AN INVESTIGATION ON FATIGUE DELAMINATION GROWTH IN MULTIDIRECTIONAL COMPOSITE LAMINATES

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ABSTRACT

Delamination is one of the most important failures in composite laminates due to lack of reinforcement in thickness. It can gradually propagate under fatigue loading and finally cause failure of a composite structure. With the increasing applications of these materials in engineering and the requirements on light weight structures, how to characterize fatigue delamination growth and develop reliable prediction models become critical issues [1].

Fibre bridging is an important phenomenon during delamination growth. The presence of bridging fibres in the wake of crack front can hold fracture surfaces and prohibit crack propagation, resulting in interlaminar resistance increase. It is, therefore, of great importance to take fibre bridging into account in delamination study. A vast number of researches have been conducted under quasi-static loading and corresponding prediction models have been developed [2-3]. This shielding mechanism still exists in fatigue delamination, whereas little attention has ever been paid into this case.

Unidirectional double cantilever beam (DCB) specimens have been recommended in the ASTM standard and widely employed in the characterization of interlaminar resistance under either quasi-static or fatigue loading. However, a growth number of quasi-static studies provided evidence that the use of DCB specimens with 0//0 interface sometimes can underestimate delamination resistance, especially in case of crack growth combined with large-scale fibre bridging [4-5]. It is, therefore, meaningful to do researches on DCB specimens with different ply orientations.

To have in-depth understanding on fatigue delamination growth with fibre bridging in multidirectional composite laminates, DCB specimens with 45//45 interface were manufactured. The stacking sequence was carefully designed as $[(\pm 45/0_{12}/\mp 45)//(\pm 45/0_{12}/\mp 45)]$ in present study, 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 [6-9]. All mode I fatigue tests were performed on a 10KN MTS machine at a frequency of 5Hz under displacement control with the same stress ratio R=0.5 in ambient conditions.

In our previous studies [5,10-12], it has been reported that the use of the Paris relation, see Eq.(1), in interpreting fatigue delamination with fibre bridging violated the similitude principle. Particularly, the obtained Paris resistance curves decreased shift with crack propagation, which meant the same value of ΔG can result in different da/dN values. And it has been proven that the presence of fibre bridging was the main reason for this retardation effect. Similar trend is also observed in fatigue delamination of multidirectional composite laminates, as shown in Fig.1. As a result, ΔG is not a reasonable parameter to determine the similitude in fatigue delamination with fibre bridging.

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

where c and n are two curve-fitting parameters of the Paris relation; G_{Imax} and G_{Imin} represent the maximum and minimum *SERR*s under fatigue loading, which can be calculated via the Modified Compliance Calibration (MCC) method, recommended in the ASTM D5528-01 standard. The magnitude of fatigue crack growth rate *da/dN* can be evaluated via the 7-point Increment Polynominal Method, recommended in the ASTM E647-00 standard.

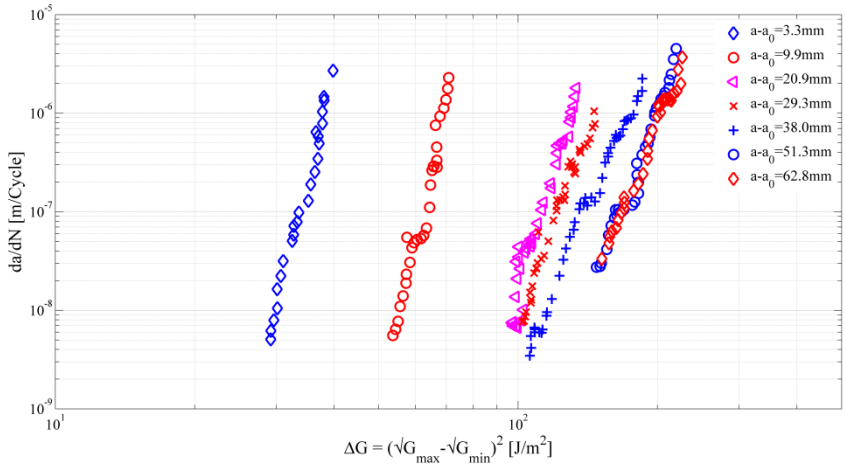


Figure 1: The Paris representation of fatigue delamination with fibre bridging

Delamination is an energy dissipation procedure, obeying the first law of thermodynamics. In present study, energy principles are used to interpret fatigue delamination with fibre bridging in the perspective of energy balance. The results clearly indicate that the amount of energy release is independent of fibre bridging, as shown in Fig.2. Most energy dissipation is indeed concentrated in damage evolution around crack front. Fibre bridging just periodically stores and releases strain energy, but has little contribution to permanent energy release unless there is failure in it.

