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A critical plane-based model for mixed-mode delamination growth rate prediction under fatigue cyclic loadings

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ABSTRACT

A critical plane-based mixed-mode delamination growth model for composite materials under fatigue loadings is proposed in this study. A brief review for mixed-mode delamination is given and the special focus in the study is on a critical plane-based fracture criterion since it can automatically adapt for different local failure modes. An equivalent energy release rate range suitable for fatigue analysis is proposed for the delamination growth rate prediction under general proportional and non-proportional multiaxial loadings. The proposed methodology is validated with extensive experimental data available in the open literature. A general good agreement is observed between model predictions and experimental observations. Finally, some discussion and conclusions are drawn based on the proposed model.

1. Introduction

Fatigue damage accumulation and growth in metallic and composite materials is critical for the structural integrity evaluation. In recent years, composite materials have been widely used for structural components, especially in the field of aerospace engineering. Many aircraft components, from secondary structures (aileron, flaps, elevator, and rudders) to primary structures (tailplane, floor beams, and fleet), are made of composite materials due to their superior performances. (see Fig. 17)

Among many different failure modes in composite laminates, delamination is one of the unique and most common failure modes [23]. The defects within composite materials may be introduced during the manufacturing process or due to impact loadings [11]. Even though the small interlaminar delamination may not affect structures much under static loadings, the continued delamination growth may become the dominant failure modes under cyclic fatigue loadings and the service life will be decreased significantly [5,40]. Thus, accurate prediction of service life considering delamination growth under fatigue loadings is critical in designing various structural components considering fatigue damage accumulation, which is the major objective of the proposed study.

In order to predict service life of materials under fatigue loadings, some empirical or semi-empirical methods have been proposed to describe the crack propagation process [8,25,28,29]. Among them, the well-known Paris' law is widely adopted in describing the fatigue behavior by the relationship of crack growth rate (da/dN) and stress intensity factor range (ΔK) [28,29]. The Paris' law describes the log-linear relationship in the $da/dN \sim \Delta K$ curve as

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

where C and m are the empirical parameters, which can be calibrated from the fatigue experimental data. The stress intensity factor is widely used for metallic materials as the fatigue fracture driving force parameter. The energy release rate is more commonly used for composite materials [27,42]. Based on the similar formulation for mode I crack propagation, some models have been developed to predict the mixed-mode crack propagation in composite materials [7,13,16,31,33]. For most mixed-mode delamination criteria, a brief review and comparison can be found in Ref. [23]. Most mixed-mode delamination growth models did not consider the effect of nonproportional loadings on the fatigue crack growth. The nonproportional loadings may have significant impact on the fatigue crack growth behavior [21,22,39]. Thus, it is necessary to take this effect into consideration in developing a sound mixed-mode fatigue delamination growth rate prediction model.

This study proposes a new critical plane-based mixed-mode delamination propagation model under fatigue loading based on a critical plane approach [21–24]. The proposed mixed-mode delamination model is developed based on the critical plane hypothesis (i.e., the multiaxial fatigue damage can be correlated with the stress/strain on a plane). In the proposed method, only two types of basic material properties under pure mode I and mode II delamination are required to predict mixed-mode delamination failure in composite materials under

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general mixed-mode fatigue loadings. Compared with existing models, the proposed mixed-mode delamination prediction model has two unique advantages: (1) It can automatically adapt for different local failure modes of composite materials under mixed-mode loading conditions; (2) nonproportional loading effect can be handled since the critical plane varies under different loading paths. To demonstrate the validity of present fatigue failure prediction model, some representative experimental data for various composite materials are collected and compared with model predictions.

This paper is organized as follows. First, some existing mixed-mode crack growth rate prediction models will be briefly reviewed. Next, the derivation of the new mixed-mode fatigue delamination growth model will be described in detail. Following this, model prediction using the proposed model is compared with some representative experimental data for different composite materials for model validation. Some discussions on the load ratio effects, non-proportional loading effect, and comparison with existing models are presented. Finally, some discussions and conclusions will be drawn based on the comparisons and observations.

2. Existing mixed-mode fatigue delamination growth models

Many efforts have been made to modify the well-known Paris' law to predict the delamination growth rate in composite materials under mixed-mode loadings. Most existing mixed-mode delamination growth rate prediction models are developed by establishing an empirical relationship between the two energy release rate (G) components (i.e., under pure mode I and pure mode II) and the crack growth rate. According to the formulation of these models, they can be classified into two categories: 1) superposition of two individual delamination growth components under different modes (e.g., Eq. (2)); 2) modified Paris' law formation for the delamination growth with respect to a combination of the two G terms (e.g., Eq. (3)).

$$\frac{da}{dN} = B_1(C_I)[f_1(\Delta G_I)]^{r_1(m_I)} + B_2(C_{II})[f_2(\Delta G_{II})]^{r_2(m_{II})} \tag{2}$$

$$\frac{da}{dN} = B_3(C_I, C_{II})[f_3(\Delta G_I, \Delta G_{II})]^{r_3(m_I, m_{II})} \tag{3}$$

where C_I, m_I, C_{II}, and m_{II} are Paris's law parameters of pure mode I and pure mode II, respectively. B_i, f_i, and r_i are generic function symbols. Details are shown below.

