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Mode I fatigue delamination growth with fibre bridging in multidirectional composite laminates

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Abstract:

Fatigue delamination in multidirectional composite laminates was experimentally investigated in present study. Both the Paris relation and a modified Paris relation (with a new similitude parameter) were employed to interpret fatigue delamination with significant fibre bridging. The results clearly demonstrated that fatigue delamination was independent of fibre bridging, if a reasonable similitude parameter was used in data reduction. As a result, a master resistance curve can be fitted to determine fatigue crack growth with different amounts of fibre bridging. The energy principles were subsequently used to provide physical interpretation on fatigue delamination. The results indicated the energy release for the same fatigue crack growth remained constant with fibre bridging. Bridging fibres in most cases just periodically stored and released strain energy under fatigue loading, but had little contribution to real energy release. The master resistance curve was finally applied to predict fatigue delamination with fibre bridging. Acceptable agreement between predictions and experiments was achieved, demonstrating the validation of the modified Paris relation in fibre-bridged fatigue delamination study.

Keywords: Fatigue; Delamination; Fibre bridging; Multidirectional composite laminates

1. Introduction

Advanced composite laminates have been widely used in aerospace engineering for the requirements on light-weight structures and fuel efficiency. These materials take advantages of excellent properties, i.e. high strength-to-weight and stiffness-to-weight ratios. However, they suffer disadvantage of poor interlaminar property, due to lack of reinforcement in thickness direction. This weak point can easily result in delamination propagation between neighbored layers under either quasi-static or fatigue loading. It has been widely admitted that delamination was one of the most important damage in composite laminates and must be well considered in composite structural design [1-15]. This damage indeed became a big obstacle and challenge in applications of composites in critical engineering parts and limited their weight saving potential. It is, therefore, meaningful and significant to have in-depth understanding on mechanisms and prediction models for delamination in composite laminates.

A critical literature review on fatigue delamination growth in composite laminates and adhesive bonds has been completed by Pascoe et al [1]. Four category methods have been used in the characterization of delamination behavior under fatigue loading. In this classification, methods based the fracture mechanics were widely used, in which fatigue crack growth was correlated to the stress intensity factor *K* (*SIF*) or the strain energy release rate *G* (*SERR*). And the Paris relation has been admitted as one of the most important achievements in fatigue crack growth study in the last several decades. It has been widely used in scientific studies and structural designs, even though some researchers have noticed that it was no more than an empirical correlation and not based on physical understanding of fatigue crack growth [1]. In addition, there was no consensus on the similitude parameter in fatigue delamination studies in composite laminates. People alternatively employed the maximum *SERR* G_{max}, the *SERR* range ΔG, or combinations of them as similitude to determine fatigue crack growth [3-7].

It is worth noting that there is no standard for mode I fatigue delamination growth. To address this problem, the ASTM D30 Committee and the European Structural Integrity Society Technical Committee 4 (ESIS TC4) have performed separate round-robin mode I fatigue tests on unidirectional double cantilever beam (DCB) specimens to investigate the influence of a series of factors [7,14,15]. Even though some achievements have been obtained, the standard is still undergoing discussion at this moment. Unidirectional DCB specimens have been commonly used to determine mode I interlaminar crack growth behavior of a composite material under fatigue loading [3,6,8-13]. Hojo et al [3] experimentally investigated fatigue delamination behavior under different stress ratios. And a two-parameter power law relation was proposed to determine fatigue delamination. In following studies [6,8], they provided research on fatigue delamination in composite laminates with interlaminar reinforcement. Cartié et al [9] experimentally investigated fatigue delamination behavior in z-pin reinforced composite laminates. Shivakumar et al [10] proposed a total fatigue life model to determine delamination behavior in subcritical, linear and final fracture domains via mode I fatigue tests conducted on unidirectional DCB specimens. Argüelles et al [11] investigated the onset and crack propagation behavior under fatigue loading with unidirectional DCB specimens. Coronado et al [12] tried to determine fatigue delamination behavior at different temperatures. It was found that crack growth decreased with elevated temperatures. Khan et al [13] developed a two-parameter power law relation to characterize fatigue delamination behavior via experiments conducted on unidirectional DCB specimens.

Referring to delamination results under quasi-static loading [16-18], interface configuration had important effects on crack growth behavior. It was reported that the use of unidirectional DCB specimens sometimes can cause conservative results and underestimate interlaminar property, especially for delamination with large-scale fibre bridging [17]. In detail, initiation crack growth may be independent of ply orientation, whereas crack propagation was significantly dependent of interface configuration. The presence of fibre bridging during delamination was the main reason for this dependence, as more bridging fibres were observed in delamination of multidirectional composite laminates. As a result, a growing number of research have been conducted on multidirectional laminates to have further understanding on delamination behavior under quasi-static loading [19,20].

