Composites: Part A 63 (2014) 103–109

Contents lists available at ScienceDirect

Composites: Part A

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

Bridging effect on mode I fatigue delamination behavior in composite laminates

Liaojun Yao [a,b,*], René Alderliesten [b], Meiying Zhao [a], Rinze Benedictus [b]

[a] School of Aeronautics, Northwestern Polytechnical University, Xi'an, PR China
[b] Structural Integrity & Composites Group, Faculty of Aerospace Engineering, Delft University of Technology, Netherlands

ARTICLE INFO

Article history:
Received 11 December 2013
Received in revised form 25 February 2014
Accepted 16 April 2014
Available online 24 April 2014

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

ABSTRACT

This paper discusses the bridging effect of fibres on mode I fatigue delamination growth in unidirectional and multidirectional polymer composite laminates based on a series of double cantilever beam (DCB) tests. From the results, there is sufficient evidence that fibre bridging can decrease the crack growth rate da/dN significantly, and using only one fatigue resistance curve to determine the delamination behavior in composite materials with large-scale fibre bridging may be inadequate. The bridging created in fatigue delamination is different from that of quasi-static delamination at the same crack length. So it is incorrect to use the resistance curve (*R*-curve) from quasi-static delamination tests to normalize fatigue delamination results.

1. Introduction

Advanced composite laminates are often used in aeronautical and space applications for their high mechanical performance in strength and stiffness, the ability of tailor-design, and low density compared to metals. However, due to the lack of reinforcement in the thickness direction, these materials are sensitive to out of plane loading. As a result, they are susceptible to delamination, which could be induced during low velocity impact or manufacture.

Fatigue delamination, one of the most critical failure modes in carbon fibre reinforced plastic (CFRP), may gradually cause strength and stiffness degradation and finally lead to catastrophic failure of the component during its service life. A majority of papers have been published on this topic based on various experimental or numerical methods to characterize delamination behavior [1–11]. In experimental studies, most researchers applied a Paris relation, which has proven to be a useful and effective method to describe the fatigue crack growth in metals, to study the fatigue delamination in CFRP. However, instead of using the stress intensity factor K as the control parameter, they employed the strain energy release rate G to determine the Paris relation for fatigue delamination growth in composite materials. This relates to the complexity of calculating K around a crack tip in inhomogeneous materials [12]. According to the relationship between crack growth rate da/dN and ΔG established by the experimental studies, other searchers tried to develop a numerical model to predict fatigue delamination growth based on the cohesive zone formulation [1–3].

However, most of the previous studies on fatigue delamination in CFRP did not pay enough attention to the influence of fibre bridging, which is very common in composite materials. Based on quasi-static results, the fracture toughness G_{IC}, will increase from an initial value to a plateau value with crack extension [13–17]. The reason for this is that, bridging fibres will hold the crack tip and effectively reduce the stress intensity factor around the crack tip. And the plateau value means at a certain delamination length, bridging reaches its maximum and after that it becomes stable with further delamination.

The objective of current investigation is to verify whether or not fibre bridging has an influence on fatigue delamination resistance and what kind of influence it is. In this work, DCB specimens were designed with both unidirectional and multidirectional layups and applied in mode I quasi-static and fatigue delamination tests. Based on the experimental test results, this paper provides a conclusion about the influence of fibre bridging on fatigue resistance.

2. Background

Characterizing the fatigue delamination resistance in composite materials is important and essential for their damage tolerant design and reliability assessment. DCB specimens are commonly used for determining the interlaminar resistance under Mode I quasi-static and fatigue loading.

* Corresponding author at: School of Aeronautics, Northwestern Polytechnical University, Xi'an, PR China.
E-mail address: ylj20001986@126.com (L. Yao).

http://dx.doi.org/10.1016/j.compositesa.2014.04.007
1359-835X/

In previous studies, researchers have studied the influence of some important factors on fatigue delamination and tried to develop a prediction model for composite materials. Because the stress ratio *R* is an important parameter in describing cyclic loading, some researchers attempted to study the R-ratio effects on fatigue crack growth [4–6]. To increase fatigue delamination properties, different interlayer toughened carbon fibre/epoxy laminates were studied by Hojo et al. [7]. Some researchers investigated the influence of temperature on fatigue crack growth in composite laminates [8,18]. Two similar fatigue life models were proposed and applied to predict fatigue delamination resistance curves [9,10], according to experimental studies and the three typical domains in Paris scheme. Most of the previous studies employed a Paris relation to describe the fatigue crack resistance in composite materials. However, no consensus on the similitude parameter in this Paris relation for fatigue delamination has been reached at present, leading to confusion in understanding fatigue delamination results. To solve this problem, according to the similitude principle and the superposition rule in linear elastic fracture mechanics, theoretical analysis and comparison studies of different definitions of control parameter in characterizing fatigue test results were proposed and discussed [11].

