Mode I fatigue delamination growth in composite laminates with fibre bridging

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To my family

Contents

Summary

“Mode I fatigue delamination growth in composite laminates with fibre bridging”

by

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Advanced composite materials have been commonly used in aerospace engineering, because of their good mechanical properties and attractive potential for creating lightweight structures. Susceptibility to delamination is one of the most important issues in the applications of these materials. This disadvantage can prohibit the application of composite materials in primary aerospace structures and limit their lightweight potential. Therefore, characterizing fatigue delamination growth behavior in composite laminates is important for the applications of these materials in aerospace, as it provides the necessary information for the damage tolerance design philosophy.

Fibre bridging is an important shielding mechanism during delamination growth in composite laminates. It can increase the fracture toughness by restraining the crack opening and inhibit delamination growth. However, there is no reliable method to take into account of its contribution to fatigue delamination growth. Thus, investigation of this phenomenon and development of a prediction method is required.

The objective of this investigation is to study mode I fatigue delamination growth with fibre bridging in composite laminates and provide physics-based interpretations of fatigue delamination growth. Two approaches are applied to interpret the fatigue delamination growth behavior according to different perspectives. In the engineering perspective, the Paris relation is applied. However, in the physics-based perspective, energy principles are used.

The bridging effect on fatigue delamination growth is first investigated by a series of fatigue tests. The Paris relation is used to interpret the fatigue data. It demonstrates that fibre bridging can significantly decrease the fatigue crack growth rate, making it

invalid to use a single fatigue resistance curve to determine fatigue delamination with bridging. A new method, still based on the Paris relation, is developed to predict fatigue delamination growth with fibre bridging, by correlating the curve fitting parameters with the amount of bridging fibres.

Fatigue delamination growth is physically explained according to the energy conservation law. It is found that bridging fibres periodically store and release strain energy upon loading and unloading cycles. However, they have no contribution to the real strain energy release, unless the bridging fibre pullout or fails. This can lead to the invalidity of using the strain energy release rate (*SERR*) determined by the fixed grip assumption for quasi-static crack growth to interpret fatigue crack growth. Therefore, the *SERR* commonly used is not a suitable similitude parameter to determine fatigue delamination growth.

Energy principles are subsequently used to interpret the stress ratio effect in fatigue delamination growth. A concept of fatigue fracture toughness is proposed to describe the steady fatigue delamination growth, in which little or no bridging fibre pullout or failure occurs. Therefore, all energy dissipation in the steady delamination growth is concentrated on the new crack generation. The fatigue fracture toughness is observed to be interface configuration independent but significantly stress ratio dependent. The mechanisms related to this are interpreted by fractographic observation. Using the concept of fatigue fracture toughness, the stress ratio effect on fatigue delamination growth can be explained with a clear physical background.

Samenvatting

“Mode I vermoeiingsdelaminatiegroei in composietlaminaten met vezeloverbrugging”

door

Liaojun YAO

Geavanceerde composietmaterialen worden veel gebruikt in de luchtvaart- & ruimtevaarttechniek, vanwege hun goede mechanische eigenschappen en aantrekkelijke potentie voor het creëren van lichtgewicht constructies Gevoeligheid voor delaminatie is één van de belangrijkste schadeproblemen bij de toepassing van deze materialen. Dit nadeel kan de toepassing van composieten in primaire luchtvaartconstructies verbieden en de potentie tot lichtgewicht toepassingen limiteren. Daarom is het karakteriseren van vermoeiingsdelaminatiegroei in composietlaminaten belangrijk voor de toepassingen van deze materialen in de lucht- & ruimtevaart, aangezien dit de benodigde informatie levert voor de schade-tolerant ontwerpfilosofie.

Vezeloverbrugging is een belangrijk afschermingsmechanisme tijdens delaminatiegroei in composietlaminaten. Het kan de breuktaaiheid vergroten door het beperken van de scheuropening en tegengaan van delaminatiegroei. Er is echter geen betrouwbare methode om rekening te houden met de bijdrage van vezeloverbrugging aan vermoeiingsdelaminatiegroei. Onderzoek naar dit fenomeen en het ontwikkelen van een voorspellingsmethode is dus vereist.

Het doel van dit onderzoek is het bestuderen van mode I vermoeiingsdelaminatiegroei in composietlaminaten met vezeloverbrugging en het leveren van interpretaties van vermoeiingsdelaminatiegroei met een natuurkundige basis. Er worden twee aanpakken toegepast, om het vermoeiingsdelaminatiegroeigedrag volgens verschillende perspectieven te interpreteren. In de engineering-aanpak wordt de Paris vergelijking toegepast. Echter, in de natuurkundige benadering wordt gebruik gemaakt van energie-principes.

Het effect van vezeloverbrugging op vermoeiingsdelaminatiegroei wordt eerst onderzocht middels een serie vermoeiingsproeven. De Paris vergelijking wordt gebruikt om de vermoeiingsdata te interpreteren. Dit toont aan dat vezeloverbrugging

de scheurgroeisnelheid significant kan verlagen. Dit betekent dat het niet gerechtvaardigd is om een enkele vermoeiingsweerstandskromme te gebruiken om vermoeiingsdelaminatie met vezeloverbrugging te bepalen. Er wordt een nieuwe methode ontwikkeld — nog steeds gebaseerd op de Paris vergelijking— om vermoeiingsdelaminatiegroei met vezeloverbrugging te voorspellen, door het correleren van de *curve-fit* parameters met de hoeveelheid overbruggende vezels.

Vermoeiingsdelaminatiegroei wordt natuurkundig verklaard volgens de wet van energiebehoud. Er wordt gevonden dat overbruggende vezels periodiek rekenergie opslaan en loslaten tijdens belastings- en ontlastingscycli. Ze dragen echter niet bij aan de echte loslating van rekenergie, tenzij de overbruggende vezels *pull-out* of falen ondergaan. Dit maakt het ongepast om de rekenergieloslatingssnelheid (*SERR*) —bepaald volgens de *fixed grip* aanname voor quasi-statische scheurgroei— te gebruiken voor het interpreteren van vermoeiingsdelaminatiegroei. De veelgebruikte SERR is dus niet een geschikte gelijkheidsparameter om vermoeiingsdelaminatiegroei te bepalen.

Energieprincipes worden vervolgens gebruikt om het effect van spanningsratio op vermoeiingsdelaminatiegroei te interpreteren. Er wordt een vermoeiingsbreuktaaiheid concept voorgesteld om stabiele vermoeiingsdelaminatiegroei te beschrijven, waarin weinig tot geen *pull-out* of falen van overbruggende vezels plaatsvindt. Alle energiedissipatie wordt bij stabiele delaminatiegroei dus geconcentreerd op het genereren van nieuwe scheur. Er wordt gevonden dat de vermoeiingsbreuktaaiheid onafhankelijk is van raakvlakconfiguratie, maar significant afhankelijk is van de spanningsratio. De hieraan gerelateerde mechanismen worden geïnterpreteerd door fractografische observaties. Met het concept van vermoeiingsbreuktaaiheid kan het effect van spanningsratio op vermoeiingsdelaminatiegroei met een duidelijke natuurkundige achtergrond worden verklaard.

1

Introduction

1.1 Background

Advanced composite materials are often used in aeronautics and space engineering for their high strength-to-weight ratio and stiffness-to-weight ratio, the ability of tailor-design, etc. The requirements for fuel efficiency and lightweight structures have led to a great increase in the application of advanced composite materials in both military and commercial aircraft.

Increasing structures are made of composites, instead of metals, with the improvement of composite design and manufacturing technology and further understanding of their damage mechanics. In modern aircraft, such as the Boeing 787 Dreamliner and Airbus A350XWB, advanced composite materials make up 50% and 53% respectively of the structural weight [1].

Among different kinds of composite materials, carbon fibre reinforced polymer (CFRP) is one of the most attractive composites for aerospace engineering. This material contains two different elements, carbon fibre as reinforcement and epoxy as matrix. The stiffness and strength of a composite are mainly dependent on the properties of the reinforcement. The primary function of the matrix is to bind, support and protect the reinforcement. The macroscopic mechanical and physical properties of composite laminates are determined by several factors, including mechanical and physical properties of reinforcement and matrix, fibre/matrix interface, etc.

Because of the complexity of composite materials, different kinds of damage can occur in the application to composite structures, e.g. fibre breakage, matrix cracking, delamination between the adjacent layers, etc. Furthermore, there are interaction effects between the different types of damage, making it difficult to accurately characterize the damage evolution.

Composite laminates are susceptible to delamination, due to the lack of reinforcement in the thickness direction between adjacent layers. There is ample evidence to demonstrate that delamination is one of the most important and common damage type among all types of damage [2]. This damage can be induced by stress concentration, overload, low velocity impact or bad layup design, etc [3]. Delamination can propagate under fatigue loading, cause gradual strength and stiffness degradation, and finally lead to catastrophic failure of composite structures during their service lives. Studying fatigue delamination, therefore, has become necessary but challenging in the last several decades.

1.2 Scientific Research Motivation

Characterizing fatigue delamination in composite laminates is important for the application of these materials, as it provides the necessary information as input for a damage tolerance design philosophy.

Most people attempted to correlate fatigue crack growth rate with the concept of stress intensity factor (*SIF*) or strain energy release rate (*SERR*) in fracture mechanics to interpret the phenomenon of crack growth [1,4-5].However, it is noteworthy that these correlations are empirical methods. They are at most curve fittings to describe the fatigue crack growth behavior. They are not based on physical reasoning. This may lead to controversy in the interpretation of the fatigue crack growth behavior, such as the stress ratio effect.

Thus, it is necessary to provide insight into the fundamental mechanisms of fatigue crack growth as the first stage in investigating it. Based on the observation of the mechanisms, prediction models with clear physical background can be gradually developed to determine the fatigue crack growth. The stress ratio effect in fatigue crack growth can be physically interpreted.

Fibre bridging is a significant phenomenon in delamination in composite materials. Bridging fibres can increase the interlaminar resistance by restraining the crack opening during crack extension [6-8]. Methods to capture this phenomenon in quasi-static crack growth have been established. Prediction models have been developed with consideration of its contribution to crack growth [9-10]. However, this is not true for fatigue delamination. In fact, limited studies have been performed to focus on the bridging phenomenon in fatigue delamination growth. Thus, it is necessary and important to have a better understanding of fibre bridging effect in fatigue crack growth in order to eventually develop prediction models.

The first question raised here is what are the bridging effects on fatigue delamination growth and how to take into account these effects in a prediction model. The second question is how to interpret fatigue crack growth with physical reasoning.

1.3 Research Problems and Framework

This study tries to investigate the fibre bridging effect in fatigue delamination growth and provide an interpretation of fatigue delamination growth with clear physical meaning. The main questions can be summarized as

1. Bridging is common in crack growth in composite materials. What is the effect of bridging on fatigue delamination growth and how to take account of this contribution?

2. Crack growth is an energy dissipation process. It must obey the laws of physics on energy conservation. Energy principles, therefore, are reasonable for fatigue crack growth studies. How to provide a physical explanation of fibre bridging using the energy principles?

3. There is no consensus on stress ratio effect in fatigue crack growth. Is there a stress ratio effect or not? What damage mechanisms are related to the stress ratio effect?

To answer the above questions, mode I fatigue experiments have been conducted on Double Cantilever Beam (DCB) specimens.

The outline of this dissertation can be described as follows:

A literature review on the mode I fatigue delamination growth in composite materials is provided and discussed in Chapter 2.

A detailed introduction of the DCB specimen design and manufacturing, experiment test procedures and measurement techniques is given in Chapter 3.

An investigation of bridging effect on mode I fatigue delamination growth behavior in composite laminates is given in Chapter 4.

In Chapter 5, a new method is developed to describe the fatigue delamination growth behavior in composite laminates with large-scale fibre bridging.

In Chapter 6, the validity of the normalization method is thoroughly discussed and analyzed. Energy principles are applied to investigate the bridging phenomenon in fatigue delamination growth. A discussion on the use of strain energy release rate in fatigue delamination growth is given.

Subsequently, the energy principles are used to interpret the stress ratio effect on fatigue crack growth in Chapter 7. A concept of fatigue fracture toughness is proposed to physically explain the stress ratio effect in fatigue crack growth.

The final chapter outlines the conclusions and recommendations for future studies in fatigue delamination growth using the energy principles.

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2

Literature review on mode I fatigue delamination growth in composite materials

2.1 Introduction

This chapter provides a brief and critical literature review on previous studies of mode I fatigue crack growth in composite materials. The Paris relations adopted in fatigue delamination studies are introduced in section 2.2. Studies on the stress ratio effect on fatigue crack growth are critically reviewed in section 2.3. The fibre bridging effect and the normalization method in fatigue data analysis are introduced and discussed in section 2.4.

2.2 Paris relation

Fatigue crack growth 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 [1-3]. The prediction methods and models can be classified into four major categories [1]:

1. Stress/strain based methods
2. Fracture mechanics based methods
3. Cohesive zone models
4. Extended finite element models

In this classification, methods based on the fracture mechanics concepts of stress intensity factor (*SIF*) *K* and strain energy release rate (*SERR*) *G* have been widely employed to investigate crack growth.

In fracture mechanics, the concept of *SIF* is used to determine the stress field around a crack tip. Using this concept, crack growth criteria and prediction models have been proposed to describe the quasi-static crack growth as well as the fatigue crack growth. In fatigue crack growth studies, Paris and co-workers [2,3] first found an approximately linear relation between the *SIF* and the fatigue crack growth rate *da/dN*, if *da/dN* was plotted against the *SIF* on a double logarithm scale implying a power law relationship. The crack growth therefore can be determined by the calculation of the *SIF*. Basic forms of Paris relations are given by

$$\frac{da}{dN} = c(\Delta K)^n \tag{2.1}$$

$$\frac{da}{dN} = c(K_{max})^n \tag{2.2}$$

Where c and n are two curve-fitting parameters. ΔK and K_{max} are the range and maximum *SIF* in a fatigue load cycle. Some people believe that c and n are material properties. However, these two coefficients are related to the stress ratio R or the mean stress of the fatigue load cycle.

Instead of using the *SIF* as the similitude parameter, people usually employ the *SERR* to determine the Paris relation for composite materials. This relates to the complexity of *K* calculation around a crack tip in inhomogeneous materials or the interface of 2 dissimilar materials [4] and the relation between *K* and *G* [5]. This relation is shown by Equation (2.3).

$$G = \frac{K^2}{E'} \tag{2.3}$$

Where E' is a stiffness that is associated with stress state in the vicinity of the crack front. E' is equal to the Young modulus E in plane stress state and is equal to $\frac{E}{1-V^2}$ in plane strain state.

Thus Paris relations based on *SERR* are usually used to determine the fatigue delamination growth in composite materials or adhesively bonded structures [6-29]. The Paris relation was initially used to investigate fatigue delamination in fibre metal laminates by Roderick [6,7]. This relation was subsequently applied to determine fatigue crack growth in the studies of other researchers [8-12]. Basic forms of Paris relations in fatigue crack growth in composite materials are given by

$$\frac{da}{dN} = c(\Delta G)^n \tag{2.4}$$

$$\frac{da}{dN} = c(G_{max})^n \tag{2.5}$$

2.3 Mode I fatigue delamination growth

2.3.1 Stress ratio effect on mode I fatigue crack growth

The stress ratio *R*, the ratio of minimum stress to maximum stress in a cycle, is an important factor in the characterization of fatigue loading. It has a significant effect on fatigue crack growth in composite materials. A large number of studies have been performed on this effect.

In a study of Gustafson [13], the fatigue crack growth rate *da/dN* was plotted against the maximum *SERR* G_{max} and the *SERR* range $\Delta G=G_{max}-G_{min}$. A stress ratio effect was evident if *da/dN* was correlated to the maximum *SERR*, but became ambiguous once *da/dN* was plotted against the *SERR* range. Hojo [14] made the same conclusions in another study on fatigue delamination growth in composite laminates.

Mall [15] investigated the stress ratio effect on fatigue crack growth in bonded structures. Both maximum *SERR* and *SERR* range were used to interpret the experimental data. The stress ratio effect was obvious in the application of G_{max} as similitude parameter. It became ambiguous using $\Delta G=G_{max}-G_{min}$ as the similitude parameter. Mall therefore concluded that *SERR* range should be the driving force for fatigue crack growth.

In the study of Atodaria et al [16-18], both of the maximum *SIF* and *SIF* range were used as similitude parameters in the Paris relations. They observed that fatigue crack growth was significantly stress ratio dependent. It increased with the increase of the stress ratio when da/dN was correlated with ΔK, but decreased when da/dN was correlated with K_{max}.

Shahverdi [26] conducted an investigation on the stress ratio effect on fatigue crack growth in bonded structures. Both G_{max} and ΔG were applied in the Paris relations to interpret the experimental results. The stress ratio effect observed in this study was the same as in previous studies [13-15].

Most previous studies on the stress ratio effect in fatigue crack growth were based on the Paris relations, either in the form of da/dN against G_{max} (K_{max}) or da/dN against ΔG (ΔK). The stress ratio effect is observed to be significant using Paris relations. The stress ratio effect on fatigue crack growth seems to be similitude parameter dependent. In case of G_{max} or K_{max}, crack growth is lower with the increase of stress ratio. This is completely opposite to using *SERR* or *SIF* range.

2.3.2 Similitude parameter in the Paris relations

There is no consensus on the formulation of similitude parameter in the Paris relation. The maximum *SERR* G_{max} and the *SERR* range ΔG were alternatively used to correlate the fatigue crack growth [13-15,18,20-28].Some people [14,15,20-28] believed that G_{max} played a dominant role in the fatigue delamination growth and attempted to correlated crack growth with G_{max}. However, others argued that G_{max} failed to take account of the minimum *SERR* G_{min} in a fatigue cycle and its contribution to the crack growth. The *SERR* range, therefore, was recommended in the Paris relations [13-15,18,26].

It is worth noting that there is controversy on how to determine the *SERR* range in fatigue loading. Some people tended to take the difference between the minimum and maximum *SERR*, i.e. $G_{max} - G_{min}$ in fatigue crack growth studies[13-15], while others preferred to use $\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$ [4,18,30]. For this controversy, Rans et al [31] provided a thorough discussion and analysis on the formulation of *SERR* range using the similitude principle. It was evident that the first definition of *SERR* range, $G_{max} - G_{min}$, is a function of both amplitude and mean stress. The second definition of *SERR* range, $\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$, is only dependent on the stress amplitude and is equivalent to *SIF* range ΔK. On this point, they suggested that the *SERR* range should be redefined as $\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$. The authors also argued that using the inappropriate definition of *SERR* range will lead to misinterpreting the fatigue results.

Based on the study of Rans [31], Khan et al [32,33] made a comparison on the fatigue data interpretation with different formulations of *SERR* range. It was concluded that using G_{max}-G_{min} as the similitude parameter to explain fatigue results may lead to the stress ratio effect on fatigue crack growth being ambiguous. But there was still a clear stress ratio effect in fatigue crack growth once the fatigue crack growth was corrected with $\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$, as shown in Figure 2.1. Thus, the definition of *SERR* range as $\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$ seems to be a more reasonable similitude parameter in the interpretation of fatigue data with stress ratio effect compared to $G_{max} - G_{min}$.

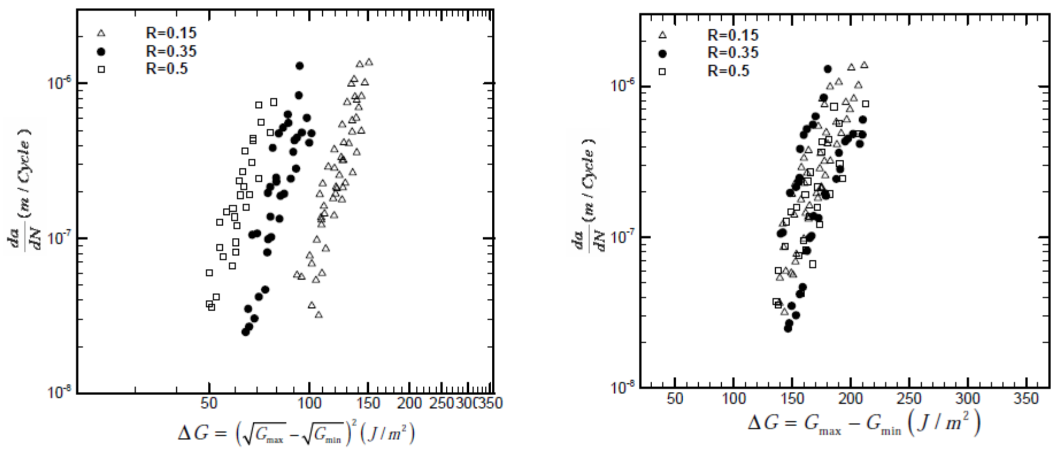


Figure 2.1 Fatigue crack growth rate against

different definitions of *SERR* range [32]

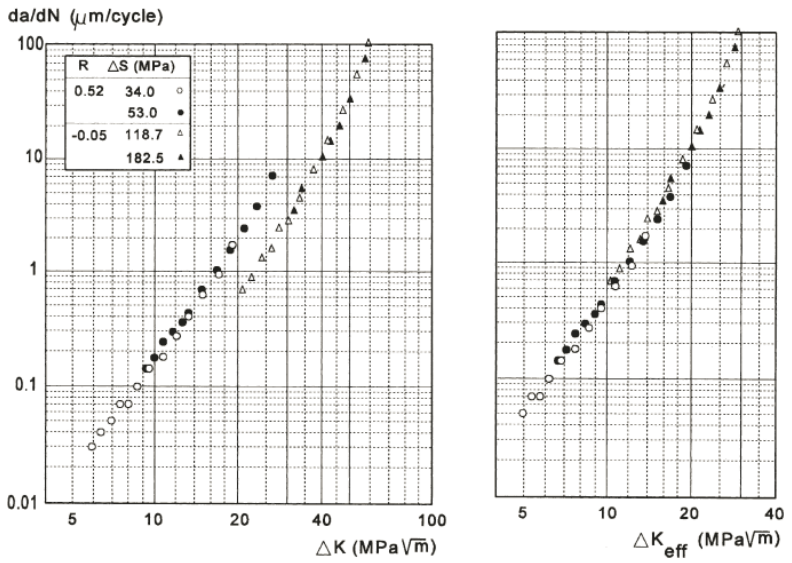
2.3.3 Crack closure in fatigue delamination growth in composite materials

In metals, Elber's crack closure theory has been used to interpret the stress ratio effect [34]. Crack closure is the phenomenon that the crack surfaces come into contact during unloading before the tensile stress reaches the minimum load in a fatigue cycle. It is more obvious in fatigue tests with low stress ratio. The major reason for crack closure in metals is plastic deformation around the crack front. This phenomenon will cause an effective load amplitude to be smaller than the applied amplitude. With consideration of crack closure, an effective *SIF* range was therefore proposed to characterize the fatigue crack growth in metals, see Equation (2.6).

$$\Delta K_{eff} = K_{max} - K_{closure} \tag{2.6}$$

Where $K_{closure}$ is the *SIF* at the load that crack closes.

The stress ratio effect on fatigue crack growth disappears when using ΔK_{eff} as the similitude parameter to interpret the fatigue data [35], as shown in Figure 2.2. This is reasonable. The effective *SIF* range ΔK_{eff} are actually related to both ΔK and the stress ratio R. Thus, the effect of stress ratio on the fatigue crack growth has been considered by ΔK_{eff}.



(a) da/dN as a function of ΔK (b) The results of (a) plotted as a function of ΔK_{eff}

Figure 2.2 Fatigue crack growth correlated to ΔK and ΔK_{eff} in Al-alloy (2024-T3) at different stress ratios [35]

However, in a study by Khan [36], plasticity was not observed in fatigue delamination growth in composite laminates. Thus, the mechanism for crack closure in composite materials differs from that in metals. In his study, crack closure was only observed to occur at low stress ratios in the composite laminates, because of fibre/matrix debris and misaligned damaged fibres on the fracture surfaces. But this phenomenon was not observed at high stress ratios, where stress ratio effect is still present. As a result, it is not reasonable to use the crack closure theory to explain the stress ratio effect in fatigue delamination growth in composite materials.

2.3.4 Two-parameter fatigue crack growth models

Some researchers explained the stress ratio effect by highlighting the fact that a load cycle and its effect on fatigue crack growth cannot be uniquely described by a single parameter [14,16-18,33,37-39]. A typical constant amplitude cyclic load is given in Figure 2.3. To uniquely determine a fatigue load at least two parameters should be used. Neither maximum *SERR* nor *SERR* range provides enough information to fully describe a fatigue loading. Two-parameter models were therefore proposed to characterize fatigue crack growth.

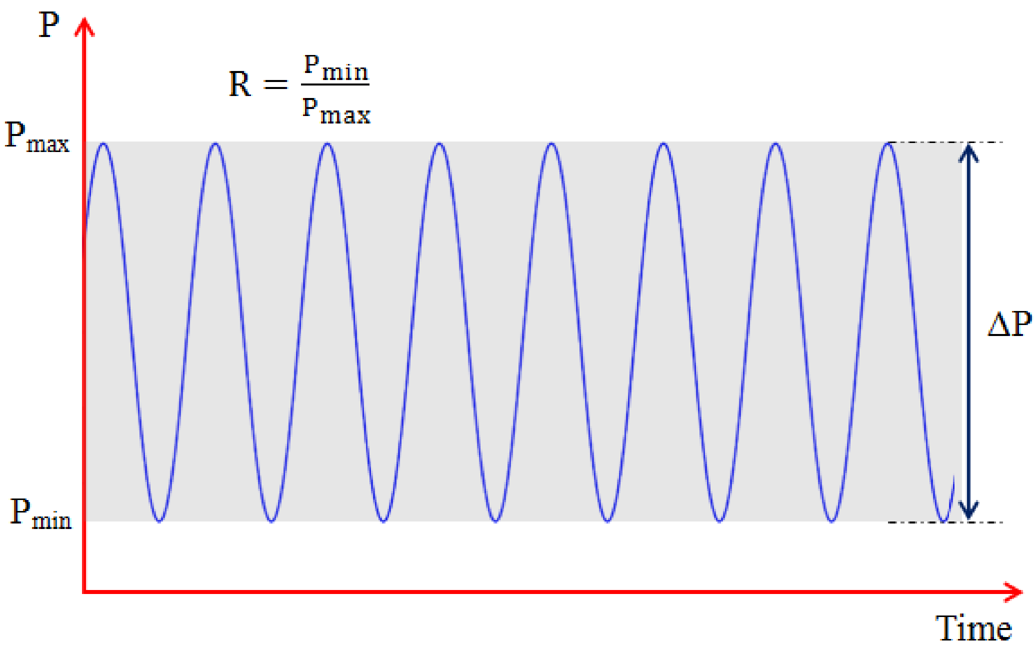


Figure 2.3 Constant amplitude fatigue load

Hojo [14] proposed an empirical model to characterize the fatigue delamination growth in composite laminates using K_{max} and ΔK as the similitude parameters. This model can be expressed as

$$\frac{da}{dN} = c\Delta K^{(1-\gamma)n} K_{max}^{\gamma n} \tag{2.7}$$

Here γ is an empirical material parameter that varies between 0 and 1. A high γ indicates that fatigue delamination growth is significantly determined by the maximum *SERR*. The fatigue damage mechanics in this case seem to be similar to quasi-static delamination. A low γ means that the *SERR* range plays an important role in fatigue crack growth. Thus, the damage mechanics in fatigue loading is different from that in quasi-static loading.

Hojo's model has been further developed by other researchers to investigate the fatigue delamination growth in composite materials in the form of *SERR* [31,37]. In a study of Rans et al [31], the equivalent form of Equation (2.7) was reproduced as

$$\frac{\mathrm{da}}{\mathrm{dN}} = \mathrm{c}\left(\sqrt{\mathrm{G_{max}}} - \sqrt{\mathrm{G_{min}}}\right)^{2(1-\gamma)} \mathrm{G_{max}^{\gamma n}} \tag{2.8}$$

Jia and Davalos [37] proposed a new model to determine the fatigue crack growth in wood/fibre reinforced polymer laminates. This model is given by

$$\frac{\mathrm{da}}{\mathrm{dN}} = \mathrm{c}\left(\Delta \mathrm{G}^{(1-\gamma)} \mathrm{G_{mean}^{\gamma}}\right)^{\mathrm{n}} \tag{2.9}$$

where G_{mean} is the mean *SERR* in a fatigue load.

Atodaria [16-18] also proposed a two-parameter model. This model is given by

$$\frac{\mathrm{da}}{\mathrm{dN}} = \mathrm{c}\left(\Delta \mathrm{K} \mathrm{K_{average}}\right)^{\mathrm{n}} \tag{2.10}$$

where $K_{average}$ can be determined by

$$\mathrm{K_{average}} = \left[\frac{1}{\mathrm{M}} \sum_{\mathrm{K_{th}}}^{\mathrm{K_{max}}} \mathrm{K}^{\omega}\right]^{\frac{1}{\omega}} \tag{2.11}$$

Here M is the partition number between the threshold to the maximum *SIF* in a fatigue cycle; ω is a weight factor determined by experiments.

Recently, a new two-parameter model was proposed by Khan et al [33,38,39]. In their study, the fatigue loading was characterized by a monotonic part G_{max} and a cyclic part ΔG. Based on fractography, dominant features of a fatigue fracture surface were determined first. Correlations between these features and each individual part of a fatigue load, G_{max} and ΔG, were subsequently established. Based on these correlations, a new model was proposed to determine the fatigue crack growth. The general form of this model is given by

$$\frac{da}{dN} = A(G_{max})^m + B(\Delta G)^n \tag{2.12}$$

where A, B, m and n are curve fitting parameters.

The stress ratio effect on fatigue crack growth vanished using two-parameter models to interpret the experimental data, as shown in Figure 2.4.

