International Journal of Fatigue 117 (2018) 327–339

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Predicting matrix and delamination fatigue in fiber-reinforced polymer composites using kinetic theory of fracture

Faisal H. Bhuiyan, Ray S. Fertig III*

Department of Mechanical Engineering, University of Wyoming, Laramie, WY 82071, USA

ARTICLE INFO

Keywords:
A. Polymer-matrix composite fatigue
B. Fatigue
C. Multiscale modeling
D. Progressive damage analysis

ABSTRACT

Prediction of fatigue in fiber-reinforced polymer (FRP) composites demands progressive damage analysis tools that account for constituent physics of the problem. In this work, a matrix fatigue failure methodology based on the kinetic theory of fracture (KTF) is developed that uses the physics of the matrix constituent to track damage in both lamina and interlaminar regions. This model is calibrated from either off-axis lamina or ± 45 laminate fatigue tests. Using this methodology, finite element simulations of open-hole coupons comprised of three different laminates subjected to tension-tension fatigue loading are performed. The coupons consist of the unidirectional IM7/977-3 lamina with available calibration and validation data. In this work, both intra-ply matrix cracks and inter-ply delamination mechanisms are simulated. The resultant residual stiffness and the damage accumulation inside the plies due to matrix failure with a specific number of fatigue cycles are benchmarked against published experimental data. The results show good agreement with this data for all three laminates.

1. Introduction

Fiber-reinforced polymers (FRPs) are becoming the material of choice for weight-critical structures due to their superior specific-strength and specific-stiffness properties, tailorability to design requirements, etc. This is especially true for aerospace structures such as aircraft wings and fuselages, helicopter rotors, wind turbine blades, etc. These aerospace structures operate under long-term cyclic loading, e.g., the typical life expectancy of a wind turbine blade is 20 years continuously running, by which time a blade would go through millions of load cycles. Failure of these structures often has severe consequences. As a result, durability prediction of FRP composites has been a subject of extensive research over the past few decades [1–31]; however, a unified tool for fatigue prediction of FRP composites has yet to emerge. Essentially, fatigue models can be divided into three broad categories: fatigue life models, phenomenological models, and progressive damage models. Fatigue life models do not model the actual degradation mechanism, instead use stress-life or Goodman diagrams in conjunction with some fatigue failure criteria. Phenomenological models use some degradation law for stiffness or strength based on macroscopically observable properties, which is in contrast with the progressive damage models where degradation is modeled in direct relation to the damage occurring in the constituents. The shortcomings of fatigue life models and phenomenological models are that they pertain to specific material systems, stacking sequences, load histories, and environments. Consequently, these models are not suitable for prediction of fatigue life of realistic composite structures under arbitrary loading and environmental effects. There is a wealth of information available in the literature on fatigue prediction in composites. Different aspects of fatigue behavior of FRP composites were expertly reviewed by Sendeckyj [14], Reifsnider [15], Stinchcomb and Bakis [16], Saunders and Clark [17], Philippidis [29], Post et al. [30], etc. Various composite fatigue modeling techniques present in the literature were extensively reviewed by Degrieck and Van Paepegem [7]. Garnich and Akula reviewed progressive failure analysis of FRP composites [32]. Recent developments in delamination simulations and experiments of composite laminates were reviewed by Tabiei and Zhang [31]. In the following, the authors provide a brief summary of relevant progressive damage models existing in the literature. Interested readers are referred to the aforementioned review articles for a comprehensive discussion of the numerous work performed in this field.

Matrix cracking is the primary damage mode under fatigue loading. Highsmith and Reifsnider [18] introduced the so-called shear lag model to capture stiffness degradation of composites due to matrix cracking. Matrix cracking-induced stiffness degradation modeling scheme has also been employed by Nusimer and Tan [19], El Mahi et al. [20], Pradhan et al. [21], Smith and Ogin [22], etc. Continuum Damage Models (CDMs) and fracture mechanics models are widely used for

* Corresponding author.
E-mail address: rfertig@uwyo.edu (R.S. Fertig).

https://doi.org/10.1016/j.ijfatigue.2018.08.007
Received 26 April 2018; Received in revised form 2 August 2018; Accepted 4 August 2018
Available online 10 August 2018
0142-1123/

failure prediction of composite materials – CDMs predict damage initiation based on an appropriate failure criterion and subsequently employ a stiffness degradation mechanism to model the effects of damage, while fracture mechanics models are mainly used for modeling delamination. A CDM treating internal damage variables as tensors/vectors were introduced by Talreja [23,24], where matrix cracking and delamination damage modes are captured with the assumption that the damage modes do not interact with each other. Allen et al. [25], Lee et al. [26] developed similar models to predict composite fatigue. Despite the advancement made in the development of CDMs, such models are typically based on heuristics rather than physical basis. Shokrieh and Lessard [27,28,33,34] introduced the generalized residual material property degradation model for unidirectional composites, where different damage modes were identified and a Hashin-type polynomial failure theory was developed for each mode. A single master curve for residual strength and stiffness was determined, and finally fatigue life under the application of an arbitrary stress-state and different stress ratios was calculated via the use of a normalized constant-life diagram. However, this phenomenological model requires a lot of material characterization data for residual stiffness and strength.

