Composites Part A 110 (2018) 21–28

Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

Thickness effects on fibre-bridged fatigue delamination growth in composites

Liaojun Yao[a,*], Hao Cui[b], R.C. Alderliesten[c], Yi Sun[a], Licheng Guo[a]

[a] *Department of Astronautics Science and Mechanics, Harbin Institute of Technology, Harbin, PR China*
[b] *School of Aerospace, Transport and Manufacturing, Cranfield University, United Kingdom*
[c] *Structural Integrity and Composites Group, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands*

ARTICLE INFO

Keywords:
B. Fatigue
B. Delamination
Fibre bridging
A. Polymer-matrix composites (PMCs)

ABSTRACT

This paper provides an investigation on thickness effects on fibre-bridged fatigue delamination growth (FDG) in composite laminates. A modified Paris relation was employed to interpret experimental fatigue data. The results clearly demonstrated that both thickness and fibre bridging had negligible effects on FDG behaviors. Both energy principles and fractography analysis were subsequently performed to explore the physical reasons of this independence. It was found that the amount of energy release of a given crack growth was not only independent of fibre bridging, but also thickness. Fibre print was the dominant microscopic feature located on fracture surfaces, physically making the same energy dissipation during FDG. Furthermore, the present study provides extra evidence on the importance of using an appropriate similitude parameter in FDG studies. Particularly, the strain energy release rate (*SERR*) range applied around crack front was demonstrated as an appropriate similitude parameter for fibre-bridged FDG study.

1. Introduction

Composite laminates, with widespread use in high-tech industry, are vulnerable to delamination growth, owing to lack of reinforcement in thickness direction. This damage can gradually propagate under cyclic loading and may finally result in catastrophic failure of a composite structure during its service life. In the past, engineers usually applied *no crack growth* philosophy in composite structural design, which can significantly reduce weight-saving potential of composites. Since 2009, the US Federal Aviation Administration (FAA) has changed the design philosophy of composite structures from *no crack growth* to *slow crack growth* in the certification procedure [1]. This change makes it even crucial to have in-depth understanding of FDG in composites.

People indeed have paid a lot of attention into FDG, and as a result, a vast number of research papers have been published on this topic [2–8]. Pascoe et al. [5] gave a critical literature review on FDG studies in both composites and adhesive bonds. It was reported that methods based on the fracture mechanics were useful to determine FDG behaviors. Particularly, the Paris relation and its variations have been successfully employed in FDG studies. In these relations, fatigue crack growth rate da/dN was usually correlated to the *SERR*. However, one should bear in mind that there was no consensus on the specific expressions of *SERR* in these relations. Researchers usually would like to use the maximum *SERR* [2–4], *SERR* range [2,6], or combinations of them [2,3,7,8] as similitude parameter to interpret FDG behaviors. The selection of an appropriate similitude parameter was one of the most important issues in FDG studies [5]. The lack of consensus on this parameter can cause controversy in fatigue data interpretation, taking stress ratio effects as examples [2–6].

Fibre bridging is a unique and important shielding mechanism frequently observed in delamination of composite laminates. The presence of bridging fibres in the wake of a crack front can bridge fracture surfaces and prohibit crack growth. Significant studies have been conducted on quasi-static delamination [9–11]. As a result, the corresponding experiment and prediction methods have been developed to characterize this shielding phenomenon. However, to the best knowledge of the authors, not enough attention has ever been paid into FDG with fibre bridging.

Hojo et al. [12] proposed a G_{max}-constant test program to evaluate FDG behaviors with fibre bridging. Hwang et al. [13] completed FDG tests with width tapered DCB specimens under constant *SERR* range. Both of them found that the presence of fibre bridging can significantly retard fatigue crack growth rate. Khan et al. [10] made a comparison on FDG with and without fibre bridging by removing part of fibre bridging via a thread cutting method. The results also demonstrated that fibre bridging can decrease fatigue crack growth. Yao et al. [14–16]

---

[*] Corresponding author.
E-mail address: L.Yao@hit.edu.cn (L. Yao).

https://doi.org/10.1016/j.compositesa.2018.04.015
Received 5 February 2018; Received in revised form 11 April 2018; Accepted 15 April 2018

experimentally examined FDG with different amounts of fibre bridging and proposed empirical power law relations to determine fibre-bridged FDG behaviors. Furthermore, it was reported that the significance of fibre bridging was related to loading regime. Similar conclusion was also made by Stutz et al. [17], in which bridging stress distribution in quasi-static delamination was much higher than that in fatigue. As a result, one can reason that the resistance curve (*R-curve*) obtained in quasi-static delamination cannot well represent resistance increase in fatigue delamination. In addition, it has been proven that stress ratio also affected the significance of fibre bridging, due to crack closure or other unknown reasons [16,18]. Particularly, fibre bridging of a high stress ratio delamination was much more significant than that of a low stress ratio.

To take fibre bridging into account, people usually applied the normalized *SERR* range, i.e. $\Delta G/G_{IC}(a\text{-}a_0)$, or the normalized maximum *SERR*, i.e. $G_{max}/G_{IC}(a\text{-}a_0)$, as similitude parameter in FDG studies [3,7,13,19]. Particularly, in the studies of Murri et al. [3] and Hwang et al. [13], they used quasi-static *R-curve* to normalize G_{max} in fatigue data analysis. However, it is questionable to directly use quasi-static data in FDG studies, as there was difference in the amount of fibre bridging generated in quasi-static and fatigue loading [14,16,17]. To address this problem, in the studies of Zhao et al. [7,19], the resistance increase in fatigue delamination was determined via a *compliance method* and subsequently used in FDG study. Once the normalized parameter was employed, fatigue data scatter can be reduced significantly and clear trend of FDG can be observed.