For fatigue delamination, limited research has ever been reported to be performed on multidirectional composite laminates. Zhao et al [18,21,22] conducted experiments on fatigue delamination with multidirectional composite laminates. Significant fibre bridging was observed as well. And a normalized power law relation was proposed to determine fatigue delamination behavior. Yao et al [17,23] carried out fatigue delamination tests on DCB specimens with different ply orientations and gave thorough discussions on bridging effects on fatigue delamination. Banks-Sills et al [24,25] experimentally examined fatigue delamination behavior in woven composites via DCB specimens with multidirectional interfaces. The fatigue delamination results were first interpreted via the Paris-type relations, and subsequently explained via a modified Hartman-Schijve equation.

According to the previous studies [17,18,21-23], even significant fibre bridging can exist in crack growth of multidirectional composite laminates. The presence of fibre bridging can significantly affect fatigue delamination behavior. One then reasonably ask what about fatigue delamination in this condition, and how to well characterize fatigue crack growth behavior. To this end, the objective of present research is to explore fibre-bridged fatigue delamination in multidirectional composite laminates and to provide an evaluation on the effectiveness of both the Paris relation and a modified Paris relation in fatigue delamination study.

2. Material and Experimental procedure

2.1. Material and specimen preparation

DCB specimens with 45//45 interface were manufactured and tested to investigate fatigue delamination with different amounts of fibre bridging. The stacking sequence was designed as $[(\pm 45/0_{12}/\mp 45)//(\pm 45/0_{12}/\mp 45)]$, with consideration of avoiding crack jumping and minimizing both residual thermal stress and non-uniform energy release rate distribution across the width of the crack front [19,20,26-28].

Composite laminates were fabricated by hand-lay-up of 32 thermosetting unidirectional carbon/epoxy prepreg layers of M30SC/DT120. A 12.7μm Teflon film was inserted in the middle plane of these laminates during the hand-lay-up process to act as an initial delamination with a_0=60mm. The laminates were cured in vacuum in an autoclave at a pressure of 6 bars and curing temperature of 120 ℃ for 90 min. After curing, all laminates, with a nominal cured thickness of 5mm, were C-scanned to detect potential imperfections. The panels were cut by a diamond coated saw into 25mm width beams with 200mm length. And only these samples where no obvious defects were detected were fatigue tested. A pair of aluminum loading blocks, 25mm width by 20mm length with 6mm thickness, was adhesively bonded onto a specimen at the side of the Teflon insert for load introduction.

One side of a DCB specimen was coated with a thin layer of white typewriter correction fluid to enhance visibility of the delamination front during fatigue test. A strip of grid paper was pasted on the coated side of the specimen to aid in measuring crack propagation length.

2.2 Experimental procedure

All fatigue tests were conducted on a 10KN MTS machine under displacement control at a frequency of 5Hz with the same stress ratio *R*=0.5 in ambient conditions. A computer controlled digital camera system was employed to monitor crack growth at the maximum displacement with pre-defined intervals during the tests. The force, displacement and cycle number information were automatically stored in an Excel file every 100 cycles, enabling data evaluation after the tests. The fatigue experimental set-up is demonstrated in Fig.1.

It is worth noting that crack growth can gradually decrease with decreasing *SERR* in displacement controlled tests. The tests were, therefore, manually terminated to save test duration once crack growth nearly retarded. Subsequently, the specimen was tested with increased displacements at the same stress ratio. This sequence was repeated several times to generate fatigue delamination with different amounts of fibre bridging. With this test procedure, multiple delamination resistance curves were obtained, with each one representing the resistance equivalent to a specific fatigue crack length.

The concept of *R-curve* was a convenient way to determine the significance of fibre bridging. This method was also used in present study to represent the critical resistance increase in fatigue crack growth because of fibre bridging. However, the critical interlaminar resistance of a given fatigue delamination length cannot be directly determined in the fatigue test, as the fatigue load was much lower than the critical load. To address this problem, a loading-unloading cycle was conducted on the specimen after a fatigue test until load-displacement curve became nonlinear to measure delamination resistance as well as to determine the maximum and minimum displacements used in subsequent fatigue test.

2.3 Fatigue data reduction

The Paris relation has been widely used to determine fatigue crack growth in composite laminates. This relation can be summarized as Eq.(1). The *SERR*s, i.e. G_{max} and G_{min} under fatigue loading, can be calculated with the Modified Compliance Calibration (MCC) method, recommended in the ASTM D5528-01 standard, see Eq.(2). The 7-point Increment Polynominal Method, recommended in the ASTM E647-00 standard, was applied to determine the fatigue crack growth rate *da/dN*.

$$\frac{da}{dN} = c(\Delta G)^n = c\left[\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2\right]^n \quad (1)$$

where *c* and *n* are two curve-fitting parameters of the Paris relation.

$$G = \frac{3P^2C^{(1/3)}}{2A_1Bh} \quad (2)$$

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

A modified Paris relation, in terms of *da/dN* against the *SERR* range around crack front ΔG_{eff}, has been proposed in a recent study by the authors [31]. This new model can be summarized as Eq.(3). It was also used in fatigue data reduction in present study as a comparison to the Paris relation.

$$\frac{da}{dN} = c^*\left(\Delta G_{eff}\right)^{n^*} = c^*\left[\left(\sqrt{G_{tip,max}} - \sqrt{G_{tip,min}}\right)^2\right]^{n^*} = c^*\left[\frac{G_0}{G_{fc}(a-a_0)}\Delta G\right]^{n^*} \quad (3)$$

Where c^* and n^* are two curve-fitting parameters of the modified Paris relation; G_0 is the fatigue delamination resistance with no fibre bridging; $G_{fc}(a\text{-}a_0)$ represents the critical resistance increase with fatigue crack extension.

