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A novel interpretation of fatigue delamination growth behavior in CFRP multidirectional laminates

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ABSTRACT

Two Paris-type models are proposed to characterize the fatigue delamination growth (FDG) behavior in CFRP laminates. The crack-driving forces denoted by two definitions of the strain energy release rate (SERR) range against the fatigue delamination resistance of composite materials are introduced to control the FDG. The first definition is the square of the difference between the square root of maximum SERR and that of minimum SERR. The second one is the arithmetic difference between the maximum and minimum SERR. A series of fatigue delamination tests of CFRP multidirectional laminates under various stress ratios and mode-mixity ratios were carried out. Among different Paris relations, the FDG rate corrected by the first model exhibits a linear relationship with *R*-ratio dependency, and the second model further removes the *R*-ratio dependence, under different mode-mixity ratios, on a log-log scale. The experimental results indicate that the presented models can provide more generic descriptions and a proper interpretation of the FDG behavior in CFRP multidirectional laminates.

1. Introduction

Composite laminates consisting of continuous carbon-fiber-reinforced plies are now widely employed in engineering structures due to their improved performance over conventional metallic materials. However, the lack of through-thickness reinforcement means that delamination between two adjacent layers is one of the most serious damaging behaviors in laminated structures [1–5]. When subjected to fatigue loading, delamination usually originates from manufacturing flaws or interlaminar stress raises and propagates after initiation, which causes the degradation of the structural behavior and even the catastrophic failure of the laminated structures [6]. To increase the fatigue life and reliability of composite structures, numerous efforts have been made to understand the fatigue delamination growth (FDG) behavior in unidirectional laminates [7]. However, regarding widely applied multidirectional laminates, the studies are still limited due to the complication that both material properties and mechanical factors affect the FDG behavior and some different phenomena, such as fiber bridging, crack migration and matrix cracking. Furthermore, plies with different orientations in the multidirectional laminates usually make the delamination grow in mixed modes [8].

Fracture mechanics approaches have been very useful in providing phenomenological descriptions of different failure processes in materials. Analogous to metal crack growth in terms of the stress intensity factor K, the FDG rate in composite laminates is known to be correlated to different formulations of the strain energy release rate (SERR) G, which usually exhibits a linear relationship on a log-log scale. The use of G is preferred over the use of K when characterizing the steady-state FDG in composite laminates due to the relative ease on the calculation of G during tests and the avoidance of oscillatory singularities of complex K solutions for inhomogeneous layered materials. Analogous to the Paris relation for metal crack growth, a consensus view stating that the FDG rate possessing the phenomenal and functional form given below has been reached, because the FDG rate demonstrates a linear relationship on a log-log scale with different formulations of the SERR from experimental observations:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = Cf(G)^{r} \quad (1)$$

where C and the exponent r are material constants, which must be determined experimentally.

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So far, the formulation of $f(G)$ for quantifying the delamination growth has still been the bone of contention in the research community. For a cyclic loading that causes a variation of the SERR from G_{min} to G_{max}, the stress state ahead of the crack tip is expected to be described by G_{max}, the stress ratio R and the mode-mixity ratio φ, because these parameters describe both the intensity and variation of the stress field and exhibit the experimentally observed effect on the delamination growth behavior in composite laminates [1]. Up to now, the FDG behavior under cyclic loadings have been extensively investigated, and various models have been proposed by numerous researchers [9]. Kenane and Benzeggagh [10] as well as Tumino and Cappello [11] used G_{max} to characterize the FDG behavior under mixed mode loadings. The prevalent use of G_{max} is due to its importance in assessing static failure limits. However, it neglects the information of the minimum load [12], which results in R-ratio dependency. Hojo et al. [13] studied the near-threshold growth of mode I fatigue delamination in unidirectional laminates made of T300/914 and Toray P305 prepregs. Their results showed that the FDG rates were related to G_{max}, $\triangle G = G_{max} - G_{min}$ and $\triangle K$. It was found that the R-ratio effect was negligible in the stable growth stage for T300/914 laminates when the FDG rates were corrected with $\triangle G$, while a small dependency existed for Toray P305 laminates. Hence, a complex controlling parameter $\Delta K_{eq} = \Delta K(1-R)^{\gamma}$ was proposed to merge various stress ratio curves into a single one. However, Rans et al. [12] thought that the characterization of fatigue crack/delamination growth based on K rather than G should not be fundamentally different, because K and G are equivalently parameters in linear elastic fracture mechanics. They highlighted a potential misinterpretation of the FDG behavior when $\triangle G$ was chosen as the arithmetic difference between G_{max} and G_{min}, which is analogous to the use of $\triangle K$. Therefore, a new definition of the G range, $G_{\Delta P} = (\sqrt{G_{max}} - \sqrt{G_{min}})^2$, which was defined using a linear superposition approach and in accordance with the principle of similitude for characterizing metal crack growth, was presented to remove the R-ratio dependency when adopting $\triangle G = G_{max} - G_{min}$. This expression was also used in other studies [14–16]. Wang et al. [17] firstly introduced the material resistance in the expression of delamination growth rate. They suggested that G should be normalized by the fracture toughness (G_c) rather than being entered into the Paris relation directly. The quantity G/G_c presented the real crack-driving force relative to the material resistance. This approach was subsequently adopted by many other researchers [18–22]. In this approach, the fracture toughness is assumed to be a constant value. However, an obvious R-curve exhibiting the relationship between the fracture toughness and delamination length shows that the fracture toughness was actually variable [4,23]. Shivakumar et al. [24], Chen et al. [25] and Murri [26] proposed that G should be normalized by G_c(a) in the Paris relation. They supposed that the quasi-static delamination curve presented the changing resistance against delamination growth, which accounted for the fiber bridging during mode I fatigue loading, and they further used the curve to determine the variable fracture toughness G_c(a). This normalization lowered the exponent in the Paris relation and also reduced the spread of the FDG data. However, the magnitude of fiber bridging during the fatigue loading is different from that during the quasi-static loading [26]. For specimens with various interface configurations, higher or lower resistance against the fatigue delamination can be found during the fatigue tests relative to the fracture toughness obtained from the quasi-static tests [27]. Thus, it is doubtful whether the value of G_c(a) obtained from quasi-static tests can present the real changing resistance against the delamination growth during the fatigue loading. Consequently, Zhang et al. [28–30] presented a concept of fatigue delamination resistance $G_{cf}(a)$ to characterize the material resistance during a fatigue loading. They also proposed a re-loading method and a compliance method to determine the fatigue delamination resistance. A formulation of G_{max}/G_{cf} was applied to study the mode I and mixed I/II mode FDG behavior in multidirectional laminates with a stress ratio of $R = 0.1$.