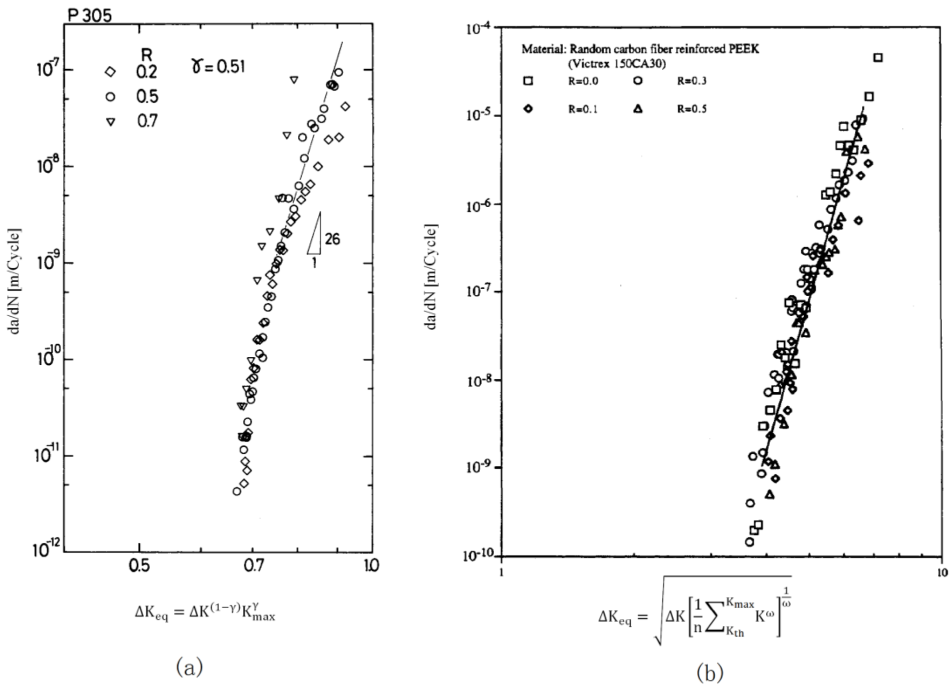


Figure 2.4 Two-parameter fatigue models

(a) Hojo's model; (b) Atodaria's model

However, it is worth noting that these models are still empirical models and cannot physically explain the stress ratio effect. In the first three models [14,16-18,37], the monotonic component G_{max} and cyclic component *SERR* range of a fatigue cycle were multiplied to generally determine the crack growth. However, the damage mechanisms under monotonic and cyclic load are different. The interaction effects between damage in monotonic and cyclic load are not identified. Thus, it is questionable to simply multiply the G_{max} and *SERR* range as the similitude parameter to correlate fatigue delamination growth. Particularly, in Hojo's model, it was found that the parameter γ was not a constant value for the same material. It seemed to be crack growth rate dependent [20]. Hence, γ may be not a material property.

Khan et al [30] further argued that this model only worked in a specific range of fatigue crack growth rates and the discrepancy of this model became more obvious at a high crack growth rate. For the model of Atodaria [16-18], there was no reasonable method suggested to determine the parameter M to divide a single fatigue load cycle [30]. The hypothesis that the weight factor ω was load independent is unreasonable either. Because the contribution of a high load level to the damage evolution should be larger than a low load level. In Khan's studies [33,38,39], the interaction effects between G_{max} and ΔG were carefully investigated using SEM fractography. He concluded that the effects of G_{max} and ΔG on the morphology were independent. The fatigue crack model was therefore a linear superposition of damages related to G_{max} and ΔG in his study. However, Khan still used the Paris relation to determine fatigue crack growth.

These two-parameter models attempted to explain the stress ratio effect on fatigue crack growth by the unique description of the fatigue loading. With these models, people indeed have a further understanding of the contribution of each load part, G_{max} and ΔG, to fatigue crack growth. Even though most of two-parameter models are still empirical curve fits, they can provide detailed information and clues for the further studies on the stress ratio effect.

2.4 Fibre bridging in delamination growth

Fibre bridging is an important shielding mechanism in delamination growth in composite materials under quasi-static and fatigue loading. Bridging fibres in the wake of delamination front will restrain the crack opening and decrease the stress intensity around the crack tip. Thus, they inhibit delamination propagation.

There is ample evidence that interlaminar toughness will increase with the delamination extension due to fibre bridging. A large number of studies have been conducted to investigate this phenomenon in quasi-static delamination growth [33-41]. As a result, methods have been developed to characterize its contribution in quasi-static loading. The concept of the resistance curve (R-curve), plotting *SERR* against crack propagation length, is commonly applied to describe the resistance increase in quasi-static crack growth. However, this method only phenomenologically describes the bridging effect on quasi-static crack growth.

To have a better understanding of bridging, Suo [40] provided a thorough discussion on this for quasi-static delamination. A method was proposed to quantify the bridging stress distribution in the bridging area. This method has been subsequently used in fibre bridging studies [41,42]. Botsis [43-45] recently developed a new method to determine the bridging stress distribution using fibre bragg grating sensors.

However, few studies on the effect of fibre bridging in fatigue delamination growth have been published. Hwang and Han [49] were the first to investigate fatigue delamination growth combined with fibre bridging. They observed that the crack growth rate decreases because of fibre bridging. Hojo [20] proposed constant G_{max} tests to investigate the bridging effect during fatigue delamination growth. Again bridging decreases the delamination growth rate.

Recently, Khan et al [33,36] introduced a fibre cutting method to get rid of bridging during the fatigue crack growth, in order to investigate the bridging effect on the crack growth behavior and stress ratio. Besides the decrease in fatigue crack growth, it was also observed that both minimum and maximum load decrease once bridging fibres were removed. However, fibre bridging has no or little influence on the stress ratio. Thus, a single resistance curve could be used to determine the fatigue crack growth with or without bridging. An example of fatigue delamination growth with or without fibre cutting is given in Figure 2.5. There is clear evidence that all data from tests with same stress ratio is located on the same resistance curve.

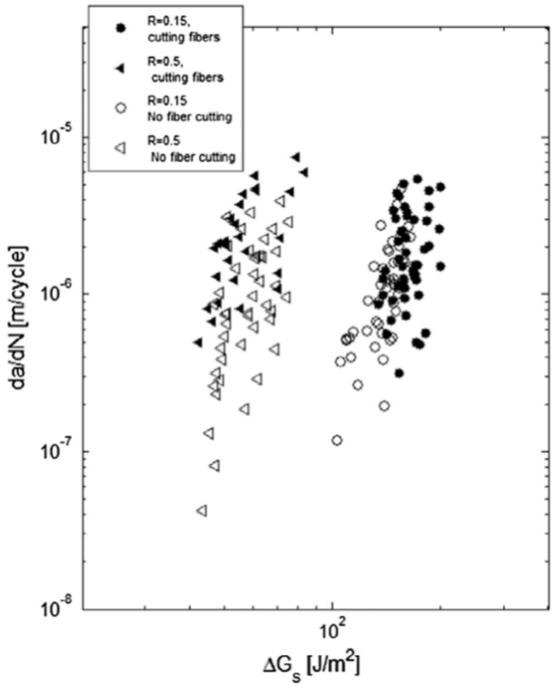


Figure 2.5 Fatigue tests with and without bridging fibre cutting [36]

Gregory et al [50] proposed a fibre bridging model to investigate the fatigue delamination growth behavior in composite materials. In their studies, the total *SIF* in crack growth was physically divided into two parts, i.e. $K_{tip}=K_{applied}-K_{bridging}$. Experimental fatigue data could be appropriately interpreted by the similitude parameter of K_{tip}. The trend, however, seemed to be ambiguous once using $K_{applied}$ as the similitude parameter. This indicates that the fibre bridging has significant effect on the data interpretation and inappropriate use of similitude parameter can lead to misinterpret the results.

All the above studies on bridging in fatigue delamination growth were generally based on Paris relations and lacked of a physical explanation. The questions that arise here are what are the bridging effects in fatigue delamination growth and how should they physically be explained and appropriately taken into account.

2.5 Normalization method in fatigue data analysis

A normalization method is used in some fatigue delamination studies [21,25,27,49,52-58]. This application of a normalization method in fatigue delamination growth studies originates from the concept of determining the relative driving force of a material [51]. A discussion on the validity of this approach has been presented by Pascoe [1]. In practice, the *SERR*, i.e. G_{max} or ΔG, in fatigue delamination growth is normalized with the quasi-static critical *SERR*. The general forms of the Paris relations after normalization can be summarized as

$$\frac{da}{dN} = c\left(\frac{G_{max}}{G_{IC}}\right)^n \tag{2.13}$$

$$\frac{da}{dN} = c\left(\frac{\Delta G}{G_{IC}}\right)^n \tag{2.14}$$

The critical *SERR* is not a constant value in case of crack growth with fibre bridging, making the application of a constant *SERR* unreasonable. Instead of using a constant *SERR*, Poursartip [52] recommended to normalize fatigue data with the quasi-static R-curve. Hwang [49] used this normalization to establish a Paris type relation for fatigue delamination study. Murri [53,54] also normalized G_{max} in fatigue tests with the quasi-static R-curve in her studies and developed a Paris type relation to characterize the fatigue delamination growth in composite laminates.

Zhang [25] proposed a 're-loading approach', in which specimen with a certain fatigue crack length was quasi-statically loaded to obtain the corresponding fracture toughness, and used this fracture toughness, instead of the R-curve that from quasi-static delamination tests, to normalize fatigue results. But this method has the shortcoming that the damage state of the specimen is destroyed during the re-loading cycle [1]. To overcome this disadvantage, in the following studies [55,56], a new method, called compliance approach, was used to determine the resistance. The hypothesis of the compliance approach is that specimens with fatigue or quasi-static delamination that demonstrated the same force and displacement response should have the same resistance.

The normalization was also used to develop prediction models with consideration of threshold region and unstable crack growth region. These models derives from 4 basic assumptions mentioned by Shivakumar [21] and covers three typical regions, i.e. threshold region, stable and unstable crack growth regions, of a fatigue delamination growth. A general form of these models has first been given by Martin and Murri [57]

$$\frac{da}{dN} = c(G_{max})^n \frac{\left[1-\left(\frac{G_{th}}{G_{max}}\right)^{n1}\right]}{\left[1-\left(\frac{G_{max}}{G_c}\right)^{n2}\right]} (G_{th} \leq G_{max} \leq G_c) \qquad (2.15)$$

where G_{th} is the threshold; G_c is the critical *SERR* in quasi-static delamination.

In these models, crack growth becomes to infinite once G_{max} is approaching G_c, equivalent to quasi-static delamination growth. There is no crack growth once G_{max} is equal to the threshold value. These models with similar forms to equation (2.15) were proposed by other researchers. In a study of Shahverdi [27], constant quasi-static resistance was used in the model, as equation (2.16), to predict the stress ratio effect on fatigue crack growth in adhesively bonded structures. However, in other studies [21,58], the R-curve, G_{IR}, was applied to take into account of bridging effect on the increase of toughness in delamination growth, see Equation (2.16).

$$\frac{da}{dN} = c\left(\frac{G_{max}}{G_{IR}}\right)^n \frac{\left[1-\left(\frac{G_{th}}{G_{max}}\right)^{n1}\right]}{\left[1-\left(\frac{G_{max}}{G_{IR}}\right)^{n2}\right]} (G_{th} \leq G_{max} \leq G_{IR}) \qquad (2.16)$$

It should be kept in mind that the damage mechanics in quasi-static crack growth differs from that in fatigue. There is no evidence to support the assumption that there is a correlation between fatigue resistance and quasi-static resistance. As a result, there is no consensus on the application of the normalization method in fatigue data analysis [1].

2.6 Conclusions

This chapter provides a brief review on the present studies on mode I fatigue delamination growth in composite materials. The Paris relations are often used to interpret the fatigue crack growth. However, this method is curve-fitting. To have a better understanding of fatigue delamination, a method based on physical interpretation of this issue should be developed.

The stress ratio effect is a significant phenomenon in fatigue crack growth. Some explanations have been proposed to interpret this effect. However, the damage mechanisms related to this effect in composite laminates is still not clear.

A limited number of studies have been performed on fibre bridging, leading to lack of understanding of its mechanism and contribution to fatigue crack growth. There is no reliable method to take account of its effect on fatigue delamination growth. It is therefore necessary to further study this phenomenon and to develop a method that takes into account of its contribution.

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3

Experiments and measurement technique description

3.1 Introduction

This chapter provides information associated with the mode I fatigue delamination tests of this thesis. This includes layup sequence design, manufacturing of specimens, experimental set-ups, measurement techniques and experimental procedures. In particular, section 3.2 gives an introduction on stacking sequence design for multidirectional DCB specimens. The manufacturing process is described subsequently. Section 3.3 and 3.4 describe the quasi-static and fatigue delamination setups and data reduction methods respectively. Section 3.5 provides detailed information of experiments related to the study on the fibre bridging effect. In section 3.6, a special test procedure is described to study fatigue crack growth with different amount of fibre bridging. To verify the validity of the normalization method in fatigue data analysis, a special test program is presented in Section 3.7. In section 3.8, experiments for studying the stress ratio effect are introduced.

3.2 Material and specimen manufacturing

3.2.1 Lay-up sequence design

Unidirectional DCB specimens are commonly used to study the delamination growth behavior in composite materials. However, an increasing number of studies have demonstrated that delamination growth is significantly interface configuration dependent [1-3]. Thus, quasi-static delamination studies have been conducted on multidirectional DCB specimens recently [4-9]. However, for studying fatigue delamination, most experiments were still performed on unidirectional DCB specimens, regardless of effect of layup sequence on crack growth.

To investigate the fatigue delamination growth behavior in composite laminates including the effect of fibre orientation at the interface, DCB specimens with 0//0 interface and 45//45interface (// indicates the delamination plane) were made of CFRP M30SC/DT120, a prepreg with high strength and modulus carbon fibre/toughened thermosetting epoxy. This prepreg was supplied by Delta-Tech S.p.a Italy and its elastic properties are summarized in Table 3.1.

Table 3.1 Elastic property of M30SC/DT120 prepreg [10]

Longitudinal elastic modulus E_{11} [GPa]	155
Transverse elastic modulus E_{22} [GPa]	7.8
In plane Poison ratio v_{12}	0.27
In plane shear modulus G_{12} [GPa]	5.5

Composite laminates for unidirectional DCB specimens were made of 32 plies of the prepreg with a unidirectional layup. A pre-crack was introduced in the middle plane of the laminates by inserting a Teflon layer with 12.7μm thickness during the hand-lay-up process. The stacking sequence for unidirectional DCB specimens was $[(0_{16})//(0_{16})]$.

For multidirectional specimens, the layup sequence had to be designed with the consideration of three issues, i.e. crack jumping and non-uniform strain energy release rate distribution across the width of the crack front and residual thermal stress.

Crack jumping is a crack plane migration phenomenon during delamination growth that crack propagates from the pre-cracked plane to the neighbor layers. This phenomenon should be avoided during delamination growth. Robinson [11] suggested introducing a delaminated edge along the DCB specimen to avoid crack jumping.

Experimental results demonstrated that crack jumping can be avoided to a certain extent by this method. But using a delaminated edge can lead to difficulty in the monitoring of the crack front during the test. Morais [2] and Andersons [4] made a conclusion that bending stiffness degradation of a DCB specimen was the reason for crack jumping. Sebaey [5,6] investigated this problem with both numerical and experimental approaches. As a result, a layup sequence was recommended for multidirectional DCB specimens.

A non-uniform strain energy release rate distribution is an important issue when investigate the delamination growth in multidirectional DCB specimens. A non-uniform distribution means the strain energy release rate in the centre of a DCB specimen is different from that in the edge region. This causes a curvature of the delamination front, as shown in Figure 3.1. An interpretation for this phenomenon is the difference of stress state. It is plane strain state in the middle of DCB specimen and plane stress state in the edge region. As a result, crack propagation in the middle of DCB specimen is faster than that at the borders.

Davidson [7,8] found that longitudinal/transverse bending coupling and bending/twisting coupling of a multidirectional DCB specimen have important influence on the shape of the delamination front. Two dimensionless factors, D_c and B_t, were proposed to quantify these coupling effects. The definitions of D_c and B_t are given by Equation (3.1) and Equation (3.2).

$$D_C = \frac{{D_{12}}^2}{D_{11} D_{22}} \tag{3.1}$$

$$B_t = \frac{|D_{16}|}{D_{11}} \tag{3.2}$$

where D_{11}, D_{22}, D_{12} and D_{16} are stiffness coefficients of the DCB specimen.

In ideal conditions, these two parameters should be zero. However, in practice, D_c was recommended to be no more than 0.25 and B_t should be approaching zero, to minimize the non-uniform strain energy release rate distribution in delamination growth.

The third issue associated with multidirectional specimen layup design is the residual thermal stress. According to previous studies [4,7,9,11], the layup was recommended to be balanced and symmetric for DCB specimens with *θ//θ* interface, i.e. [Θ/-Θ//-Θ/Θ] (Θ represents a sub-layup with symmetric stacking sequence). It was recommended to be anti-symmetric for DCB specimens with *θ//-θ* interface, i.e. [Θ/-Θ//Θ/-Θ].

According to previous studies on the layup design, especially the recommendation from Sebaey [5,6], the stacking sequence for DCB specimen with 45//45 interface was designed as $[(\pm45/0_{12}/\mp45)//(\pm45/0_{12}/\mp45)]$. Two factors, D_c and B_t, for this stacking sequence are given in table 3.2. D_c is smaller than the recommended limit 0.25 and B_t is relatively small.

Table 3.2 Parameter D_c and B_t for multidirectional layup

D_C	0.167
B_t	0.032

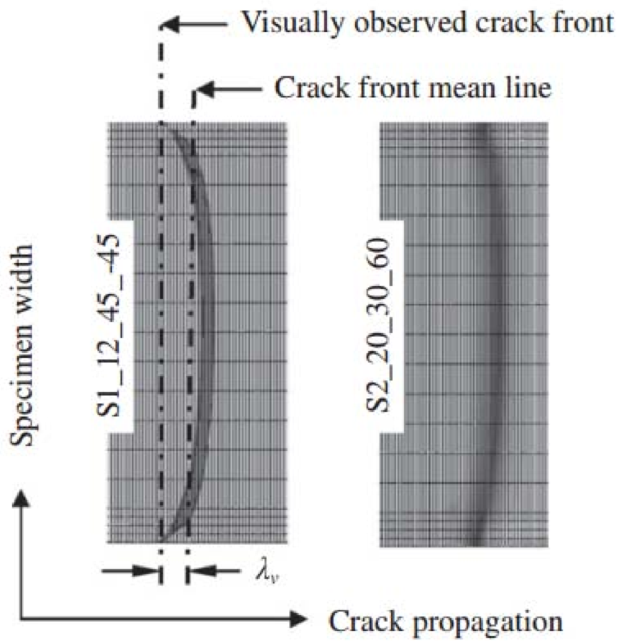

Figure 3.1 Curvature of the delamination front

in multidirectional DCB specimen[5]

3.2.2 Specimen manufacturing

Composite laminates were laid up with the designed stacking sequences and cured in an autoclave. A recommended curing procedure from the supplier is illustrated in Figure 3.2. Laminates were cured at a pressure of 6 bars and a temperature of 120℃ for 90 minutes.

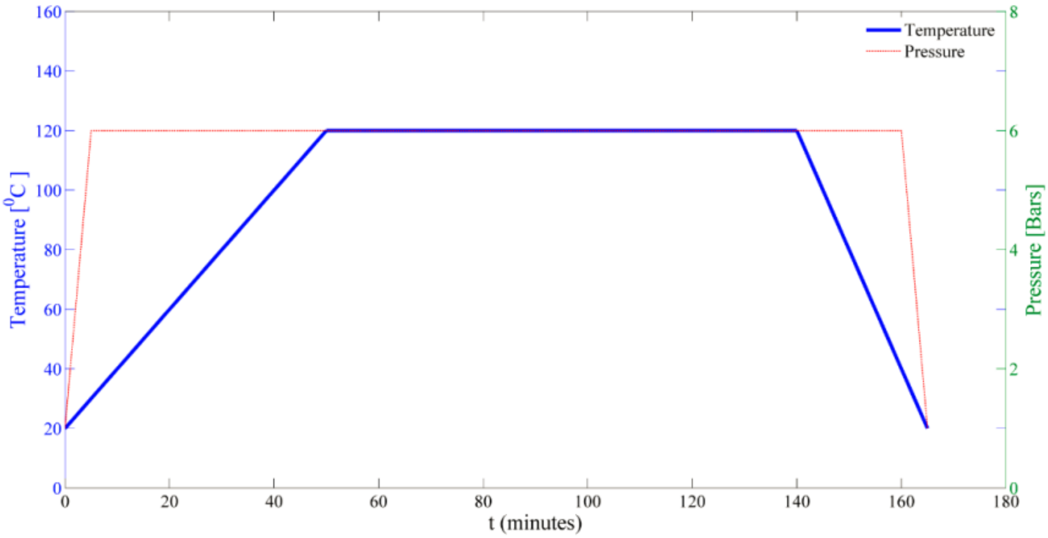

Figure 3.2 M30SC/DT120 curing procedure.

After curing, the laminates were C-scanned for imperfections, as shown in Figure 3.3. Then, DCB specimens, 200 mm length by 25mm width with nominal thickness of 5mm, were cut from areas of the panel without obvious imperfections using a diamond-coated cutting machine. A pair of aluminum blocks, 25mm width by 20mm length with 6mm thickness, was adhesively bonded to the specimen's end for load introduction, as shown in Figure 3.4. One side of the specimen was coated with thin typewriter correction fluid to enhance visibility of the delamination front during the test. A strip of grid paper was pasted on the specimen side to aid in measuring the delamination length.

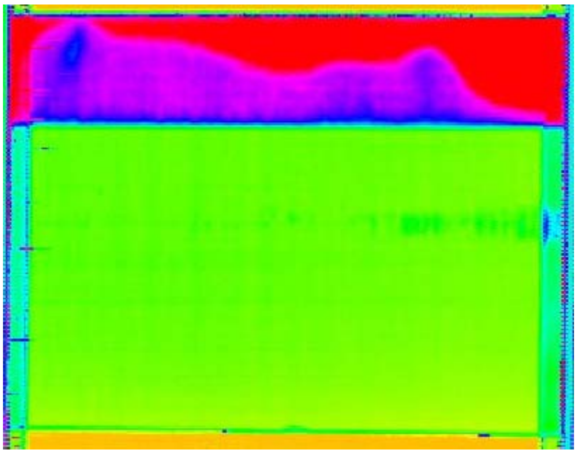

Figure 3.3 C-scan result

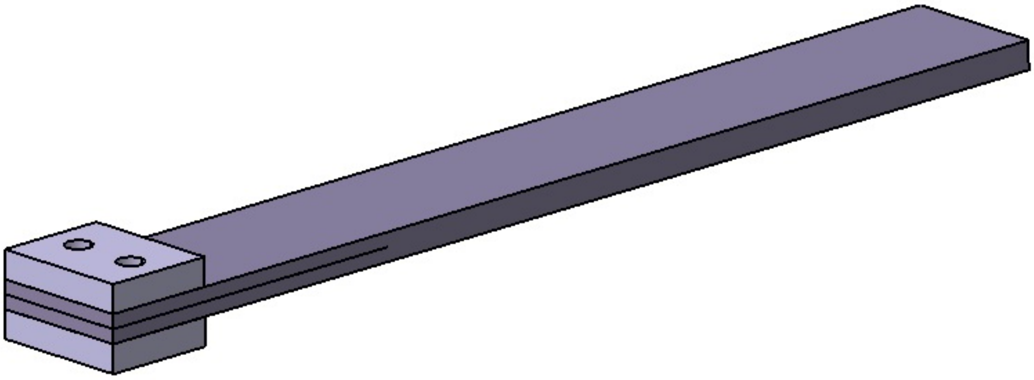

Figure 3.4 DCB specimen

3.3 Quasi-static delamination growth experiment

Quasi-static delamination tests were performed according to ASTM D5528 [12]. This standard has been widely used to characterize mode I delamination growth behavior in composite laminates and adhesively bonded structures under monotonic loading.

All quasi-static tests were carried out on a 20kN tensile-compression Zwick machine. They were performed under displacement control with an applied displacement rate of 1mm/min. A high resolution digital camera and computer system was used to monitor the delamination growth by automatically recording an image of the specimen edge every 5 seconds. The load and displacement information was stored in an Excel file enabling data analysis after the tests. The quasi-static experimental setup is shown in Figure 3.5.

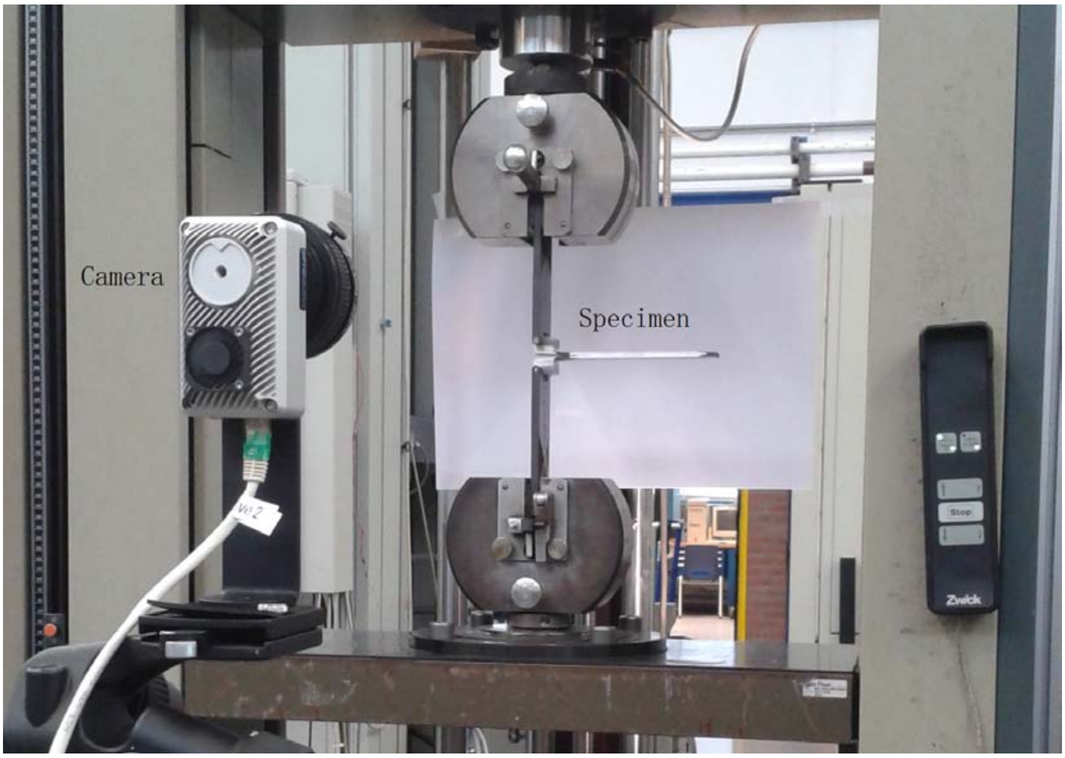

Figure 3.5 Quasi-static experimental setup

3.4 Fatigue delamination growth experiments

3.4.1 General information on fatigue experiments

Hitherto, there is no standardized test procedure for mode I fatigue delamination growth in composite materials. In order to establish an experimental standard to guide future studies, the European Structural Integrity Society Technical Committee 4(ESIS TC4) and the American Society for Testing and Materials, International, Subcommittee D30.06 (ASTM D30.06) have finished round robin tests to investigate a series of factors in mode I fatigue delamination growth with unidirectional DCB specimens [13-17]. These factors include the control mode (load control vs. displacement control), test frequency, data reduction methods, etc.

In general, fatigue crack growth tests can be conducted on specimens with either displacement control or force control. Under displacement control, the increase of specimen compliance resulting from the delamination propagation will lead to the reduction of the effective applied loading and to the decrease of the fatigue crack growth rate with increasing cycle number. It is worthwhile to highlight that displacement controlled fatigue tests take the advantage of starting the test with a really fast initial crack growth using an applied load close to the critical load [14]. As a result, a large range of fatigue crack growth rates could be obtained after the tests.

Under force control, the increase of specimen compliance due to crack propagation will lead to the increase of the applied displacements. As a result, the fatigue crack growth rate will accelerate from a relatively low level to a high level and may finally cause quasi-static failure, once the applied maximum load is larger than the critical force at a given crack length. The disadvantage of force control is that it is hard to determine a reasonable maximum force at the beginning of a fatigue test to obtain a large range of da/dN values [14]. A low initial maximum force will lead to a very long test duration.

Therefore, all fatigue tests in this study were conducted on a 10kN hydraulic MTS machine under displacement control at a frequency of 5Hz. Prior to each fatigue test, the specimen was quasi-statically loaded to generate a natural crack tip with visual crack growth onset. Then, the fatigue test was conducted on the specimen with a given stress ratio R. Images of the fatigue crack extension at one side of the specimen were automatically recorded at the maximum displacement during the test with a digital camera controlled by the computer system. The interval was set to be every 100 cycles in the first 5000 fatigue cycles, every 500 cycles in the following 15000 fatigue cycles, and every 1000 cycles when the fatigue cycle number exceeded 20000. The load, displacement and number of cycles were automatically stored in an Excel file every 100 cycles enabling data evaluation after the test. The experimental set up is demonstrated in Figure 3.6.

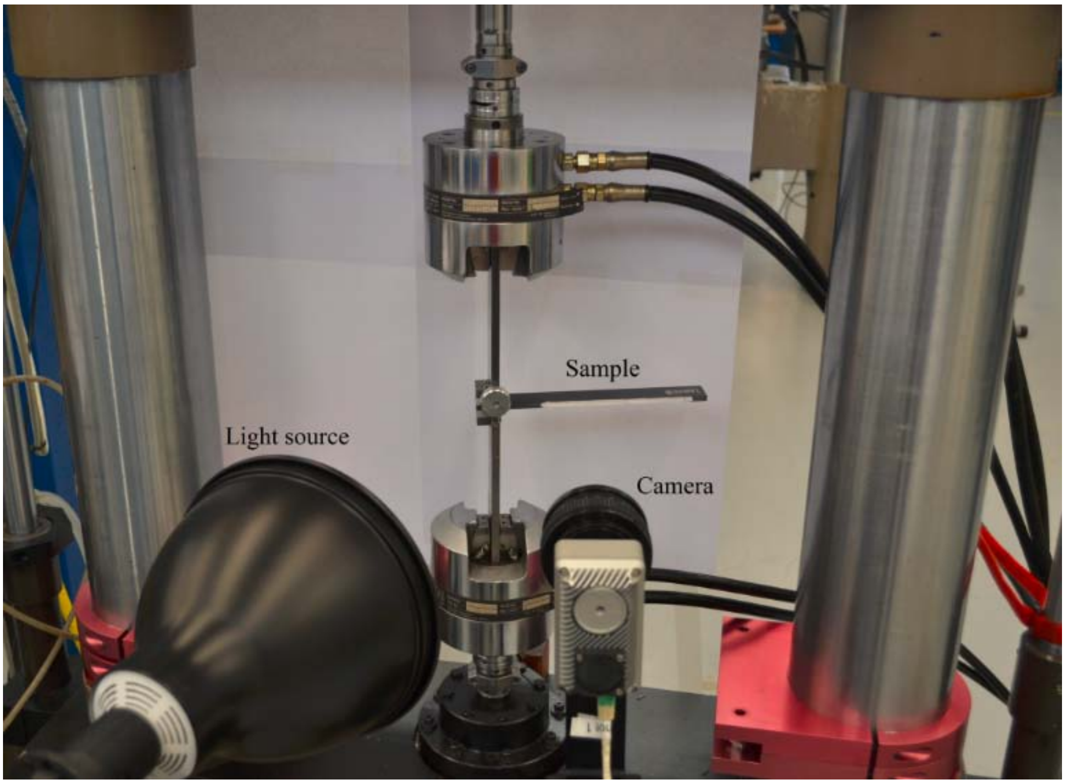

Figure 3.6 Fatigue experimental setup

Several groups of fatigue experiments were carefully organized to investigate the fatigue delamination growth in composite laminates. The specific test procedure for each group of tests is actually dependent on the research topic and the corresponding hypothesis. Detailed information on different groups of fatigue tests will be introduced in the following sections.