Similitude principle plays an important role in fatigue crack characterization. According to this principle, *the same value of a similitude parameter should result in the same fatigue crack growth, and vice versa*. This can be used to verify whether a similitude parameter used in fatigue crack growth study is valid or not. Particularly, if the same value of a similitude can cause the same crack growth, it is a reasonable similitude parameter. Otherwise, it cannot well represent the similitude.

Apart from using the two Paris-type relations to interpret fatigue crack growth with fibre bridging in multidirectional composite laminates, energy principles were also applied to have physical understanding on fatigue delamination as well as to provide explanations on the effectiveness of different similitude parameters used in present study. In practice, it is easy to quantify the applied work U against fatigue cycle number N with the information recorded during the tests. Taking a derivative between U and N, the energy release rate dU/dN can be determined. And a correlation between da/dN against dU/dN can be obtained. With this correlation, energy release during fatigue delamination can be well evaluated and analyzed. In the perspective of energy balance, this evaluation can not only physically explain fatigue delamination behavior, but also improve one's understanding on the real role of fibre bridging in fatigue crack growth.

3. Results and discussion

One multidirectional DCB specimen was repeatedly fatigue tested with the same stress ratio R=0.5 to provide enough raw data for investigation on delamination growth with significant fibre bridging. A loading-unloading cycle was conducted on the specimen after each fatigue test to determine the critical interlaminar resistance G_{fc} with fatigue crack extension a-a_0. Both the Paris and the modified Paris relations were employed to interpret fatigue crack growth. The energy principles were subsequently applied to physically explain fatigue delamination behavior in the perspective of energy balance. And SEM examinations were finally conducted to explore damage mechanisms related to energy release in fatigue delamination.

3.1 Interlaminar resistance increase in fatigue delamination of multidirectional composite laminates

In quasi-static delamination, the increase of interlaminar resistance with crack growth can be well characterized via the concept of *R-curve*, in terms of the critical resistance G_{fc} against crack extension a-a_0. This method was employed here to determine the critical resistance increase in fibre-bridged fatigue delamination.

According to the test procedure introduced in section 2.2, the critical interlaminar resistance at several fatigue crack lengths can be evaluated. Fig.2 summarizes delamination resistance at several crack intervals. The critical resistance initially increased with crack growth and finally became constant if crack length exceeded a certain level (fatigue *R-curve*). It has been widely admitted that the presence of fibre bridging was the main reason for the increase of this critical resistance. More fibre bridging can be present in a longer crack, making more energy release of the same crack extension [17,29,30]. The plateau of the critical resistance indicated fibre bridging became saturated after crack propagation was long enough. In this state, the new generation of fibre bridging around crack front was comparable to the amount of fibre bridging disappearing at the end of bridging region, leading to an equilibrium state with further crack extension.

Linear and nonlinear models have been proposed to describe the critical resistance increase because of fibre bridging [32]. The results illustrated in Fig.2 apparently demonstrate a linear increase between the critical resistance G_{fc} and crack extension a-a_0. Thus, the linear relationship was used in present study to represent resistance increase in fatigue delamination growth. This relation indeed played an important role in the use of the modified Paris relation in fatigue data reduction.

A higher magnitude of the *R-curve* means more fibre bridging in delamination growth. With a comparison to the fatigue *R-curve* of unidirectional composite laminates under the same stress ratio [33] (see Fig.3(a)), one can draw a conclusion that more bridging fibres can be present in fatigue delamination of multidirectional composite laminates. This means the significance of fibre bridging in fatigue crack growth is dependent of ply orientation. Similar conclusion has been made in quasi-static delamination, in which the interlaminar resistance of 45//45 interface was much higher than that of 0//0 interface [17]. Furthermore, quasi-static results of 45//45 interface reported in previous study [17] were compared with corresponding fatigue data to highlight the resistance difference between quasi-static and fatigue delamination, as shown in Fig.3(b). The results clearly indicate there is fibre bridging difference in monotonic and fatigue loading. In summary, fibre bridging significance is dependent on both interface configuration and load regimes (i.e. quasi-static vs. fatigue) in delamination growth in composite laminates.

3.2 Fatigue data reduction with the Paris and the modified Paris relations

All fatigue data were first explained with the Paris relation, as illustrated in Fig.4. Fatigue delamination is apparently dependent of crack scale. It decreases significantly with crack propagation. Particularly, the obtained Paris resistance curves decrease shift from left to right in the graph and finally converge into a single one. The presence of fibre bridging is the main reason for the decrease shift of the resistance curves [17,23]. More fibre bridging can be present in the wake of the crack front of a longer delamination. These bridging fibres can significantly restrain crack opening and release stress concentration around crack front. The results also indicate the required ΔG of a given crack propagation rate is not constant, but dependent of crack scale. It rises with crack extension and then forms a plateau if fibre bridging has fully developed.

