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Fatigue life prediction of laminated composites using a multi-scale M-LaF and Bayesian inference

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ABSTRACT

This paper presents a probabilistic model for fatigue life estimation of composite laminates using a high fidelity multi-scale approach called M-LaF (Micromechanics based approach for Fatigue Life Failure). To this end, square and hexagonal representative unit cells are introduced to calculate constituent stresses using a bridging matrix between macro and micro stresses referred to as the stress amplification factor matrix. The M-LaF is based on the constituent level input data that makes it possible to predict fatigue life of a variety of laminates with any possible fiber volume fraction. The M-LaF model parameters are calibrated as posterior distribution using the Bayesian inference methodology. A reference test data from literature was used for parameter calibration. The calculated posterior statistics were then used to calculate probabilistic fatigue life estimates of sample laminates. The predicted S–N curves are in good agreement with the test data for a range of composite laminas as well as laminates with different fiber volume fractions and under diverse stress ratios. As an illustration, the above approach was applied to a wind turbine blade to show the effect of multi-axial loading on the fatigue life of composite laminates.

1. Introduction

Fatigue failure mechanisms in composite materials are different than in metals. In general, fatigue in a material is caused by a non-conservative deformation process where the creation of new surface area causes the energy loss that leads to failure. In metals, the initiation of a single crack and its intermittent propagation until catastrophic failure governs the fatigue life of the structure. On the other hand, fatigue in composite materials is due to multiple damage mechanisms. There are many factors that govern the damage growth in composite materials such as relative stiffness of the fiber and matrix, ply stacking sequence, load direction, and loading rate [1].

The fatigue life of composites can be evaluated using methods that include S–N curves, energy based approaches, stiffness based fatigue models, and strength degradation models. Hashin and Rotem [2] presented a simple fatigue failure criterion expressed in terms of S–N curves obtained by uniaxial cyclic testing of unidirectional specimens. Here, the criterion is proposed for unidirectional laminates only. Information about stress interaction between laminas in non-unidirectional laminates and its effects on failure was lacking. Also, this macroscopic failure criterion did not focus on the developing damage during cyclic loading. The critical element concept of Reifsnider and Stinchcomb [3] represents a non-linear fatigue life prediction methodology for layered composites which accounts for fatigue damage initiation and growth as well as final failure. This methodology assumes that a representative volume can be chosen such that the stress state in that volume is typical in the laminate, and failure of this element causes final failure. To predict fatigue life using the critical element concept, S–N relations of unidirectional composites are still needed. The fatigue life prediction methodology developed by Himmel [4] requires prior experimental information on the relevant fatigue damage and failure processes. Here the critical element model was used as a starting point to simulate the fatigue behavior of composites.

Energy-based criteria incorporate both stresses and strains; the multiplication of these components represents energy. In this approach, the damage is related to input energy which cannot give any information about the failure mechanism [5,6]. This energy-based method is only applicable for unidirectional composites, and it is difficult to extend it to multidirectional laminates because calculation of strain energy from stress/strain redistribution in fatigue would be difficult. Additionally, this approach is not appropriate for handling fatigue under variable loading. Natarajan et al. [7] proposed a strain energy density based fatigue model. That model

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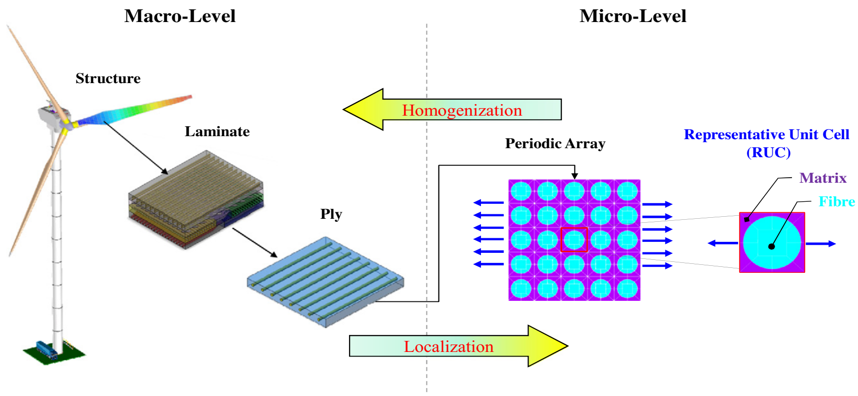

Fig. 1. Macro and micro structural levels in composite [25].

performs well for tension–tension and bending fatigue experiments, but did not investigate the influence of combined loadings such as tension–torsion fatigue.