3.4.2 Fatigue data reduction

Based on raw data, force, displacement and crack length, the *SERR* can be calculated using the methods recommended in the ASTM standard [12]. Three data reduction methods are recommended to determine the *SERR* during delamination growth in the standard. They are the Modified Beam Theory (MBT) method, Compliance Calibration (CC) method and Modified Compliance Calibration (MCC) method. The *SERR* values determined with the three different methods differ by no more than 3.1%. The MCC method is alternatively used to determine the *SERR* in the present work. The relation for the *SERR* calculation according to the MCC is given by

$$G_I = \frac{3P^2C^{(2/3)}}{2A_1Bh} \quad (3.3)$$

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 Paris relations are commonly applied to interpret the fatigue crack growth behavior. In agreement with the Paris relation [18], all fatigue test results are presented in terms of crack growth rate da/dN versus *SERR* range ΔG as a traditional way to interpret the experimental data, see Eq.(2.4).

The 7-point Incremental Polynomial Method, recommended in ASTM E647 [19], was employed to determine the fatigue crack growth rate.

Besides the Paris relations, a new approach is used to interpret experimental fatigue data. The basic hypothesis is that the energy dissipation is directly related to the crack growth according to energy principles. A high fatigue crack growth rate is related to a high energy dissipation rate, and vice versa. In other words, there should be an intrinsic relationship between the amount of energy dissipation and the formation of new crack surface. A new parameter, energy dissipation rate dU/dN, is proposed to characterize the delamination growth behavior with clear physical meaning.

With the load and displacement measured in the fatigue tests, one can quantify the applied work U, see equation (3.4), against fatigue cycle number N throughout the entire test.

$$U = 0.5P_{max\,,N}\delta_{max\,,N} \tag{3.4}$$

where $P_{max,N}$ and $\delta_{max,N}$ are the maximum force and displacement in the *Nth* fatigue cycle. With a derivative between U and N, the strain energy release per cycle, i.e. dU/dN, can be determined.

The calculation of applied work U with Eq.(3.4) is based on the assumption that P-δ response is linear in a single fatigue cycle. Fatigue delamination is a progressive damage process and the damage accumulation in a single cycle is fairly limited and its effect on the P-δ response is assumed to be negligible.

3.5 Fibre bridging effect study

3.5.1 Objective

Fibre bridging will inhibit crack growth by restraining the opening of fracture surfaces and causing increase of interlaminar resistance. The objective of this group of quasi-static and fatigue experiments, given in Table 3.3 and 3.4, is to investigate the fibre bridging effect on mode I fatigue delamination in composite laminates and to have a better understanding of its effect on fatigue resistance curve. Bridging effect study is the first step for the development of a method to describe fatigue delamination growth with fibre bridging.

3.5.2 Experimental program

DCB specimens with 0//0 and 45//45 interface were tested in both quasi-static and fatigue loading to investigate the fibre bridging in delamination growth. Quasi-static delamination tests were conducted to determine the delamination resistance curve and obtain general information of fibre bridging in different layup sequences. For each interface, 5 DCB specimens were quasi-statically tested. An overview of the quasi-static tests is given in Table 3.3.

There are 4 groups of fatigue experiments that were conducted to investigate fibre bridging in fatigue delamination growth. The test matrix is given in Table 3.4. Detailed information on the test procedure for each group of tests is given in Chapter 4.

Table 3.3Test matrix for quasi-static delamination growth

Specimen	Interface
UDCB 1	0//0
UDCB 2	
UDCB 3	
UDCB 4	
UDCB 5	
MDCB 1	45//45
MDCB 2	
MDCB 3	
MDCB 4	
MDCB 5	

Table 3.4 Test matrix for the investigation of fibre bridging effect

Test title	DCB specimen	Interface	Stress ratio
Basic fatigue test	UDCB 6	0//0	0.1
	UDCB 7		
	UDCB 8		
	UDCB 9		0.5
	UDCB 10		
Steady bridging state test	UDCB 11	0//0	0.1
	UDCB 12		
	UDCB 13		
	UDCB 14		
	UDCB 15		
Fibre cutting test	MDCB 6	45//45	0.5
	MDCB 7		
Resistance slope change test	MDCB 8	45//45	0.1
	MDCB 9		
	MDCB 10		

3.6 Fatigue delamination growth with different amount of fibre bridging

3.6.1 Objective

The objective of this group of experiments, given in Table 3.5, can be divided into two parts. The first aim is to establish a new approach to characterize fatigue delamination growth with different amount of fibre bridging. The second target is to provide data for the interpretation of the bridging phenomenon using energy principles.

3.6.2 Experimental program

The basic assumption for the tests given in Table 3.5 is that the amount of fibre bridging present in the wake of crack tip is related to the crack length. In other words, before fibre bridging has full developed, a long crack length indicates more bridging fibres existing in the wake of crack front, and vice versa.

According to this assumption, DCB specimens were fatigue tested multiple times but at the same stress ratio. In each test, the delamination growth rate gradually decreased with decrease of *SERR*. The test was stopped when the crack growth had nearly retarded. Subsequently, the test was repeated with increased displacements but keeping the stress ratio the same. This sequence was repeated until the maximum displacement capacity of the test machine was reached.

According to this test procedure, multiple delamination resistance curves were obtained, with each curve representing the resistance equivalent to a specific fatigue pre-crack length, i.e. delamination length at which that particular fatigue test was initiated.

In total, 6 DCB specimens with 0//0 and 45//45 interface were fatigue tested at a stress R=0.1 and R=0.5, respectively. The test matrix is given in Table 3.5.

Table 3.5Test matrix for fatigue tests with different amount of fibre bridging

Specimen	Interface	Stress ratio
UDCB 16	0//0	0.1
UDCB 17		0.1
UDCB 18		0.5
UDCB 19		0.5
MDCB 11	45//45	0.5
MDCB 12		0.5

3.7 Assessment of the damage state in quasi-static and fatigue delamination

3.7.1 Objective

The objective of the damage state study is to verify the similarity or difference between quasi-static and fatigue delamination growth in composite laminates. This study can provide evidence for the controversy in the application of the normalization approach, i.e. using quasi-static fracture resistance to normalize the fatigue results [17,20-22].

3.7.2 Experimental program

It is impossible to obtain the quasi-static fracture toughness at any moment in a fatigue delamination test. A specific test procedure was therefore adopted to enable quantification of the damage state similarity between quasi-static and fatigue crack growth.

The hypothesis is that if the damage state for quasi-static and fatigue delamination at the same crack length is similar, the obtained fatigue delamination resistance curves for the same stress ratio should also be the same or similar. While if there are obvious differences between the two cases, this would imply that the damage states in quasi-static and fatigue delamination at the same crack length are different. Through comparison of fatigue test results from specimens with the same quasi-static and fatigue pre-crack length, differences and similarities between damage states were investigated.

With the fatigue experiments described in section 3.6, multiple delamination resistance curves have been obtained. Each of these resistance curves, except the first one without pre-fatigue delamination, represents fatigue resistance with a certain amount of bridging fibres generated during the previous fatigue delamination growth.

In order to make a comparison of the damage state in quasi-static and fatigue delamination growth, two DCB specimens for each interface configuration were quasi-statically tested to generate a pre-crack, at which point the quasi-static test was terminated. This quasi-static pre-crack length was taken to be equal to one of the pre-crack lengths obtained with the fatigue tests on UDCB 18 and MDCB 11. Subsequently, all specimens were fatigue tested with a stress ratio R=0.5 until the delamination growth nearly retarded. Test matrix is given in table 3.6.

Table 3.6Test matrix for fatigue tests with quasi-static pre-crack

<table>
<tr><th>Specimen</th><th>Interface</th><th>Stress ratio</th><th>Pre-crack length [mm]</th></tr>
<tr><td>UDCB 20</td><td rowspan="2">0//0</td><td rowspan="4">0.5</td><td>40.4</td></tr>
<tr><td>UDCB 21</td><td>50.1</td></tr>
<tr><td>MDCB 13</td><td rowspan="2">45//45</td><td>10.1</td></tr>
<tr><td>MDCB 14</td><td>30.1</td></tr>
</table>

3.8 Stress ratio effect on fatigue delamination growth

3.8.1 Objective

The stress ratio effect is an important phenomenon in fatigue crack growth studies. A large number of studies have been performed to investigate this effect. However, there is no agreement on the reason for the stress ratio effect and no clear understanding of the physical mechanisms behind this effect.

The aim of the present work is to investigate the stress ratio effect in fatigue delamination growth. To give a physical explanation, energy principles are used to analyze the data. A damage mechanism investigation on the stress ratio effect is implemented with SEM observation of the fracture surface.

3.8.2 Experimental program

In the stress ratio effect study, DCB specimens with 0//0 and 45//45 interface configurations were used to identify stress ratio effect. The test procedure has been introduced in section 3.4.1. Specimens with 0//0 interface were tested under R=0.1 and R=0.5. Multidirectional specimens were tested under three stress ratios, i.e. R=0.1, R=0.2 and R=0.5. The test matrix is given in Table 3.7.

Table 3.7 Test matrix for stress ratio effect study in fatigue delamination growth

<table>
<tr><th>Specimen</th><th>Interface</th><th>Stress ratio</th></tr>
<tr><td>UDCB 11</td><td rowspan="4">0//0</td><td rowspan="2">0.1</td></tr>
<tr><td>UDCB 12</td></tr>
<tr><td>UDCB 22</td><td rowspan="2">0.5</td></tr>
<tr><td>UDCB 23</td></tr>
<tr><td>MDCB 8</td><td rowspan="4">45//45</td><td>0.1</td></tr>
<tr><td>MDCB 15</td><td rowspan="2">0.2</td></tr>
<tr><td>MDCB 16</td></tr>
<tr><td>MDCB 17</td><td>0.5</td></tr>
</table>

3.9 Conclusions

This chapter provides a description of the specimen manufacturing, experimental test set-ups and data reduction methods in the present research work.

Several fatigue tests were designed to investigate the bridging effect on fatigue delamination growth and to develop a new approach to include its contribution. To verify the validity of the normalization method, a specific test procedure was executed for the damage state investigation in quasi-static and fatigue crack growth. Fatigue tests with different stress ratios were also conducted in order to reveal the stress ratio effect on fatigue delamination growth.

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4

Bridging effect on fatigue delamination growth behavior

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L. Yao, R. Alderliesten, M. Zhao, R. Benedictus. Characterization of the fibre bridging contribution in mode I fatigue delamination in composite laminates. ASC/US-J 16/ASTM D30 Conference. 2014.9

This chapter discusses the bridging effect on mode I fatigue delamination growth behavior in composite laminates based on mode I delamination tests discussed in section 3.5. From the results, there is sufficient evidence that fibre bridging can significantly decrease the fatigue crack growth rate *da/dN*. This makes the invalidity of using only one fatigue resistance curve to determine the delamination property in composite materials with large-scale fibre bridging. In addition, fibre bridging affects the slope of the Paris resistance curve.

4.1 Introduction

Characterizing the fatigue delamination growth resistance in composite materials is important and essential for their damage tolerant design and reliability assessment. In previous studies, researchers have investigated the influence of some important aspects of fatigue delamination growth. These issues include stress ratio effect, temperature, interlayer reinforcement, similitude parameters, etc [1-10].

There is sufficient evidence that interlaminar toughness will increase with the delamination extension due to fibre bridging. Bridging is a typical phenomenon in polymer and ceramic materials. In quasi-static delamination, the interlaminar fracture toughness will increase from an initial value to a plateau value with crack extension [11-14]. The reason for this resistance increase is fibre bridging. Bridging fibres in the wake of crack front will hold the crack surfaces and effectively reduce the stress intensity factor around the crack tip. The plateau value means that at a certain delamination length, fibre bridging has fully developed and after that it becomes stable with further delamination growth.

Methods have been developed to characterize its contribution to quasi-static crack growth. Suo [11] provided a thorough discussion about the bridging in quasi-static delamination in composite materials and presented a model to evaluate the bridging stress distribution along the bridging area. Since the shape of the 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 delamination growth [11,12,14,17]. Stutz [15-16] evaluated the contribution of bridging to the fracture toughness with unidirectional DCB specimens in both monotonic and fatigue loading using a fibre bragg grating sensor. He concluded that the exponential bridging model was more accurate than the bilinear model, when comparing numerical and experimental results.

However, reliable methods to evaluate the bridging effect on fatigue delamination growth 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 [18] normalized the maximum *SERR* in the fatigue tests with the R-curve obtained from quasi-static delamination tests, to develop a Paris type relation. Zhang[19] also used a similar normalization method to analyze the experimental fatigue data. Gregory [8] proposed a fibre bridging model to study the bridging effect on Mode I fatigue delamination at different temperatures. Instead of using a normalization method, he proposed a theoretical method to calculate the bridging contribution to the total *SERR* around the delamination front and excluded its contribution when used Paris relation to interpret the data.

It seems that the influence of bridging on fatigue delamination is still not very clear at present, even though people acknowledge its influence exists and take it into consideration in the formulation of fatigue prediction models.

The objective of the current investigation is to verify whether or not fibre bridging has an influence on fatigue delamination resistance and what the nature of its influence 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, as discussed in section 3.5. Based on the experimental test results, this chapter provides an investigation of the influence of fibre bridging on fatigue resistance.

4.2 Experimental results and discussion

4.2.1 Quasi-static test results

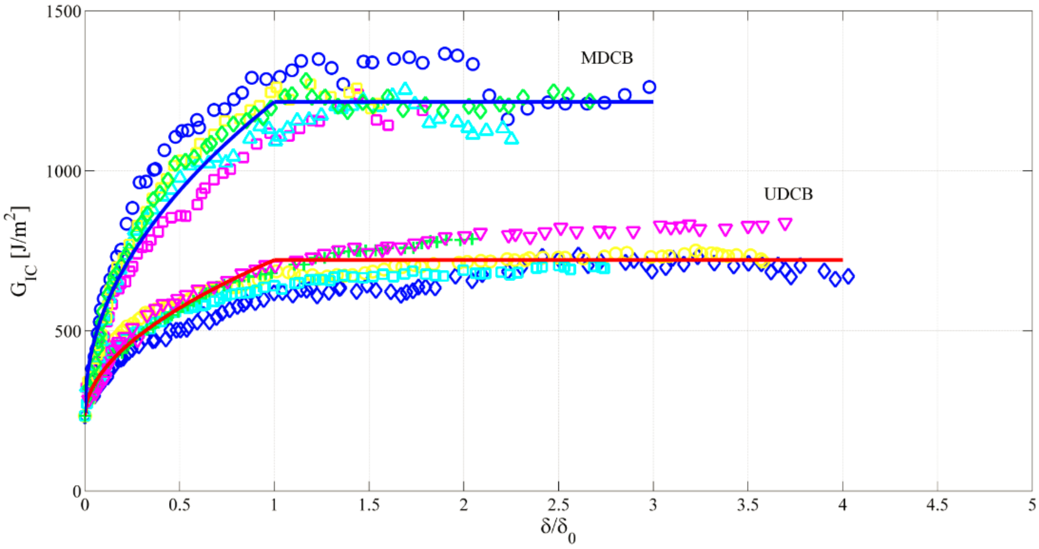
The aim of the quasi-static tests is to determine the quasi-static delamination resistance curve and to identify whether the bridging phenomenon differs for different ply orientations.

Five specimens of each interface were quasi-statically tested, see Table 3.3 in section 3.5.2. Figure 4.1(a) shows the increasing *SERR* versus local crack opening displacement δ. Figure 4.1(b) shows the increasing *SERR* versus the crack extension $a-a_0$. It is clear that the initial G_{IC}-value for both interfaces is almost the same. Some researchers [20] believe that this value is the interlaminar toughness without influence of bridging, and that it is independent on the interface configuration. With δ and $a-a_0$

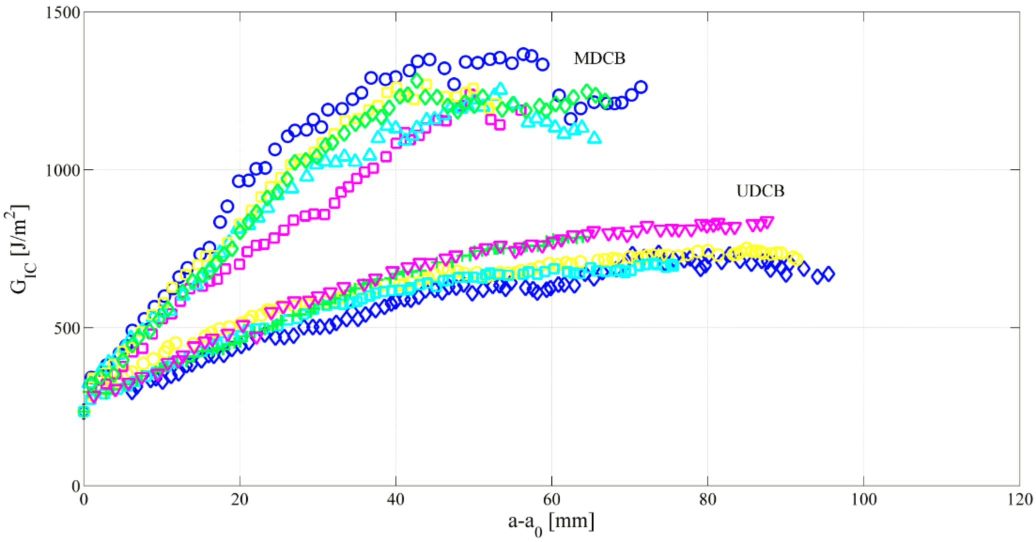
increase, G_{IC} reaches a plateau value for each interface because of fully developed fibre bridging. This occurs after the crack extensions exceed 50mm in the unidirectional DCB specimens and 40mm in the multidirectional DCB specimens. Noticeably, the plateau value for the 45//45 interface is 70% higher than that for the 0//0 interface, which indicates that more fibre bridging occurs at the 45//45 interface, see Figure 4.2. SΦrensen[12,14] thoroughly discussed the large-scale bridging in composite materials and presented a model to reveal the bridging relation, see Equation(4.1). In the current study, this model is applied to describe the quasi-static delamination results by curve fitting, see Figure 4.1(a).

$$G_{IC} = G_0 + \Delta G_{ss} \left(\frac{\delta}{\delta_0}\right)^{(1+\alpha)} (0 \leq \delta \leq \delta_0) \tag{4.1}$$

where G_0 is the strain energy release rate at the initial crack growth; δ is the local crack opening displacement; δ_0 is the critical crack opening displacement at which point delamination growth reaches a stable state; G_{IC} is the energy release rate at a given crack opening displacement δ; α is a curve-fitting parameter. The parameters of the curve fitting are summarized in Table 4.1.



(a) G_{IC} vs. δ/δ_0

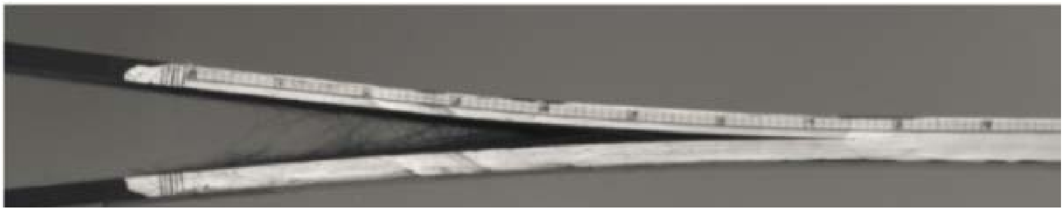


(b) G_{IC} vs. a-a_0

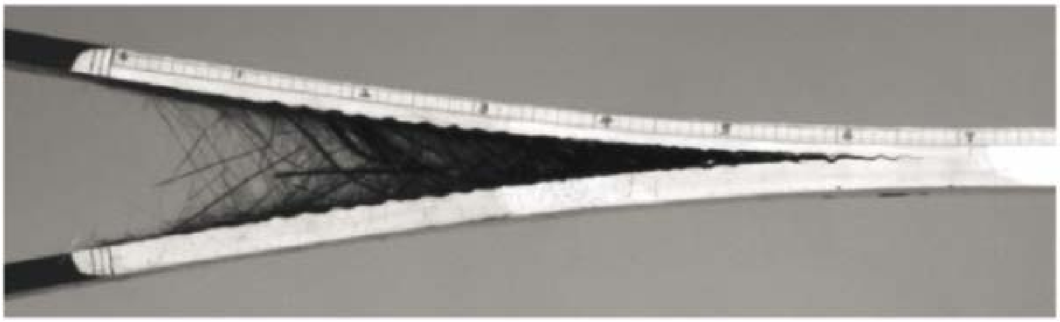
Figure 4.1. Experimental results for quasi-static delamination growth

Table 4.1 Summary of the parameters in the curve fitting

Interface	G_0 [J/m^2]	ΔG_{ss} [J/m^2]	δ_0 [mm]	α
0//0	234.72	486.67	3.46	-0.4694
45//45	244.71	970.94	5.44	-0.5138



(a) 0//0 Interface



(b) 45//45 Interface

Figure 4.2. Fibre bridging in quasi-static delamination

Quasi-static test results reveal that fibre bridging is obvious in mode I delamination extension, especially in the multidirectional DCB specimens. It will increase the G_{IC} from a relative low initial value to a high value. After it reaches a steady state, G_{IC} will remain constant in the subsequent crack extension.

4.2.2 Fatigue test results

In total, four groups of fatigue experiments were conducted with 0//0 or 45//45 interface DCB specimens to investigate the bridging effect on fatigue delamination, see Table 3.4 in section 3.5.2.

4.2.2.1 Basic DCB test

Based on the quasi-static results, the first group of fatigue tests was conducted with unidirectional DCB specimen at the stress ratio of R=0.1 and 0.5. The objective of these tests is to provide basic information about the bridging effect on fatigue delamination resistance.

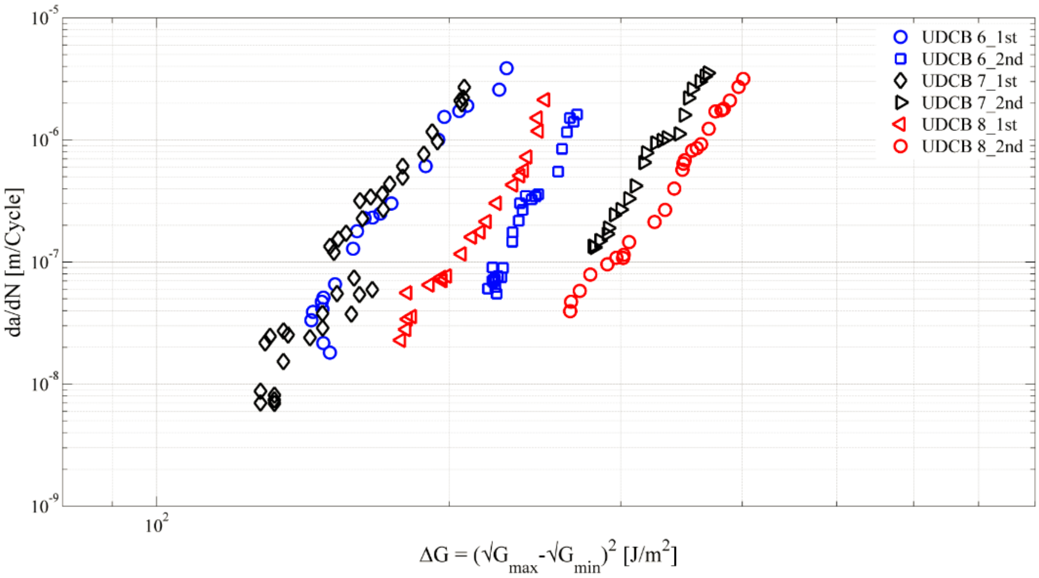
The assumption here is that the amount of bridging fibres created in delamination growth is related to the crack length. A specific test procedure was therefore designed to quantify this difference in this group fatigue tests. First, a DCB specimen was quasi-statically tested until the crack propagated 5-10 millimeters. Then this specimen was fatigue tested until the fatigue delamination growth had nearly retarded. The specimen was subsequently quasi-statically tested again until the crack extended about 10-15 mm. Then, a second fatigue test was performed on this specimen with increasing maximum and minimum displacements but the same stress ratio until delamination retardation.

A total number of 3 specimens under the stress ratio of R=0.1 and 2 specimens under the stress ratio of R=0.5 were fatigue tested using this procedure twice and three times respectively. The results for different stress ratios are plotted in Figure 4.3. It is evident that bridging has an influence on the obtained crack resistance curves. The longer the crack length, the further curves shift from left to right in the chart. That means at a given ΔG, see Equation (4.2), crack growth rate da/dN is lower in a longer crack, compared to the crack growth rate in a short crack.

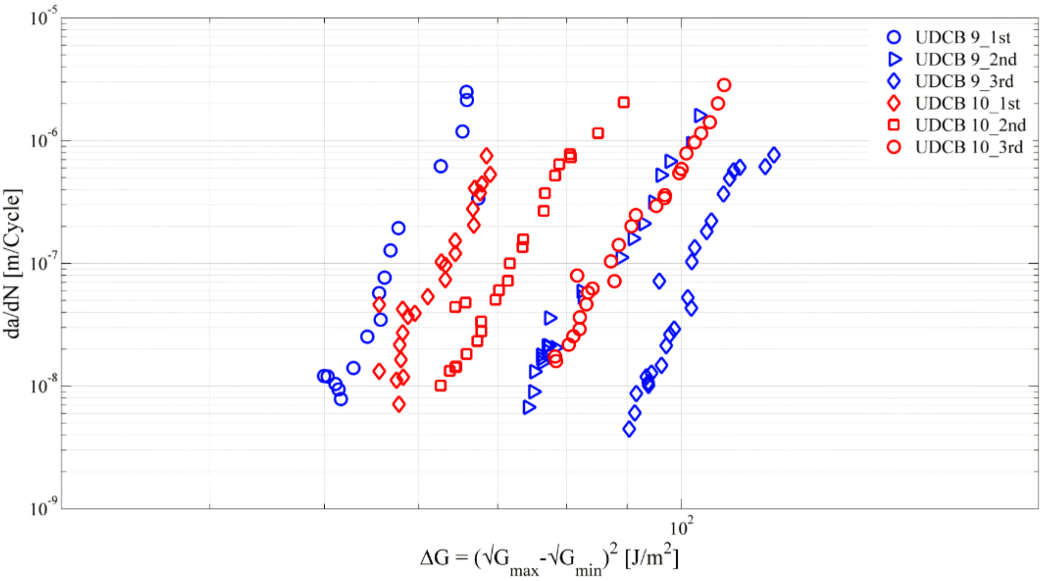
$$\Delta G = \left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2 \tag{4.2}$$

where G_{max} and G_{min} are the corresponding maximum and minimum strain energy release rate in the cyclic loading.

The reason for this is that the longer the crack length, the more bridging fibres will be present behind the crack front. As a result, intact bridging fibres in the wake of the crack tip will restrain the crack opening and a large amount of energy is absorbed by the straining of bridging fibres during fatigue crack extension.



(a) *R*=0.1



(b) *R*=0.5

Figure 4.3. Fatigue resistance curves at different stress ratios

4.2.2.2 Steady bridging state in fatigue

The R-curve in quasi-static delamination growth will reach a plateau value, at which point the damage zone, defined as the length of fibre bridging region [17], attains a steady state. A large number of bridging fibres will appear in this area. There may be a similar steady state in fatigue delamination growth. In other words, after a certain crack length, the Paris curves in Figure 4.3 will not shift further right. To verify this assumption, a second series of tests was carried out with five unidirectional DCB specimens under the stress ratio of R=0.1. The lengths of the crack, created in quasi-static test before the fatigue test, were 3mm, 60mm and 70mm, respectively.

The crack resistance curves for various quasi-static crack lengths are shown in Figure 4.4. For the same quasi-static length, the obtained resistance curves are close to each other. With the increase of the quasi-static crack length, the resistance curves evidently shift to the right. However, the resistance curves for DCB specimens with 60mm and 70mm quasi-static crack length converge to a single curve. This means that there is also a plateau state in fatigue delamination in composite materials. These results give evidence to support the previous assumption and explanation about the bridging effect on fatigue resistance curve, see section 4.2.2.1. Furthermore, these results also indicate that, in case of large-scale bridging, its effect on fatigue resistance is significant. It will decrease the crack growth rate *da/dN* obviously at a longer pre-crack length. And there is a limit of its effect on the decreasing of crack growth rate. This means that, after bridging fibres have fully developed, the obtained fatigue resistance curve will not shift to right further and finally converge to be a single curve in the resistance graph.

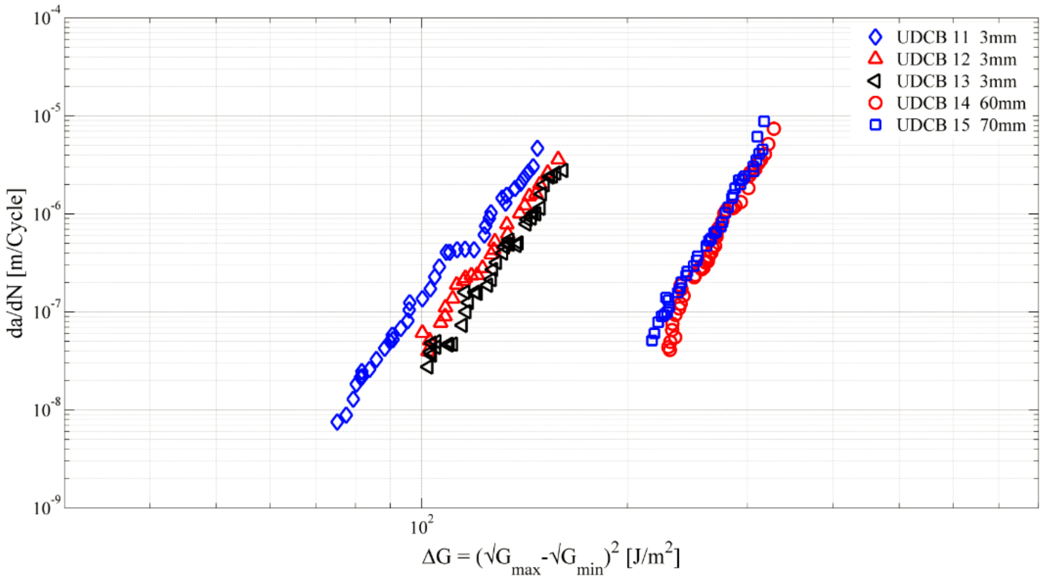


Figure 4.4. Fatigue resistance curve with fully developed fibre bridging

4.2.2.3 Fibre cutting fatigue test

A method to cut the bridging fibres was introduced to get rid of the bridging effect on fatigue delamination [21,22]. In the tests, a saw with glass fibre thread was used to cut the bridging fibres or pull out them from the matrix to eliminate their effect on fatigue delamination growth. Here, a similar method was applied to get rid of the bridging fibres during the fatigue tests. In total, two specimens were used to provide information about the effect of bridging on fatigue delamination behavior.

