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In-situ fatigue life prognosis for composite laminates based on stiffness degradation

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ABSTRACT

In this paper, a real-time composite fatigue life prognosis framework is proposed. The proposed methodology combines Bayesian inference, piezoelectric sensor measurements, and a mechanical stiffness degradation model for in-situ fatigue life prediction. First, the composites stiffness degradation is introduced to account for the composites fatigue damage accumulation under cyclic loadings and a new growth rate-based stiffness degradation model is developed. Following this, the general Bayesian updating-based fatigue life prediction method is discussed. Several sources of uncertainties and the developed stiffness degradation model are included in the prognosis framework. Next, an in-situ composites fatigue testing with piezoelectric sensors is designed and performed to collected sensor signal and the global stiffness data. Signal processing techniques are implemented to extract damage diagnosis features. The detected stiffness degradation is integrated in the Bayesian inference framework for the remaining useful life (RUL) prediction. Prognosis performance on experimental data is validated using prognostics metric. Finally, some conclusions and future work are drawn based on the proposed study.

1. Introduction

The use of composite materials in engineering application has drawn extensive attention recently, which is mainly due to their better characteristics in the fatigue resistance and strength to weight ratio compared to metallic materials. Fatigue induced damage may cause serious safety concerns and/or performance degradation during long term lifetimes. In realistic applications, stress concentration are introduced at weaker sections, such as windows, joints, etc., that are susceptible to delamination, matrix cracking, and fiber breakage damages. Composite specimen with notches or holes have been studied extensively to simulate these conditions in laboratory conditions [1–3]. For example, fatigue response of carbon/epoxy laminates containing circular hole was experimentally investigated and various types of laminate layup have been studied in [4,5]. Sub-critical fatigue damage development in open-hole composite specimen were investigated both experimentally and numerically [6,7].

Many existing studies have been done on explicitly incorporating the different types of damages (e.g. cracks, delamination) in the damage evolution model for the fatigue life prediction [6,8–11]. The progressive damage propagation within composite-metal interface or post-buckled laminates has been investigated in [12–15], in which new interface elements are developed to capture the cohesive behavior of delamination growth under fatigue loading. Majority of these methods are based on finite element method (FEM), which focuses on the mechanisms investigation and modeling. In-situ fatigue life prognosis that directly uses these models will be very difficult due to the computational complexity. In addition, the diagnosis and quantification of various types of damages in-situ is a challenging problem, which makes the prediction based on the high fidelity FEM model very difficult. Some researchers use an alternative approach for life prediction at the macro level, which is based on the strength or stiffness degradation induced by fatigue loading [16–21]. Whitworth [20] proposed a statistical model that describes the residual stiffness using a two-parameter Weibull distribution. In [21], a normal distribution was proposed to predict the residual stiffness of composite laminates. In both approaches, the residual stiffness model ignores the effect of applied stress which is generally not true for fatigue problems. Shirazi and Varvani-Farahani [22] proposed to use the stiffness degradation to develop a fatigue damage model for a unidirectional fiber-reinforce polymer (FRP) laminates system. A relationship between the stiffness reduction

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and the remaining fatigue life ratio was developed. This model is relatively difficult for the in-situ fatigue prediction because the field measurements for stiffness are very difficult and the knowledge of ultimate fatigue life is not available beforehand. Unlike the stiffness measurement in the library conditions, it is difficult to obtain stiffness reduction measurements directly under service conditions. Thus, it would be desirable if the stiffness degradation can be inferred using a feasible structural health monitoring system. Lamb wave-based damage detection methods are more widely used [23,24] for structural health monitoring because of their low cost and high efficiency [25]. Lamb waves can propagate in thin plate without too much dispersion in certain modes [26]. Based on the fact that Lamb wave propagation is highly dependent on material stiffness, it is expected that stiffness degradation will be captured by the received Lamb wave signal propagating through the specimen. Since piezoelectric sensors are embedded in the structure, system health can be measured in-situ on a continuous basis, which lays foundation for more effective RUL prognosis.

Based on the above brief review, the proposed study tries to develop a macro level stiffness degradation model that can be used for in-situ fatigue life prediction at different stress levels. Two major components are required for the proposed study: (1) a stiffness degradation model that depends on the different loading conditions and correlates with the fatigue life; (2) in-situ measurements of stiffness degradation that can provide current damage state for the remaining life prediction. This paper is organized as follows. First, a growth rate-based stiffness degradation model is proposed to express the stiffness evolution kinetics under different constant amplitude loading. Next, a general Bayesian inference framework is discussed for real time fatigue life prognosis using the developed stiffness degradation model with in-situ measurements. Following this, a Lamb wave-based fatigue testing setup is given, in which both sensor signal and true stiffness degradation measurements are collected periodically. A diagnosis model for stiffness estimation using measured piezoelectric sensor signal is discussed and is incorporated in the Bayesian prognosis framework. Model verification and validation is performed using experimental measurements to show the performance of the proposed approach.

