with the post-processing methodology have therefore enabled the novel contributions described in the present paper as follows:

1. Investigation and quantification of the influence of VA block loading and change in R-ratio on the crack density evolution process in GFRP when compared to CA loading results.
2. Derivation of stochastic fatigue failure parameters for off-axis crack initiation and propagation in terms of Weibull distribution parameters along with the derivation of classical S-N and Paris' Law relationships.
3. Comparison of the predicted stiffness degradation obtained from a micro-mechanical model utilising high fidelity off-axis crack evolution data with measured stiffness degradation and a ply discount approach.