Both specimens were first quasi-statically tested until a crack length of 15mm. Then, one was fatigue tested at a stress ratio of R=0.5. However, the second one was loaded to 80% of the critical load to execute the cutting procedure. Because of the dimension of the blade, cutting could be performed up to 5-6mm behind the crack front and thus only a part of the bridging fibres were cut. After this, a fatigue test was conducted on this specimen with the same stress ratio, i.e. R=0.5.

From these experiments, two different fatigue resistance curves were obtained, see Figure 4.5. It is clear that the resistance curve moves left once bridging fibres have been cut. Theoretically, if all the bridging fibres could be cut in the specimen, the left fatigue resistance curve in Figure 4.5 should shift left further and converge to a single curve representing fatigue delamination with no fibre bridging. The results also show that bridging will decrease significantly the crack growth rate at the same ΔG, which is equivalent to a shift to the right of resistance curve.

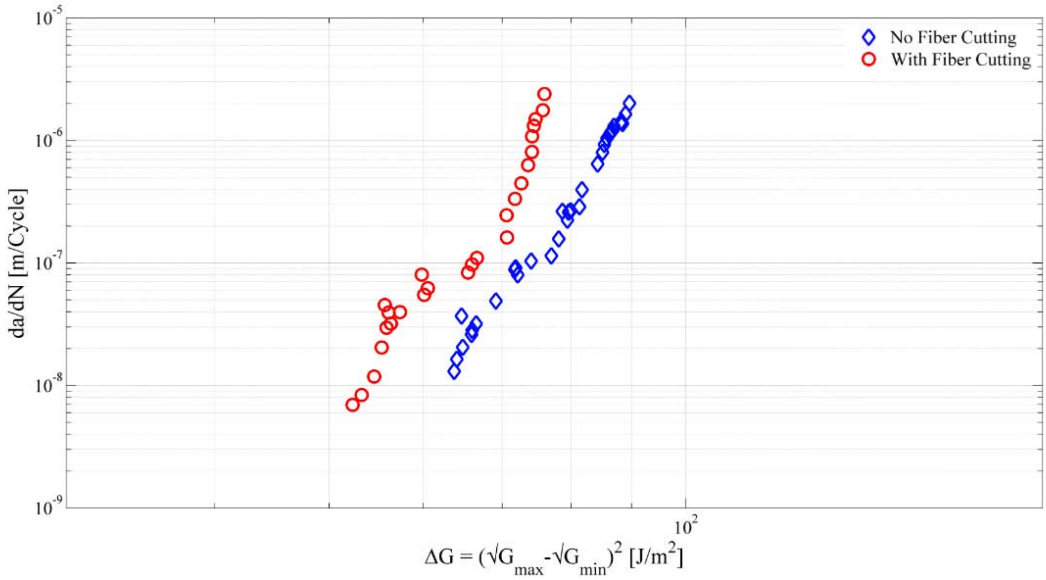


Figure 4.5. Fatigue resistance curve for fibre cutting

4.2.2.4 Bridging effect on the slope of Paris curve

All the above results give clear evidence that bridging will decrease the crack growth rate by shifting the location of fatigue resistance curve from left to right in the graph.

Provided that bridging has influence on resistance curve, the upper part of the curve relates to crack growth with little or no bridging, and the bottom part relates to the crack growth with bridging. Here, it is worth to mention that the crack growth rate *da/dN* is decreasing in the displacement control fatigue test. As a result, the obtained resistance curve is generated from high *da/dN* to low *da/dN* in the test. Since the resistance curve will shift from left to right with the increase of bridging, it could be argued that the curve is steeper at the bottom part than at the upper part. Thus, if bridging is completely eliminated during fatigue delamination, the slope of the curve would be less steep, running from the upper data point.

Three specimens with 45//45 interface were used to investigate the bridging influence on the slope of resistance curve. All fatigue tests were performed under the stress ratio of R=0.1 with 3mm initial quasi-static delamination. The test results obtained from unidirectional specimens with 3mm quasi-static delamination in section 4.2.2.2 are also used here to investigate the effect of bridging on the slope of resistance curve.

The Paris equation, $\frac{da}{dN} = C(\Delta G)^n$, was used to describe the results for both unidirectional and upper part of multidirectional specimens, see Figure 4.6. Now let us take a closer look at crack resistance curves. The slope for the resistance curves is more or less the same at the beginning for each ply configuration, since there is little bridging at the beginning of crack growth. However, the slope change for the unidirectional specimens is not as obvious as in the multidirectional specimens with increasing delamination. Taking the quasi-static test results as a reference, much more bridging is created in the multidirectional specimens than that in the unidirectional. In fatigue, similar conditions may occur. As a result, the slope of the curves is steeper at the end of resistance curve in the multidirectional specimens.

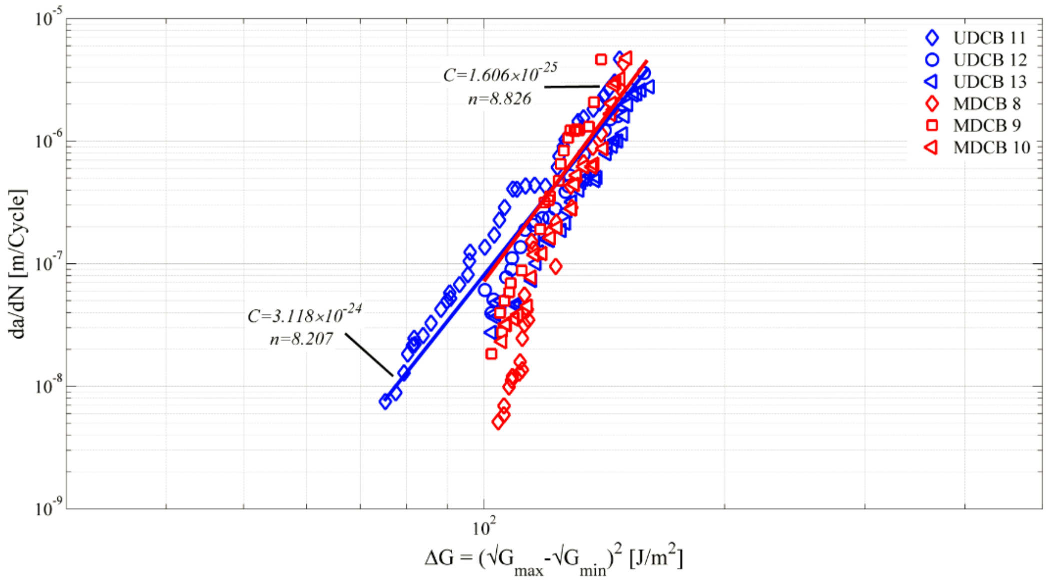


Figure 4.6. Bridging effect on the slope of fatigue resistance curve

4.3 General discussion on fibre bridging effect

A series of experiments has been performed on DCB specimens to investigate the Mode I fatigue delamination in polymer composite materials with obvious presence of bridging. The results indicate that fibre bridging will shift fatigue resistance curve from left to right in the crack resistance graph and decrease the crack growth rate at a given ΔG significantly. A single resistance curve is therefore not enough to completely determine the fatigue delamination growth behavior with fibre bridging. Similar but not the same to quasi-static delamination growth, there is a plateau state in fatigue delamination. In the plateau state, fibre bridging becomes saturation, making the resistance curves finally converge to a single curve. Theoretically, series resistance curves, locating in-between the most left resistance curves representing delamination growth without fibre bridging, and the most right ones representing delamination growth with fully developed fibre bridging, should be used to determine the fatigue delamination growth behavior with fibre bridging.

Khan [22] developed a mechanistic fatigue model based on fracture mechanism using fractography. However, he did not report the bridging effect on fatigue delamination growth similar to the current study. The primary reason for this is that in the study of Khan, the resistance curve was limited to a *da/dN* range of one order of magnitude, which means that the crack propagation is not sufficient to generate enough bridging to result in a significant curve shift. The difference at most can be observed as part of scatter in their results. While, in the current study, the results range over three orders of magnitude in *da/dN* and bridging has been sufficiently developed in the fatigue tests. So the bridging effects on crack growth are more obvious.

4.4 Conclusions

The fatigue delamination behavior in polymer composite materials under mode I fatigue loading has been investigated based on a series of tests. From current investigation, it is concluded that fibre bridging has an important effect on fatigue delamination growth. With the increase of bridging, crack growth rate *da/dN* at a given ΔG will significantly decrease and the corresponding resistance curve will shift from left to right in the resistance graph. There is a plateau state of fibre bridging in fatigue delamination like the plateau state in quasi-static delamination growth. The resistance curves will converge to be a single curve once bridging fibres have fully developed.

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5

Characterize fatigue delamination growth with fibre bridging

This chapter is partly reproduced from

L. Yao, R.C. Alderliesten, R. Benedictus. The effect of fibre bridging on the Paris relation for mode I fatigue delamination growth in composites. Submitted to Composite Structures (Under revised)

Fibre bridging plays an important role in fatigue delamination growth in composite materials. It will decrease the crack growth rate significantly with increase of delamination length. The self-similar crack propagation principle is not valid in this case. In this chapter, a Paris type correlation is developed to describe fatigue delamination growth with fibre bridging. This method is based on correlations between Paris parameters and the amount of fibre bridging. The bridging contribution to fatigue crack growth can be considered using these correlations.

5.1 The mechanism of fibre bridging

Fibre bridging is an important phenomenon during delamination growth in composite materials. The bridging fibres, acting as a shielding mechanism, will tie both fracture surfaces during crack growth. More strain energy should be applied and subsequently consumed to overcome this constraint in the form of fibre pullout or fibre breakage.

As a consequence, the fracture resistance increases with the development of fibre bridging.

In quasi-static delamination, the fracture resistance increases from an initial value to a plateau, due to the contribution of fibre bridging present behind the crack front. The R-curve, with the relationship between fracture resistance and corresponding crack length, is commonly used to describe the increase in interface resistance. However, the R-curve should not be considered to be a material property, because the shape of the R-curve is significantly dependent on the specimen geometry, especially the thickness [1-3]. From the R-curve, the bridging contribution to the total strain energy release or resistance can be generally described by an increase of *SERR* from an initial value corresponding to the onset crack growth to a plateau after the bridging has fully developed. However, this method cannot provide detail information of bridging effect on the stress distribution around the crack front, furthermore, cannot explicitly identify the bridging related failures in crack growth, i.e. either bridging fibre breakage or fibre pullout from the matrix. It can only provide the average contribution from the failures related to bridging to the total strain energy release in delamination and cannot quantitatively determine the amount of strain energy release from each failure. To accurately characterize the bridging contribution, many attempts have been carried out to determine the bridging stress distribution along the bridging area. There is evidence that the bridging stress will exponentially decrease with the increase of crack opening displacement [4,5].

In fatigue loading, some researchers attempted to use the Paris relations to interpret bridging effect during delamination propagation. Hojo [6] proposed a G_{max} constant fatigue test to study the fatigue crack growth behavior. From the bridging effect study reported in Chapter 4, it is evident that the fatigue crack growth rate decreases significantly with the development of fibre bridging. To take into account of its contribution, a normalization method has been proposed, where the *SERR* in cyclic loading is normalized with the quasi-static *SERR* [7-10]. However, recent fatigue delamination studies have demonstrated that it is not correct to apply quasi-static test results to normalize fatigue experiment data, due to the obvious difference in the resistance between quasi-static and fatigue delamination growth [5,11].

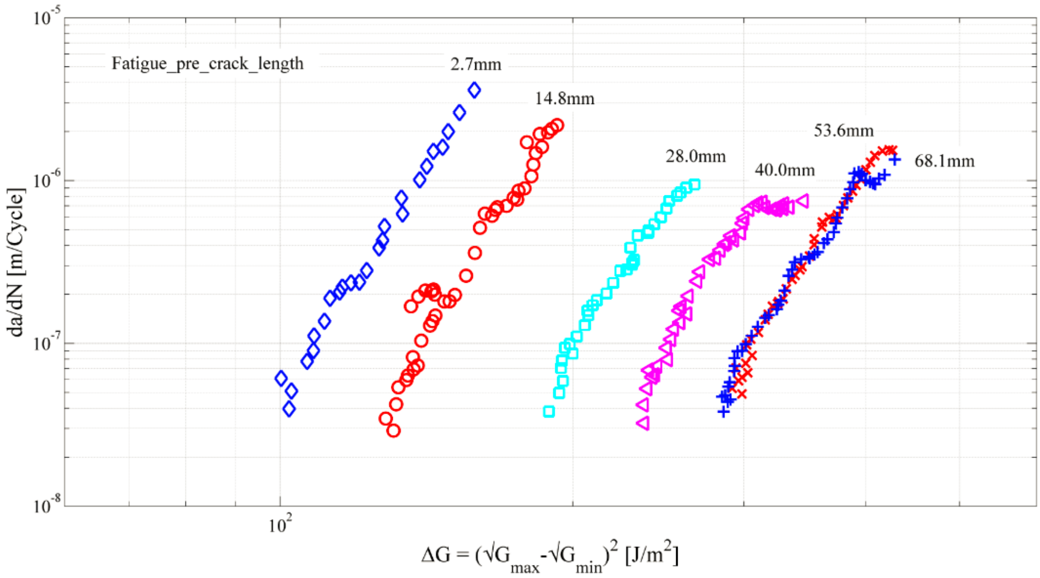
5.2. Results and discussion

All DCB specimens were first fatigue tested with the procedure introduced in section 3.6, to generate a series of resistance curves accounting for different amounts of fibre bridging. In order to take the stress ratio effect into consideration, specimens were tested with stress ratio R=0.1and R=0.5.

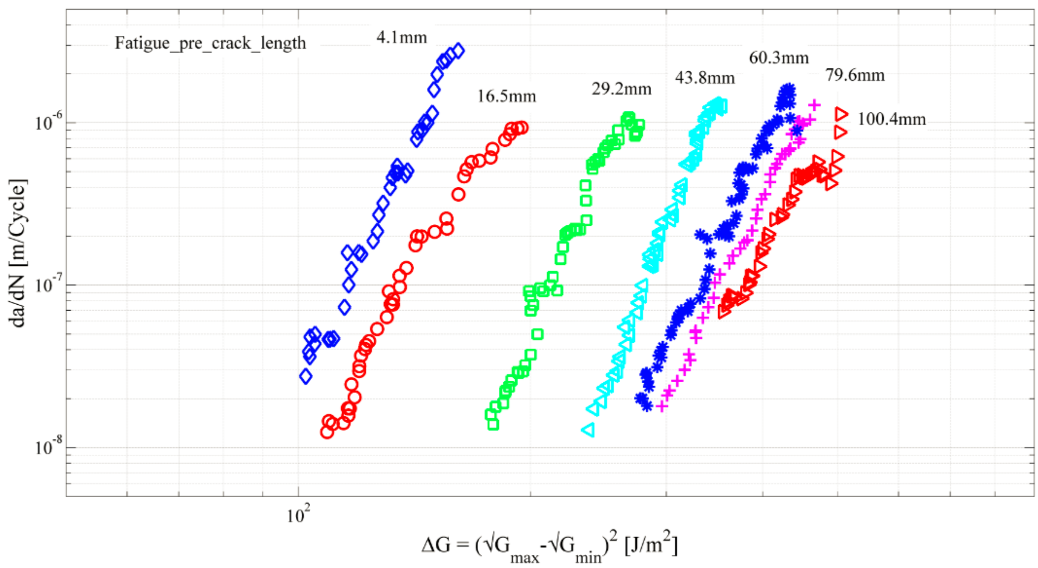
The results are illustrated in Figure 5.1, Figure 5.2 and Figure 5.3, in the form of crack growth rate *da/dN* measured from the fatigue tests against ΔG calculated with the formula recommended in ASTM D5528. There is a clear shift in the obtained resistance curves with the increase of fatigue delamination lengths. A detailed discussion and explanation of this phenomenon has been given in Chapter 4. It is the bridging fibres that restrain the crack surface. This phenomenon is even more obvious for long crack lengths.

Generally, the resistance curves, shown in Figure 5.1 to Figure 5.3, shift from left to right in the delamination resistance graph and finally converge to a single curve, once fibre bridging has fully developed. The most left resistance curves represent fatigue crack growth without or with limited fibre bridging. The most right resistance curves represent fatigue crack growth with fully developed fibre bridging. The curves located in-between describe the fatigue delamination resistance with fibre bridging to a certain degree. One could conclude that it is inappropriate to use the most left resistance curves illustrated in Figure 5.1 to Figure 5.3 to determine fatigue delamination behavior, as it may result in substantially conservative predictions. However, usage of the most right ones cannot guarantee the safety of structures during their service lives.

Technically, the Paris resistance curve can be used to predict fatigue crack growth based on the similitude principle and is valid for self-similar crack growth. The parameters C and n in the Paris relation are demonstrated to be constant at a given load. However, the appearance of fibre bridging can break the principle of self-similar crack growth, making it invalid to use a single resistance curve to characterize fatigue crack growth, as shown in Figure 5.1 to Figure 5.3. This indicates that the parameters in the Paris relation are not constant but significantly dependent on the amount of bridging. Therefore, correlating these parameters with fibre bridging seems to be a reasonable way to account for the bridging effect on fatigue crack growth.

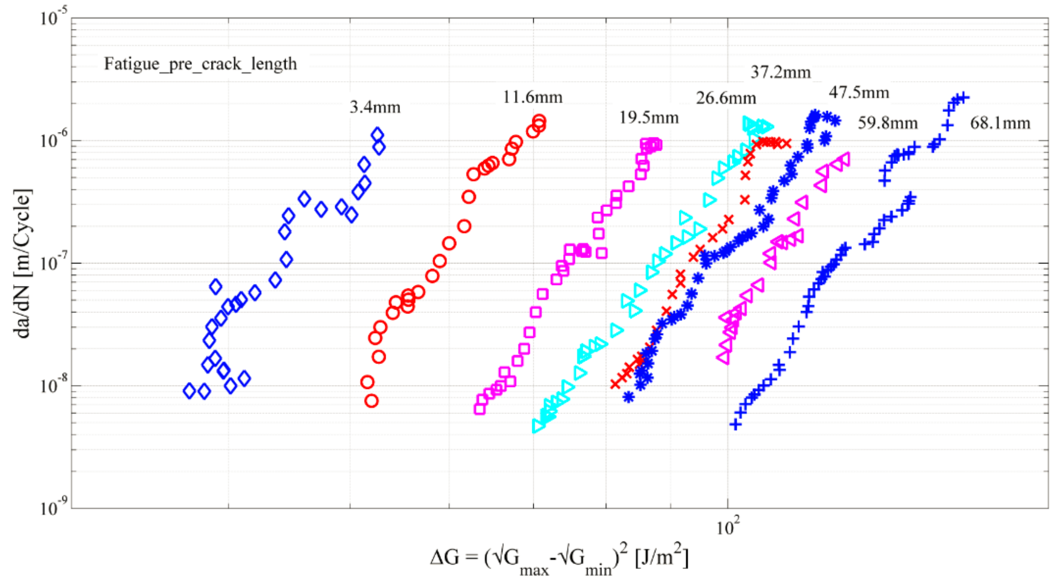


(a) Specimen UDCB 16

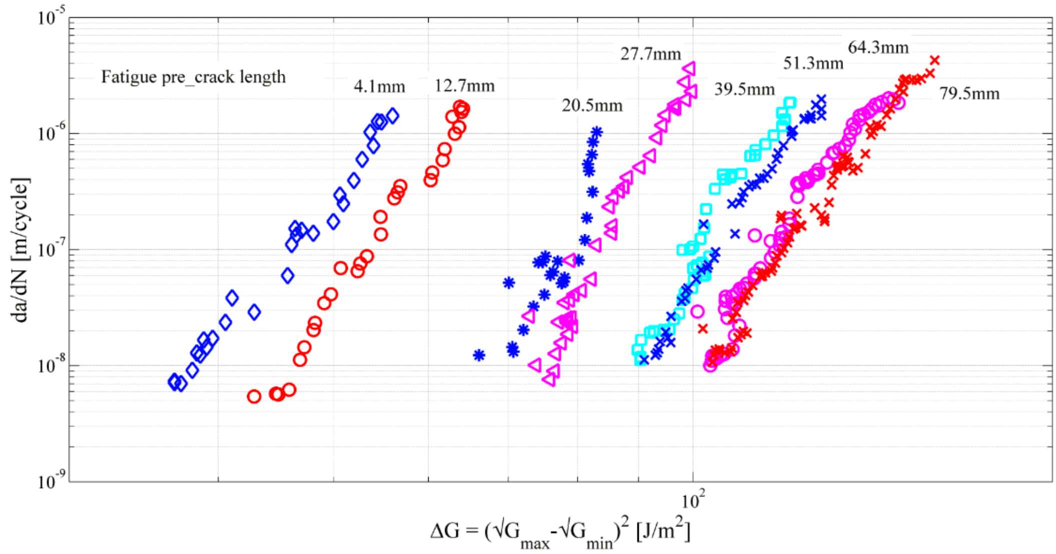


(b) Specimen UDCB 17

Figure 5.1 Fatigue resistance curves with different amount of fibre bridging in the 0//0 interface at R=0.1



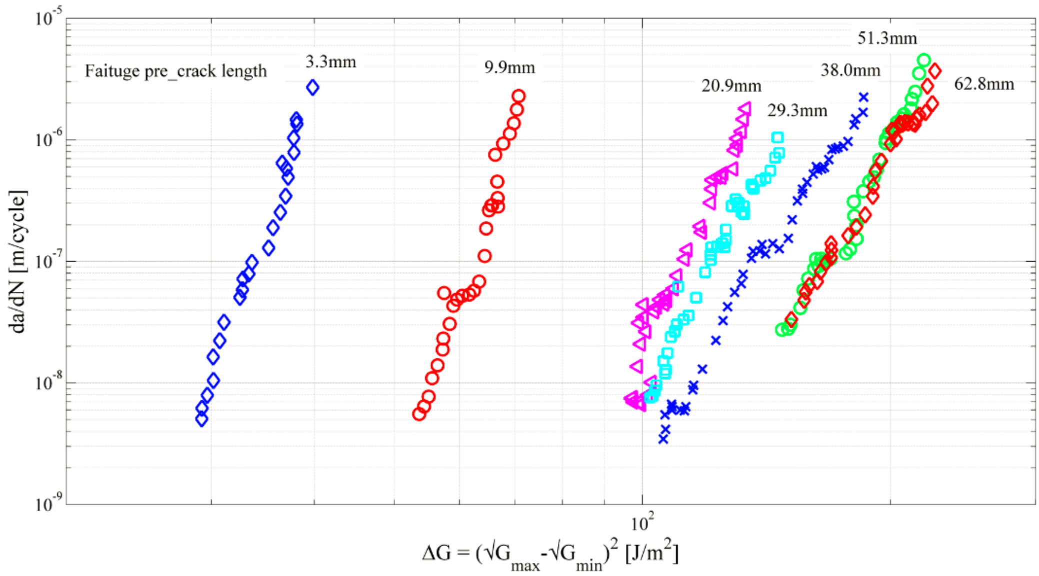
(a) Specimen UDCB 18



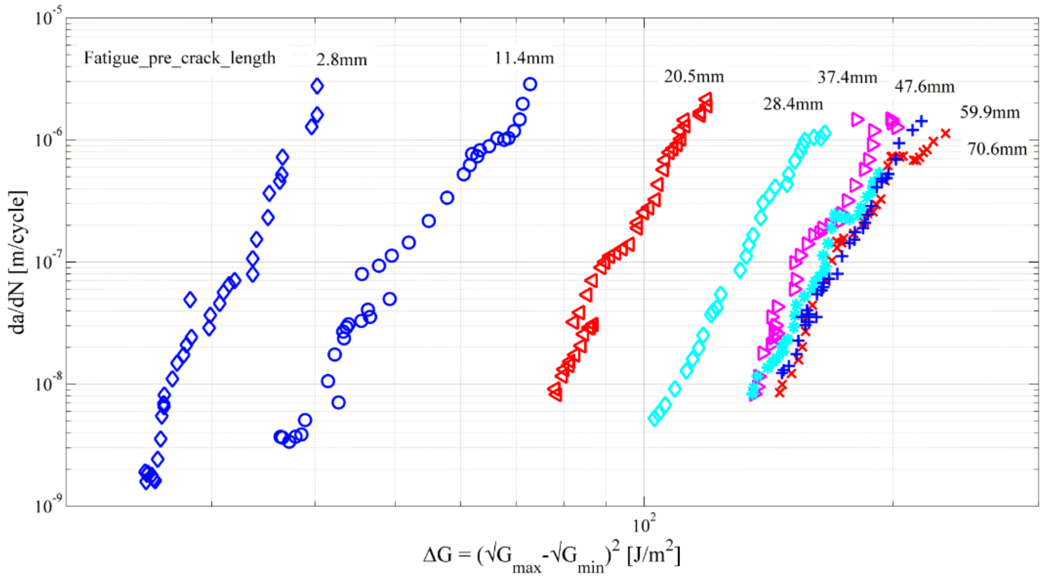
(b) Specimen UDCB 19

Figure 5.2 Fatigue resistance curves with different amount of fibre bridging

in the 0//0 interface at R=0.5



(a) Specimen MDCB 11



(b) Specimen MDCB 12

Figure 5.3 Fatigue resistance curves with different amount of fibre bridging in the 45//45 interface at R=0.5

In quasi-static delamination studies, crack extension a-a_0 is commonly applied to represent the increase of interface resistance with fibre bridging, e.g. such as in the R-curve approach. Referring to this, crack extension a-a_0 is a reasonable parameter to represent fibre bridging in fatigue delamination growth. The bridging contribution can be considered in a new Paris type relation with the correlations between curve fitting parameters and the crack growth extension a-a_0.

5.3 Incorporating fibre bridging in the method

5.3.1 0//0 Interface

Based on the fatigue data illustrated in Figure 5.1 to Figure 5.3, the coefficients *C* and *n* in the Paris relation are correlated with the amount of fibre bridging using linear regression. In the first step, the Paris relation is linearized for the regression analysis on the exponent *n*. The linearized relationship between crack growth rate *da/dN* and the *SERR* range is give in Equation (5.1).

$$log\left(\frac{da}{dN}\right) = nlog(\Delta G) + log(C) \tag{5.1}$$

For the 0//0 interface, the exponent *n* remains constant with the increase of fatigue crack length at a given stress ratio. However, it is stress ratio dependent, as shown in Figure 5.4. The average values of *n* are respectively 9.55 and 15.365 for the stress ratios of 0.1 and 0.5.

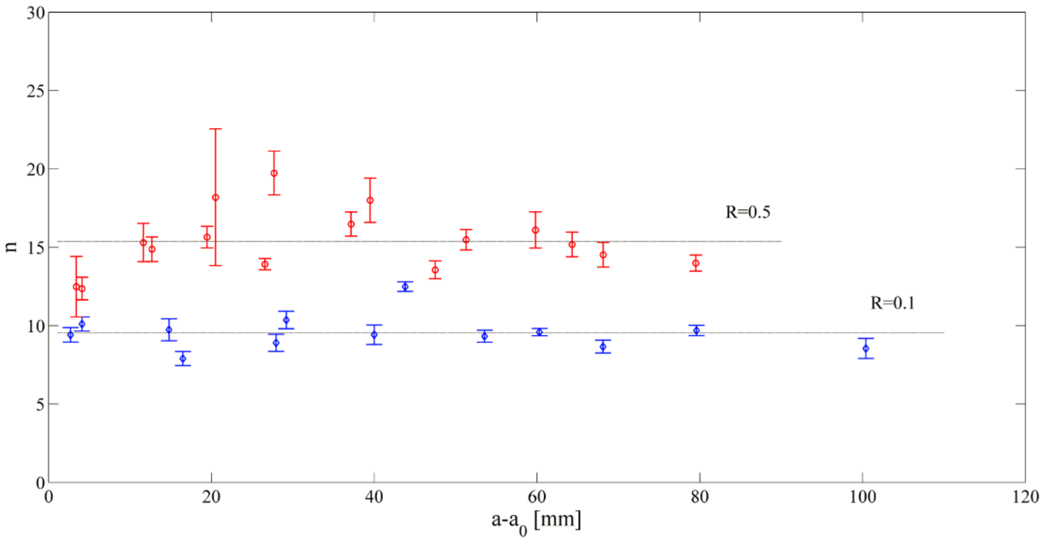


Figure 5.4 *n* vs. a-a_0 in the 0//0 interface

In the second step, linear regression is applied to evaluate the coefficient *C* using the exponent *n* obtained from Figure 5.4. In mathematics, the coefficient *log(C)* is the intersection point between the linearized Paris equation and the ordinate, as shown in Figure 5.5. At a given coefficient *n*, *log(C)* will gradually decrease as the resistance curves shift to the right in the graph.

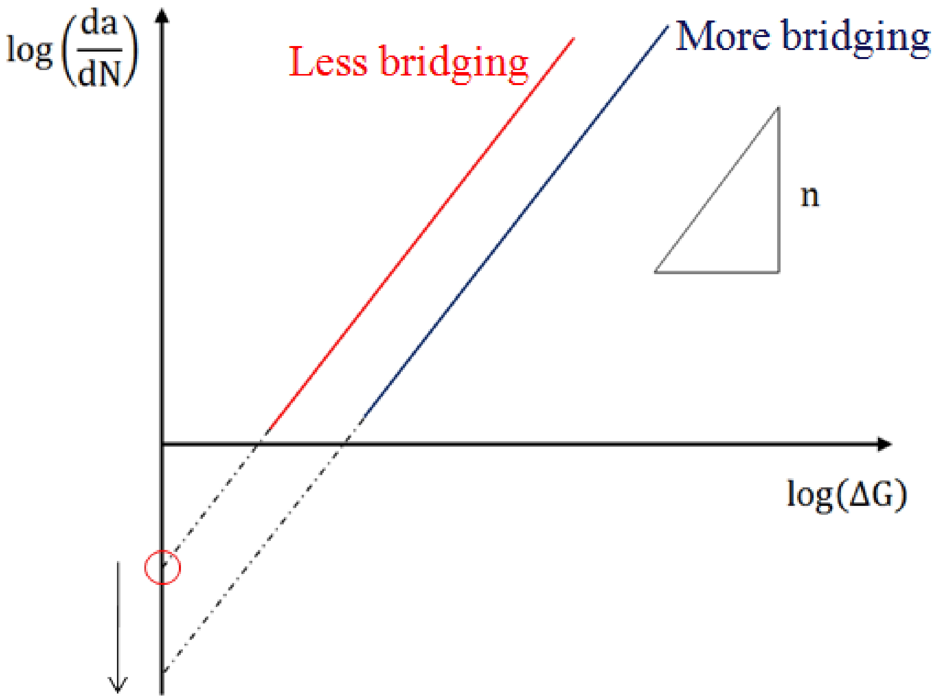


Figure 5.5 Schematic of *log(C)* decrease with the increase of fibre bridging

The results of regression analysis on *log(C)* are illustrated in Figure 5.6. Generally, it decreases at the beginning of crack growth and finally becomes stable. The reason for the decrease of *log(C)* has been schematically explained in Figure 5.5. A constant *log(C)* represents a plateau state during fatigue delamination growth.

