Composites Part B 132 (2018) 97–106

Contents lists available at ScienceDirect

Composites Part B

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

A validation of a modified Paris relation for fatigue delamination growth in unidirectional composite laminates

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ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form
4 August 2017
Accepted 3 September 2017
Available online 4 September 2017

Keywords:
Fatigue
Delamination
Fibre bridging
Composite laminates

ABSTRACT

The aim of this paper is to provide evidence on the validation of a modified Paris relation in fatigue crack growth with fibre bridging. Energy principles were first applied to investigate energy release in fatigue delamination growth. A comparison between the Paris and the modified Paris relations was completed subsequently. The application of the Paris relation can artificially cause different resistance curves of fatigue delamination with fibre bridging, violating the hypothesis of similitude and the energy dissipation results. However, the use of the modified Paris relation can result in a master resistance curve, which is physically consistent with the law of similitude and the energy release regulations. This derives from using an appropriate similitude parameter in data reduction. It is therefore reasonable to use the strain energy release rate (*SERR*) actually applied on the crack front, rather than the total applied *SERR*, as similitude to correlate fatigue crack growth. The master resistance curve was finally employed to predict fatigue results from literature. Acceptable agreement between predictions and experiments was achieved, validating the effectiveness of the modified Paris relation in determining fatigue crack growth with fibre bridging.

1. Introduction

Composite laminates have been widely used in engineering, due to their excellent mechanical properties. These materials usually contain two different elements, i.e. fibre as reinforcement and epoxy as matrix. Because of the complexity of composites, different kinds of damage can occur in the applications of them in engineering structures under fatigue loading, such as fibre breakage, fibre kinking, matrix cracking, fibre/matrix debonding and delamination [1–3]. And a large number of experimental and numerical studies have been conducted to explore damage mechanisms and to develop reliable models for composite materials [4–10].

Delamination is one of the most important failure types in the applications of composite laminates [3–8]. This kind of damage can gradually propagate under fatigue loading, initially resulting in strength and stiffness degradation and finally causing catastrophic failure of a composite structure during its service life. In addition, it is really difficult to have a real-time monitor on this damage and its propagation, as it usually occurs between neighbored layers. It is, therefore, of great importance to investigate fatigue delamination behavior and develop reliable models to characterize this kind of damage.

Several factors can have effects on the evolution of this damage, e.g. stress ratio $R = P_{min}/P_{max}$, mixed-mode rate, interface configuration, interlaminar reinforcement, temperature and moisture [11–17]. Among these factors, stress ratio has been reported many times to be one of the most important factors in fatigue delamination characterization. And a vast number of researches have been conducted to determine fatigue crack behaviors under different stress ratios [18–23]. However, there was no consensus on *R*-ratio dependence in fatigue crack growth. Particularly, its effect on fatigue crack growth seemed similitude parameter dependent. In case of using the maximum strain energy release rate (*SERR*) in data analysis, fatigue crack growth can decrease significantly with stress ratio increase [18–20]. On the contrary, the application of the *SERR* range can cause obvious increase in fatigue crack growth with stress ratio increase [18,21,22]. In a recent study based on energy balance [24], it has been reported that delamination resistance was stress ratio dependent. And the resistance was much higher for

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http://dx.doi.org/10.1016/j.compositesb.2017.09.007
1359-8368/

delamination of a high stress ratio, as compared to that of a low stress ratio. This finding has been applied to physically interpret stress ratio dependence.

Fibre bridging is a significant and unique shielding phenomenon during delamination growth in composite materials [25–27]. This mechanism can bridge fracture surfaces and prohibit crack propagation. In quasi-static delamination studies, the concepts of *R-curve* and bridging law $\sigma(\delta)$ were usually used to phenomenally and physically interpret this toughening mechanism [26,28,29]. Corresponding experimental and semi-experimental methods have been gradually developed to quantify the *R-curves* and traction-separation laws. Prediction models based on these two concepts have been successfully developed to represent delamination growth [29,30]. However, it is worth noting that researches dealing with fatigue delamination with fibre bridging remained scarce, even though people knew it existed [21,31]. With the widespread applications of composite materials in high-tech industry, a growth number of attention has been paid into fibre bridging under fatigue loading in the last several years. In the framework of *R-curve*, Zhao et al. [32,33] developed a *compliance approach* to correlate fatigue delamination resistance with quasi-static delamination resistance. Other people extended the concept of bridging law from quasi-static to fatigue delamination. Sophisticated methods that can quantify bridging stress distribution under fatigue loading have been gradually developed [21,31,34,35]. The determined traction-separation laws clearly demonstrated that bridging stress can exponentially decay with the increase of crack opening displacement δ. Other people attempted to investigate fibre bridging via its consequence in fatigue delamination growth [36,37]. It has been explicitly reported that fibre bridging had significant retardation effects on fatigue delamination growth and made the Paris resistance curves decrease shift. This meant crack growth of a given *SERR* was not the same, but dependent of crack scale. As a result, it was inappropriate to use a single Paris resistance curve to represent fatigue delamination with different amounts of fibre bridging [37].

