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Scaling parameter for fatigue delamination growth in composites under varying load ratios

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Fatigue delamination growth in composite laminates is strongly influenced by mean loads or load ratios. Description of this behaviour currently relies on empirical curve fitting, which renders it difficult to predict fatigue lives of composite structures subjected to variable amplitude fatigue loading. This paper presents a new scaling parameter that is consistent with the similitude concept and incorporates the crack-tip shielding effects of fibre bridging under fatigue loading. Static and fatigue experiments were carried out on IM7/977-3 composite laminates under mode I and mode II. Large-scale fibre bridging was observed as a major toughening mechanism under both static and fatigue loading. To correctly account for the effect of fibre bridging, an inverse method was developed to determine the traction stresses acting in the crack wake. The new scaling parameter, accounting for the effect of bridging by cross-over fibres, is shown to unify the fatigue growth rates under different load ratios obtained in this study.

1. Introduction

In aerospace applications, composite structures must be designed for no-growth or slow fatigue crack growth, according to the current airworthiness regulations [1], to prevent manufacturing defects or in-service damage (e.g. resulting from low energy impact) from reaching the safety limits. Traditionally, this is typically accomplished by employing low design allowable strains, validated by fatigue tests demonstrating that defects of the minimum detection size do not grow under service loading. Although slow-growth (near threshold region) mode is permitted in demonstrating compliance with airworthiness regulations, the no-growth criterion is more commonly used, due to the lack of a better design criterion for slow fatigue crack growth of composites under fatigue loading. Since delamination crack has been observed to propagate under fatigue loading far below the static fracture loads [2], existing composite structure designs using the no-growth criterion often carry additional weight to mitigate the risk of fatigue failure from service-induced damage. To fully take advantage of the lightweight characteristics of composite materials and to reduce the high cost burden of existing design practices, it is important to quantify the near-threshold growth behaviour to ensure the continuous airworthiness of composite structures during service [1] without excessive component and full-scale testing.

In contrast to metallic alloys, fibre-reinforced composites are highly anisotropic and inhomogeneous. The strain energy release rate (G), rather than the stress intensity factor (K), is commonly used to correlate fatigue delamination growth rates. This is because the solution for K is highly complex for inhomogeneous materials and can result in oscillatory stresses between plies of different elastic properties [3]. The growth of delamination damage in composite laminates is conventionally described in terms of the strain energy release rate G by a Paris-law type of relation given below, with C and exponent m being fitting parameters that depend on materials, load ratios, and temperature,

$$\frac{da}{dN} = C(\Delta G)^m \quad (1)$$

where the cyclic strain energy release rate ΔG is defined as the difference between the applied maximum and minimum values [4–7],

$$\Delta G = G_{max}^{app} - G_{min}^{app} \quad (2)$$

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One major drawback of the above ΔG definition is that it does not conform to the similitude principle (i.e. crack-tip conditions are uniquely defined by a single loading parameter) similar to ΔK for isotropic materials [8–10]. Moreover there is a potential ambiguity in this definition for negative load ratios ($R = P_{min}/P_{max} < 0$). For example, ΔG equals zero under fully reversed loading ($R = -1$), because the G_{max}^{app} and G_{min}^{app} are equal. In addition, strong load ratio effects under positive load ratios ($R > 0$) have been observed for both mode I fatigue behaviour when ΔG is employed as the correlating parameter [9,11]. Consequently the coefficients C and m in Eq. (1) must be empirically determined for a given specific load ratio [4].

To avoid the ambiguity associated with ΔG, the maximum strain energy release rate G_{max}^{app} has been used as a correlating linear elastic fracture mechanics parameter. However G_{max}^{app} inherently cannot account for the influence of load ratios. Hence Andersons et al. developed a model based on linear damage accumulation to predict the effects of load ratios on mode I and II delamination fatigue behaviour [12]. While reasonably good correlation can be obtained, the model requires a number of additional parameters which must be calibrated or determined experimentally. Allegri et al. proposed a two-parameter fatigue delamination model for mode II loading [13], which was later extended to account for both load ratios and mixed mode ratios [14]. Jones and colleagues proposed a modified Hartman–Schijve relation for composite delamination [15] and bonded joints [16], in which the threshold and toughness values are calibrated experimentally for varying load ratios.