From the results shown in Fig.4, it is inappropriate to use a single Paris resistance curve to determine fatigue delamination with fibre bridging. The use of a single one can cause either overestimation or underestimation results. Particularly, the use of the most left one can lead to conservative predictions, whereas the use of the most right ones cannot guarantee safety. To address this problem, some attempts have been carried out to take account of the resistance curves located in-between in fatigue delamination studies [23]. And an empirical power law relation has been proposed to determine fatigue crack growth with significant fibre bridging.

According to the similitude principle, the same value of a similitude parameter, e.g. ΔG, should result in the same crack growth. The results shown in Fig.4 clearly demonstrate the same value of ΔG can lead to different fatigue crack growths. Thus, ΔG is not a reasonable similitude parameter for fatigue delamination with fibre bridging. Furthermore, it is worth noting that the original purpose of using ΔG is to represent the load amplitude applied on crack front, i.e. crack driving force. It is valid for fatigue delamination with no fibre bridging. However, this is not true for delamination with fibre bridging. Because of bridging, ΔG is the sum of *SERR* around crack front and *SERR* in bridging fibres. And it has been proven that only the former part had real contribution to fatigue crack growth [31,34]. Thus, ΔG in this case cannot well determine the crack driving force for fatigue delamination. The magnitude of *SERR* in bridging fibres is significantly dependent of crack length, leading to increase of ΔG at a given value of da/dN with crack extension. Recalling the original purpose of using ΔG in fatigue delamination, the *SERR* around crack front should be employed to appropriately correlate fatigue delamination with significant fibre bridging. And a modified Paris relation based on this parameter has been proposed in previous study, see Eq.(3) [31].

For comparison, the same data sets were interpreted with the modified Paris relation and summarized in Fig.5. Obvious difference shown in Fig.4 is eliminated and fatigue delamination with different amounts of fibre bridging becomes the same, indicating the same crack growth of the same value of ΔG_{eff}. And a master resistance curve can be fitted to determine fatigue crack growth. This agrees well with the results observed in fatigue delamination in unidirectional composite laminates, in which a master resistance curve can be fitted to determine fatigue delamination with different amounts of fibre bridging [31,33]. According to the similitude principle, the *SERR* range indeed applied on crack front seems a reasonable similitude parameter in the characterization of fatigue crack growth with fibre bridging.

It should be stressed that the applications of the modified Paris relation can significantly reduce experimental workloads and save test duration in determining fibre-bridged fatigue delamination. Once the master resistance curve shown in Fig.5 is established with limited tests, fatigue delamination with different amounts of fibre bridging can be well determined. This is really useful and important for engineering. Additionally, one should note that this new power law relation is not only valid for delamination with significant fibre bridging, but also effective for delamination with no fibre bridging. In the later situation, $G_{fc}(a-a_0)$ keeps constant and equates to G_0. As a result, Eq.(3) is reduced to Eq.(1). In the opinion of the authors, this means delamination with no fibre bridging can be treated as a special case of delamination with fibre bridging. And the modified Paris relation is an even more general form of the Paris relation for fatigue crack growth study.

Fig.6 gives a comparison on fatigue data analysis with the Paris and the modified Paris relations of one time fatigue test, to highlight an advantage of applying the modified Paris relation in fatigue data analysis. Obvious difference was observed between different data representations. Particularly, the data set explained via the modified Paris relation locates on the left side of the results interpreted via the Paris relation, due to the extraction of fibre bridging in data reduction. Additionally, the slopes of different data representations are not the same. It is much steeper in the Paris representation, in comparison with the modified Paris representation. This feature is really important for the applications of the modified Paris relation in engineering designs. A larger value of the slope indicates strong sensitivity between *da/dN* and the *SERR*. This means a small uncertainty in the *SERR* calculation can cause significant error in fatigue delamination prediction. The decrease in the slope can significantly reduce this sensitivity, which is really beneficial to accuracy improvement as well as to engineering applications.

3.3 Fatigue delamination analysis with energy principles

One should note that the Paris type relations are phenomenological methods to represent fatigue crack growth in metals and composite laminates. Delamination is an energy consumption procedure, obeying the first law of thermodynamics. Energy principles were therefore employed to physically explain fatigue crack growth behavior. Particularly, the amount of energy release in fatigue delamination with fibre bridging can be schematically represented via Eq.(4) [34].

$$\frac{dU}{dN} = \frac{dU}{da}\frac{da}{dN} = \left(\frac{dU_a}{da} + \frac{dU_{br}}{da}\right)\frac{da}{dN} \quad (4)$$

where dU_a/da represents energy dissipation because of new crack generation; dU_{br}/da represents energy dissipation in bridging fibres.