The relation between *log(C)* and $a\text{-}a_0$ is demonstrated to be stress ratio dependent. It linearly decreases with crack growth at a stress ratio R=0.1, but bi-linearly decreases at a stress ratio R=0.5. This difference can be interpreted with mathematical reasoning. According to Equation (5.1), *log(C)* can be determined with

$$log(C) = log\left(\frac{da}{dN}\right) - nlog(\Delta G) \tag{5.2}$$

Referring to Figure 5.4, n remains constant with crack growth. Thus *log(C)* is only a function of *log(ΔG)* at a given fatigue crack growth rate. An intrinsic relationship should exist between *log(C)* and *log(ΔG)*. In other words, if there is a linear relationship between *log(ΔG)* and $a\text{-}a_0$, the similar relation should also exist between *log(C)* and $a\text{-}a_0$. A nonlinear relation between *log(ΔG)* and $a\text{-}a_0$ can make the relation between *log(C)* and $a\text{-}a_0$ nonlinear.

Figure 5.7 provides the increase of *log(ΔG)* with the crack growth at *da/dN*= 1×10^{-6}m/Cycle. Linear increase is observed for *R*=0.1 and bi-linear increase of *log(ΔG)* is observed for *R*=0.5. Obviously, these differences correspond to the differences in Figure 5.6. However, the first kink point of *R=0.5* is still unknown at this moment. Extra data and tests should be used to solve this problem in the future.

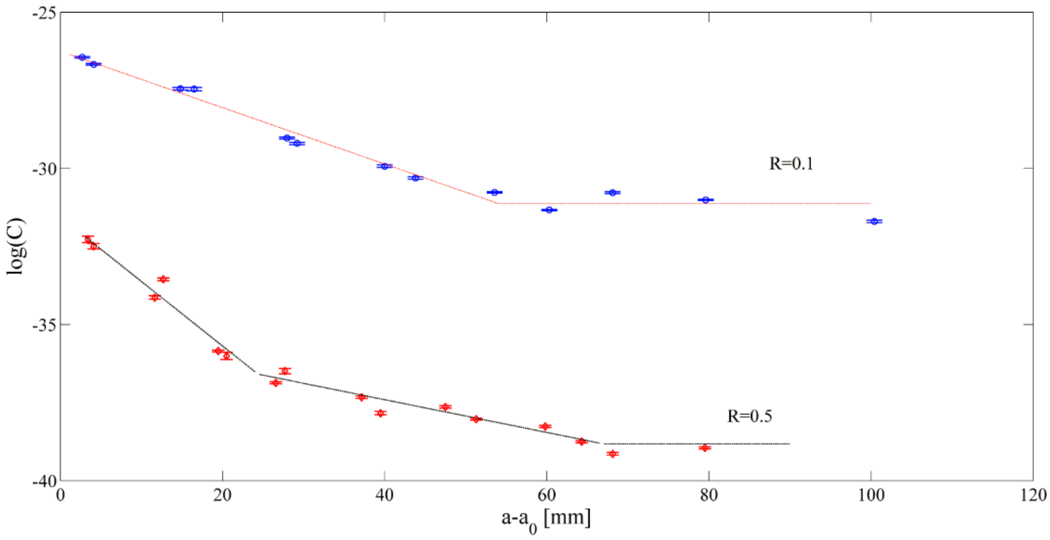


Figure 5.6 *log(C)* vs. $a\text{-}a_0$ in the 0//0 interface

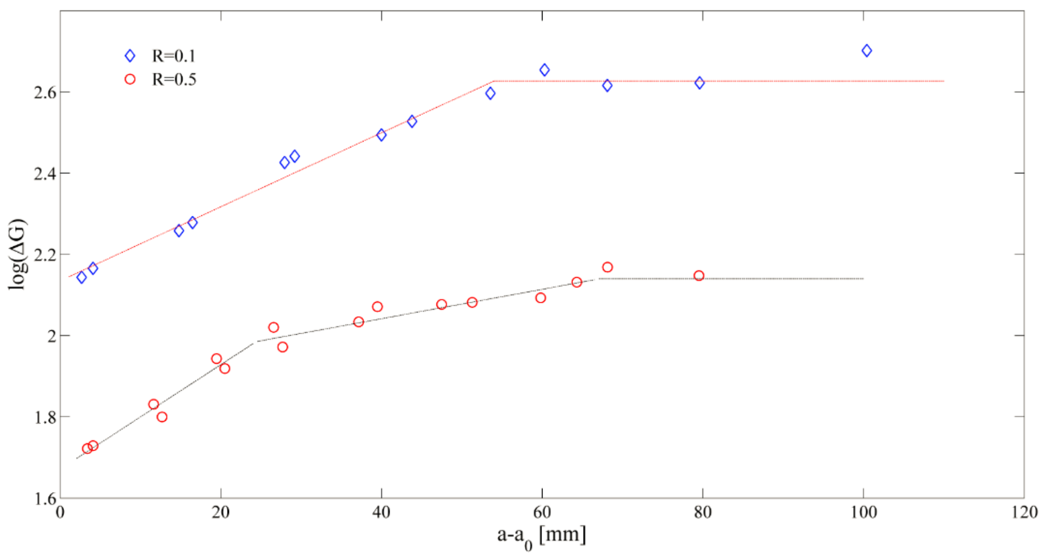


Figure 5.7 *log(ΔG)* vs. $a\text{-}a_0$ in the 0//0 interface (*da/dN* = 1×10^{-6}m/Cycle)

5.3.2 45//45 Interface

The same analysis procedure is also used for the 45//45 interface. It reveals that the exponent *n* linearly decreases with the increase of fatigue crack length and finally becomes constant once the crack length is longer than a certain value, as shown in Figure 5.8.

The relation between *n* and a-a_0 of the 45//45 interface is different from that of the 0//0 interface. The main reason for this difference can be explained with the difference in the amount of bridging fibres generated in delamination growth. Fibre bridging is more pronounced in the 45//45 interface compared to that in the 0//0 interface. Thus, it has more influence on the exponent *n* with crack propagation in the 45//45 interface.

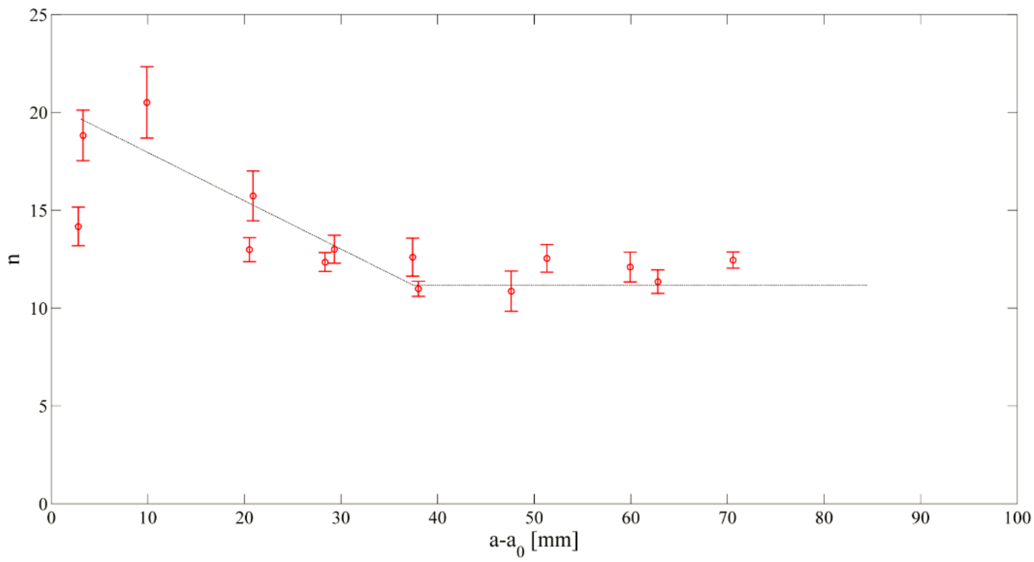


Figure 5.8 *n* vs. a-a_0 in the 45//45 interface

The regression analysis results of *log(C)* versus a-a_0 are illustrated in Figure 5.9. The parameter *log(C)* first decreases until the crack extension is around 20mm. However, *log(C)* increases noticeably once the crack extension exceeds 20mm and finally keeps constant due to the fully developed fibre bridging.

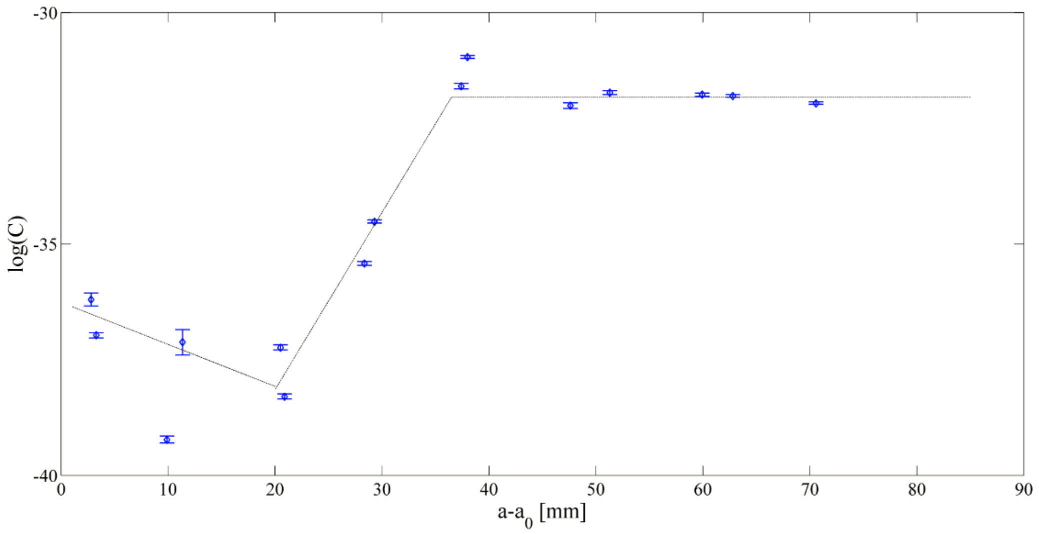


Figure 5.9 *log(C)* vs. $a\text{-}a_0$ in the 45//45 interface

It is worth noting that *log(C)* are both *n* and $a\text{-}a_0$ dependent during fatigue crack growth in the 45//45 interface. The decrease of *n* can lead to an increase in *log(C)* if the Paris curves do not shift in the resistance graph. A schematic explanation for this increase is given in Figure 5.10. The shift of resistance curves will decrease *log(C)*, as shown in Figure 5.5. The value of *log(C)* therefore is a balance of these two different effects on the intersection between linearized Paris equation and the ordinate. In Figure 5.3, the shift seems to be obvious in the first three times fatigue tests with pre-crack length less or around 20mm. Thus, the shift phenomenon plays a dominant role in the determining of *log(C)*, leading to the decrease of *log(C)* with the increase of crack length. In the subsequent several fatigue tests, the shift is less substantially. The change of exponent *n* may have more influence on *log(C)* and the values of *log(C)* increase with crack propagation. This parameter finally becomes constant once fibre bridging has fully developed.

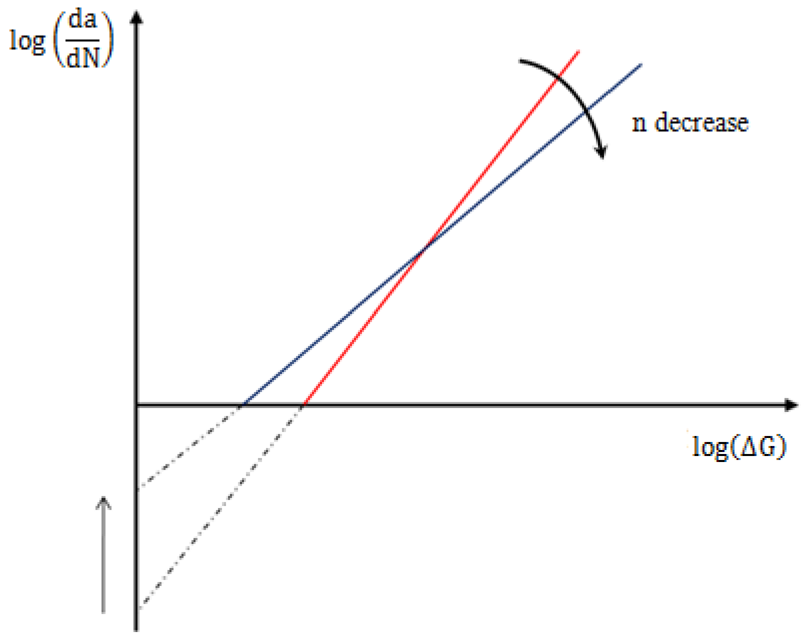


Figure 5.10 Schematic of *log(C)* increase due to exponent *n* decrease

Here, the prediction model can be extended according to above discussion. This method remains an empirical model based on Paris relation. The general form of the Paris type relation can be given as

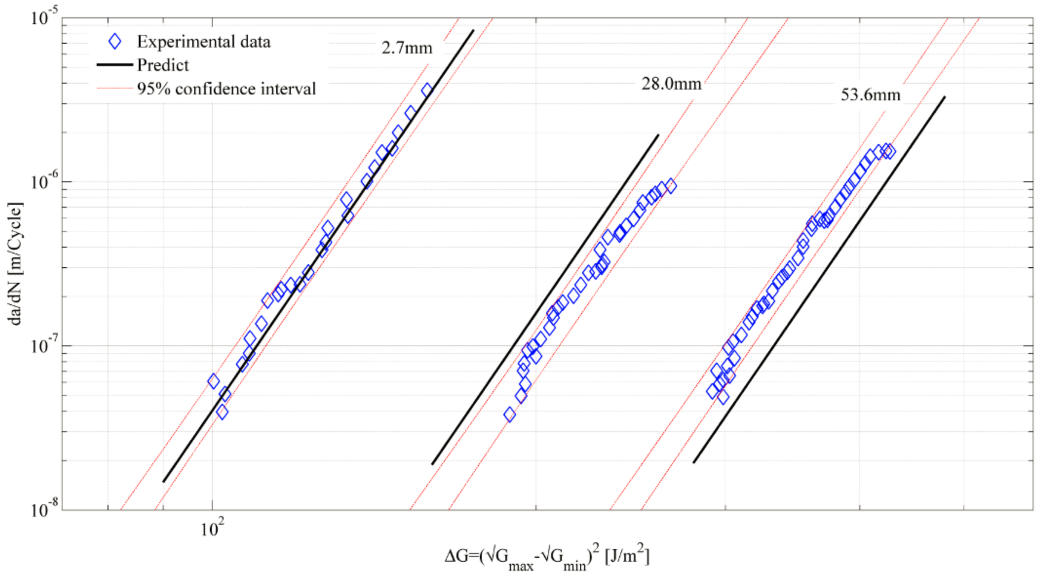
$$\frac{da}{dN} = C(a - a_0, R)\Delta G^{n(a-a_0,R)} \tag{5.3}$$

In this equation, both *C* and *n* are correlated to the crack extension a-a_0, equivalent to the amount of bridging. The bridging contribution to crack growth therefore can be considered in this model.

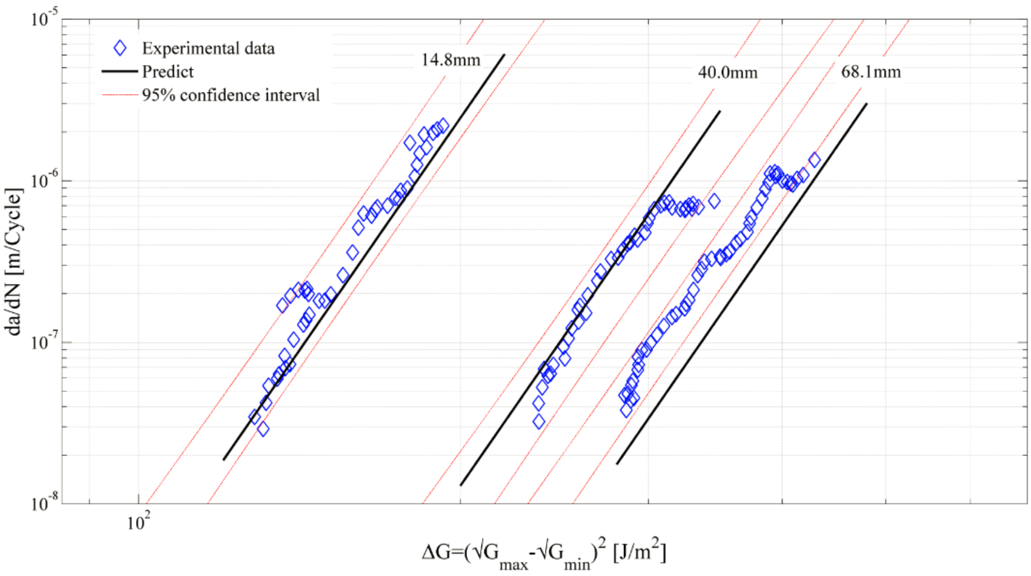
5.4 Verification

To verify whether the proposed relationship of Equation (5.3) describes all data well enough, the method here is verified with the original data present in section 5.3. This verification is considered necessary, because the values of *n* seem to correlate substantially better with the fatigue data for R=0.1 than for R=0.5, see Figure 5.4 and 5.8. To verify whether the *n* and *C* values according to Figure 5.4, 5.6, 5.8 and 5.9, Figure 5.11 to 5.13 illustrate the correlation with the data sets present before in Figure 5.1 to 5.3. Figure 5.11 and 5.12 respectively present the predicted results for the 0//0 interface with a stress R=0.1 and R=0.5. Figure 5.13 presents the predictions for the 45//45 interface. The limits of the 95% confidence interval of each experimental data set are determined by a linear regression analysis [12].

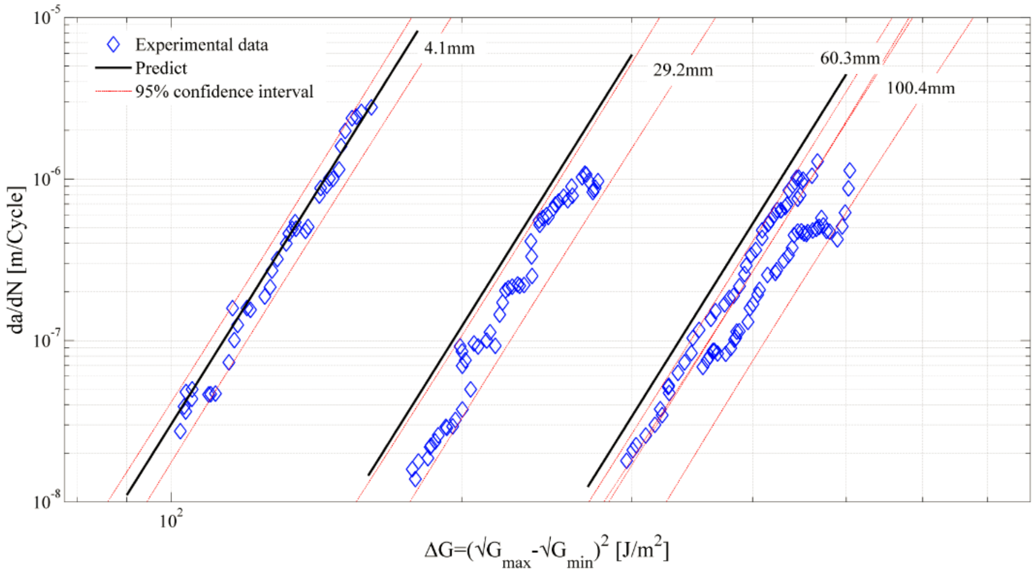
Most predictions for the 0//0 interface show a good agreement with the experimental data and locate in or close to the 95% interval. This means the bridging contribution to fatigue delamination growth can be appropriately considered in the Paris type relation. However, the deviation of the predictions for the 45//45 interface seems to be larger compared to that for the 0//0 interface in three cases as shown in Figure 5.13. The predicted results do not locate in the 95% confidence intervals. The slopes of the resistance curves also differ from the experimental data.



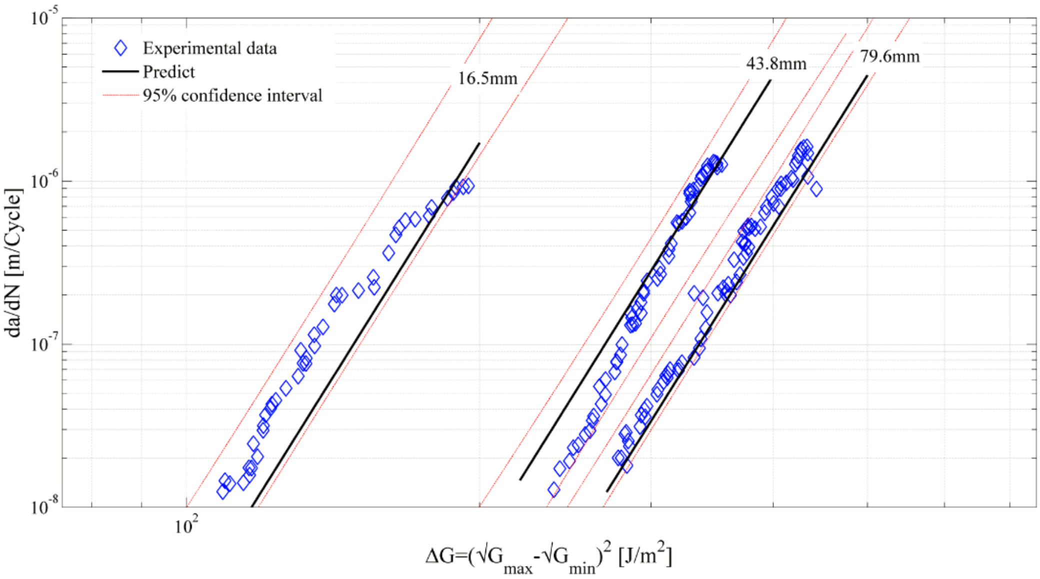
(a) UDCB 16 prediction_1



(b) UDCB 16 prediction_2

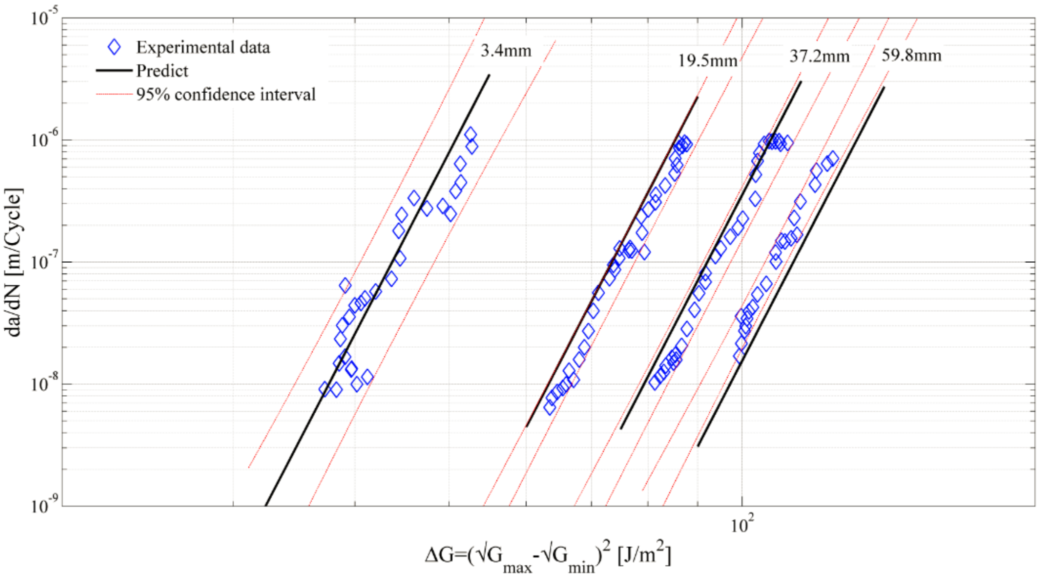


(c) UDCB 17 prediction_1

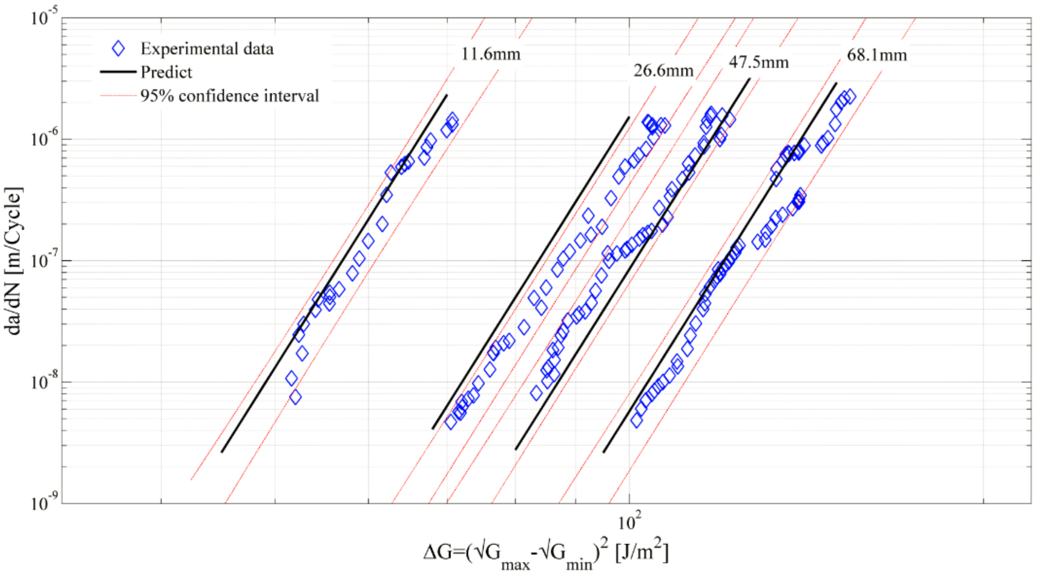


(d) UDCB 17 prediction_2

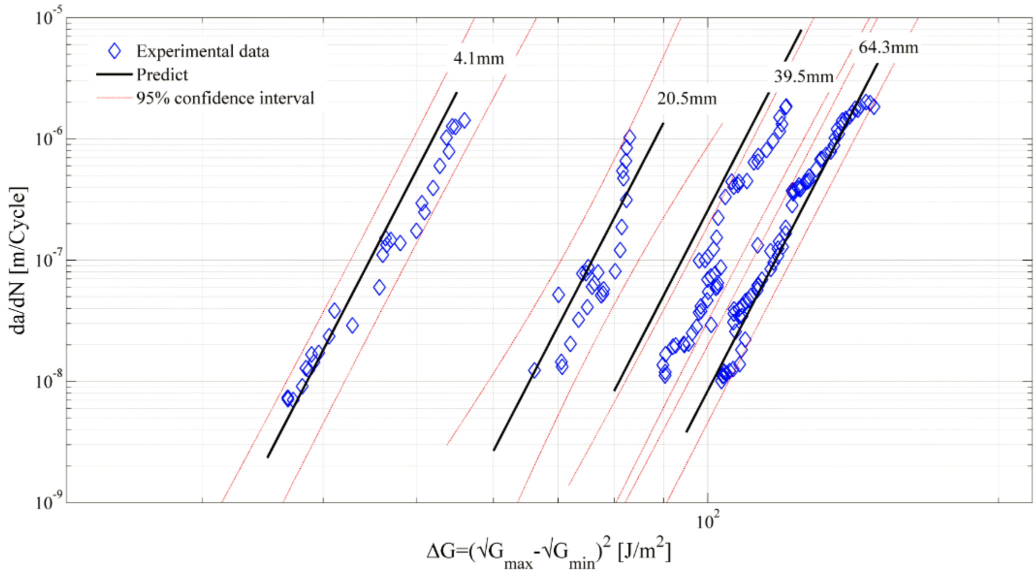
Figure 5.11 Predictions for the 0//0 interface at *R*=0.1



