Composites: Part A 78 (2015) 135–142

Contents lists available at ScienceDirect

Composites: Part A

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

Interpreting the stress ratio effect on delamination growth in composite laminates using the concept of fatigue fracture toughness

Liaojun Yao *, R.C. Alderliesten, R. Benedictus

Structural Integrity & Composites Group, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 1 July 2015
Accepted 6 August 2015
Available online 14 August 2015

Keywords:
B. Fatigue
B. Delamination
B. Fracture toughness
Energy principles

ABSTRACT

This paper provides a study on fatigue delamination growth in composite laminates using energy principles. Experimental data has been obtained from fatigue tests conducted on Double Cantilever Beam (DCB) specimens at various stress ratios. A concept of fatigue fracture toughness is proposed to interpret the stress ratio effect in crack growth. The fatigue fracture toughness is demonstrated to be interface configuration independent but significantly stress ratio dependent. An explanation for this phenomenon is given using SEM fractography. Fracture surface roughness is observed to be similar in different interfaces at the same stress ratio. But it is obviously more rough for high stress ratio in comparison with that for low stress ratio, causing the fatigue resistance increase. Therefore, the stress ratio effect in fatigue crack growth can be physically explained by a difference in resistance to crack growth.

1. Introduction

The requirements for fuel efficiency and lightweight structures have led to a great increase in the use of advanced composite materials in both military and commercial aircraft. Although composite materials have a lot of advantages, they are susceptible to delamination between adjacent layers, because there is lack of reinforcement in the thickness direction. This damage mode can result from stress concentration, over loading, or impact, and propagate under fatigue loading. Delamination can lead to stiffness and strength degradation and in the end cause the catastrophic failure of a structure during its service life.

Fatigue delamination has attracted a lot of attention in the last few decades, and a large number of papers have been published to characterize this phenomenon and to develop prediction models [1–11]. The prediction methods and models can be classified into four major categories [1]: Stress/strain based methods, fracture mechanics based methods, cohesive zone models and extended finite element models. In this classification, methods based on the fracture mechanics concepts of stress intensity factor (*SIF*) and strain energy release rate (*SERR*) have been widely employed to investigate crack growth in composite laminates under quasi-static loading. As a result, a standard has been established for performing quasi-static delamination tests. However, for fatigue delamination, there is no standard to follow. In fact, there is even no consensus on the similitude parameter to interpret experimental fatigue data, which seems to lead to different conclusions, for example for the stress ratio effect in fatigue delamination growth.

The stress ratio is an important factor in describing fatigue loading and characterizing fatigue crack growth behavior. Large numbers of studies have been conducted on stress ratio effect in fatigue delamination growth [2–8]. Stress ratio effect in fatigue crack growth seems to be similitude parameter dependent. In case of maximum *SERR*, delamination growth is lower with the increase of stress ratio. This is completely opposite to using the *SERR* range. Some researchers explained this by highlighting the fact that the load cycle and its effect on fatigue crack growth cannot be uniquely described by a single parameter [3,9–11]. Therefore, two-parameter models were proposed to characterize the fatigue crack growth behavior in these studies. The similitude parameters used in these models, are usually maximum *SERR* and *SERR* range. The stress ratio effect seems to vanish using these models. However, the fundamental mechanisms related to the stress ratio effect are still unknown. Questions arise here as to whether or not there is stress ratio effect and what damage mechanisms relate to the effect? These questions cannot be answered by the aforementioned studies, because all of them are empirical curve fits, and do not provide a physics-based explanation.

Recently, studies on fatigue delamination growth in composite laminates and adhesively bonded structures have been reported that evaluate the phenomena using energy principles [12–15]. In these studies, the concept of the energy dissipation rate dU/dN is correlated to the fatigue crack growth rate da/dN. Comparing to

* Corresponding author. Tel.: +31 0623344172; fax: +31 (0)152781151.
E-mail address: ylj20001986@126.com (L. Yao).

http://dx.doi.org/10.1016/j.compositesa.2015.08.005
1359-835X/

an artificial *SERR* at a single point, dU/dN has the advantage of determining energy change during the entire fatigue cycle and physically relating to the crack growth increment generated in that cycle, which is more suitable for fatigue crack growth studies [12].

These energy principles are used in the present work to investigate the stress ratio effect in fatigue delamination growth in composite laminates. This paper aims to provide a physical interpretation of the stress ratio effect in fatigue crack growth.

2. Fatigue delamination experiment

2.1. Material and specimen configuration

DCB specimens with 0//0 or 45//45 interface were designed and manufactured for mode I fatigue delamination tests (// indicates the delamination propagation plane). The layup sequence for the DCB specimens with 45//45 interface was $[(\pm45/0_{12}/\mp45)//(\pm45/0_{12}/\mp45)]$. The layup sequence for the DCB specimens with 0//0 interface was $[(0_{16})//(0_{16})]$.