There are sufficient evidences that interlaminar toughness will increase with the delamination extension due to fibre bridging behind the crack tip. Bridging is a typical phenomenon in polymer and ceramics composites. Methods have been developed to characterize its contribution during quasi-static crack growth. Suo et al. [13] gave a thorough discussion about the bridging in composite materials in quasi-static delamination and presented a model to evaluate the bridging stress distribution along the bridging area. Since the shape of *R*-curve is dependent on the specimen geometry, especially for large-scale bridging, a bridging law, which describes the bridging stress distribution in the bridging area, was proposed to characterize the bridging phenomenon in the delamination growth [14]. Stutz et al. [19–20] evaluated the contribution of bridging on the fracture toughness with unidirectional DCB specimens in both monotonic and fatigue loading using fibre bragg grating sensors. He concluded that the exponential bridging model was more accurate than the bilinear model, when comparing numerical and experimental results. And the exponential, three-linear and bilinear models are three commonly used models to describe the bridging effect in quasi-static delamination [19,21].

However, reliable methods to evaluate bridging effects on fatigue delamination have not been proposed yet. To consider the influence of fibre bridging on fatigue delamination and to reduce the scatter in test results, a normalization method is commonly applied. Murri [22] normalized the G_{Imax} in the fatigue tests with the *R*-curve obtained from quasi-static delamination tests, to get a Paris relation. Zhang et al. [23] normalized the fatigue delamination resistance based on a compliance equivalence between quasi-static and fatigue delamination, and used it, instead of static resistance, to normalize the Paris equation. This method is based on the assumption that specimens in quasi-static or fatigue delamination with the same compliance have the same damage state. On the other hand, Gregory and Spearing [18] proposed a fibre bridging model to study the bridging effect on Mode I fatigue delamination at different temperatures. Applying this model, the data scatter was significantly reduced and clear trends were found. It can be concluded that the influence of bridging on fatigue delamination is still not very clear at present, even though people believe its influence exists and try to take it into consideration in the formulation of fatigue predict model.

Accordingly, the main objective of present paper is to study the influence of bridging on fatigue delamination growth in composite laminates.

3. Material and specimen configurations

To have a better understanding about the bridging effect on fatigue delamination growth, DCB specimens with two different orientation configurations, 0//0 and 45//45 (// indicates the delamination plane) were designed and tested. For multidirectional specimens, based on previous studies [15,24], the layup sequence was designed as $[(\pm45/0_{12}/\mp45)//(\pm45/0_{12}/\mp45)]$, 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.

The material applied here was carbon/epoxy prepreg M30SC/DT120 (high strength and modulus carbon fibre/toughened thermosetting epoxy). Laminates were laid in the designed stacking sequences and a Teflon insert with 12.7 μm thickness was placed in the middle plane of the laminates to introduce an initial delamination. Laminates were cured in the autoclave at a pressure of 6 bars and curing temperature of 120 °C for 90 min. After curing, the laminates were C-scanned for imperfections. Samples were taken from these areas where no imperfections were identified. DCB specimens, 200 mm length by 25 mm width with thickness of 5 mm, were cut from the panel with a diamond-coated cutting machine.

4. Experimental procedures

A series of DCB specimens has been tested in both quasi-static and fatigue condition. The experimental setups for quasi-static and fatigue tests are shown in Fig. 1.

Firstly, quasi-static tests were conducted to determine the quasi-static delamination resistance curve and to have a general idea about the bridging phenomenon at different ply orientations. These tests were carried out on a 20 kN tensile-compression Zwick machine. All tests were performed under displacement control with an applied displacement rate of 1 mm/min. A digital camera and computer system was used to monitor the delamination growth by automatic recording an image of the specimen edge every 5 s.

Fatigue tests were conducted after the quasi-static tests. These tests were performed on a 10 kN MTS machine under displacement control at a frequency of 5 Hz with the stress ratio $R = 0.1$ or 0.5. The same digital camera and computer system was employed to determine the fatigue crack extension during the fatigue test.

The Modified Compliance Calibration (MCC) method in ASTM D5228 was employed to calculate the strain energy release rate in quasi-static and fatigue tests.

The 7-point Incremental Polynomial Method, recommended in ASTM E647-00, was used to determine the delamination growth rate da/dN.

5. Experimental results and discussion

5.1. Quasi-static test results

Five specimens of each configuration were tested quasi-statically. Fig. 2(a) shows the increasing G_{IC}–value vs. local crack opening displacement δ and Fig. 2(b) shows the G_{IC}–value vs. crack extension $a–a_0$. It is clear that initial G_{IC}–value for both interfaces is almost the same. Some researchers [25] believe that this value is the property of the interlaminar without influence of bridging and is independent on the interface configuration. With δ and $a–a_0$ increasing, G_{IC} reaches a plateau value for each interface because of bridging, after the crack extensions exceed 50 mm in unidirectional DCB specimens and 40 mm in multidirectional DCB specimens. Noticeably, the plateau value for 45//45 interface