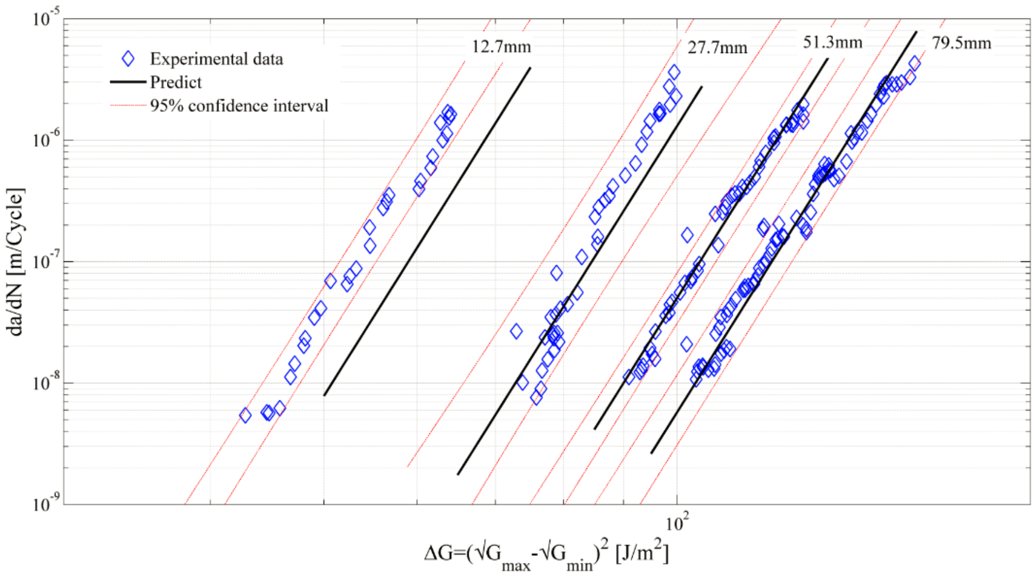
(a) UDCB 18 prediction_1



(b) UDCB 18 prediction_2

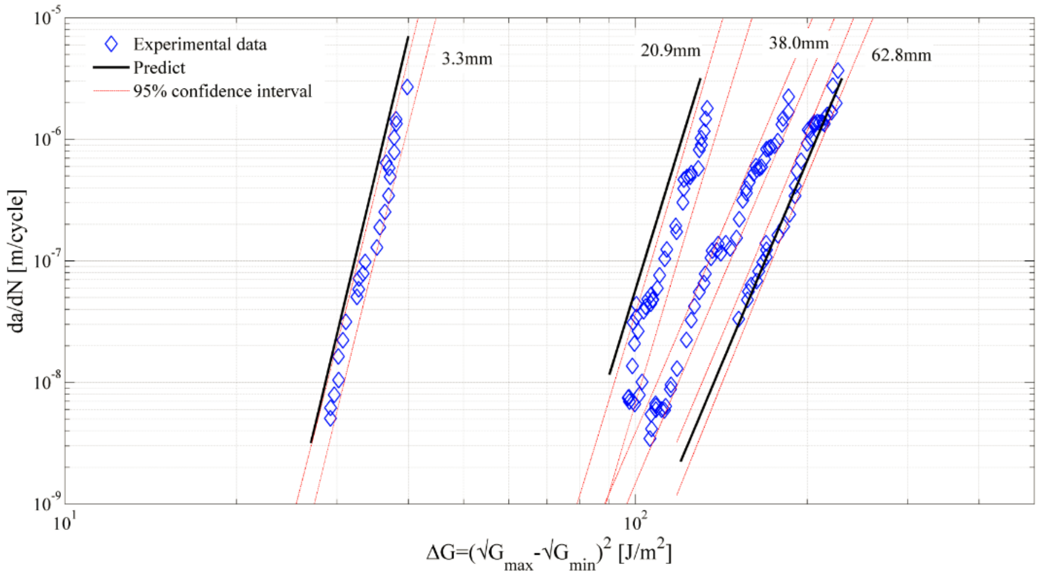


(c) UDCB 19 prediction_1

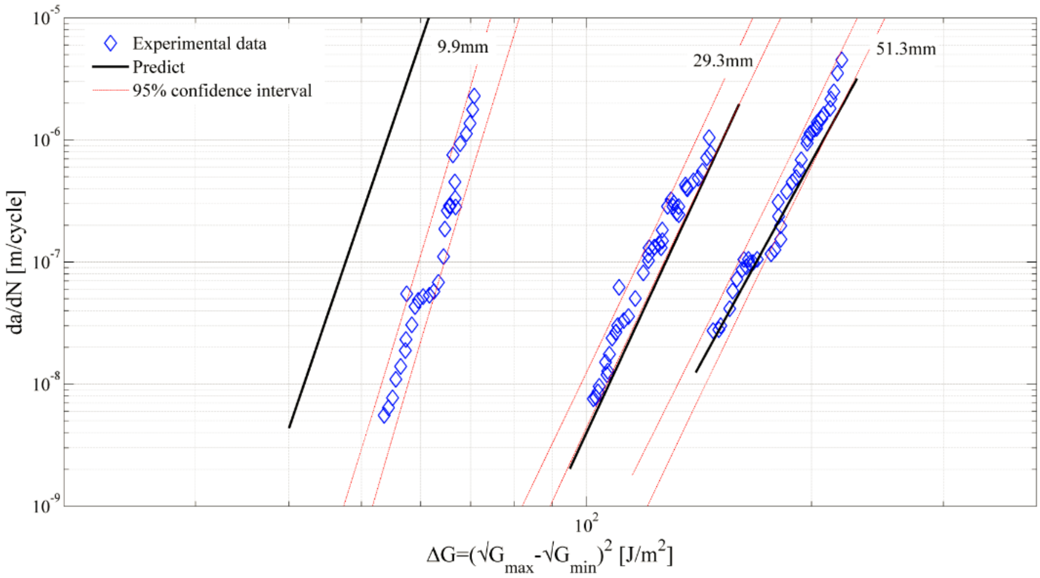


(d) UDCB 19 prediction_2

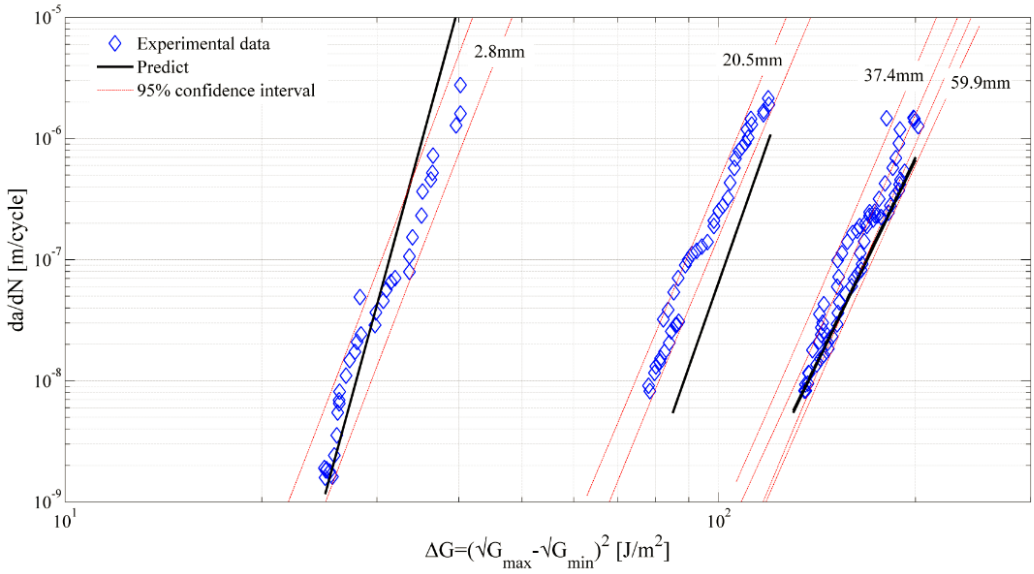
Figure 5.12 Predictions for the 0//0 interface at R=0.5



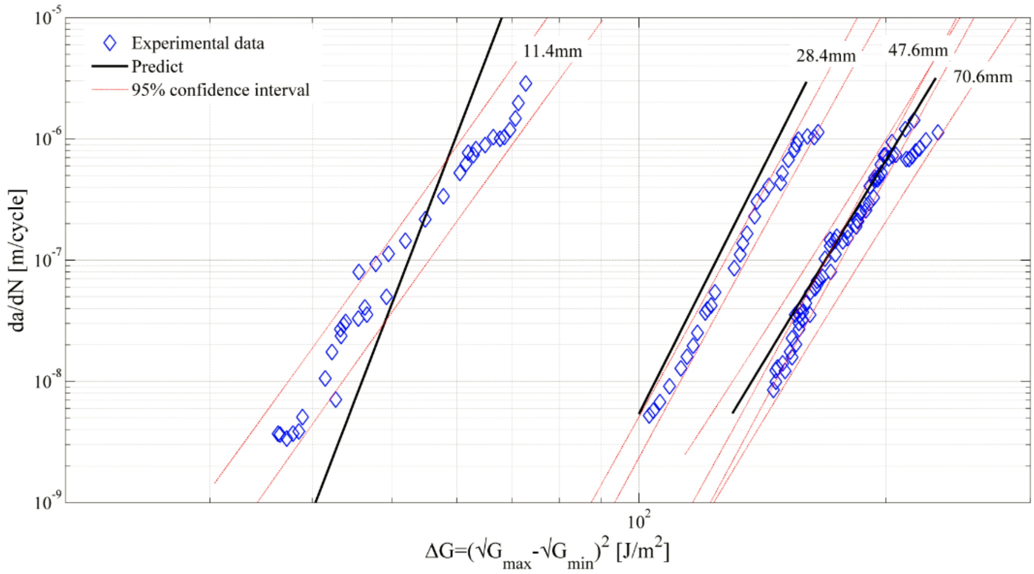
(a) MDCB 11 prediction_1



(b) MDCB 11 prediction_2



(c) MDCB 12 prediction_1



(d) MDCB 12 prediction_2

Figure 5.13 Predictions for the 45//45 interface at R=0.5

5.5 Method discussion

The Paris equation is extended to characterize fatigue delamination growth with fibre bridging. In nature, Paris relation is a curve fitting method to interpret fatigue crack growth behavior. Because of this, the model presented in this chapter is no more than a curve fit and contains the inherent shortcoming of the Paris relation. It cannot provide a physics-based explanation of the fatigue crack growth or the bridging effect.

The method proposed in this chapter can be used to determine the fatigue crack growth accounting for fibre bridging. There is evidence that the amount of bridging is related to a series of factors, such as stress ratio, ply orientation, specimen thickness and so on. Obeying the similitude principle, a large number of tests should be conducted to investigate the influence of these factors on the parameters in the Paris relation first. The correlations between these parameters and fibre bridging can be established subsequently. The fatigue crack growth behavior therefore can be determined by combining these correlations in the Paris relation.

There are limitations of present method. It is an empirical method to quantify the effects of fibre bridging in mode I fatigue delamination growth in composite laminates. It is worth noting that the bridging contribution to the total strain energy release can be classified into at least two aspects, i.e. energy release related to fibre pullout from matrix and energy release related to bridging fibre failure. As a result, the *SERR* calculated is the sum of energy dissipation associated with different kinds of failure during delamination. However, the validity of using *SERR* as similitude parameter in fatigue delamination growth analysis is questionable according to the physical definition of it. This issue will be further discussed in the Chapter 6.

5.6 Conclusions

Fibre bridging has significant effect on the fatigue delamination growth. Fatigue crack growth with bridging is not self-similar, causing the invalidation of using one resistance curve to determine fatigue crack growth. To overcome this shortcoming, the Paris relation is further developed to take into account of the bridging effect by correlating the curve fitting parameters, C and n, with the amount of bridging. The Paris relation is extended to determine fatigue delamination with fibre bridging. The fatigue crack growth can be determined by this new Equation (5.3), according to a comparison between the predicted results and experimental results.

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6

Fundamental understanding of delamination growth using the energy principles

This chapter is reproduced from

L. Yao, R.C. Alderliesten, M. Zhao, R. Benedictus. Discussion on the use of the strain energy release rate for fatigue delamination characterization. Composites Part A: Applied Science and Manufacturing 2014. 66: 65-72

This chapter discusses the use of the *SERR* as a parameter to characterize fatigue delamination growth in composite materials. Based on the observed difference in fatigue delamination response, it is argued that the fibre bridging generated during quasi-static and fatigue loading is significantly different, making normalization of fatigue data with quasi-static *SERR* meaningless. From the physics perspective, bridging fibres should not impose any strain energy release during fatigue delamination, unless they fail, i.e. fibre pullout or breakage. This is subsequently supported by analysing the earlier mentioned experiments with an energy approach. When the applied strain energy normalized against the applied number of cycles is plotted against the fatigue delamination growth rate, all data approximately coincides to a single curve. It is therefore concluded that the current use of *SERR* to characterize fatigue delamination growth is not in agreement with the physical concept of strain energy release.

6.1 Introduction

With the introduction of advanced fibre reinforced polymer composites in primary aircraft and spacecraft structures, it has become essential to fully characterize these materials under relevant loading conditions. In particular, with the damage tolerant design principles, it has become eminent to fully understand the damage mechanics under quasi-static and fatigue loading. In the past decades, a significant amount of research has been performed to address the problem of delamination growth in composite materials [1-13], which is deemed the most important damage mechanism from the strength and stiffness point of view.

There seems to be a fair agreement on how to approach quasi-static delamination growth. Test standard has been established. But consensus on fatigue delamination growth has not yet been achieved. This lack of consensus is attributed to various aspects of fatigue delamination characterization. The first aspect concerns the selection of the parameter describing the similitude. Many authors proposed the use of the maximum *SERR* to characterize fatigue delamination growth [1-6], whereas others preferred to use the *SERR* range [7-13]. Concerning the latter, most people tend to take the difference between the minimum and maximum *SERR*, i.e. $G_{max} - G_{min}$ [7-10], while others proposed to use $\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$ [11-13]. In fact, it has been demonstrated how data may be misinterpreted if the similitude parameter is not well defined [12].

Another aspect which lack consensus is attributed to the presence of fibre bridging. As an artefact of the common experiments on double cantilever beam specimens, fibres are bridging the interface during delamination, increasing the apparent fracture toughness of that interface. In quasi-static tests, this is observed as an increase in resistance with increasing delamination lengths, which led to the proposal to work with a delamination onset *SERR* and a plateau *SERR* [14-15].In fatigue delamination growth, this fibre bridging also plays a role in the experiments and various methods have been proposed to account for it [6,16]. However, they all seem hindered by the presence of a so-called stress ratio or stress ratio effect, which makes a general method difficult. As a result, people tend to normalize the *SERR* with quasi-static fracture toughness values, or develop a delamination resistance relation similar to the Paris relation, which utilized critical *SERR* parameters obtained with quasi-static tests [6,17,18].

This chapter aims to contribute to this topic discussing the validity of most proposed approaches concerning fatigue delamination characterization. In particular, the use of quasi-static data in representing fatigue delamination resistance is critically evaluated and discussed. In addition, the validity of the *SERR* in characterizing delamination in fatigue loading is thoroughly analyzed and discussed.

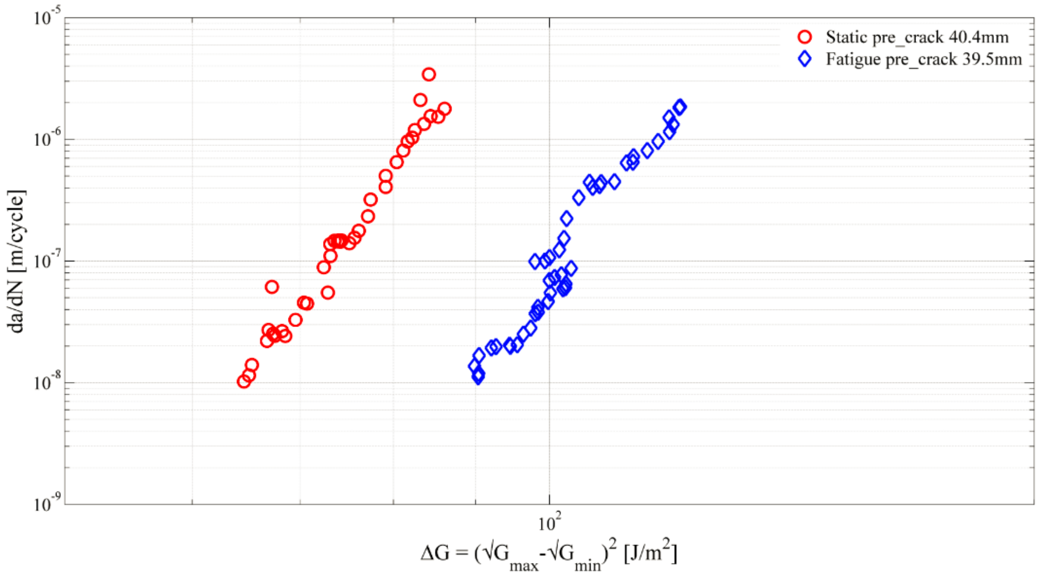
6.2 Results and discussion

6.2.1 Delamination resistance

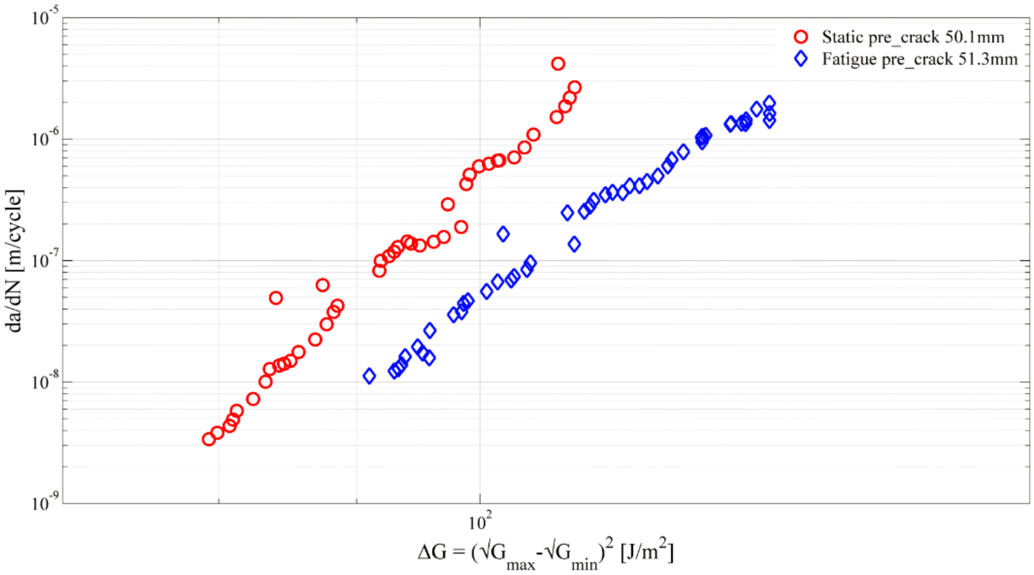
Two specimens, UDCB 19 and MDCB 11 with different interface geometries, were repeatedly fatigue tested at various fatigue pre-crack lengths. The obtained resistance curves are shown in Figure 5.2(b) and Figure 5.3(a). With the increase of pre-crack length, the resistance curve shifts from left to right in the delamination resistance graph and finally converges to a single curve at the most right of the graph. It seems reasonable to assume that bridging is the main reason for this phenomenon. The amount of bridging is related to the crack length and there seems a maximum influence of bridging. This is represented by the most right resistance curve in which bridging has fully developed during delamination.

The other two specimens for each interface configuration with quasi-static pre-crack lengths were also fatigue tested. The results of *da/dN* versus ΔG for unidirectional and multidirectional DCB specimens with similar quasi-static and fatigue pre-crack lengths are illustrated in Figure 6.1. There is a clear difference in all four cases. For the 0//0 interface, the resistance curves obtained from specimens with fatigue pre-cracks locate at the right side of the corresponding curves derived from specimens with quasi-static pre-cracks. Comparing with quasi-static delamination, more bridging is generated in fatigue delamination at the same crack length in the 0//0 interface. For the 45//45 interface, however, this difference still exists, but in an opposite fashion. Here, more bridging seems to be created in quasi-static crack growth, compared to in fatigue crack growth.

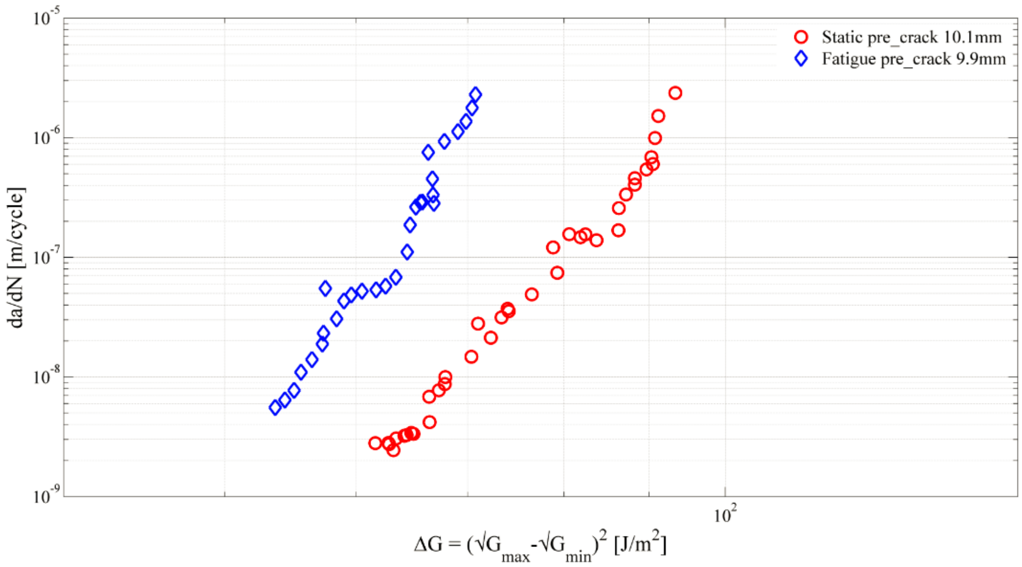
With this experimental data, it can be concluded that the damage state for quasi-static and fatigue delamination is different at the same crack length in composite laminates with large scale bridging. Bridging is the major reason for this kind of difference. Hence, quasi-static bridging clearly provides a different response under fatigue loading compared to fatigue bridging. As a result, it is deemed questionable to use the quasi-static experimental data to normalize the fatigue test result with the purpose of decreasing scatter of fatigue data or establishing a fatigue prediction model. The inappropriateness of correcting fatigue delamination resistance data with quasi-static fracture toughness is also stipulated by the different responses observed for the two interfaces, i.e. 0//0 and 45//45. The fatigue delamination resistance once corrected with the associated quasi-static data would scale up or down depending on the direction of quasi-static resistance in a rather inconsistent manner.



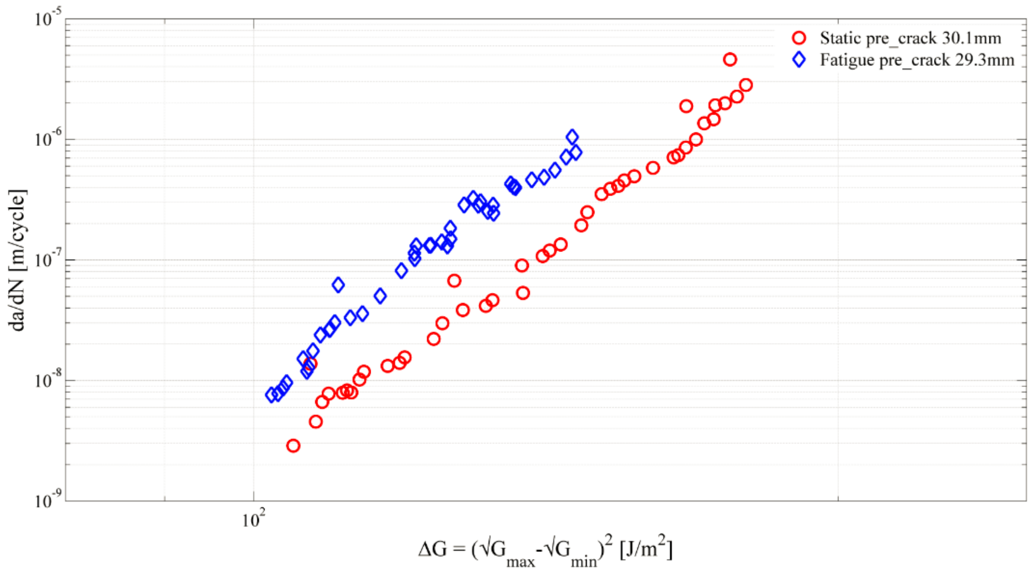
(a) Specimens UDCB 19 and UDCB 20 with 40mm pre-crack lengths



(b) Specimens UDCB 19 and UDCB 21 with 50mm pre-crack lengths



(c) Specimens MDCB 11 and MDCB 13 with 10mm pre-crack lengths



(d) Specimens MDCB 11 and MDCB 14 with 30mm pre-crack lengths

Figure 6.1 Different damage states in quasi-static and fatigue delamination

The concept of *SERR*, corresponding to the release of strain energy in delamination or crack growth, initially originated from Griffith and Irwin's study on quasi-static crack growth [22-23]. In fixed grip condition, all energy is preserved within the specimen, because no additional work is applied. This implies that the total amount of energy absorbed by unit fracture surface should equate to the rate of loss of strain energy from the surrounding elastically strained material, which is defined as critical *SERR* in fracture mechanics. However, load and displacement change continuously during cyclic loading. Consequently, the assumption of fixed grip condition is inapplicable to fatigue loading conditions. The assumption of fixed grip condition, as proposed by Griffith and Irwin may be applicable to quasi-static delamination growth, but becomes inadequate to describe the fatigue delamination extension. Hence, one may expect a different influence of fibre bridging on the response in quasi-static and fatigue loading conditions. In quasi-static loading, the bridging fibres are increasingly strained with the applied load or crack opening displacement and pullout from the matrix, ultimately resulting in fibre failure during delamination. The strain energy stored in these bridging fibres is released upon fibre failure, affecting the *SERR*. This condition may not occur in fatigue. Bridging does not change the strain energy release response during fatigue; the strain energy is released from bridging fibres upon unloading, which is taken up again by the bridging fibres in the next loading cycle. As a result, bridging has no contribution to strain energy release in fatigue, unless bridging fibres pullout or fail.

There is another aspect related to the fixed grip condition assumed by Griffith and Irwin that requires considerations for fatigue delamination. In the fixed grip condition, the strain energy has been introduced into the panel or laminates by the applied work. During the application of this work, no crack growth is assumed, which implies that the strain energy released upon a crack extension Δa, indeed yields the strain energy release ΔU. Hence, the *SERR* is calculated with $(dU/da)/B$ for crack propagation in a DCB specimen, see Figure 6.2.

However, assuming that the fatigue load cycle can be captured with ΔG, implicitly assumes a non-existent release of strain energy. Both the *SERR* at maximum and minimum load relate to a crack extension Δa that occurs in fixed grip condition at that particular load level. Thus, it is assumed that the load is increased from minimum load to maximum load without any crack increment. Subsequently, a crack extension Δa occurs instantaneously, after which unloading occurs without further crack increment. In this sequence, however, the total *SERR* is equal to G_{max}, instead of ΔG, because the strain energy below minimum load is in fact also released.

The problem here, however, is in the assumption that the crack increment occurs instantaneously at maximum load, instead of during the increase of load from minimum to maximum load. Generally, the crack extension takes place while loading from minimum to maximum load, which continuously alters the applied work in a way that is in disagreement with the assumptions of Irwin. Hence, the strain energy released between minimum and maximum load is the difference between the work applied while loading from minimum to maximum, and the work applied while releasing the load from maximum to minimum load. This energy release is substantially smaller than what is calculated with ΔG, see Figure 6.2.

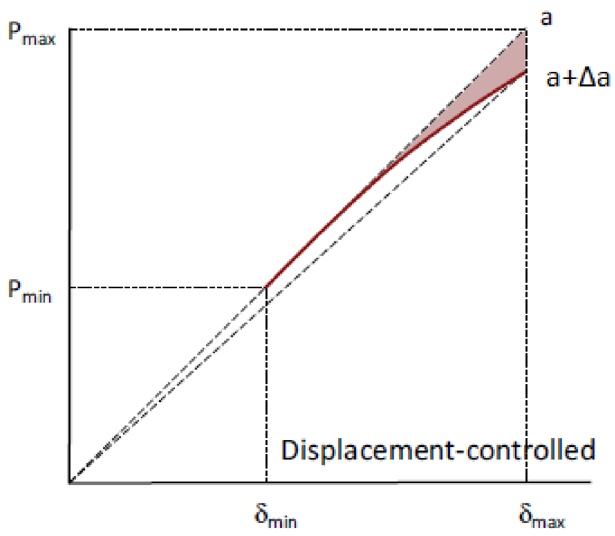


Figure 6.2 Non-linear response during fatigue loading [24]

Hence, the effect illustrated in Figure 5.2(b) and Figure 5.3(a) may be completely artificial and related to the underlying assumption of fixed grip condition in the way that *SERR* in cyclic loading is calculated. From the concept of energy balance, the real loss of strain energy should be equated to fatigue delamination. There should be an intrinsic relationship between fatigue delamination and strain energy release in the entire fatigue tests.

6.2.2 Strain energy release in fatigue delamination

With the loads and displacements measured during the fatigue tests, one can quantify the strain energy release throughout the entire test and provide applied work U, see Equation (3.4), versus number of cycle N chart. An illustration is given for specimen UDCB 19 in Figure 6.3 .The slope of this curve constitutes the strain energy release per cycle, i.e. dU/dN.

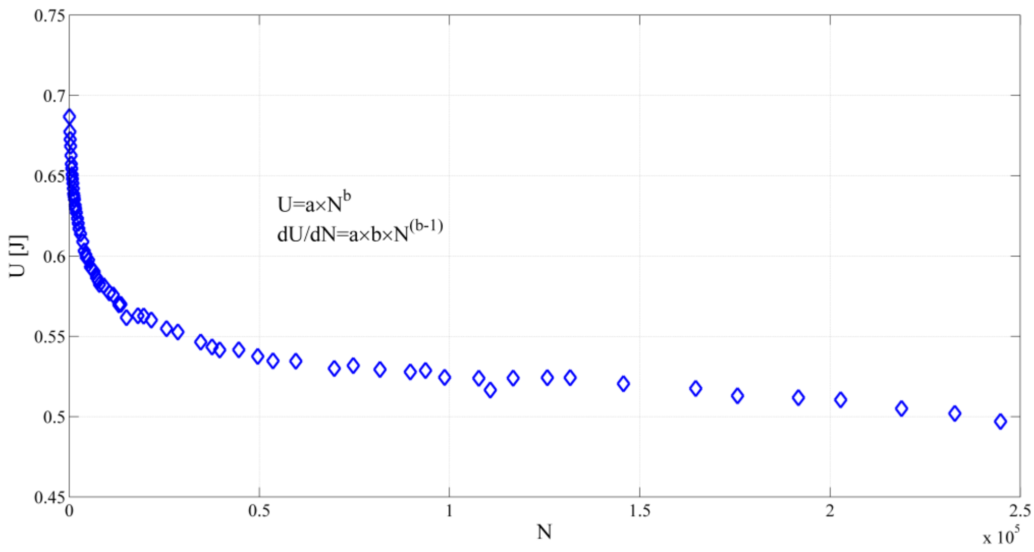


Figure 6.3 Applied work *U* versus number of cycles *N*

First, in force controlled fatigue tests, the calculation of strain energy release is a little bit more complicated, because the strain energy will increase due to the increase in the displacement. As a result, the strain energy release related to crack extension is equal to the difference in strain energy minus the work done due to displacement increase.

However, fatigue experimental data from displacement controlled tests is essentially equivalent to the data from force controlled tests, given that the contribution of this work has been excluded. The primary reason that fatigue tests were preferred to be conducted under displacement control is that fatigue loading automatically decreases during delamination growth. As a result, the corresponding *SERR* and crack growth rate decrease with delamination growth. The *SERR* and delamination growth under force control increase with delamination extension, making the test control a bit more difficult. Additionally, the specimen may fail catastrophically in this way, as the critical fracture load drops to the level of maximum applied fatigue load during the test [25].

