THE CONCEPT OF FATIGUE FRACTURE TOUGHNESS IN FATIGUE DELAMINATION GROWTH BEHAVIOR

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ABSTRACT

This paper provides a study on mode I 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 significantly stress ratio dependent. An explanation for this phenomenon is given using SEM fractography. Fracture surface is observed to be rougher 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

Composite laminates have been widely used in military and commercial aircraft due to their high strength-to-weight ratio and stiffness-to-weight ratio, the ability of tailor-design, low density compared to metals and so on. But they are susceptible to delamination due to the lack of reinforcement in thickness direction. Delamination can initiate and propagate under fatigue loading, leading to the failure of composite structures in their service lives.

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]. Most of previous studies on fatigue delamination are based on Paris correlations. In these correlations, fatigue crack growth is correlated to stress intensity factor (SIF) for metals. In composite materials, fatigue crack growth is usually correlated to strain energy release rate (SERR). This is due to the complexity in the calculation of SIF in inhomogeneous materials and SERR is equivalent to SIF in principle.

In these correlations, stress ratio is a significant phenomenon in fatigue crack growth. 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.

In addition, other people would like to use crack closure theory to interpret the stress ratio effect. Damage mechanics for crack closure in metals differs from that for composite laminates. Plasticity deformation is the major reason for crack closure in metals. However, plasticity is not observed in composite laminates. The reason for crack closure in composite laminates results from fibre and matrix debris, damaged fibres on fracture surface. In a study of Khan [12], crack closure was only observed in fatigue delamination with low stress ratio. There was no crack closure in high stress ratio. As a result, it is impossible to explain the stress ratio effect in fatigue crack growth in composite laminates using crack closure theory.

Most of previous studies on fatigue crack growth are based on empirical curve fits and do not provide a physical explanation of stress ratio effect. Recently, studies on fatigue delamination growth in composite laminates and adhesively bonded structures have been reported that evaluate the phenomena using energy principles [13-15]. In these studies, the concept of the energy dissipation rate $dU/dN$ is correlated to the fatigue crack growth rate $da/dN$. Comparing to 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 the cycle, which is more suitable for fatigue crack growth studies [13].

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

The composite laminates were produced by hand-lay-up of 32 layers of unidirectional carbon/epoxy prepreg M30SC/DT120. During the manufacturing process, a 12.7μm 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 minutes. After curing, all laminates were C-scanned in order to detect potential imperfections. Then the panels were cut by a diamond saw into 200mm 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 test procedure

All fatigue tests were conducted on a 10kN hydraulic MTS machine at room temperature under displacement control at a frequency of 5Hz. 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 Figure 1.

![Fatigue experimental set-up](image)

Figure 1: Fatigue experimental set-up

Prior to fatigue testing on the specimens, they were quasi-statically loaded to create a 2-3mm 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. In the second part, all data is reanalyzed using the energy principles.

The $SERR$ in mode I fatigue delamination tests was calculated with the Modified Compliance Calibration (MCC) method, recommended in ASTM D5228, see Eq. (1).

$$G_I = \frac{3\rho^2C^{2/3}}{2A_1Bh}$$

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 using Paris correlations

DCB specimens were fatigue tested at stress ratios 0.1 and 0.5. All data was 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 Figure 2. Without exception, a significant stress ratio effect can be observed. The fatigue crack growth rate increases with the stress ratio increase using the SERR range as the similitude parameter. This is completely opposite to using the maximum SERR as the similitude parameter.

![Figure 2: Experimental fatigue data interpreted with Paris correlations](image)

4. Fatigue data analysis using energy principles

All experimental fatigue data interpreted with the Paris relations is reanalyzed using the energy principles and expressed in the form of $\frac{da}{dN}$ 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
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 $N$ [13]. The energy dissipation rate, $dU/dN$, in fatigue crack growth is determined as

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

Referring to the definition of fracture resistance in fracture mechanics, the component $dU/dA$ in Eq.(3) 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 [13-14], there seems an approximately linear relationship between $dU/dN$ and $da/dN$, which indicates a constant $G$ in fatigue delamination growth. It postulated here that if this $G$ value keeps constant in fatigue crack growth, the crack growth is self-similar.

Figure 3 shows the data analysis with energy principles for fatigue tests at the stress ratio $R=0.1$. At the beginning of the fatigue test, the total energy dissipated per unit crack growth in the delamination decreases with the crack propagation. This trend ends with a constant $G$ value after the fatigue crack growth rate is around or below $2 \times 10^{-7}$ m/Cycle. The constant $G$ value is 101.9 J/m$^2$. This indicates a stable delamination state with self-similar crack growth. In stable crack growth, all energy dissipation concentrates to damage evolutions around the crack front, i.e. new crack generation, and no or relatively little energy release relates to the failure in bridging fibres. However, this is not true in the beginning of fatigue crack growth. Bridging fibre failure plays an important role and causes more energy dissipation, therefore leading to a high $G$ level at the beginning of fatigue test as shown in Figure 3.
According to previous studies [13], bridging fibres periodically store strain energy in the loading cycle and release strain energy in the unloading cycle, without permanent energy release related to damage. So there is no contribution to the real strain energy release rate in fatigue delamination growth, unless there is failure in the bridging fibres. To take account of bridging fibre failure at high fatigue crack growth rates, $\frac{dU}{dN}$ in Eq.(3) can be explicitly expressed as

$$\frac{dU}{dN} = \frac{dU_a}{dN} + \frac{dU_{br}}{dN} = \left(\frac{dU_a}{dA} + \frac{dU_{br}}{dA}\right) \frac{dA}{dN} = \left(G_f + \frac{dU_{br}}{dA}\right) \frac{dA}{dN}$$

where $dU_a$ is the amount of energy dissipation related to crack growth; $dU_{br}$ is the total energy dissipation associated with bridging fibre failure.