Composite laminate condition can be assessed by its stiffness condition. This will also help to gage fatigue resistance or can be useful in lifetime predictions. The fatigue modulus degradation approach was given by Hwang in which fatigue life was calculated using strain failure criteria [8]. The concept of fatigue modulus is different than elastic modulus; the stiffness is degraded once initial damage occurs. This degradation in the stiffness can be noted by reduction in the dynamic modulus (or secant modulus). The dynamic modulus is the slope of the extremities of a stress/strain hysteresis loop. The damage evolution function and dynamic modulus is based on some assumption or experimental results which limits its usage. Also, some difficulties have been found in predicting the cumulative damage under stress dependent strain. In the residual stiffness model given by Whitworth [9,10] an equivalent cycles approach for variable amplitude loading was used. This methodology relies on the limiting assumption that the response of a structure is independent of load history. Additional studies by Hahn and Kim [11], Hashin [12], and Yang et al. [13] are among the other researchers that have considered the degradation of the fatigue or dynamic modulus as indicators of fatigue damage.

In strength degradation models [14–16], life is predicted by calculating the effect of each load cycle on residual strength, until the load exceeds the remaining strength. The expected advantage of this approach is that the sequence effects of random loads can be implicitly included. The successful application of the strength-based method requires a description of the post-fatigue strength, which entails considerable experimental effort. Akshantala [14] assessed the fatigue life of Carbon Fiber Reinforced Plastic (CFRP) laminates by employing a micromechanics approach. He employed fracture mechanics analysis of micro cracking for fatigue in composites. Conventional fracture mechanics analysis of fatigue crack growth normally uses a Paris law that relates crack growth rate with applied stress intensity factor. However, in micro cracking, there is no observation of crack growth, but it is feasible to measure the rate of increase in crack density per cycle, which is the most computationally expensive part of the method.

Jen and Lee [17] proposed a modified version of the well known Tsai Hill failure criterion for plane stress fatigue. This strength-based model does not account for damage accumulation and does not consider specific damage mechanisms. This requires prior knowledge of fatigue strengths as function of number of cycles, which can only be determined experimentally. Recently, Sarfaraz et al. [18] developed a semi empirical hybrid formulation for composite materials under constant amplitude fatigue. However, they achieved improved model accuracy in both Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) regimes, but still required power law fitting functions or parameters. All these criteria are macroscopic and work at the ply level but do not directly take into account the constituents' failure modes. Also, a large number of mechanical properties are required to particularly apply these models for structural analysis.

Despite the fact that so many efforts have been made into predicting fatigue life of laminated composite materials, so far there is not a well-established and widely accepted approach for life prediction of these materials. Micromechanics is getting attention in industry more recently as it requires fewer tests, thus saving time and accelerates product development. There are various models proposed to predict the behavior of composite materials based on properties of composite components, such as the rule of mixture (ROM), modified role of mixture (MROM), and method of cells (MOC). These micromechanics based methods provide response insight into the constituents and help to better understand the fatigue mechanisms in composites. The successful implementation of this approach requires characteristics of the constituents beforehand which are not easy to obtain. Some researchers back-calculated constituent properties from lamina properties using a simple rule of mixture [19]. Others calibrated material properties in a deterministic fashion with the aid of genetic algorithms and gradient-based techniques [20,21]. These calibrated values are the mean parameters and did not reflect any uncertainty due to the materials' natural variability. In contrast to deterministic approaches, a Bayesian approach can provide conditional probability and calibrates parameters with test data [22,23]. Bayesian methods are presently becoming popular in science and engineering as a means to calculate probabilistic inference [24]. In these methods, expert opinion or previous information is reflected in prior distributions which are basically a wide range of possible realistic values of the parameters to be calibrated. These values are updated using a likelihood formulation with test data to determine posterior distributions.

The objective of this work is to estimate the probabilistic fatigue life of laminated composites using novel combination of a Micromechanics based model for Fatigue Life Failure (M-LaF) with a Bayesian inference approach. The aim is to develop a unified framework for the representation and quantification of uncertainty present in the fiber and matrix properties with the use of the Bayesian inference approach in order to calculate probabilistic composite fatigue failure. The proposed framework is applied to glass-fiber reinforced composite laminates. The paper is organized as follows. In Section 2, the M-LaF framework is described; with an emphasis on explanation of the fatigue failure criterion is presented. A comprehensive presentation of the Bayesian inference technique is given in Section 3. Section 4 details the computational implementation of M-LaF with Bayesian inference approach. Results with discussions are presented in Section 5. In Section 6, the application