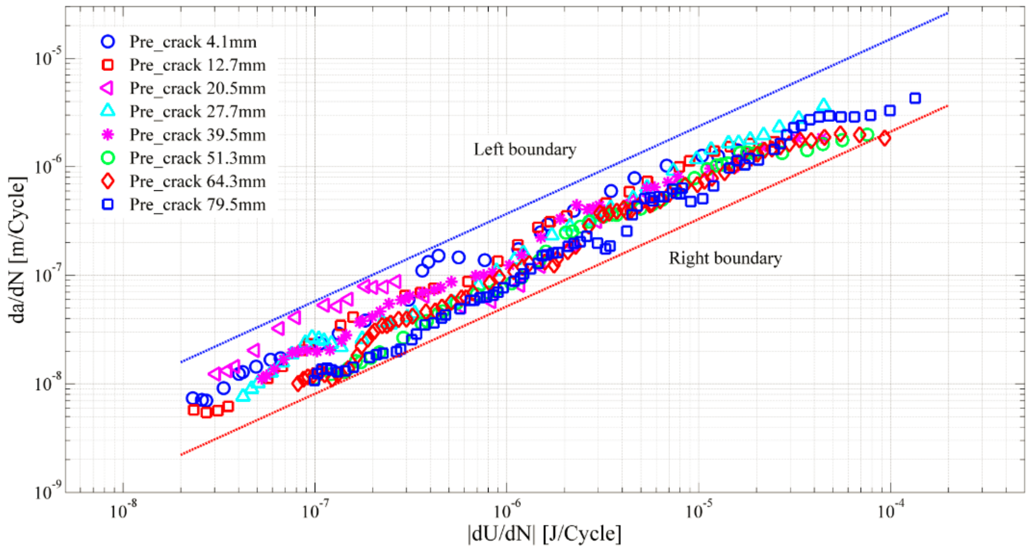
In another study [26], it is demonstrated that fatigue tests under displacement control and force control yielded the same conclusion. It indicates that the relationship between *da/dN* and *dU/dN* is also valid if the fatigue test is performed with the force controlled.

From the point of energy balance, the loss of energy is absorbed by fatigue crack extension. Thus, there should be a profound relationship between *da/dN* and *dU/dN*. Hence, the experimental data shown in Figure 5.2(b) and Figure 5.3(a) can be reproduced in the new format, i.e. *dU/dN* against *da/dN*. The results are shown in Figure 6.4 for specimen UDCB 19 and MDCB 11. All curves indeed seem to coincide to a single curve, which evidently demonstrates that fibre bridging has little or limited influence on the effective strain energy release during fatigue delamination growth.

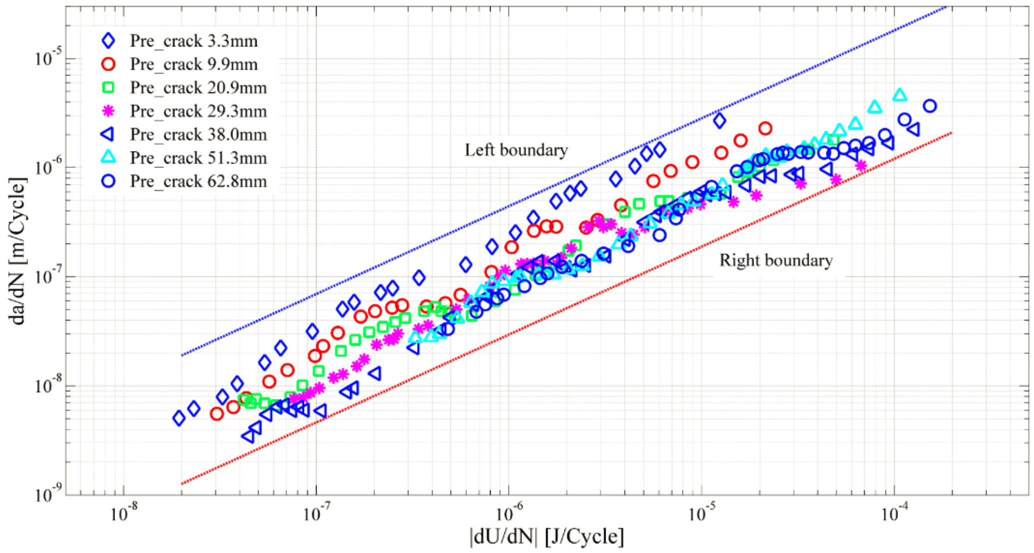
Now, let us take a closer observation on the resistance curves in Figure 6.4. For the 0//0 interface, it is difficult to see obvious differences between the data with the increase of pre-crack length. For the 45//45 interface, however, there is small offset in the results depending on the pre-crack length. According to the previous study, more bridging is generated in the multidirectional interface compared to the unidirectional interface [19]. Although less visible in Figure 6.4 (a) for the 0//0 interface, there seems a tendency for the curves to move slightly to the right with increasing pre-crack length. All data is positioned between the two indicated boundaries, with the left boundary representing the case of absence of bridging, whereas the right boundary represents fully developed bridging.

The explanation is that upon crack extension in presence of fibre bridging, some of the released energy is absorbed by the bridging fibres, reducing the crack growth rate, while limiting the strain energy release. As explained before, this absorbed energy remains in the bridging fibres and is not permanently released. The more bridging fibres are present, the further the crack growth rate is limited at similar levels of strain energy release. Once a balance is formed between the addition of bridging fibres due to crack extension and the failure of bridging fibres that actually do contribute to permanent strain energy release, bridging is considered fully developed. This is represented by the right-hand boundaries in Figure 6.4.

From the results in Figure 6.4, it can be concluded that the contribution to strain energy release of bridging fibres that fail is rather limited in fatigue delamination. Thus, during cyclic loading, strain energy is periodically stored and released in bridging fibres without affecting the permanent strain energy release. Only upon failure of bridging fibres, strain energy is permanently released contributing to the *SERR*. As a consequence, the *SERR* calculated by the fixed grip condition is artificial and violates its physical nature in cyclic loading.



(a) Specimen UDCB 19



(b) Specimen MDCB 11

Figure 6.4 *da/dN* vs. *dU/dN* for specimens with fatigue pre-crack

Figure 6.5 shows a comparison of all experimental fatigue data with various fatigue pre-crack lengths in both unidirectional and multidirectional specimens. The right-hand boundary of the multidirectional specimen is positioned right from the unidirectional results. This is because more bridging fibres were generated in the 45//45 interface. The greater shift from left to right for the 45//45 interface implies more strain energy is released by the failure or pullout of bridging fibres, compared to that in the 0//0 interface. The fact that both data sets predominantly overlap illustrates that the strain energy release mostly responds to the extension of delamination. The bridging fibres have no significant influence on the *SERR*, as the energy taken up by the bridging fibres remains within the specimen and is not permanently released. Only when fibres fail, strain energy is permanently released. This aspect is evidently similar for the different interfaces.

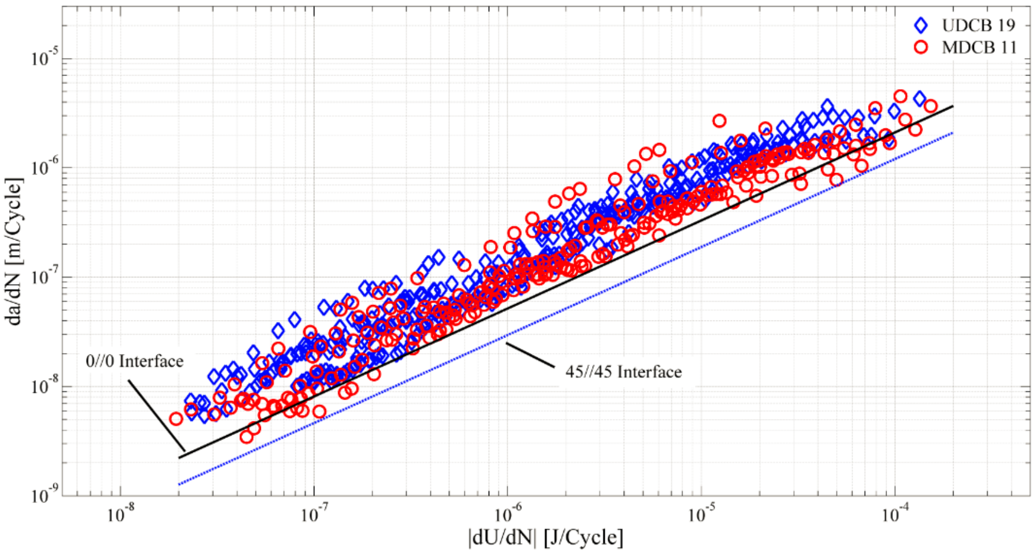
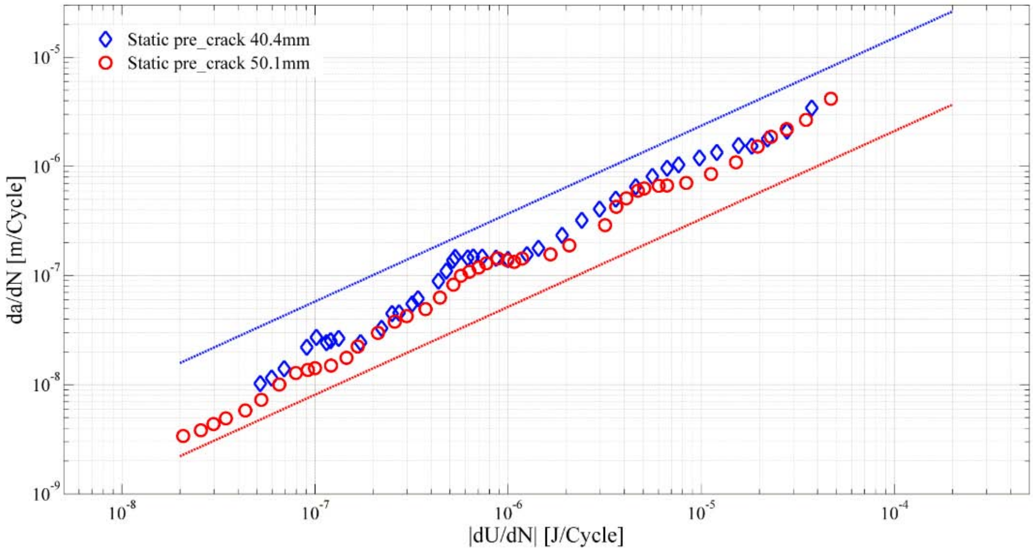


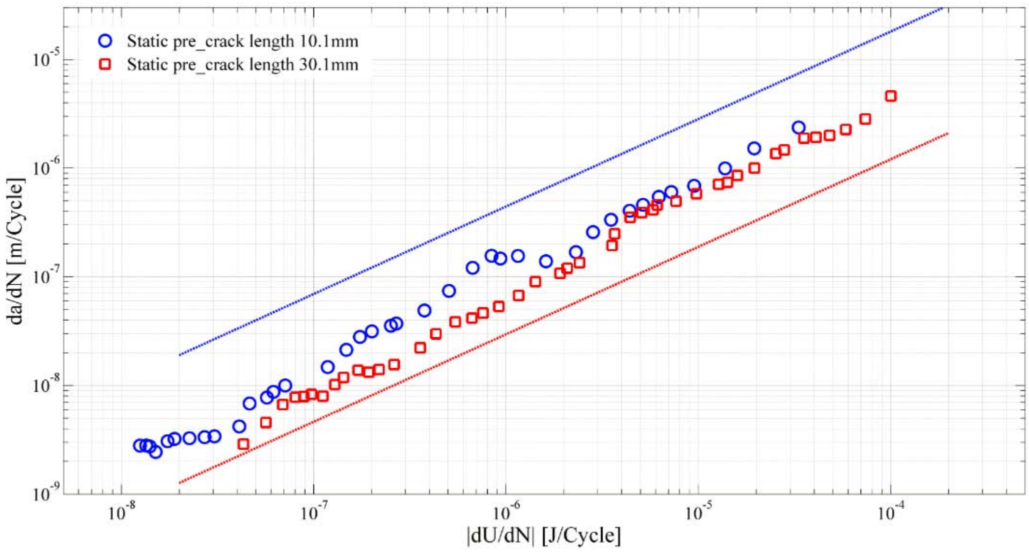
Figure 6.5 Specimen UDCB 19 and MDCB 11

Fatigue experimental data for specimens with various quasi-static pre-cracks were also re-analyzed in the new format, i.e. *da/dN* vs. *dU/dN*, as illustrated in Figure 6.6 with the left and right boundary lines obtained from specimen with different fatigue pre-crack lengths for each interface configuration in Figure 6.4. In all cases, all the data locate within the scope of the narrow band, which implies that bridging created during quasi-static delamination still has little influence on the effective strain energy release in fatigue delamination growth.

Taking a closer look at the fatigue results, there seems a slight shift from left to right in the results with increasing the quasi-static pre-crack lengths. This trend corresponds to what has been observed for the fatigue tests with fatigue pre-crack lengths. The reason for the small shift is also the same to that for specimen with distinct fatigue pre-crack lengths, i.e. more bridging fibres tend to fail with a long delamination length compared to that with a short delamination. These results provide further evidence for the conclusions that bridging has little influence in the contribution of the effective *SERR* during fatigue loading. The strain energy is only periodically stored and released in bridging fibres without permanent strain energy release. Permanent strain energy release only occurs when these bridging fibres fail.



(a) Specimen UDCB 20 and UDCB 21



(b) Specimen MDCB 13 and MDCB 14

Figure 6.6 *da/dN* vs. *dU/dN* for specimens with quasi-static pre-crack

6.3 Discussion on the nature of *SERR*

According to the presented experimental data, it seems incorrect to use quasi-static delamination test results to normalize the fatigue delamination test results in a da/dN versus ΔG presentation. The damage states for these two delamination growth mechanisms are obviously different. It is thus recommended to verify the difference and similarity in damage states in quasi-static and fatigue delamination before deciding to use a normalization method to decrease scatter in fatigue data or establish fatigue prediction models. Normalization only works when the damage states for different loading conditions at the same crack length are the same or at least very similar.

This study also shows that the strain energy release rate should not be expressed as $(dU/da)/B$, but more as dU/dN in fatigue loading, i.e. the strain energy released per cycle. The strain energy release rate $(dU/da)/B$ originates from the fixed grip condition for quasi-static crack growth, which evidently is not suitable to the conditions in fatigue crack growth.

Technically, one can question whether the *SERR* is the right parameter to describe the delamination growth under fatigue loading. It is as Irwin stated [23]: the *SERR* is the result of crack extension; it is not the cause of it. The fact that Irwin correlated dU to da, was because he searched for a stability condition in a quasi-static condition, i.e. fixed grip. This means that the driving force for delamination extension in fatigue cannot be equalled to the *SERR*, as that is merely the consequence of crack extension. Alternatively, one may look for the amount of energy offered and how much of that is actually consumed in crack growth (visible in dU/dN), but that requires that one also calculates how much of the energy is actually consumed each time by bridging fibres.

6.4 Conclusions

The damage state in quasi-static and fatigue delamination at the same crack length is different. This indicates that the amount of bridging generated during crack extension is loading type dependent. Furthermore, this difference seems to be related to interface geometry. As a consequence, it is incorrect to apply quasi-static results to normalize fatigue results, unless the damage state between these two loading conditions for a certain interface configuration is similar.

According to the fatigue experimental data expressed in the new format, i.e. *da/dN* versus *dU/dN*, there is sufficient evidence that bridging fibres actually have little contribution to the real *SERR*. The function of bridging is only periodically storing and releasing strain energy upon loading and unloading without permanent strain energy release. Only when fibre pullout or failure occurs in bridging fibres, strain energy is permanently released from the bridging fibres contributing to *SERR*. The *SERR* calculated based on the fixed grip condition for quasi-static crack growth is not suitable to cyclic loading, as it violates the physical nature of strain energy release. As a consequence, the *SERR* as commonly applied is not a reasonable parameter to characterize fatigue delamination growth. It is therefore recommended to investigate and establish a fatigue delamination prediction model based on the correct principle of energy balance and using energy as the driving force for delamination analysis in future studies.

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7

Interpreting the stress ratio effect using the energy principles

This chapter is reproduced from

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L. Yao, R. Alderliesten, R. Benedictus. The concept of fatigue fracture toughness in fatigue delamination growth behavior. ICCM 20, 2015. Copenhagen.

This chapter provides a study on fatigue delamination growth in composite laminates using energy principles. Experimental data has been obtained from fatigue tests conducted on 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 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.

7.1 Introduction

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, ASTM D5528, has been established for performing quasi-static delamination tests. However, for fatigue delamination, there is no standard to follow. Only the standard ASTM 6115 has been developed to guide the fatigue delamination onset study. 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.

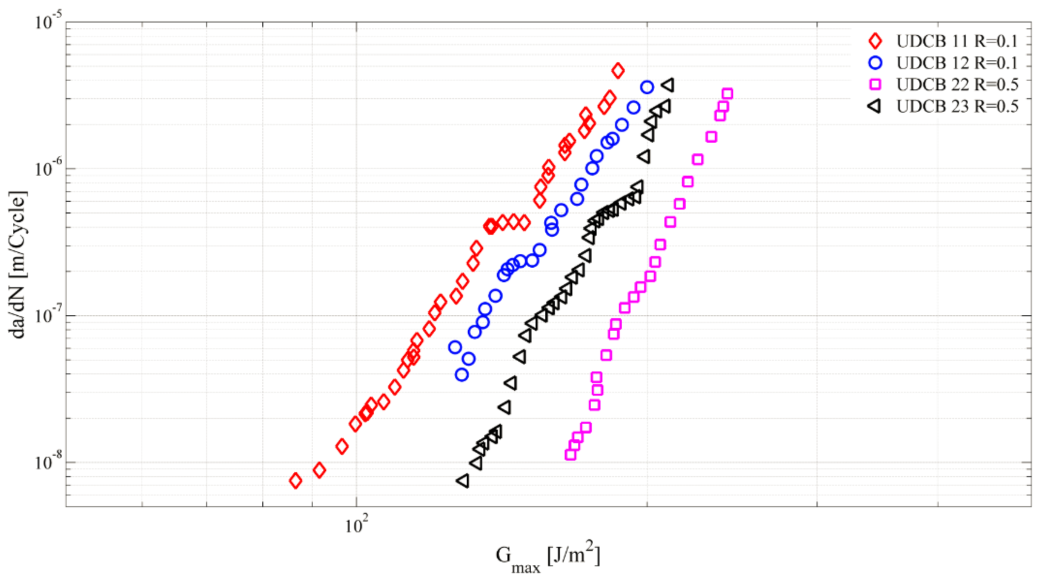
The stress ratio is an important factor in describing fatigue loading and characterizing fatigue crack growth behavior. Large numbers of studies have been conducted on stress ratio effect in fatigue delamination growth [2-8]. Stress ratio effect in fatigue crack growth seems to be similitude parameter 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 are stress ratio effects and what damage mechanisms relate to this 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 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 [12].

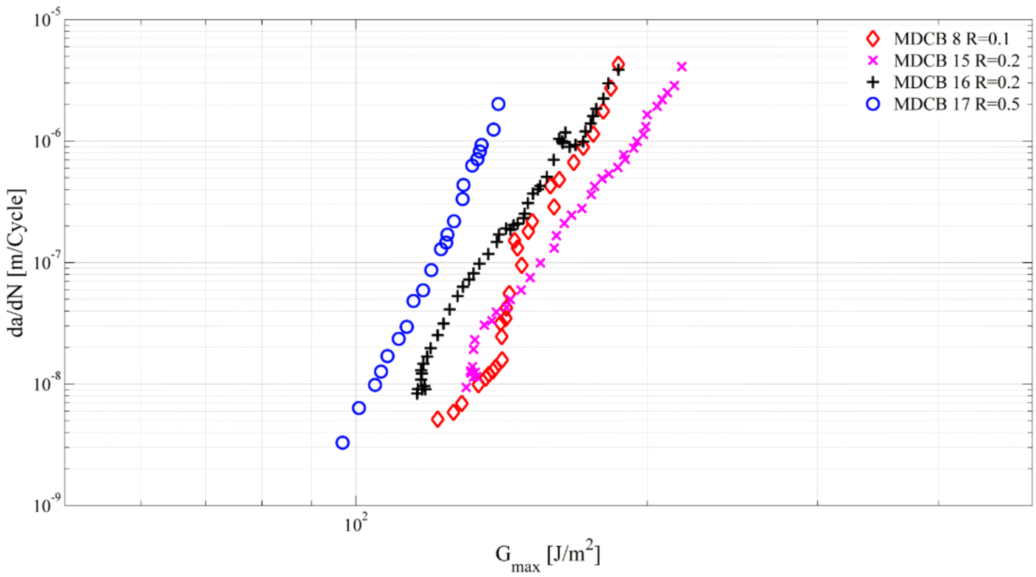
These energy principles are used in the present work to investigate the stress ratio effect in fatigue delamination growth in composite laminates. This chapter aims to provide a physical interpretation of the stress ratio effect in fatigue crack growth.

7.2 Fatigue data analysis with Paris relationship

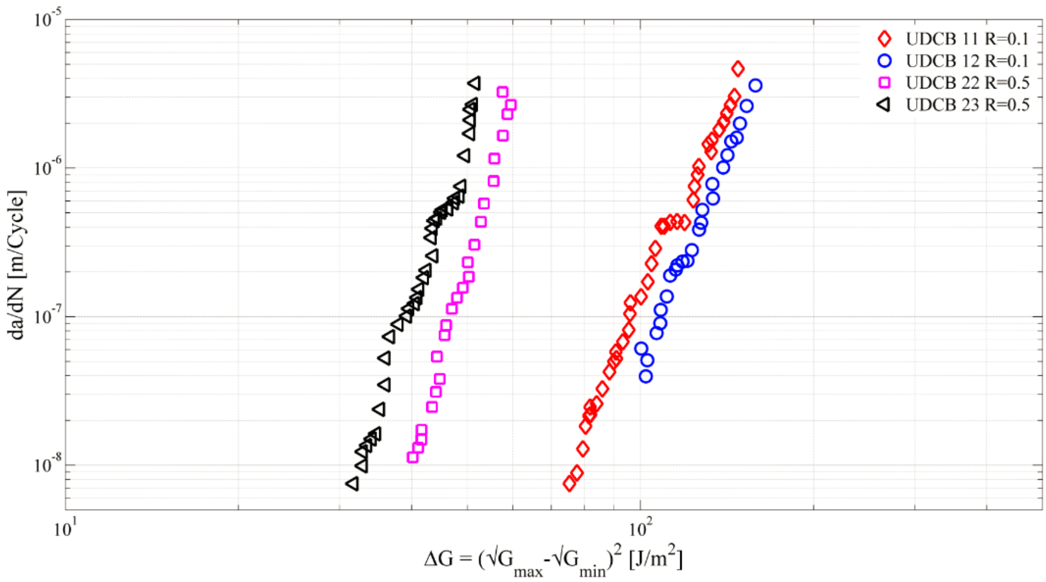
Unidirectional DCB specimens were fatigue tested at stress ratios 0.1 and 0.5. Specimens with 45//45 interface were tested at stress ratios 0.1, 0.2 and 0.5. All data was subsequently analyzed using Paris relations, either in the form of *da/dN* against the maximum *SERR* or *da/dN* against the *SERR* range, as shown in Figure 7.1. Without exception, a significant stress ratio effect can be observed.



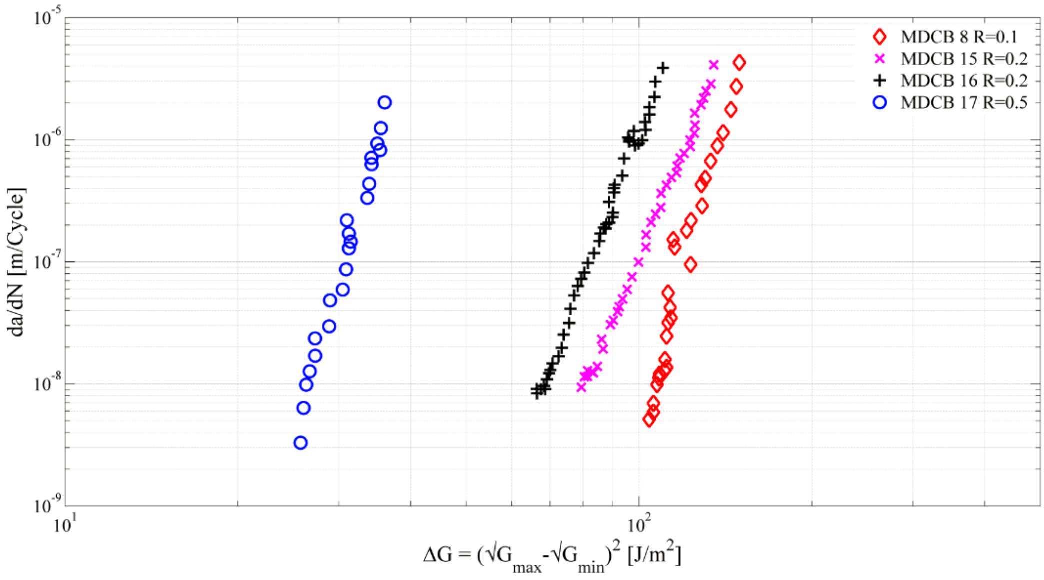
(a) *da/dN* vs. G_{max} for the 0//0 Interface



(b) *da/dN* vs. G_{max} for the 45//45 Interface



(c) *da/dN* vs. ΔG for the 0//0 Interface



(d) *da/dN* vs. ΔG for the 45//45 Interface

Figure 7.1 Experimental fatigue data interpreted with Paris correlations

7.3 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.

7.3.1 Fracture toughness definition

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

$$G = \frac{dU}{dA} \tag{7.1}$$

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

$$\frac{dU}{dN} = \frac{dU}{dA}\frac{dA}{dN} \tag{7.2}$$

Referring to the definition of fracture resistance in fracture mechanics, the component *dU/dA* in Equation (7.2) can be physically interpreted as fatigue resistance.

7.3.2 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.

Figure 7.2 shows the data analysis with energy principles for fatigue tests at the same stress ratio R=0.1, but different interfaces. 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 and below 2×10^{-7}m/Cycle. The constant *G* values are 101.9 J/m^2 for the 0//0 interface and 115.8J/m^2 for the 45//45 interface. This physically means that the total energy dissipated in new crack surface generation is identical at both interfaces and indicates a steady delamination state with self-similar crack growth. In the steady 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 pullout or failure of 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 7.2.

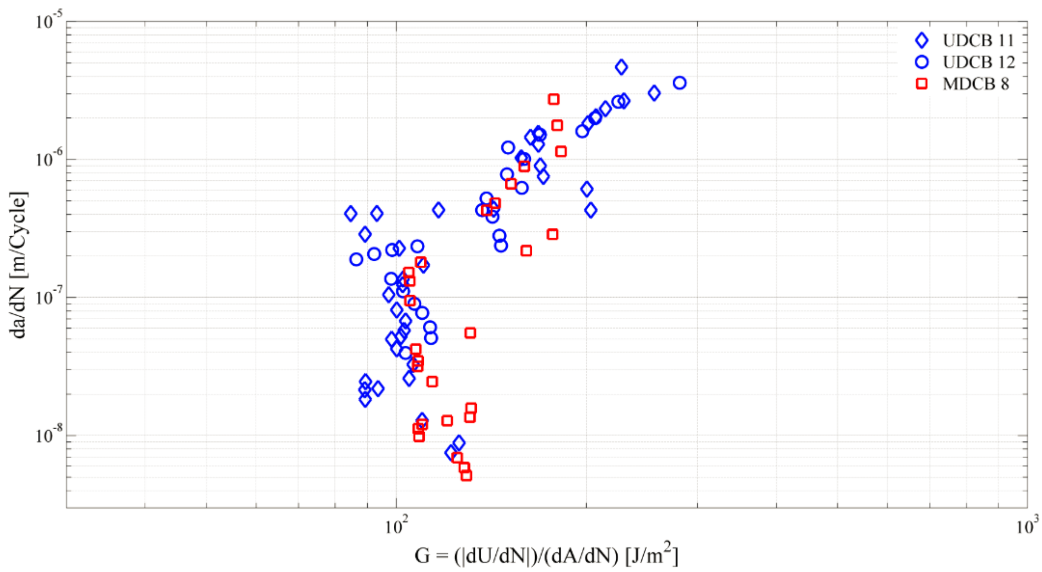


Figure 7.2 *da/dN* vs. *G* at the stress ratio of *R*=0.1

According to previous studies [12], 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 into account of bridging fibre failure at high fatigue crack growth rates, *dU/dN* in Equation (7.2) can be explicitly expressed as

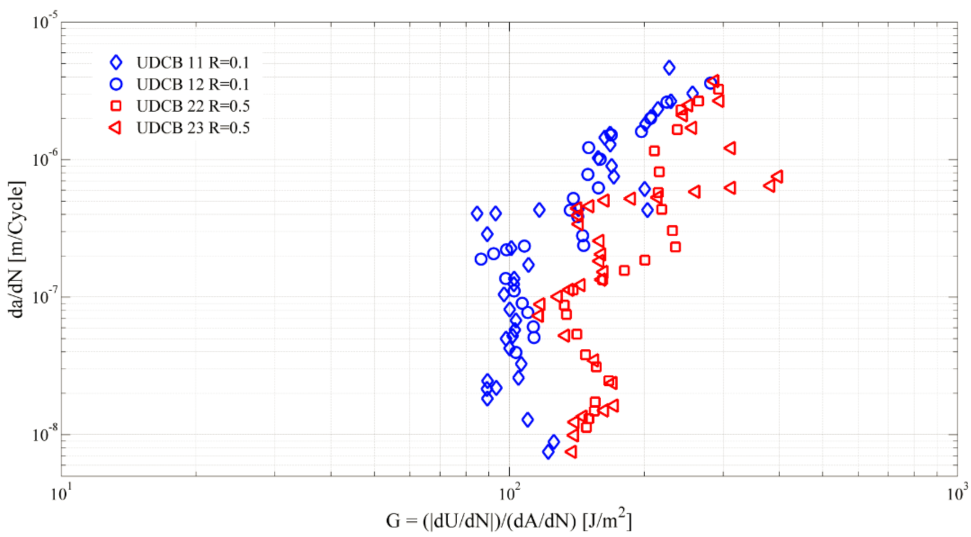
$$\frac{dU}{dN} = \frac{dU_a}{dN} + \frac{dU_{br}}{dN} = \left(\frac{dU_a}{dA} + \frac{dU_{br}}{dA}\right)\frac{dA}{dN} = \left(G_f + \frac{dU_{br}}{dA}\right)\frac{dA}{dN} \tag{7.3}$$

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

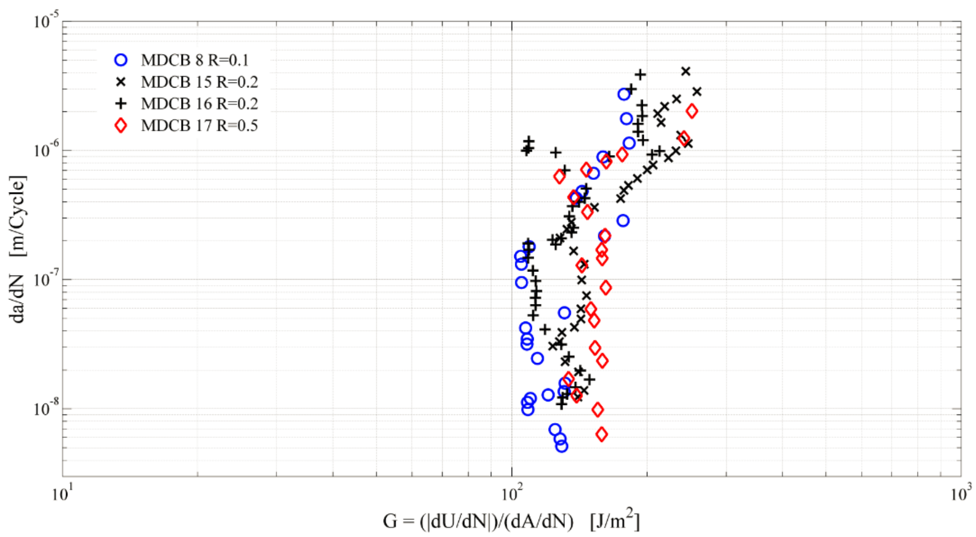
In the steady fatigue crack growth, the contribution of the component dU_{br}/dA in Equation (7.3) is limited and can be ignored. All energy dissipation is directly related to the crack growth, which is explicitly characterized as $G_f=dU_a/dA$ in Equation (7.3). G_f therefore can be defined as the fracture toughness in fatigue crack growth. It is demonstrated to be interface configuration independent as shown in Figure 7.2.