Obviously, there is still a lack of consensus on the formulations of G to interpret the FDG behavior better. Potential misinterpretations of the FDG may happen if the formulation of G is not well defined [12]. To reasonably understand the FDG behavior in composite materials, seeking an appropriate formulation is very important and is still a subject of intense current investigations. The major goal of this study is to develop a general understanding of the present FDG models and to propose empirical models with a relatively wide range of application, which could characterize the FDG under a reasonable range of cyclic loadings for multidirectional composite laminates.

2. New FDG models

The development of models based on fracture mechanics for predicting FDG over the past 40 years was summarized in detail by Pascoe et al. [31] and other researchers [19,32,33]. Most researchers deem the Paris relation with the form of Eq. (1) to be amongst the best descriptions of FDG behavior, in which the detailed formulations of G are modified to a greater or lesser extent to address some specific problems, such as the effect of R-ratio, mode-mixity and fiber bridging. Thus, when considering these factors, the idea proposed by Wang et al. [17], in which the FDG is controlled by the crack-driving force and the material resistance, is adopted in the current investigation. Two typical crack-driving force functions are used: a redefined G range $G_{\Delta P} = (\sqrt{G_{max}} - \sqrt{G_{min}})^2$ proposed by Rans et al. [12] and the ordinary G range denoted by the arithmetic difference between the maximum and minimum values $\Delta G = G_{max} - G_{min}$. In addition, the material resistance during the fatigue loading is characterized by the fatigue delamination resistance, $G_{cf}(a)$, proposed by Zhang et al. [29]. Then, two new FDG models are proposed to represent the FDG behavior in CFRP laminates accurately:

$$\frac{da}{dN} = C\left(\frac{G_{\Delta P}}{G_{cf}(a)}\right)^r = C\left(\frac{\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2}{G_{cf}(a)}\right)^r \tag{2}$$

$$\frac{da}{dN} = C\left(\frac{\Delta G}{G_{cf}(a)}\right)^r = C\left(\frac{G_{max} - G_{min}}{G_{cf}(a)}\right)^r \tag{3}$$

where C and r are empirically derived parameters determined by a curve fitting procedure. It is deemed that the two parameters have a non-monotonic relation [8] with mode mixities. Thus, different parameter sets can be obtained for different mode mixities.

In addition, the analogy is obvious between the G used in composite materials and the K used in metal crack growth. Generally, the Paris relations for the fatigue crack growth in metals are usually characterized by the parameter $\triangle K$. Because G is proportional to K^2 [33] and K is proportional to the applied force P, both $G_{\Delta P}$ and $\triangle G$ include the parameter $\triangle K$ in the following manner:

$$G_{\Delta P} = \left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2 \sim (P_{max} - P_{min})^2 \sim (K_{max} - K_{min})^2 \sim (\Delta K)^2 \tag{4}$$