According to above brief review, both *R*-ratio and fibre bridging have important effects on fatigue crack growth. People then may ask what interrelationship is between these two factors. This question has been carefully answered in recent studies via experimental and theoretical methods [38,39]. It was reported that fibre bridging had effect on the magnitude of *SERR*, but had no or negligible effect on the stress ratio indeed applied on the crack tip [38]. However, the significance of fibre bridging was *R*-ratio dependent [39]. More bridging fibre can be present in fatigue delamination of a high stress ratio. Furthermore, this can make *R*-ratio dependence of bridging law in fatigue delamination growth.

How to determine fatigue crack growth with fibre bridging becomes a big issue for the scientific and engineering communities. An empirical model, see Eq. (1), has been proposed to determine fatigue delamination with fibre bridging in unidirectional double cantilever beam (DCB) specimens under various stress ratios [40]. The validation of this power law relation has been verified by a comparison between experimental results and predictions.

$$\begin{aligned}\frac{da}{dN} &= c(a-a_0,R)\Delta G^{n(R)} \\ &= c(a-a_0,R)\left[\left(\sqrt{G_{max}}-\sqrt{G_{min}}\right)^2\right]^{n(R)}\end{aligned} \tag{1}$$

where c and n are two curve fitting parameters; a-a_0 represents crack extension; $G_{\max}$ and $G_{\min}$ are the maximum and minimum *SERR*s of a fatigue cycle.

Note that Eq. (1) implicitly indicates that the *SERR* range ΔG is not an appropriate parameter to represent the similitude in fatigue delamination, as crack growth of the same ΔG is different. A suitable parameter therefore was required to correlate fatigue crack growth. In a recent study [41], a modified Paris relation, based on the similitude principle, has been proposed to determine fatigue delamination with fibre bridging. The first validation of this model has been given via fatigue tests with a low stress ratio $R = 0.1$. The application of this relation can unify all fatigue data into a narrow band, indicating identical fatigue crack behavior of the same similitude parameter.

According to previous studies [18–23,39], both fatigue delamination and fibre bridging significance were dependent of *R*-ratio. And the question arises as does the modified Paris relation still work well for fatigue delamination growth with increased stress ratio. To answer this question, fatigue delamination tests were conducted on a unidirectional DCB specimen with a high stress ratio $R = 0.5$. Both the energy principles and two Paris-type relations were used in fatigue data analysis to explore the fatigue delamination behavior in composite laminates. And the results gave more evidence on the validation of using the modified Paris relation in fatigue delamination study.

2. Material and fatigue experiment

2.1. Material and specimen configuration

Unidirectional DCB specimens were manufactured and tested to investigate fatigue delamination behavior with fibre bridging. 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 $a_0 = 60$ 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, the laminates, with a nominal cured thickness of 5 mm, were C-scanned to detect potential imperfections. The plate was subsequently cut by a diamond saw into 25 mm width beams with 200 mm length. And 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 the specimen at the side of the Teflon insert for load introduction.

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

2.2. Experimental set-up and test procedure

Fatigue delamination test with a given stress ratio R can be conducted under displacement control or force control. However, in a recent study completed by Technical Committee 4 (TC4) of the European Structural Integrity Society (ESIS) [42], it was reported that the displacement control was more stable and resulted in less data scatter, in comparison with force control. Thus, displacement control was applied in present study. Fatigue experiments were performed on a 10 kN MTS machine under displacement control at a frequency of 5 Hz with a fixed stress ratio $R = 0.5$ in ambient conditions. A digital camera system was employed to monitor crack growth at the maximum displacement with pre-defined intervals during the entire tests. The load, displacement and cycle number were automatically stored in an Excel file every 100 cycles, enabling data evaluation after the tests.

Prior to the first fatigue test conducted on DCB specimen, the specimen was quasi-statically loaded to generate a 2–3 mm onset crack as a natural crack tip for the subsequent fatigue test. The