Fig.7 provides a typical example of energy release during an entire displacement controlled fatigue delamination test. One should keep in mind that *da/dN* can continuously decrease with crack extension in this test. The experimental data with high magnitude shown in Fig.7 obviously deviate from the straight line. This means extra energy should be consumed in crack growth at the beginning of the fatigue test. Indeed, the extra energy release is related to failure occurring in bridging fibres [34]. The total energy release dU/da in this stage, therefore, is the sum of dU_a/da and dU_{br}/da. The results shown in Fig.7 also demonstrate that the energy release of a unit crack generation can finally become constant with decrease in da/dN. This means dU_a/da plays a dominant role in this stage and dU_{br}/da has no or negligible contribution. As a result, a straight line can well characterize the energy release in fatigue delamination. It should be stressed that the number of fatigue cycles in the second stage takes up more than 95% of the total number of fatigue cycles. Thus, one can believe that energy dissipation keeps constant in most time of a fatigue delamination test and is independent of fibre bridging.

According to the energy principles, all fatigue data were analyzed and expressed in terms of da/dN against energy dissipation per cycle dU/dN, as illustrated in Fig.8. All experimental results tend to locate in a narrow band region, indicating the same or at least similar energy release of the same da/dN with crack propagation. This agrees well with the results illustrated in Fig.7, as most energy dissipation in fatigue delamination is concentrated on damage evolution around crack front, regardless of fibre bridging. As a result, a single curve can be fitted to determine the relationship between da/dN and dU/dN. This also means fatigue delamination resistance in most cases remains constant with fibre bridging development.

According to the above discussion and analysis, the use of the Paris relation in data reduction not only violates the similitude principle, but also disagrees with the energy release results. On the contrary, the use of the modified Paris relation is in line with the similitude principle as well as the energy release results. The application of the energy principles can provide important physical basis on the selection of a reasonable similitude parameter in fatigue data analysis. And it can provide solid evidence on the validation of using the modified Paris relation in fibre-bridged fatigue delamination characterization.

Fractography analysis was conducted to explore damage mechanisms related to energy release shown in Fig.8. The SEM samples, 10 mm length and 25mm width, were prepared with gold sputter-coating in vacuum for 10 min to avoid static charging in SEM due to the non-conductive nature of the material used in present study. The prepared samples were examined in a JOEL SEM at the Delft Aerospace Structural & Materials Laboratory. Fig.9 provides the SEM observations on fracture surfaces at different crack lengths with magnification of 1000 times. The typical micro-features in fatigue delamination with fibre bridging are the same. Particularly, fibre prints play a dominant role on fracture surfaces and hackles are also observed in some local location, indicating the same damage mechanisms in fatigue delamination with crack growth (i.e. fibre bridging development). This is the physical reason for the same energy release in fatigue delamination. The presence of fibre prints is a result of debonding occurring between fibres and matrix around crack front. And hackle is a typical feature generated in shear stress state, which is usually observed in mode II or mixed-mode I/II delamination. Its appearance in mode I delamination mainly attributes to local shear stress state occurring in fibre pullout from matrix in the wake of the crack front.

4. Fatigue delamination predictions via the modified Paris relation

From the above discussion, the modified Paris relation can be used to well represent fatigue delamination with different amounts of fibre bridging. In order to provide extra evidence on its validation and accuracy in fatigue delamination characterization, the master resistance curve illustrated in Fig.5 was used to predict fatigue delamination with different amounts of fibre bridging.

Another multidirectional DCB specimen was repeatedly fatigue tested four times with the same stress ratio R=0.5. Fig.10 summarizes the predictions and the experimental data in terms of da/dN against ΔG. Acceptable agreements between predictions and experiments are observed in all four cases, demonstrating the effectiveness of the modified Paris relation in fatigue delamination study.

5. Concluding remarks

Fatigue delamination with large-scale fibre bridging in multidirectional composite laminates was experimentally investigated. The use of the Paris relation, with ΔG as the similitude parameter, can artificially make crack scale dependence of fatigue delamination. In the application of the modified Paris relation, with ΔG_{eff} as the similitude parameter, a master resistance curve can be obtained to determine fatigue delamination with different amounts of fibre bridging, which agreed well with the similitude principle and the energy release results. As a result, ΔG_{eff}, rather than ΔG, is a reasonable parameter to represent the similitude in fatigue delamination with fibre bridging. The modified Paris relation can be treated as an even more general form of the Paris relation, which is not only valid for delamination with fibre bridging, but also effective for delamination without fibre bridging. The results derived from the modified Paris relation indicated that fatigue delamination was independent of fibre bridging, if the similitude was well characterized.

A physical explanation on fatigue delamination was conducted with the energy principles. It was found that the energy release during fatigue delamination in multidirectional composite laminates remained constant with fibre bridging development. Particularly, bridging fibres only had contribution to energy release at the beginning of several thousand cycles. In most cases, these bridging fibres just periodically stored and released strain energy, but had no real effect on permanent energy release. A SEM observation demonstrated the morphology on fracture surfaces at different crack lengths remained the same, indicating the same damage mechanisms during fatigue delamination with fibre bridging. Particularly, fibre prints and hackles were two micro-features generated during fatigue delamination. This was the physical reason for the same energy release of the same *da/dN* in fatigue delamination growth.

