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A novel subcycle composite delamination growth model under fatigue cyclic loadings

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ABSTRACT

A new subcycle-based delamination growth model is proposed. The key idea is to model delamination growth at any time instant within a cyclic loading, rather than the cycle-averaged growth kinetics. First, some existing models are briefly reviewed for the fatigue delamination growth analysis of composite materials. Following this, two hypotheses are given for the derivation of the subcycle delamination growth model: (1) delamination growth does not happen during the unloading path and (2) delamination growth does not happen when the applied loading is below a reference level during the loading path. Mathematical expression is given for the calculation of delamination growth rate. Next, the extension of the proposed model is discussed to use both stress intensity factor and energy release rate as the driving force parameters, which are widely used in the open literature. Finally, the model predictions are compared with extensive experimental data under different stress ratios for model validation. One of the advantages of the proposed model is that the stress ratio dependent delamination growth can be predicted. Some conclusions and future work are drawn based on the proposed method.

1. Introduction

Composite materials have been widely used for engineering components and structures, especially in the field of aerospace engineering [1,2]. Among many different failure modes, interface cracking is one of the unique and most common failure mode in composite laminates [3,4]. The small interlaminar delamination may not affect structures much under static loadings, but the continued delamination growth may become the dominant failure modes after exposure to cyclic fatigue loadings. The service life will decrease dramatically [5–7]. Thus, correct prediction of service life considering delamination growth under fatigue loads is critical in designing various structural components and requires an accurate fatigue delamination law. Two common approaches are available for the composite delamination analysis: stress intensity factor-based approach and strain energy release rate-based approach. For example, stress intensity factor (SIF) range is used for composite materials [8,9]. Due to the difficulty of extracting the stress field ahead of delamination crack tip, an alternative way is to use the strain energy release rate (SERR) as the driving force parameter for the delamination growth [10–12].

Paris' law is the most used method for fatigue delamination growth by either using the SIF or the SERR as the driving force parameters. Grogan et al. [13] developed a cohesive zone based extended finite element method (XFEM) with implementation of Paris' equation for the thermal fatigue delamination prediction of delaminated crack opening displacement and composite laminate permeability. Nixon-Pearson et al. [14] investigated the delamination and matrix crack and their interaction using a Paris-law based cohesive interface element, and reasonable agreement can be found between predictions and experimental results. Li et al. [15] proposed an analytical non-linear solution of energy release rate for piezoelectric elasto-plastic laminated beams under hygrothermal conditions. Fatigue delamination growth rate was calculated using the Paris' Law. Because stress ratio has strong effects on the fatigue delamination growth, many researchers modified Paris' law to include the stress ratio effect. O'Brien [16] developed an analytical solution for the strain energy release rate calculation, which is used as the driving force to describe the fatigue delamination crack growth as a Paris' law function. This method needs calibration for each individual stress ratios. Gustafson and Hojo [17,18] modified the classical Paris' law for carbon-fiber-reinforced polymer (CFRP) laminates with an equivalent stress range as the controlling parameters, which was first developed for mild steels [19]. This equivalent stress range is able to include the stress ratio effect with one additional fitting parameter γ. Large and small values of γ indicate the mechanism of fatigue delamination crack growth controlled by the maximum stress intensity factor and the range of stress intensity factor, respectively. Jones et al. [1] proposed a composite fatigue delamination model using an effective stress intensity factor range beyond the threshold value as the

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driving force. Andersons et al. [20] developed a one-dimensional mechanical model of delamination accumulation. The proposed delamination formulation is similar to the one Hojo proposed [17,18]. Allegri et al. [8] developed a semi-empirical delamination model for pure mode II by using the maximum strain energy release rate as the controlling fracture mechanics parameter. The stress ratio effect is included using the parameter in the power law function. Later on, Allegri et al. [21] developed a fatigue delamination law, which is able to account for mode mixty and stress ratio effect with several fitting parameters.

The brief discussion above shows that there are various different modeling approaches to simulate the fatigue delamination crack growth. Most of the existing models are based on the cycle-based formulation, which only models the cycle-averaged delamination growth and cannot investigate the smaller time scale (i.e., at the subcycle scale) delamination growth kinetics and mechanisms. Second, the stress ratio effects are handled using fitting methods, i.e., the classical Paris' law-type function are modified to include the stress ratio dependence behavior. This type approach is good for practical applications, but requires multiple stress ratio (R) testing for calibration. Little information about the mechanism explanation for the stress ratio dependent behavior is provided by such approaches.

A subcycle formulation for fatigue crack growth of metallic materials has been developed [22,23] and has been verified by multiple-resolution in situ testing under optical microscope and scanning electron microscope [24–26]. It is shown that the stress ratio dependent behavior can be predicted using a subcycle formulation with appropriate mechanisms. The basic hypotheses in the subcycle formulation are that the crack growth is not uniformly distributed within a cyclic loading and the crack only grows during a portion of the loading path. One of the motivations of the proposed study is to use the subcycle formulation for the composite delamination analysis and the stress ratio dependent effect could be predicted, if successful.