According to quasi-static studies [9,20,21], thickness had important effects on the significance of fibre bridging. However, there was no agreement on this dependence. Some researchers found that the increase of thickness can cause more fibre bridging [21], whereas other studies provided evidence that thickness had no obvious effect on fibre bridging [9,20]. At this point, it is reasonable to ask a question that what thickness effects on fibre-bridged FDG in composite laminates. The aim of present study is, therefore, to explore fibre-bridged FDG behaviors in composite laminates with different thicknesses.

2. Material and fatigue experimental program

To investigate thickness effects on fibre-bridged FDG behaviors, mode I delamination tests were conducted on unidirectional DCB specimens with three thicknesses, i.e. $h = 3.75$ mm, $h = 5.0$ mm and $h = 7.5$ mm, at the same stress ratio $R = 0.5$.

2.1. Material and specimen preparation

Composite laminates were produced by hand-lay-up of thermosetting unidirectional carbon/epoxy prepreg layers of M30SC/DT120 (high strength and modulus carbon fibre/toughened thermosetting epoxy), supplied by Delta-Tech S.p.A Italy. 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 $a_0 = 60$ mm. Three laminates with different nominal thicknesses of 3.75 mm, 5.0 mm and 7.5 mm were prepared, such to investigate the influence of laminate thickness on the fatigue crack growth performance. The laminates were cured in vacuum in an autoclave at a pressure of 6 bars and curing temperature of 120 °C for 90 min. All laminates were C-scanned to detect potential imperfections. These plates were subsequently cut by a diamond saw into 25 mm width beams with 200 mm length. Only these samples were tested where the C-scan did not reveal any obvious imperfections. A pair of aluminum loading blocks, 25 mm width by 20 mm length with 6 mm thickness, was adhesively bonded onto a specimen at the side of the Teflon insert for load introduction.

One side of a DCB specimen was coated with thin typewriter correction fluid to enhance visibility of crack front during fatigue delamination test. A strip of grid paper was pasted on the coated side of a specimen to aid in measuring crack propagation length.

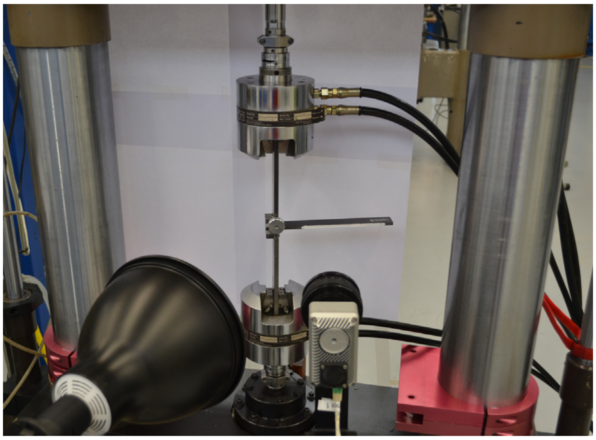

Fig. 1. Experimental fatigue setup.

2.2. Fatigue delamination program

One should note that there was no test standard for mode I FDG in composites until now [4]. In practice, fatigue tests can be conducted under either displacement control or force control. In a recent study [22], it was reported that displacement control was more stable and can result in less data scatter, in comparison with force control. Thus, displacement control was applied in present study. Particularly, all fatigue tests were performed on a 10 kN MTS machine at a frequency of 5 Hz with the same stress ratio $R = 0.5$ in ambient conditions. A computer controlled digital camera system was employed to automatically monitor crack growth at the maximum displacement with pre-defined intervals. The force, displacement and number of cycles were stored in an Excel file every 100 cycles enabling data evaluation after the test. The experimental setup is demonstrated in Fig. 1.

The amount of fibre bridging can increase with crack propagation until a full damage process zone was formed [9,10]. To determine FDG with different amounts of fibre bridging, DCB specimens were tested for several times with different applied displacements, but keeping stress ratio the same. FDG gradually decreased with crack extension and a test was manually terminated in case of crack retardation to save test duration. Subsequently, the test was repeated with increased displacements at the same stress ratio. This sequence was repeated several times until the maximum displacement capacity of the test machine was reached. With this test procedure, multiple delamination resistance curves were obtained, with each one representing delamination resistance equivalent to a specific fatigue pre-crack length, i.e. delamination length at which that particular fatigue test was initiated.

The presence of fibre bridging in delamination can enhance interlaminar resistance significantly. *R*-curve was therefore used in present study to quantitatively determine the critical resistance increase because of fibre bridging in FDG. However, one should note that it was difficult to directly evaluate the critical resistance $G_{IC}(a\text{-}a_0)$ during fatigue delamination, as fatigue load was much lower than the critical load. To address this issue, after each fatigue test, a loading-unloading procedure was added on DCB specimen to measure the critical resistance at the nonlinear point via the Modified Compliance Calibration (MCC) method recommended in the ASTM D5528-01 standard. This procedure can also provide important information for the selection of the suitable maximum and minimum displacements applied in the subsequent FDG test.

Some people may argue that load history of this test program may affect FDG behaviors. In a previous study [15], multiple fatigue delamination tests were conducted on different DCB specimens. And a uniform empirical power law relation has been successfully obtained to determine FDG with different amounts of fibre bridging. One should note that the load histories applied on different DCB specimens were