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Mode I fatigue delamination growth with fibre bridging in multidirectional composite laminates

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ABSTRACT

Fatigue delamination in multidirectional composite laminates was experimentally investigated in present study. Both the Paris relation and a modified Paris relation (with a new similitude parameter) were employed to interpret fatigue delamination with significant fibre bridging. The results clearly demonstrated that fatigue delamination was independent of fibre bridging, if a reasonable similitude parameter was used in data reduction. As a result, a master resistance curve can be fitted to determine fatigue crack growth with different amounts of fibre bridging. The energy principles were subsequently used to provide physical interpretation on fatigue delamination. The results indicated the energy release for the same fatigue crack growth remained constant with fibre bridging. Bridging fibres in most cases just periodically stored and released strain energy under fatigue loading, but had little contribution to real energy release. The master resistance curve was finally applied to predict fatigue delamination with fibre bridging. Acceptable agreement between predictions and experiments was achieved, demonstrating the validation of the modified Paris relation in fibre-bridged fatigue delamination study.

1. Introduction

Advanced composite laminates have been widely used in aerospace engineering for the requirements on light-weight structures and fuel efficiency. These materials take advantages of excellent properties, i.e. high strength-to-weight and stiffness-to-weight ratios. However, they suffer disadvantage of poor interlaminar property, due to lack of reinforcement in thickness direction. This weak point can easily result in delamination propagation between neighbored layers under either quasi-static or fatigue loading. It has been widely admitted that delamination was one of the most important damage in composite laminates and must be well considered in composite structural design [1–15]. This damage indeed became a big obstacle and challenge in applications of composites in critical engineering parts and limited their weight saving potential. It is, therefore, meaningful and significant to have in-depth understanding on mechanisms and prediction models for delamination in composite laminates.

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A critical literature review on fatigue delamination growth in composite laminates and adhesive bonds has been completed by Pascoe et al. [1]. Four category methods have been used in the characterization of delamination behavior under fatigue loading. In this classification, methods based on the fracture mechanics were widely used, in which fatigue crack growth was correlated to the stress intensity factor *K* (*SIF*) or the strain energy release rate *G* (*SERR*). And the Paris relation has been admitted as one of the most important achievements in fatigue crack growth study in the last several decades. It has been widely used in scientific studies and structural designs, even though some researchers have noticed that it was no more than an empirical correlation and not based on physical understanding of fatigue crack growth [1]. In addition, there was no consensus on the similitude parameter in fatigue delamination studies in composite laminates. People alternatively employed the maximum *SERR* G_{max}, the *SERR* range ΔG, or combinations of them as similitude to determine fatigue crack growth [3–7].

It is worth noting that there is no standard for mode I fatigue delamination growth. To address this problem, the ASTM D30 Committee and the European Structural Integrity Society Technical Committee 4 (ESIS TC4) have performed separate round-robin mode I fatigue tests on unidirectional double cantilever beam (DCB) specimens to investigate the influence of a series of factors [7,14,15]. Even though some achievements have been obtained, the standard is still undergoing discussion at this moment. Unidirectional DCB specimens have been commonly used to determine mode I interlaminar crack growth behavior of a composite material under fatigue loading [3,6,8–13]. Hojo et al. [3] experimentally investigated fatigue delamination behavior under different stress ratios. And a two-parameter power law relation was proposed to determine fatigue delamination. In following studies [6,8], they provided research on fatigue delamination in composite laminates with interlaminar reinforcement. Cartié et al. [9] experimentally investigated fatigue delamination behavior in z-pin reinforced composite laminates. Shivakumar et al. [10] proposed a total fatigue life model to determine delamination behavior in subcritical, linear and final fracture domains via mode I fatigue tests conducted on unidirectional DCB specimens. Argüelles et al. [11] investigated the onset and crack propagation behavior under fatigue loading with unidirectional DCB specimens. Coronado et al. [12] tried to determine fatigue delamination behavior at different temperatures. It was found that crack growth decreased with elevated temperatures. Khan et al. [13] developed a two-parameter power law relation to characterize fatigue delamination behavior via experiments conducted on unidirectional DCB specimens.

Referring to delamination results under quasi-static loading [16–18], interface configuration had important effects on crack growth behavior. It was reported that the use of unidirectional DCB specimens sometimes can cause conservative results and underestimate interlaminar property, especially for delamination with large-scale fibre bridging [17]. In detail, initiation crack growth may be independent of ply orientation, whereas crack propagation was significantly dependent of interface configuration. The presence of fibre bridging during delamination was the main reason for this dependence, as more bridging fibres were observed in delamination of multidirectional composite laminates. As a result, a growing number of research have been conducted on multidirectional laminates to have further understanding on delamination behavior under quasi-static loading [19,20].

For fatigue delamination, limited research has ever been reported to be performed on multidirectional composite laminates. Zhao et al. [18,21,22] conducted experiments on fatigue delamination with multidirectional composite laminates. Significant fibre bridging was observed as well. And a normalized power law relation was proposed to determine fatigue delamination behavior. Yao et al. [17,23] carried out fatigue delamination tests on DCB specimens with different ply orientations and gave thorough discussions on bridging effects on fatigue delamination. Banks-Sills et al. [24,25] experimentally examined fatigue delamination behavior in woven composites via DCB specimens with multidirectional interface. The fatigue delamination results were first interpreted via the Paris-type relations, and subsequently explained via a modified Hartman-Schijve equation.

According to the previous studies [17,18,21–23], even significant fibre bridging can exist in crack growth of multidirectional composite laminates. The presence of fibre bridging can significantly affect fatigue delamination behavior. One then reasonably ask what about fatigue delamination in this condition, and how to well characterize fatigue crack growth behavior. To this end, the present research is to explore fibre-bridged fatigue delamination in multidirectional composite laminates and to provide an evaluation on the effectiveness of both the Paris relation and a modified Paris relation in fatigue delamination study.

2. Material and experimental procedure

2.1. Material and specimen preparation

DCB specimens with 45//45 interface were manufactured and tested to investigate fatigue delamination with different amounts of fibre bridging. The stacking sequence was designed as $[(\pm 45/0_{12}/\mp 45)//(\pm 45/0_{12}/\mp 45)]$, with consideration of avoiding crack jumping and minimizing both residual thermal stress and non-uniform energy release rate distribution across the width of the crack front [19,20,26–28].

Composite laminates were fabricated by hand-lay-up of 32 thermosetting unidirectional carbon/epoxy prepreg layers of M30SC/DT120. A 12.7 μm Teflon film was inserted in the middle plane of these laminates during the hand-lay-up process to act as an initial delamination with a_0 = 60 mm. The laminates were cured in vacuum in an autoclave at a pressure of 6 bars and curing temperature of 120 °C for 90 min. After curing, all laminates, with a nominal cured thickness of 5 mm, were C-

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