7.3.3 Effect of stress ratio on the 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 7.3. Similar to what has been observed in Figure 7.2, G initially decreases and finally converges to a constant value for each stress ratio. This constant value increases from 101.9J/m^2 to 148.1J/m^2 with the increase of stress ratio from 0.1 to 0.5 in the 0//0 interface. The stable values of G for 45//45 interface are 115.8J/m^2 at R=0.1, 129.4J/m^2 at R=0.2 and 150.4J/m^2 at R=0.5. According to the change in G_f, it can be postulated 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.



(a) 0//0 Interface



(b) 45//45 Interface

Figure 7.3 *da/dN* vs. *G* at different stress ratios

7.3.4 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, experimental fatigue data from UDCB 16 and UDCB 17 with 15mm fatigue pre-crack length were reanalyzed using energy principles and plotted in the form of da/dN against $G=(dU/dN)/(dA/dN)$.

The results for these tests are given in Figure 7.4. 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 7.2, around 200J/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 7.2.

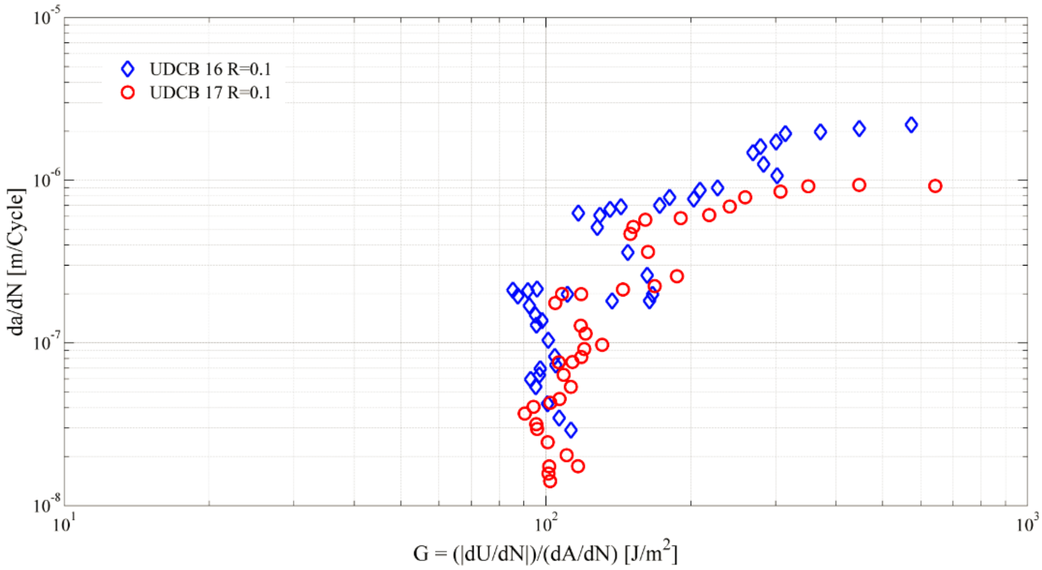


Figure 7.4 0//0 Interface with 15mm pre-crack length

7.3.5 Normalization method in fatigue data analysis

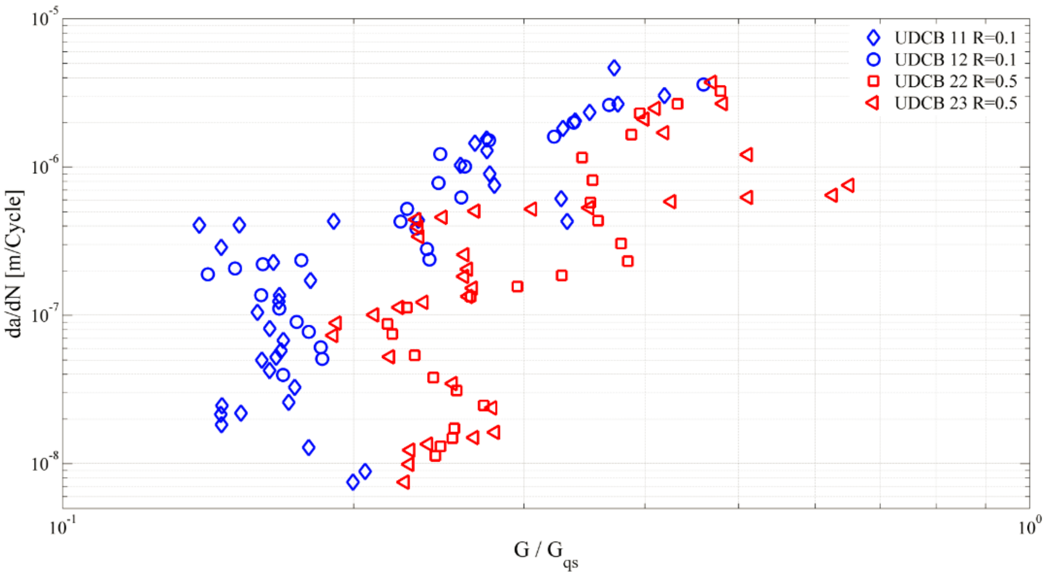
A detailed discussion on the validity of using a normalization method in fatigue data analysis has been given in previous studies [12,13]. It has been demonstrated that the damage state in quasi-static delamination growth differs from that in fatigue. Thus the concept of *SERR* is not the same in fatigue crack growth as in quasi-static, making normalization of fatigue data using quasi-static results disputable. However, in

Griffith's theory, the energy dissipation is not treated as the driving force, but as the consequence of crack growth. On this point, a correlation between quasi-static and fatigue crack growth makes sense.

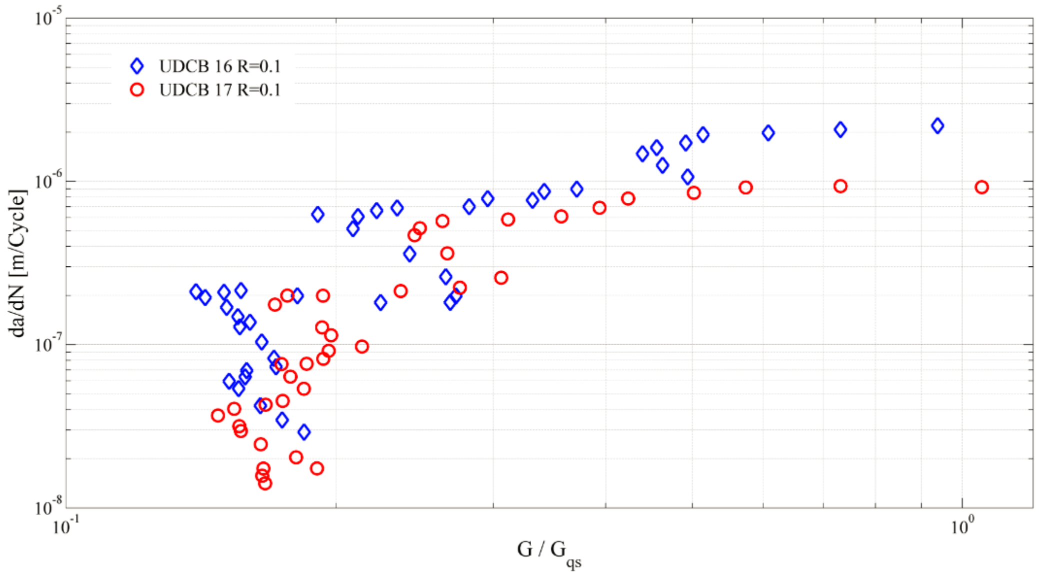
In a recent study, Amaral [15] investigated the energy release in quasi-static delamination based on the energy principles. Quasi-static delamination was treated as low-cycle fatigue crack growth. He subsequently correlated fatigue and quasi-static energy release. It is evident that quasi-static delamination is the least efficient crack propagation with the highest resistance. Considering this correlation on the energy release between quasi-static and fatigue crack growth, it seems reasonable to employ the resistance in quasi-static to normalize the fatigue results, as quasi-static providing a limit on the resistance in fatigue crack growth.

Examples of the normalization method using energy principles are illustrated in Figure 7.5. Figure 7.5(a) shows the results from tests with different stress ratios in the 0//0 interface. For each stress ratio, all data distributes between a band with abscissa value from 0 to 1.The left boundary represents self-similar fatigue crack growth, and the right boundary represents quasi-static resistance. This is also true for the data obtained from tests with 15mm pre-crack length, except one point slightly exceeds 1.

This can be explained by the failure occurring in the bridging fibres during the unloading cycle. It is worth to mention that crack closure was observed in fatigue delamination tests with low stress ratio range $0<R<0.3$ [16]. Thus, bridging fibres can damage due to the contact of fracture surfaces in the unloading cycle by compressive loading, in the end leading to the increase in dU/dN. This phenomenon is even more obvious in a long pre-crack length at the beginning of test. As a result, one point, in Figure 7.5(b), exceeds the quasi-static resistance boundary.



(a) Different stress ratios



(b) 15mm pre-crack length

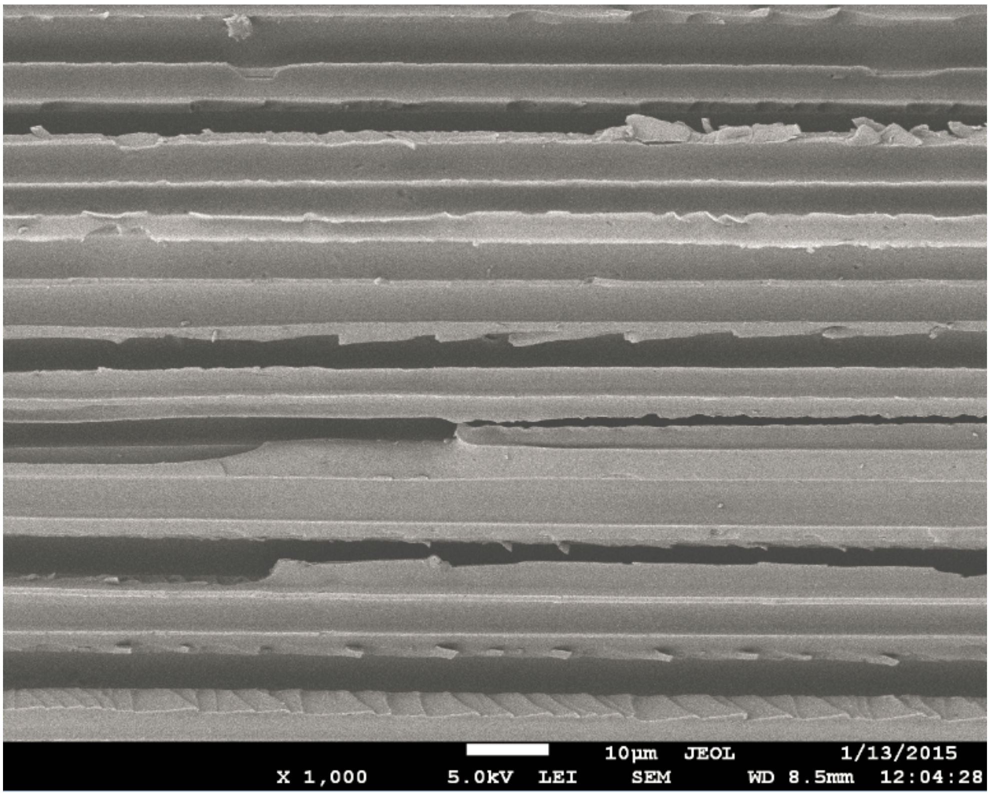
Figure 7.5 Normalization the fatigue results with quasi-static resistance

7.4 SEM analysis

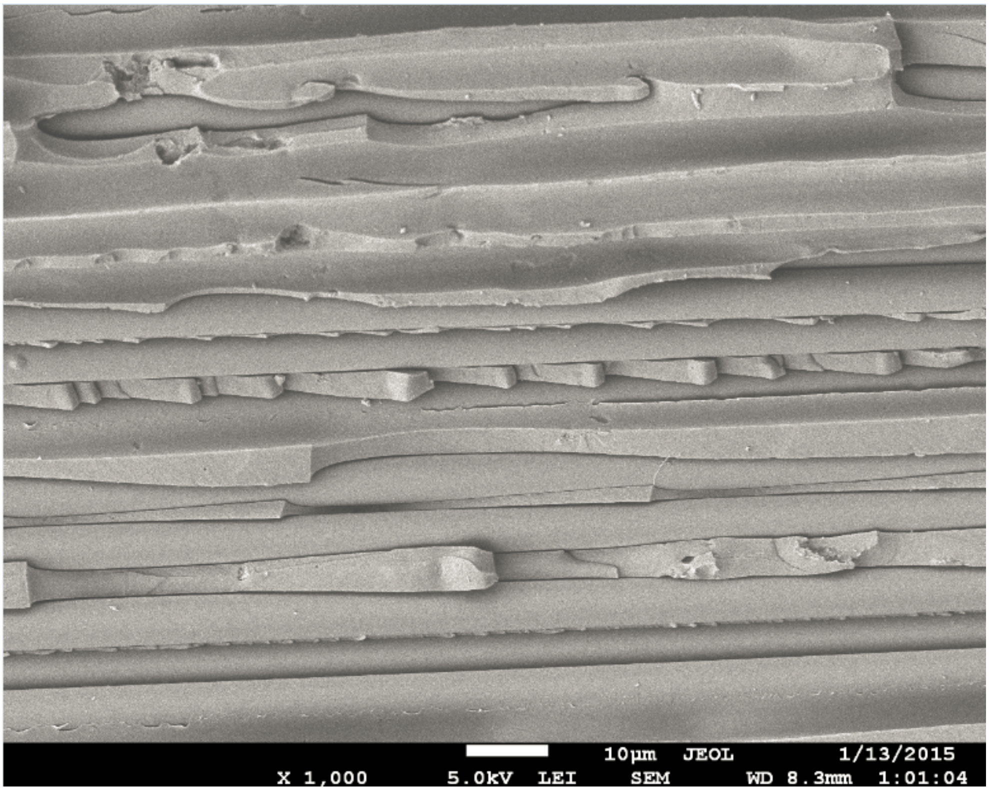
Fatigue fracture surfaces, magnified 1000 times, are shown in Figure 7.6. The dominant features on the fracture are fibre prints and cusps. Fibre prints result from disbanding between reinforcing fibres and matrix. Cusps occur in mode I delamination due to a local shear stress state existing between the fibres and the matrix [17,18].

Generally, the morphology is similar at the different stress ratios in each interface. However, taking a closer observation, the fracture surface is rougher at the high stress ratio compared to the low stress. Cusps are also more obvious 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 7.3.

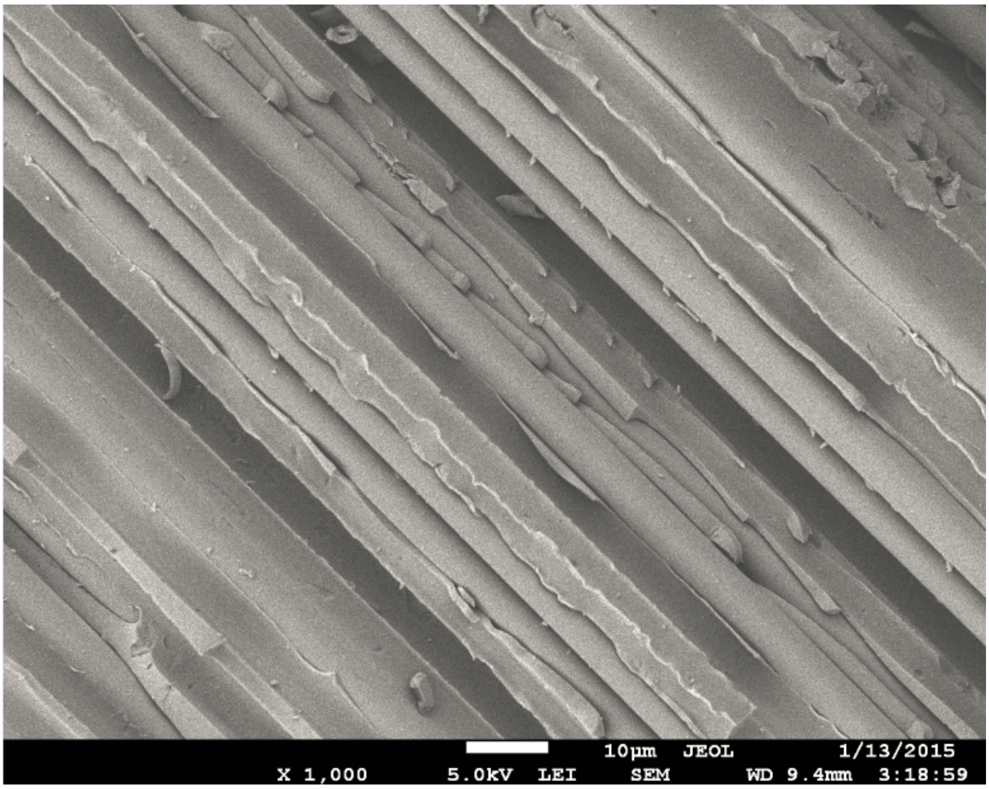
In case of different interface configurations but same stress ratio, the detailed features of fractography are identical and the roughness of the fractures seems to be similar. As a result, the fatigue resistance is interface configuration independent.



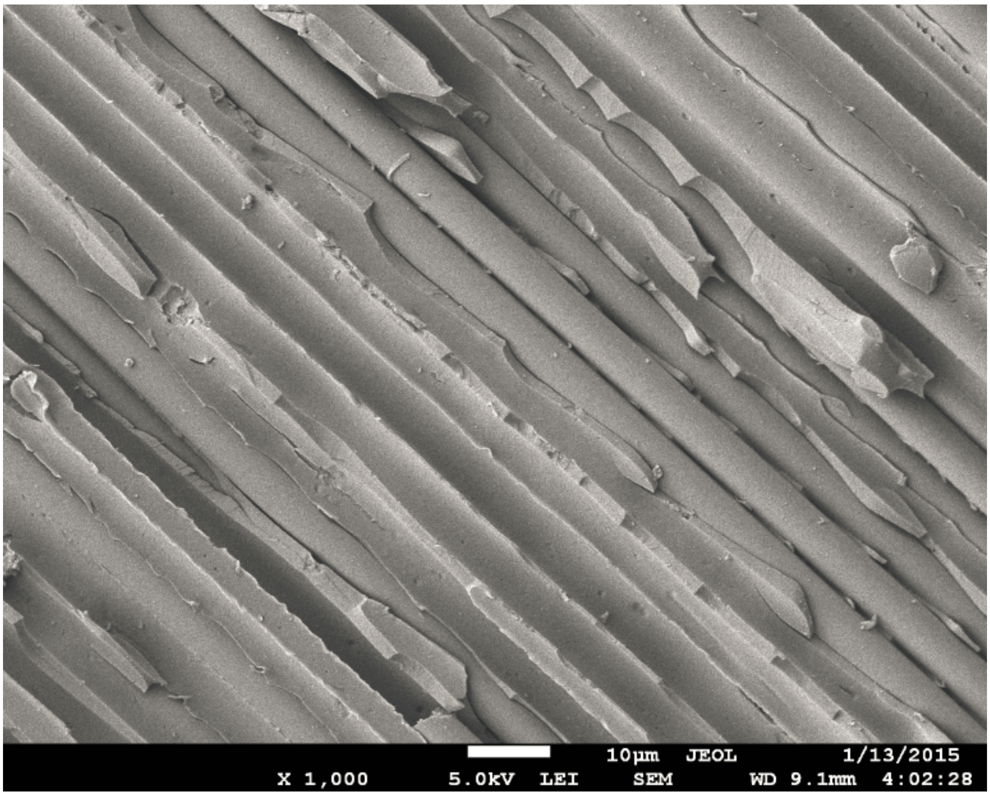
(a) 0//0 Interface R=0.1



(b) 0//0 Interface R=0.5



(c) 45//45 Interface R=0.1



(d) 45//45 Interface R=0.5

Figure 7.6 SEM observation of fracture surface at $da/dN=1\times10^{-7}$m/Cycle

7.5 Discussion on the meaning of 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_{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 $\Delta G = \left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$ as the similitude parameter, the *SERR* range is equal to $(1-R)^2 G_{max}$. In case of using $\Delta G = G_{max} - G_{min}$, the *SERR* range is equal to $(1-R^2)G_{max}$. 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 ΔG 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 ΔG as similitude parameter to interpret the fatigue crack growth. This shortcoming will disappear by using G_{max} as the similitude parameter. Therefore, on this point, G_{max} seems to be more reasonable in fatigue data analysis. However, it is worth noting that neither G_{max} nor G_{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.

7.6 Conclusions

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 interface configuration independent but significantly stress ratio dependent. At the same stress ratio, the fatigue resistance is identical. However, fatigue resistance 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 fibre prints and cusps are two dominant features on the fatigue delamination surface in composite laminates. However, 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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8

Conclusions and Recommendations

8.1 Conclusions

The investigation presented in this thesis focuses on mode I fatigue delamination growth in CFRP. Generally, two approaches were applied to interpret the fatigue crack growth behavior. The first method is based on Paris relations, in which the crack growth is linked to the fracture mechanics concept *SERR*. The second method is according to the energy principles. In this new method, the fatigue crack growth rate *da/dN* was correlated to the energy dissipation rate *dU/dN*.

From current investigation, several conclusions can be drawn with mode I fatigue crack growth in composite laminates. These conclusions are briefly summarized hereafter.

8.1.1 Bridging effect on fatigue delamination growth

Fibre bridging is obvious in mode I fatigue delamination growth, especially in multidirectional interface. This phenomenon plays a shielding mechanism in fatigue crack growth. Bridging fibres will inhibit crack growth by tying the fracture surfaces. As a result, a large amount of strain energy is absorbed by the straining of bridging fibres during fatigue crack growth.

In Paris relations, the fatigue crack growth rate decreases significantly with the development of fibre bridging, leading to the shift of resistance curves in the resistance graph. As a result, it is impossible to use only one resistance curve to determine the fatigue crack growth behavior with fibre bridging.

According to energy principles, this study demonstrated that fibre bridging has little contribution to the real *SERR*. Bridging fibres are periodically storing and releasing strain energy in loading and unloading cycle, but without contribution to permanent strain energy release, unless there is pullout or failure in them. As a result, the calculation of *SERR* based on fixed grip condition for quasi-static crack growth is not suitable for fatigue loading. An artificial *SERR* calculated according to the fixed grip condition may hinder the study of bridging effect on fatigue delamination growth.

8.1.2 Normalization method

To take into account of fibre bridging, normalization methods have been applied in fatigue data analysis. The validity of normalization was investigated by fatigue tests with same quasi-static or fatigue pre-crack lengths. From the experimental data, the damage state in fatigue crack growth differs from that in quasi-static crack growth, making the invalidity of normalizing fatigue data with quasi-static results.

8.1.3 Characterize fatigue crack growth with bridging

Studying the bridging effect on fatigue delamination growth has demonstrated that it is impossible to use only one Paris resistance curve to determine the fatigue crack growth behavior. An alternative Paris type relation was therefore proposed to characterize fatigue crack growth with fibre bridging. In this method, the coefficients in Paris relation are not constant but correlated to the amount of fibre bridging. Using this new Paris type relation, fatigue delamination growth with different amount of fibre bridging can be accurately described.

8.1.4 Stress ratio effect on fatigue crack growth

Stress ratio effect on fatigue crack growth was investigated using energy principles. The concept of fatigue fracture toughness was proposed to determine the resistance under fatigue loading. From the experimental results, the fatigue fracture toughness was demonstrated to be interface configuration dependent but significantly stress ratio dependent. The damage mechanisms related to the resistance increase were investigated by SEM fractography. The stress ratio effect on fatigue crack growth, therefore, can be physically explained by the difference of fatigue resistance in different stress ratios.

8.2 Future work

8.2.1 A general concept for fatigue crack growth prediction

Providing insight into the fundamental mechanisms of the fatigue crack growth should be the first stage in investigating it. Therefore, prediction models can be gradually developed to answer engineering questions according to the observation of physical mechanisms. However, the opposite should not happen in scientific studies.

This thesis basically explained the theory: how *da/dN* relates to the energy dissipation *dU/dN*. However, as all identified parameters are the consequence of the crack growth *da/dN*, this theory is descriptive of nature, but does not allow to be used as prediction model. So the key question in the future work is how this energy *dU/dN* can be correlated to parameters that are considered driving the damage: Work!

The work change in a fatigue load can be schematically determined as shown in Figure 8.1. The total energy in the system can be divided into two parts: monotonic work U_{mon} and cyclic work U_{cyc}. Provided there is no crack growth, U_{mon} will keep constant. U_{cyc} will increase from zero to U_{tot}-U_{mon} in the loading cycle and decrease to zero in the unloading cyclic. However, both U_{mon} and U_{cyc} will decrease, once there is crack growth. According to energy principles, the energy change in a fatigue load cycle can be determined by [1]

$$U_{mon} + U_{\uparrow} = U_{mon}^{*} + U_{\downarrow} + \frac{dU}{dN} \tag{8.1}$$

Where $U_{\uparrow}$ represents the work applied to the system in the loading part of a fatigue cycle; $U_{\downarrow}$ represents the work applied by the specimen in the unloading part of the fatigue cycle. Equation (8.1) can be rearranged as

$$\frac{dU}{dN} = (U_{mon} - U_{mon}^{*}) + (U_{\uparrow} - U_{\downarrow}) \tag{8.2}$$

Thus, the total energy dissipation *dU/dN* is the sum of energy change related to U_{mon} and U_{cyc}. According to previous study, there is an intrinsic relationship between *dU/dN* and *da/dN*. In order to determine the fatigue crack growth, it is reasonable to establish correlation between *dU/dN* with U_{mon} and U_{cyc}. A general form of this relation can be expressed as

$$\frac{dU}{dN} = f\left(U_{mon}, U_{cyc}\right) \tag{8.3}$$

Based on the concept of fatigue fracture toughness G_f, the relation between fatigue crack growth and the applied work can be determined as

$$\frac{da}{dN} = \frac{1}{G_f}\frac{dU}{dN} = \frac{1}{G_f} f\left(U_{mon}, U_{cyc}\right) \tag{8.4}$$

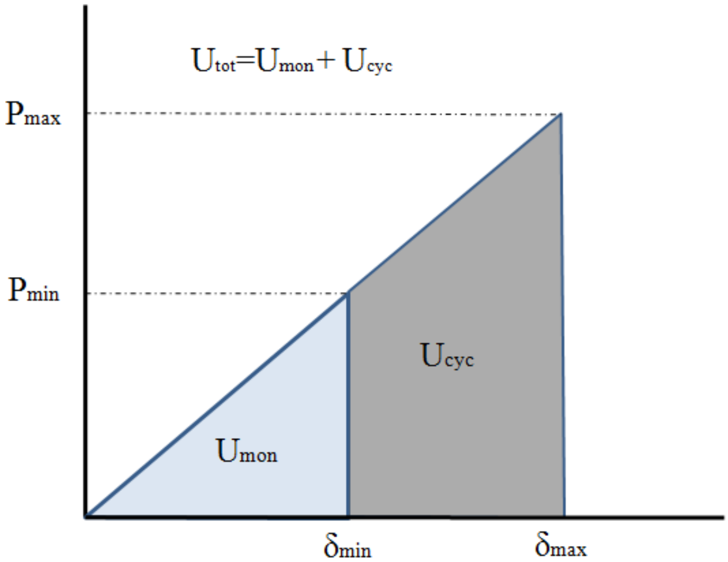

Figure 8.1 Schematic of the energy components in a fatigue load

According to Equation (8.4), fatigue crack growth behavior can be predicted. It provides a general concept to predict fatigue crack growth using energy principles. The explicit formulation of Equation (8.4) has not been established yet. It is worth noting that there is no parameter in this equation representing the geometry information of the structures. Thus, the correlation between *da/dN* and U_{mon} and U_{cyc} is probable to be geometry dependent. In other words, the fatigue crack growth may be not the same for specimen with different dimensions, even though the correlation in Equation (8.4) is similar. In order to take into account of geometric effect, Equation (8.4) should be further developed to include parameters that representing geometry.

8.2.2 Negative stress ratio effect

Mode I fatigue crack growth is under tensile loading. In this condition, the negative part of the loading is considered to have no contribution to crack growth. Thus, the method proposed in this thesis to calculate the work in fatigue cycle is suitable for the fatigue data analysis.

However, this is not true for mode II or mixed-mode I/II fatigue crack growth. In these conditions, the crack growth is totally or partly under shear loading. The value of shear load below zero still has contribution to fatigue crack growth. As a result, the work calculation used in present study is not suitable anymore. In the future study on mode II and mixed-mode I/II fatigue crack growth, researchers need to consider the work related to the negative shear load in a fatigue cycle and its contribution to crack growth.

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Curriculum Vitae

The author was born on the 9th August 1986 in Shaanxi Province, China. He received his bachelor and master degree in the major of Flight Vehicle Design from Northwestern Polytechnical University in 2008 and 2011, respectively. He subsequently started his Ph.D study in the same university. In October 2012, he got finance support from China Scholarship Council and carried out his research on fatigue delamination growth in composite materials in the Structural Integrity & Composites group, Faculty of Aerospace Engineering at TU Delft, under the supervision of Prof. Rinze Benedictus and Dr. René Alderliesten. In October 2014, he got the finance support from TU Delft to continue his Ph.D study in TU Delft.

List of Publications

Journal Papers

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