The objective of this paper is to develop a novel fatigue delamination growth formulation based on the small time scale (subcycle) growth kinetics. The key idea is to define the fatigue delamination propagation rule at any arbitrary time instant within a load cycle. The proposed method is fundamentally different from the traditional empirical or semi-empirical fatigue delamination formulation and can be used to predict the fatigue delamination growth rate at different applied loadings, such as the different stress ratio cyclic loadings. Extensive experimental data for various composite materials is collected to validate the proposed methodology. This paper is organized as follows. First, a fatigue delamination propagation model will be introduced for the subcycle fatigue formulation. Major hypotheses and mathematical expressions will be discussed in detail. Following this, the proposed method will be extended to use both SIF and SERR as the driving force parameters. Next, validation of the proposed models will be performed using several sets of experimental data available from open literature. Finally, some conclusions are drawn based on the comparisons and observations.

2. Subcycle-based fatigue delamination propagation methodology

A general methodology of fatigue delamination propagation is developed in this paper. This method is based on the subcycle delamination growth at any time instant within a loading cycle and is fundamentally different from classical fatigue delamination formulations [8,9,18,20]. Most existing methods are cycle-based fatigue delamination growth law, which are based on the relationship between the average delamination growth per cycle with the driving force parameters (SIF or SERR) (Fig. 1(a)). The key idea of the proposed method is to predict fatigue crack growth for composite materials at any time instant within a cycle, which is similar to the subcycle model for metals [22]. A schematic illustration of the proposed method is shown in Fig. 1. As shown in Fig. 1, the delamination will extend a distance, da, after a small temporal increment, dt, during loading. The delamination extension after a given lifetime can be calculated by direct time integration. Classical delamination/crack growth theory is based on the cycle averaged quantify (i.e., Δt and $\Delta K/\Delta G$). The time scale for the classical approach and the proposed approach is very different.

Two major hypotheses are made for the proposed subcycle delamination formulation. First, the delamination growth is not uniformly distributed within a load cycle (Fig. 1(b)). The delamination does not grow during the unloading path. Second, the delamination starts to growth during the loading path when the applied loading is beyond a certain reference stress level. The reference stress level is different under different loading profiles and is the mechanism for the stress ratio effect in the cycle-based formulation. If the stress intensity factor is used as the driving force parameter, the above two hypotheses can be expressed as

$$\frac{da}{dt} = H(\dot{K})H(K - K_{ref})f(K) \quad (1)$$

where $\frac{da}{dt}$ is the instantaneous crack growth rate. $H(x)$ is the Heaviside function, i.e.,

$$H(x) = \begin{cases} 1, & if \quad x > 0 \\ 0, & if \quad x \le 0 \end{cases} \quad (2)$$

K is the stress intensity factor (SIF) and $\dot{K}$ is the SIF changing rate. K_{ref} is the reference level beyond which the delamination starts to grow. $f(K)$ is a generic function to describe the delamination growth kinetics after the delamination starts to grow. In the proposed study, a power law function is used to describe the delamination growth rate once it starts to grow. Eq. (1) can be rewritten as

$$\frac{da}{dt} = H(\dot{K})H(K - K_{ref})C\left(\frac{K - K_{ref}}{K_c - K_{\max}}\right)^m \quad (3)$$

where K_c is the critical SIF when the crack growth rate is infinity. K_{max} is the maximum SIF level from the previous loading history. C and m are two calibration parameters. The above equation indicates that the crack growth rate is zero when K is approaching K_{ref}. This is the threshold condition in the experimental testing where no apparent delamination growth is observed. By performing the time domain integration on both sides of Eq. (1), the delamination length at any time point during the loading history can be obtained. The remaining questions are how to calculate the K_{ref}. Details are shown below.

In the proposed method, two mechanisms are used to describe the K_{rs}. The first mechanism is the crack closure, i.e., at the initial loading stage the delamination surfaces are in contact. The delamination will not grow if the surfaces remain in contact. The second mechanism is the strength/resistance degradation ahead of the delamination tip. After the crack is fully open, the delamination will start to grow if the applied loading is beyond the crack tip material strength/resistance. Mathematically, the K_{ref} can be expressed as

$$K_{ref} = K_{op} + K_{rs} \quad (4)$$

where K_{op} is the opening SIF level and K_{rs} is the resistance SIF ahead of the crack tip. A schematic illustration of this equation is shown in Fig. 2.

The crack closure behavior has been used extensively for the fatigue crack growth analysis of metallic materials, e.g., plasticity-induced crack closure and roughness induced crack closure