The composite laminates were produced by hand-lay-up of 32 layers of unidirectional carbon/epoxy prepreg M30SC/DT120. During the manufacturing process, a 12.7 μm Teflon film was placed in the middle plane of the composite laminates to act as an initial delamination. The laminates were put in vacuum in an autoclave at a curing pressure of 6 bars and curing temperature of 120 °C for 90 min. After curing, all laminates were C-scanned in order to detect potential imperfections. Then the panels were cut by a diamond saw into 200 mm length by 25 width beams from the region where no imperfections were observed. A pair of aluminum load-blocks, 25 mm width by 20 mm length with 6 mm thickness, was adhesively bonded onto the specimen's end for load introduction.

2.2. Fatigue experimental procedure

All fatigue tests were conducted on a 10 kN hydraulic MTS machine at room temperature under displacement control at a frequency of 5 Hz. Photographs of one side of the fatigue crack extension were automatically recorded at the maximum displacement during the test with a digital camera controlled by the computer system. The corresponding information of load, displacement and number of cycles were stored in an Excel file enabling data evaluation after the test. The experimental set-up is demonstrated in Fig. 1.

Prior to fatigue testing on the specimens, they were quasi-statically loaded to create a 2–3 mm onset crack as a natural sharp crack tip. Then, the maximum displacement at the beginning of the fatigue test was set to 80% of the critical loading in the quasi-static test. The selected stress ratio then defined the minimum displacement.

In the first part of this paper, experimental fatigue data is presented in agreement with Paris relationships between the fatigue crack growth rate and the maximum *SERR* and the *SERR* range, see Eqs. (1) and (2). In the second part, all data is reanalyzed using the energy principles.

$$\frac{da}{dN} = c(G_{max})^n \tag{1}$$

$$\frac{da}{dN} = c\left(\Delta\sqrt{G}\right)^n = c\left[\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2\right]^n \tag{2}$$

where c and n are curve fitting parameters.

The *SERR* in mode I fatigue delamination tests was calculated with the Modified Compliance Calibration (MCC) method, recommended in ASTM D5528, see Eq. (3).

$$G_I = \frac{3P^2C^{(2/3)}}{2A_1Bh} \tag{3}$$

where C is the compliance of the DCB specimen, B is the specimen width and h is the thickness of specimen. A_1 is the slope of the curve in the graph where a/h is plotted against $C^{1/3}$.

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

3. Fatigue data analysis with Paris relationship

Unidirectional DCB specimens were fatigue tested at stress ratios 0.1 and 0.5. Specimens with 45//45 interface were tested at stress ratios 0.1, 0.2 and 0.5. All data was subsequently analyzed using Paris correlations, either in the form of da/dN against the maximum *SERR* or da/dN against the *SERR* range, as shown in Figs. 2–5. Without exception, a significant stress ratio effect can be observed.

4. Fatigue data analysis using energy principles

All experimental fatigue data interpreted with the Paris relations is reanalyzed according to the energy principles and expressed in the form of da/dN against $G = (dU/dN)/(dA/dN)$ in the following sections.

4.1. Fracture toughness definition

In fracture mechanics, the strain energy release rate is defined as

$$G = \frac{dU}{dA} \tag{4}$$

where dA is the incremental increase in area of the fracture surface, which is equal to Bda for DCB specimen. dU is the amount of energy dissipated in the crack propagation.

The applied maximum load in the system is decreasing with crack propagation in a displacement controlled fatigue test. As a result, the total energy in the system is also decreasing. The energy dissipation is related to the generation of new crack, but also other mechanisms. It can be determined by plotting the applied work U against cycle number N [12]. The energy dissipation rate, dU/dN, in fatigue crack growth is determined as

$$\frac{dU}{dN} = \frac{dU}{dA}\frac{dA}{dN} \tag{5}$$

Referring to the definition of fracture resistance in fracture mechanics, the component dU/dA in Eq. (5) can be physically interpreted as fatigue resistance.

4.2. Fatigue fracture toughness

Damage evolution is an energy dissipation process obeying the laws of physics on energy conservation. Similar to quasi-static delamination, which can be quantified by the parameter of fracture toughness using the principle of energy balance, there should be a similar parameter with physical meaning, but related to fatigue damage.

In previous studies [12,13], there seems an approximately linear relationship between dU/dN and da/dN, which indicates a constant G in fatigue delamination growth. It is postulated here that if this G value keeps constant in fatigue crack growth, the crack growth is self-similar.

Fig. 6 shows the data analysis with energy principles for fatigue tests at the same stress ratio $R = 0.1$, but different interfaces. At the