2.1. Fatigue failure prediction models by superposition

By simply adding the mode I and mode II crack increments, Gustafson and Hojo [13] proposed a mixed-mode crack growth rate prediction model as

$$\frac{da}{dN} = C_I(\Delta G_I)^{m_I} + C_{II}(\Delta G_{II})^{m_{II}} \tag{4}$$

A similar model was proposed by Ramkumar and Whitcomb [31]. The authors stated that the mixed-mode fatigue crack growth rate should be determined by the maximum energy release rate components instead of the energy release rate range. Each energy release rate component is normalized by their fracture toughness, respectively. Fatigue crack growth rate is calculated as the summation of the single mode's fatigue crack growth rates. Using this concept, the mixed-mode crack propagation rate can be directly predicted using the experimental data obtained from pure mode fatigue tests. There is no extra fitting parameter in these models, which can save the effort in experimental data calibration. However, the flexibility is also limited and the accuracy of these two models has been proved to be less than some other models with more parameters [5].

2.2. Fatigue failure prediction models in the form of modified Paris' law

In order to predict the mixed-mode crack propagation rate more accurately, efforts have been made to establish models as shown in Eq. (3). In this type of mixed-mode crack growth rate prediction models, the basic form of the Paris's law does not change. However, both the empirical Paris' law parameters and energy release rate component ranges will be replaced by some other functions. As the most simple example of this type of models [34], a mixed-mode fatigue crack growth rate prediction model was proposed in the following form:

$$\frac{da}{dN} = \left(\frac{\Delta G_I}{\Delta G_T}C_I + \frac{\Delta G_{II}}{\Delta G_T}C_{II}\right)\left(\frac{\Delta G_I}{G_{Ic}} + \frac{\Delta G_{II}}{G_{IIc}}\right)^{\left(\frac{\Delta G_I}{\Delta G_T}m_I + \frac{\Delta G_{II}}{\Delta G_T}m_{II}\right)} \tag{5}$$

In this model, the energy release rate range in the Paris' law is replaced by the sum of two energy release rate range components normalized by their corresponding fracture toughness. The empirical parameters are substituted by the sum of single mode empirical parameters modified considering the weighting factors ($\Delta G_I/\Delta G_T$ and $\Delta G_{II}/\Delta G_T$), where $\Delta G_T = \Delta G_I + \Delta G_{II}$. A modified Paris' law was proposed by introducing an effective stress ratio and a dimensionless group according to the Buckingham π theorem Based on a phase angle concept [14], a fatigue crack propagation rate was proposed by modifying the Paris' law parameters considering the phase angle [16]. The mode mixity was also considered to redefine the Paris' law parameters as a function of K_{Ic} and K_{IIc} to establish a modified Paris' law as a function of the stress intensity factors [1]. As one of the most popular model to predict fatigue crack growth rate, Kenane and Benzeggagh [4] developed a model by proposing a mixed-mode failure criterion based on their experimental studies for glass/epoxy laminates, which requires two more calibration parameters. In addition to the empirical and semi-empirical models discussed above, a mixed-mode crack growth rate prediction model was established by modeling the damage accumulation in the crack region through Miner's rule to predict the fatigue crack growth rate under varying mixed-mode loading [5]. It has been shown that the mode mixity ratio plays an important role for the fatigue delamination growth [30].

The existing failure criteria disscussed above have their pros and cons. Most existing criteria requires more than three parameters to calibrate various failure loci of composite materials under fatigue loadings. It will require additional mixed-mode fatigue testing data (in addition to the pure mode I and mode II data) to calibrate these parameters. Also, the existing fatigue crack growth rate prediction models did not consider the effect of nonproportional loadings on the fatigue delamination growth. The critical plane-based criterion has been developed for metal multiaxial fatigue analysis and can take the nonproportional loading effect into consideration [21,22]; [24,41]. By extending a previously developed critical plane approach, a new fatigue crack growth rate prediction model can be established to consider the interfacial fracture mechanisms of composite materials under various mixed-mode loadings.

3. Critical plane-based mixed-mode fatigue model

In order to establish the mixed-mode crack growth rate prediction model, a multiaxial high-cycle fatigue criterion was extended for fatigue crack growth problem [21,22]. The reason to choose this model is: 1) this model is shown that it can automatically adapt for either brittle and ductile failure modes of materials and is shown to work well for stress-life curve prediction for composite materials [21,22]; 2) this stress-based model is shown to be capable of fatigue crack growth prediction for metallic materials if combined with the stress intensity factor concept. Thus, it has the potential to be modified and applied for composite fatigue delamination growth using the energy release rate concept.

This model is developed based on a critical plane hypothesis, which