The obtained master resistance curve was employed to quantify fatigue delamination with different amounts of fibre bridging. In all cases, the predictions agreed well with the experiments, demonstrating the effectiveness of the modified Paris relation in fatigue delamination characterization.

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List of the figure captions

Figure 3 Comparison of critical resistance increase

(a) Unidirectional vs. Multidirectional; (b) Quasi-static vs. Fatigue

Figure 4 Fatigue data representations via the Paris relation

Figure 5 Fatigue delamination representations via the modified Paris relation

Figure 6 Data reduction with the Paris and modified Paris relations ($f(G)=\Delta G$ for the Paris representation and $f(G)=\Delta G_{eff}$ for the modified Paris representation)

Figure 7 Correlation between da/dN and dU/dN during fatigue delamination

Figure 8 Energy release in fatigue delamination with different amounts of fibre bridging

Figure 9 SEM observations on fatigue fracture surfaces

(a) At a short crack length; (b) At a long crack length

Figure 10 Fatigue delamination predictions

(a) a-a_0=4.1mm; (b) a-a_0=11.8mm; (c) a-a_0=20.0mm; (d) a-a_0=28.4mm

Figure 1

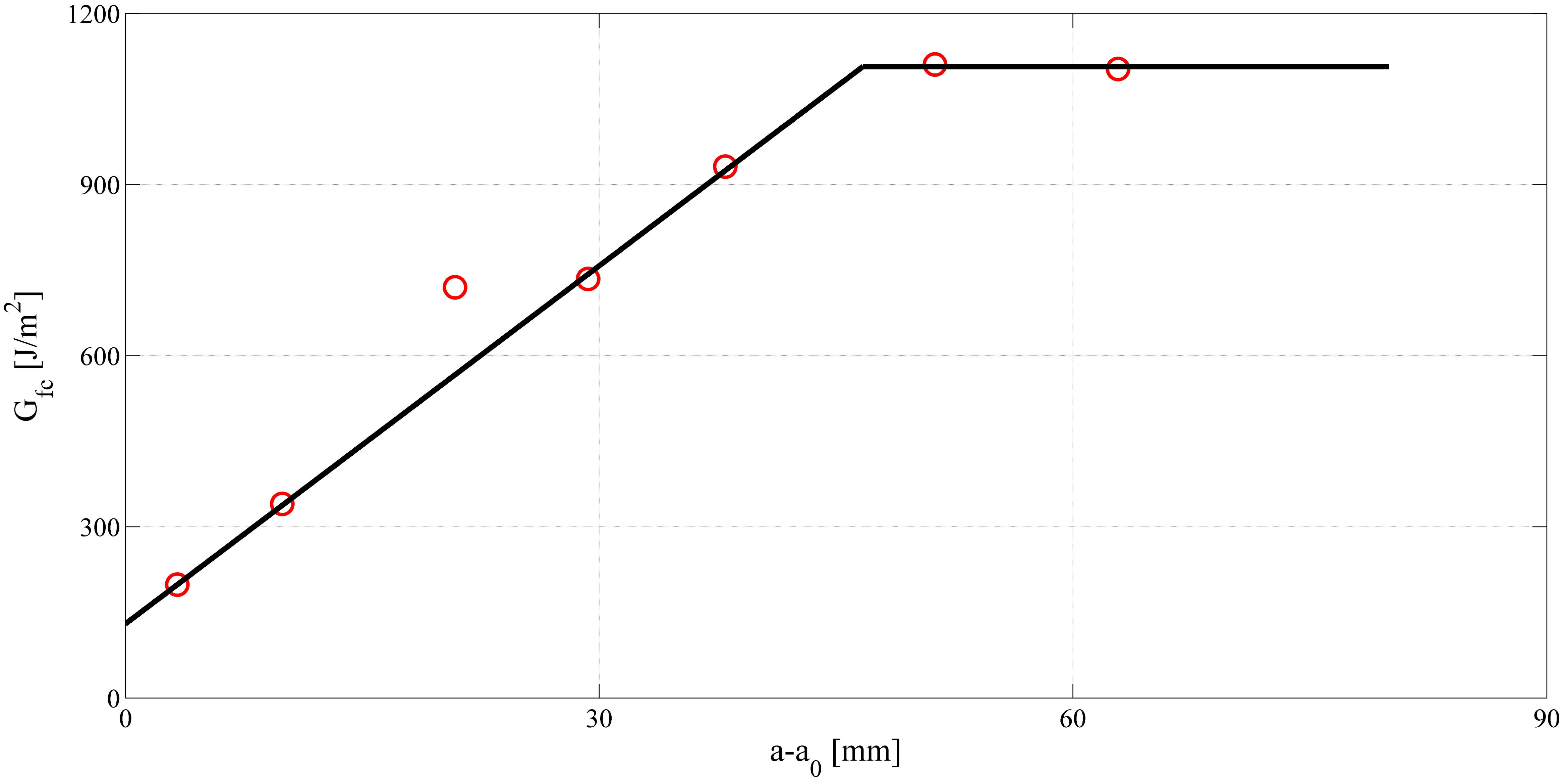


Figure 2


Unidirectional
Multidirectional
G_fc [J/m^2]
a-a_0 [mm]
(a)
Quasi-static delamination-1
Quasi-static delamination-2
Quasi-static delamination-3
Fatigue delamination
G_IC [J/m^2]
a-a_0 [mm]
(b)