Further complicating fatigue predictions, the heterogeneous and anisotropic nature of composite materials gives rise to a complex stress-state in the constituents even under simple uniaxial loadings. In addition, many different damage states such as matrix cracking, fiber-matrix debonding, delamination, fiber failure, etc. can coincide and interact with varying growth rates associated with each. These challenges make fatigue life prediction in composite structures a formidable problem and have led to the use of overly conservative design approaches for composites in aerospace structures operating under cyclic loading. Progressive damage models based on the physics of the constituents are best suited to address the problem of fatigue prediction in composites, and the composite research community is actively pursuing this path [7,14–26,33–45]. Reifsnider et al. predicted fatigue of composites using a micromechanics model based upon a volume-average constituent-level stress formulation of the composite material [5], however, did not incorporate any additional physics-based model. Mishnaevsky Jr. and Brøndsted investigated the damage growth per cycle and the effect of loading frequency on lifetime and stiffness reduction of composites under fatigue loading via the application of an analytical model utilizing the kinetic theory of fracture (KTF) [8], but they used homogenized composite stresses rather than constituent-level stresses. Fertig et al. proposed a progressive damage model for fatigue prediction of unidirectional laminas [13,46,47], which coupled KTF with volume-average matrix constituent stresses to model fatigue as a matrix-specific phenomenon using matrix-specific physics. The methodology is implemented in three separate modeling steps: (1) a homogenization/localization methodology to link composite stresses and strains to volume-average matrix stresses and strains, (2) a physics-based model for fatigue prediction of the matrix material (KTF), and (3) a link between the microscopic bond breaking in matrix and the macroscopic fatigue failure of the model. This theory is easily programmable, computationally efficient, and the requirement for material characterization data is minimal, which makes it a suitable model to use for progressive fatigue prediction of realistic composite structures. This methodology has been successfully implemented to predict both fatigue [12] and creep [48] of composite structures. Kapidžić et al. followed the earlier work of Fertig to predict fatigue bearing failure of CFRP composites at elevated temperatures and found satisfactory agreement with experimental results [9].

Since our KTF-based composite fatigue prediction methodology has been shown to successfully predict intralaminar fatigue, in this work the methodology is reviewed and extended to delamination prediction capabilities to predict the overall matrix fatigue of open-hole tension (OHT) coupons using calibration and validation data provided by the Air Force Research Lab (AFRL) [49]. The scope of this work is to investigate the failure of only the matrix constituent during tension-tension fatigue loading of composites. The results show good agreement with the experimental stiffness degradation and damage evolution plots of the OHT coupons, which indicates the success of our fatigue prediction methodology to capture the physics of the matrix constituent.

2. Kinetic theory of fracture model for composite and delamination fatigue damage

Fatigue failure of FRP composites is driven by the matrix constituent (except for the nearly-perfect axial loading case) [2–4,6], and fatigue damage predominantly accumulates in the polymer matrix constituent in the form of microcracks. These microcracks accumulate and coalesce to form a macrocrack, leading towards the catastrophic failure of the composite structure. Therefore, to accurately predict fatigue in FRPs, a modeling approach is required that accounts for the accumulation of microcracks per load cycle. Our method of using the kinetic theory of fracture satisfies this requirement and is outlined in detail in the following sub-sections.

2.1. Fatigue failure of polymers based on kinetic theory of fracture

Zhurkov [50] and Coleman [51] independently established a theory describing the relationship between polymer kinetics and time-dependent mechanical behavior nearly six decades ago. This theory is famously known as the kinetic theory of fracture (KTF). KTF models the bond-breaking phenomenon as a thermally-activated process such that the reaction rate going from a pristine state (State 1) to a microcracked state (State 2) is controlled by an activation barrier with activation energy U. Application of stress σ biases the breaking reaction by reducing the energy barrier by the amount $\gamma\sigma$, where γ is defined as the activation volume. This thermally-activated process is shown schematically in Fig. 1. The reaction rate in the polymer is expressed by the following equation

$$K_b = \frac{kT}{h}\exp\left(-\frac{U-\gamma\sigma}{kT}\right) \tag{1}$$

where K_b is the bond rupture rate, k is the Boltzmann constant, T is the absolute temperature, and h is the Planck's constant. In this form, the exponential term represents the probability of overcoming the energy barrier during any attempt and the $\frac{kT}{h}$ prefactor represents the attempt frequency. This model has been shown to successfully model the physics of time-dependent mechanical failure of polymers [51–55].

Several reaction rate models have been proposed for fracture of solids or bond breaking of polymers since the inception of KTF. Hsiao

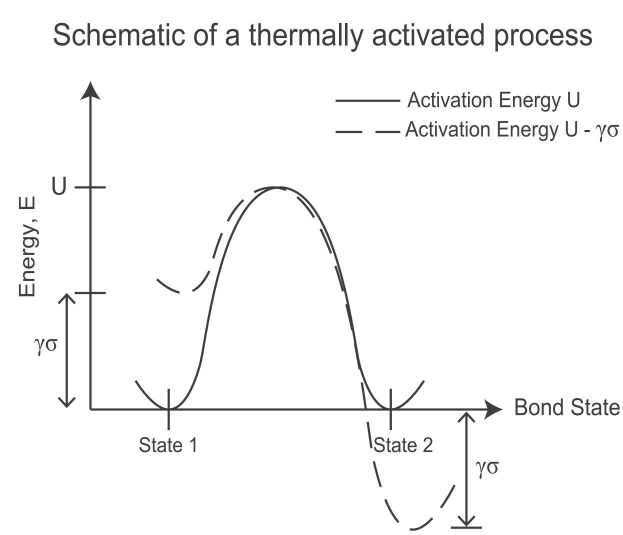

Fig. 1. Energy barrier with activation energy U and $U-\gamma\sigma$ for transition from State 1 to State 2.