Given the lack of physical basis of the ΔG definition, an alternative definition for an equivalent strain energy release rate has recently been suggested [8–10,17,18] for correlating delamination growth and disbond growth in joints,

$$\Delta G_{eq} = \left(\sqrt{G_{max}^{app}} - \sqrt{G_{min}^{app}}\right)^2 = (1-R)^2 G_{max}^{app} \tag{3}$$

It is worth noting that the equivalent strain energy release rate ΔG_{eq} differs from the conventional definition $\Delta G = (1-R^2)G_{max}^{app}$, because the strain energy release rates are proportional to the square of the applied load. The equivalent strain energy release rate ΔG_{eq} parameter assumes that delamination growth is controlled by the cyclic stress state at the crack tip, consistent with the similitude principle as ΔK for fully open fatigue cracks in isotropic materials [19]. When experimental delamination growth rate data are expressed in terms of ΔG_{eq}, the strong load ratios effects are nevertheless observed in the mode I fatigue behaviour [8–10,17,18]. Therefore additional empirical fitting parameters are still needed to correlate data pertinent to different load ratios.

In addition to the need for extensive experimental tests to determine the necessary fitting parameters, the aforementioned empirical approaches are not applicable to modelling the transient effect of overloads and underloads under variable amplitude loading, which is essential to the estimation of fatigue life under spectrum loading. Motivated by the great success of the crack closure concept in quantifying the effects of variable amplitude loading on the fatigue crack growth in metallic alloys [20–22], the present authors have recently shown that the load ratio effects on the disbond growth in bonded joints can be characterised by an effective strain energy release rate, once the plasticity-induced crack closure has been taken into account [10]. By contrast to metallic alloys and adhesives, fibre-reinforced composites are known to exhibit extrinsic toughening by fibre bridging [18,23–26].

The aim of this paper is to develop a scaling parameter that can account for the effects of fibre bridging on the growth behaviour of delamination cracks under fatigue loading. Static and fatigue tests were carried out using double cantilever beam (DCB) and end-notched flexure (ENF) specimens manufactured from unidirectional carbon-epoxy composite laminates. Then an inverse method was developed with the aid of finite element (FE) analyses to quantify the effects of fibre bridging on the strain energy release rate at the crack tip. Based on these results, a new scaling parameter is proposed which is shown to correlate well with both mode I fatigue delamination growth rates under varying load ratios.

2. Materials and methodology

2.1. Materials and specimen preparation

Composite laminates were fabricated from 24-ply unidirectional IM7/977-3 pre-pregs with a nominal ply thickness of 0.13 mm. A starter delamination was introduced in the mid-plane by inserting a 13 μm thick poly-tetrafluoroethylene (PTFE) film. The composite laminates were cured in an autoclave at 177 °C under a pressure of 538 kPa for 6 h in accordance to the manufacturer's recommended cure cycle. The test specimens were then machined from the laminates with a diamond saw into the following dimensions; 20 mm width, 170 mm length and a starter crack of $a_0 = 70$ mm. Additional piano hinges were glued to the DCB specimens with a two-component epoxy. The side of the specimens were painted with a thin coat of white, brittle correction fluid to aid visual observation of the crack.

2.2. Static test procedure

Mode I and II fracture toughness tests were performed with DCB and ENF specimens respectively using Instron 4466 with a 10 kN load cell. A schematic of the test configuration is shown in Fig. 1. The initial crack position of the ENF specimen was placed at $a_0 = 0.5L$ to provide sufficient length for delamination growth. Specimens were loaded under displacement control at a rate of 0.1 mm/min. The delamination length was measured visually from the travelling microscope. The mode I and II fracture energies, G_I and G_{II}, were then calculated using the beam theory method and are expressed in Eqs. (4) and (5) respectively [27–29].

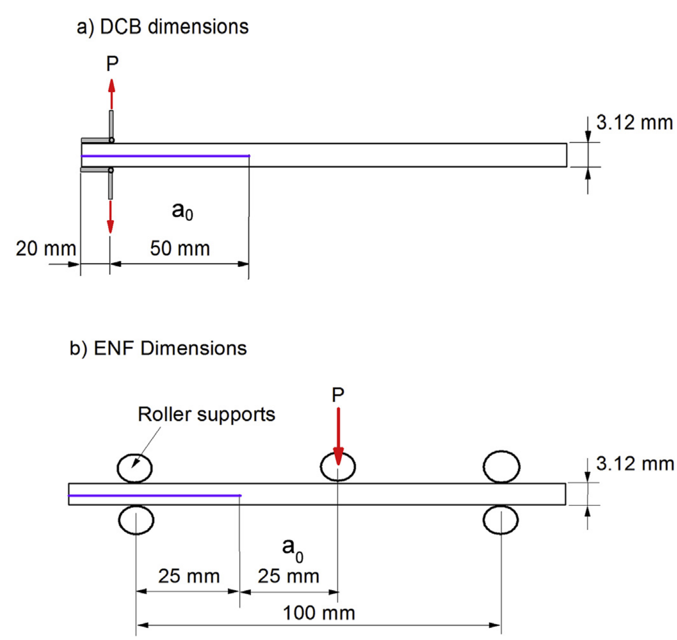

Fig. 1. Schematic of DCB and ENF test configurations.