Figure 3

10^-5
10^-6
10^-7
10^-8
10^-9
da/dN [m/Cycle]
10^1
10^2
ΔG = (√G_max-√G_min)^2 [J/m^2]
a-a0=3.3mm
a-a0=9.9mm
a-a0=20.9mm
a-a0=29.3mm
a-a0=38.0mm
a-a0=51.3mm
a-a0=62.8mm

Figure 4

da/dN=3.06×10^-17 ΔG_eff^7.47
a-a0=3.3mm
a-a0=9.9mm
a-a0=20.9mm
a-a0=29.3mm
a-a0=38.0mm
a-a0=51.3mm
a-a0=62.8mm
Fitting
da/dN [m/Cycle]
ΔGeff [J/m2]
10-5
10-6
10-7
10-8
10-9
101
102

Figure 5

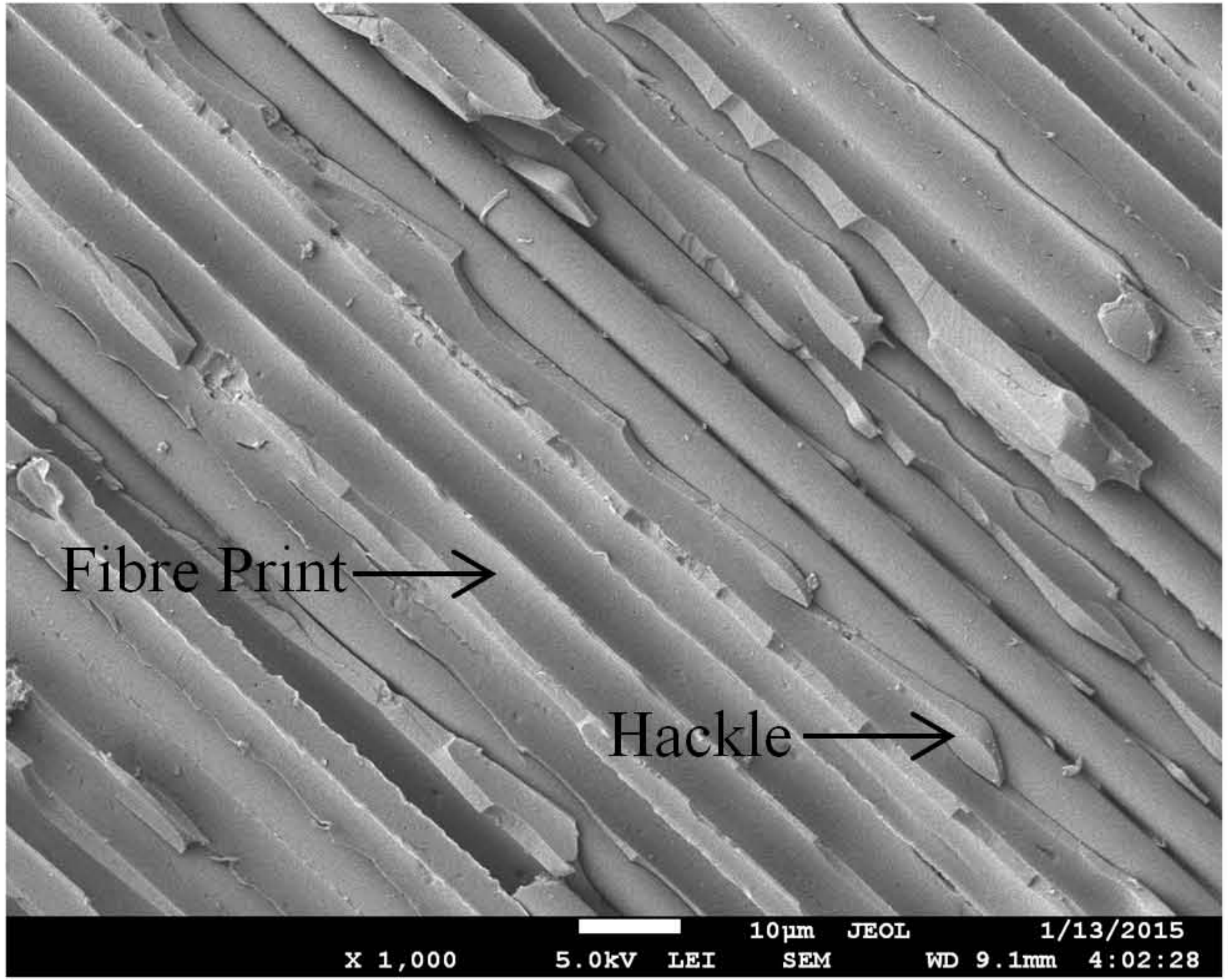

Paris relation
Modified Paris relation
da/dN [m/Cycle]
f(G) [J/m²]
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10¹
10²