In the stable fatigue crack growth, the contribution of the component $dU_{br}/dA$ in Eq.(4) is relatively limited and can be ignored. All energy dissipation is directly related to the crack growth, which is explicitly characterized as $G_f = dU_a/dA$ in Eq.(4). $G_f$ therefore can be defined as the fracture toughness in fatigue crack growth.

### 4.3 Stress ratio effect on fatigue fracture toughness

To investigate the stress ratio effect, experimental fatigue data with different stress ratios is analyzed using the energy principles, as shown in Figure 4. Similar to what has been observed in Figure 3, $G$ initially decreases and finally converges to a constant value for each stress ratio. This constant value increases from 101.9 J/m² to 148.1 J/m² with the increase of stress ratio from 0.1 to 0.5. According to the change in $G_f$, one can postulate that the fatigue fracture toughness is stress ratio dependent. With the increase of stress ratio, fatigue resistance will also increase. A physical explanation on the resistance increase will be given in the following section with SEM fractography.
4.4 Fatigue tests with long pre-crack length

The energy dissipation in fatigue crack growth will increase due to the contribution of the component $dU_{br}/dA$. Therefore, the energy dissipation in fatigue delamination growth with more bridging fibres should be even larger at the beginning of delamination growth and gradually decreases to a constant level once self-similar crack growth occurs. To verify this hypothesis, two DCB specimens with 15mm pre-crack length were fatigue tested at the stress ratio $R=0.1$.

The results for these tests are given in Figure 5. The $G$ value at the beginning of the test is relatively large, more than 500J/m$^2$. This value is much higher than that in Figure 3, around 200 J/m$^2$. The energy dissipation significantly decreases and ends in the level 103.3 J/m$^2$, which is close to the stable value given in Figure 3.
Fatigue fracture surfaces, magnified 1000 times, are shown in Figure 5. The dominant features on the fracture are fibre prints and cusps. Fibre prints result from disbonding between reinforcing fibres and matrix. Cusps occur in mode I delamination due to a local shear stress state existing between the fibres and the matrix [16,17].

Generally, the morphology is similar at the different stress ratios. However, taking a closer observation, the fracture surface is rougher at the high stress ratio compared to the low stress ratio. Cusps are also more obvious and in large-scale with the increase of stress ratio, which is in agreement with the studies conducted by Khan [10]. These differences should be the reasons for the $G_f$ increase demonstrated in Figure 4.

![Figure 5: SEM observation of fracture surface at $da/dN=1\times10^{-7}$ m/cycle](image)

(a) Stress ratio $R=0.1$

(b) Stress ratio $R=0.5$

4.6 Interpreting stress ratio effect with fatigue fracture toughness
This constant $G$ in fatigue crack growth could be defined as the fatigue fracture toughness. It can be used to provide a physical explanation of the stress ratio effect in fatigue crack growth. At a given $G_{\text{max}}$, fatigue crack growth rate is slow for high stress ratio compared to that for low stress ratio. This is because of the increase in fatigue fracture toughness. In case of using $\Delta G = \sqrt{G_{\text{max}}} - \sqrt{G_{\text{min}}}$ as the similitude parameter, the $SERR$ range is equal to $(1-R)^2G$. In case of using $\Delta G = G_{\text{max}} - G_{\text{min}}$, the $SERR$ range is equal to $(1-R^2)G$. The $SERR$ ranges in both definitions are higher for low stress ratios making crack growth rate seem to be high with the increase of stress ratio.

The major reason for the application of $\Delta G$ in fatigue delamination analysis in composite materials originates from the knowledge and studies on metals, in which fatigue crack growth is sensitive to the $SIF$ range. However, the results violate the fact that fatigue resistance is higher at a high stress ratio compared to that at a low stress ratio, when using $\Delta G$ as similitude to interpret the fatigue crack growth. This shortcoming will disappear by using $G_{\text{max}}$ as the similitude parameter. Therefore, on this point, $G_{\text{max}}$ seems to be more reasonable in fatigue data analysis. However, it is worth noting that neither $G_{\text{max}}$ nor $G_{\text{min}}$ exists in fatigue crack growth. In the views of progressive damage evolution and energy principles, fatigue damage evolution exists in the whole cycle and the total energy release is the sum of energy dissipation in each infinitesimal section, once damage occurs. Theoretically, there is only $dU/dA$ directly associated with the crack growth in each infinitesimal section. It could be defined as the resistance in fatigue delamination. As a result, the fatigue fracture toughness provides a physical explanation of the stress ratio effect.

5. Conclusion

A study on the fatigue delamination growth behavior in composite materials has been completed using the energy principles. There is sufficient evidence that the energy release remains constant in self-similar fatigue crack growth. Fatigue fracture toughness is therefore presented to characterize the delamination behavior in composite materials.

According to the experimental data, the fatigue fracture toughness is stress ratio dependent. It will increase with the increase of stress ratio. The resistance dependence on stress ratio is the physical reason for the stress ratio effect in fatigue crack growth. The mechanisms related to this dependence are investigated by SEM fractography. Fractography demonstrates that the fracture surface is rougher for high stress ratio than that for low stress ratio. Cusps are more obvious with the increase of stress ratio. As a result, more energy will be released in crack growth at high stress ratio, leading to the fatigue resistance increase.

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