2. Stiffness degradation model development

In this section, a general model for composites stiffness degradation is proposed. The key idea is to express the overall composites stiffness reduction at certain loading cycles using a growth rate kinetics. The proposed model is analogous to the well-known Paris' law for the fatigue crack growth approach. The aim is to study the composites damage progression at the tensile-tensile stage. Thus, the experimental design used the stress range and stress ratio as the controlling parameters. This experimental design is different than the classical S–N curve testing for composite materials, which uses the stress range and mean stress as the controlling parameters. With fixed stress ratio, the stiffness degradation rate is assumed to be a function of the applied stress range and the current stiffness value. Detailed the discussion is given below.

Under fatigue loadings, different forms of damage such as matrix cracking, delamination and fiber breaking will occur simultaneously or sequentially, which will eventually lead to the final failure of the entire composite component. The concept of the stiffness degradation-based life prediction is to implicitly incorporate different forms of damage mechanism into different stages stiffness degradation curve. A schematic representation of a general stiffness degradation curve for composites is shown in Fig. 1.

As shown in Fig. 1, the x-axis is the normalized fatigue life (i.e., normalized with respect to the final failure life) and the y-axis is the normalized stiffness (i.e., normalized with the stiffness before the fatigue loading). The stiffness degradation process can be divided into three distinct stages. Initially, the stiffness decrease quickly during initial loading stage. In this stage, some initial defect in the material will quickly approaches to the stable stage. After that, the stiffness decreases gradually due to the development of delamination and matrix cracking. Close to the final failure state, the stiffness drops dramatically because of the fatigue loading induced fiber breakage. The last stage is usually unstable and the specimen will fail in a very short amount of cycles.

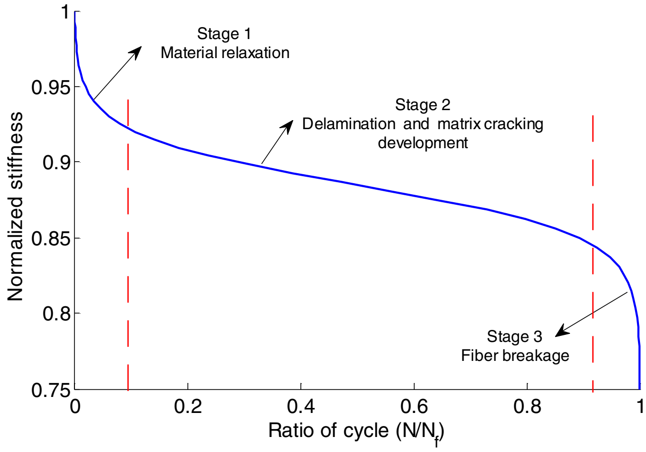

Fig. 1. The general trend for composite stiffness degradation.

In the experimental testing shown later, the initial relaxation state will stabilize within several hundreds to a few thousands cycles which is very small portion of the entire fatigue life span of composites under high cycle fatigue conditions. Ignoring the initial relaxation stage will not produce large error for the final fatigue life prediction. Thus, the proposed study will focus on the second and third stages, which can simplify the stiffness degradation model without sacrificing life prediction accuracy. In the proposed stiffness degradation model, two major hypotheses are made. First, the stiffness degradation rate is increasing monotonically and reaches its maximum at final failure stage. Second, for the same material, the stiffness degradation rate is assumed to be a function of the applied stress and the current stiffness. Based on the above assumptions, the generalized stiffness degradation model can be proposed as

$$\frac{ds}{dN} = -f(\Delta\sigma, s) \tag{1}$$

where $\Delta\sigma$ is the applied stress range. s is the current normalized stiffness, which is obtained by dividing the current stiffness under health condition. N is the fatigue cycles and $\frac{ds}{dN}$ is the stiffness degradation rate during one cycle. f is a generic function which describes the relationship between the stiffness degradation rate, the stress range, and stiffness. In the proposed study, a power law function is used to represent the general trend for the second and third stage of the stiffness degradation curve. Thus, the proposed stiffness degradation model is expressed as

$$\frac{ds}{dN} = -\boldsymbol{C}(\Delta\sigma s^{-\boldsymbol{r}})^{\boldsymbol{m}} \tag{2}$$

where $\boldsymbol{C}$, $\boldsymbol{r}$ and $\boldsymbol{m}$ are model parameters which are assumed to be positive and can be calibrated using experimental datasets. Using Eq. (2), the predicted stiffness for given fatigue cycles can be calculated by integrating both sides as

$$\int_{s_0}^{s} s^{\boldsymbol{rm}} ds = \int_{0}^{N} -c(\Delta\sigma)^{\boldsymbol{m}} dN \tag{3}$$