Figure 6

Figure 7

a-a0=3.3mm
a-a0=9.9mm
a-a0=20.9mm
a-a0=29.3mm
a-a0=38.0mm
a-a0=51.3mm
a-a0=62.8mm
da/dN [m/Cycle]
|dU/dN| [J/Cycle]
10-9
10-8
10-7
10-6
10-5
10-4
10-3

Figure 8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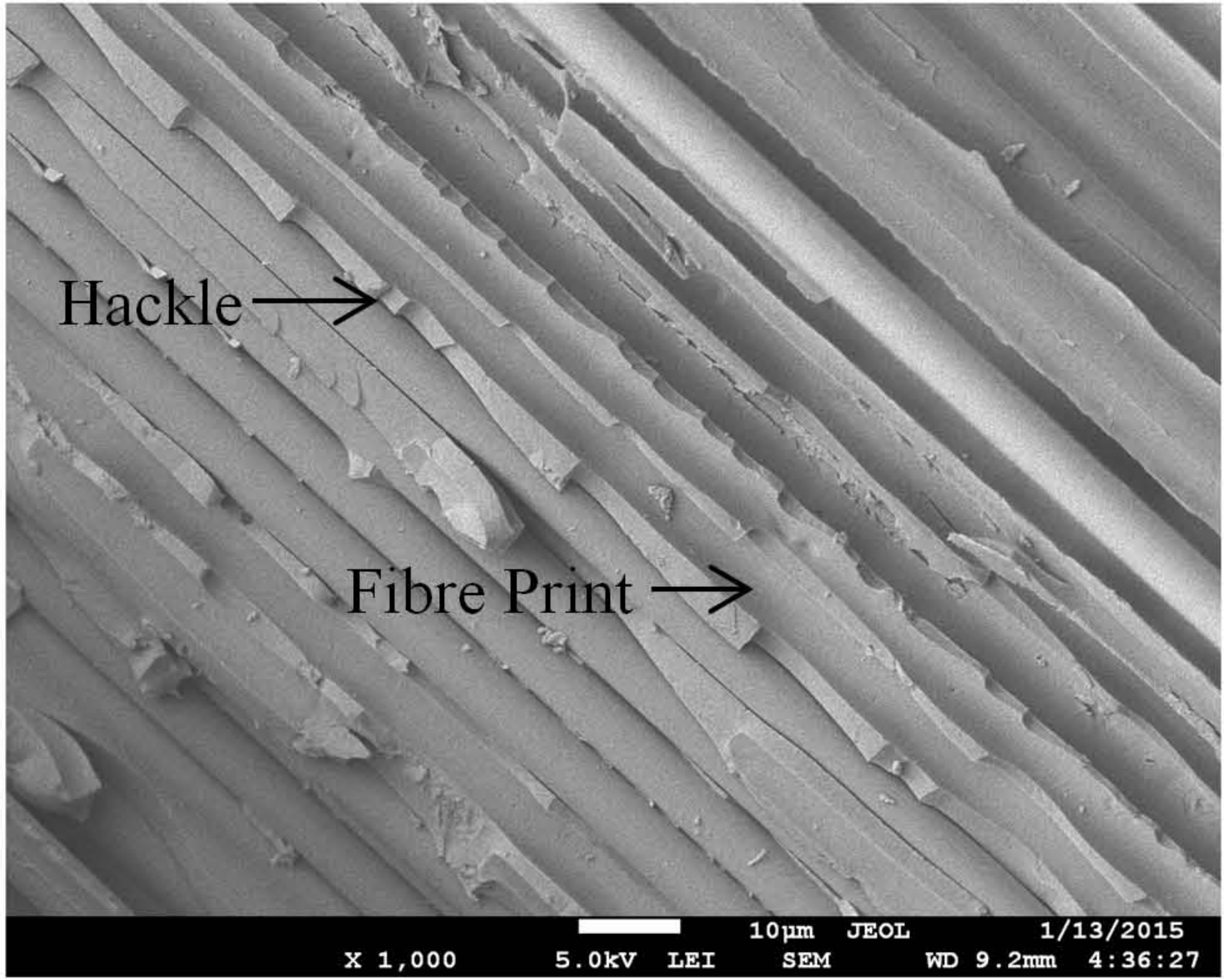
X 1,000 5.0kV LEI SEM WD 9.1mm 4:02:28

(a)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X 1,000 5.0kV LEI SEM WD 9.2mm 4:36:27

(b)

Figure 9


Experimental data
Prediction
da/dN [m/Cycle]
ΔG=(√Gmax-√Gmin)2 [J/m2]
(a)
(b)
(c)
(d)

Figure 10