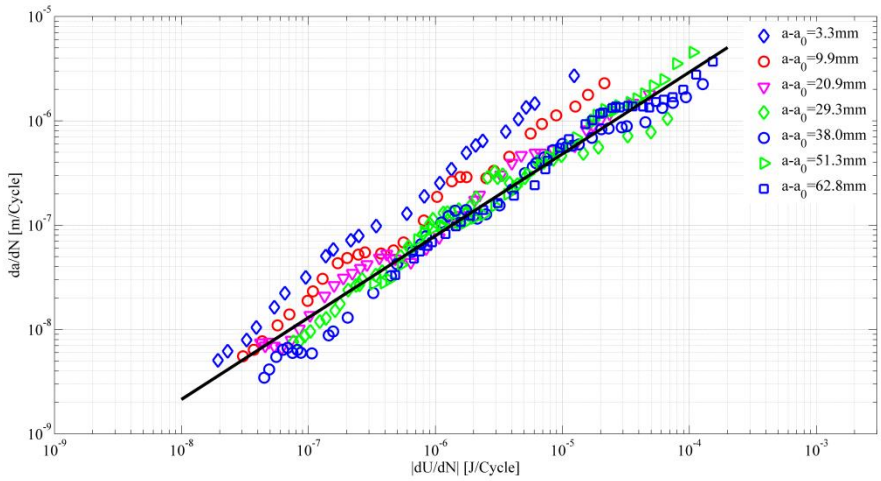
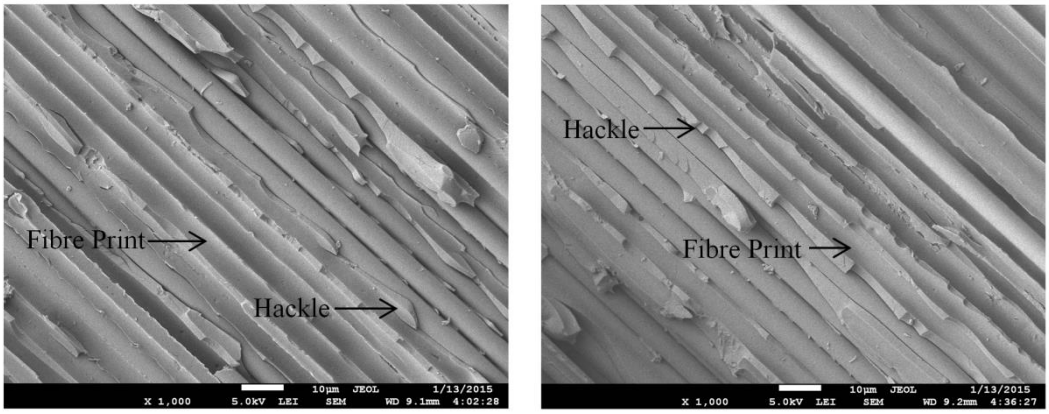


Figure 2: Energy dissipation in fatigue delamination with fibre bridging

Post-failure examination on the fracture surfaces of the DCB specimen provides an insight into the damage mechanisms in fatigue delamination with fibre bridging. The typical features located on the fracture surfaces remain the same with crack propagation, as illustrated in Fig.3. Particularly, fibre print is the dominant feature and hackle is also observed in some location. The presence of fibre print is a result of debonding between fibres and matrix during delamination. The appearance of hackles in mode I delamination mainly attributes to local shear stress during fibre pullout from matrix. As a result, the damage mechanisms remain the same with fibre bridging development, providing the physical explanations on the same energy release in fatigue delamination as shown in Fig.2.



(a) (b)

Figure 3: SEM observations on fracture surfaces

(a) Short crack; (b) Long crack

Incorporating with the similitude principle and the energy release results, the *SERR* range indeed applied around crack front, i.e. ΔG_{eff} calculated via Eq.(2) [13-14], was proposed as an appropriate parameter to represent the similitude in fatigue delamination with fibre bridging. A modified Paris relation based on this parameter, see Eq.(3), was subsequently developed to determine fatigue delamination behavior. The application of this new model can unify all experimental fatigue data into a narrow band, as shown in Fig.4. And a master resistance curve can be fitted to determine fatigue delamination growth with different amounts of fibre bridging, which is not only in line with the similitude principle, but also comparable with the energy release results. Thus, ΔG_{eff}, rather than ΔG, is recommended to represent the similitude in fatigue delamination with fibre bridging. In addition, it is worth noting that ΔG_{eff} is the same to ΔG in case of delamination without fibre bridging. This indicates that the modified Paris relation can be viewed as an even more general form of the Paris relation. It is not only valid for fatigue delamination with fibre bridging, but also effective for fatigue delamination without fibre bridging.

$$\Delta G_{eff} = \frac{G_0}{G_{fc}(a-a_0)} \Delta G \tag{2}$$

$$\frac{da}{dN} = c^* \left(\Delta G_{eff}\right)^{n^*} = c^* \left[\frac{G_0}{G_{fc}(a-a_0)} \Delta G\right]^{n^*} \tag{3}$$

where $G_{fc}(a-a_0)$ represents the increase of critical interlaminar resistance with fatigue crack propagation (fatigue *R-curve*); G_0 is the initial delamination resistance, which can be determined by the extrapolation of the fatigue *R-curve* to $a-a_0=0$; c^* and n^* are two curve-fitting parameters of the modified Paris relation.

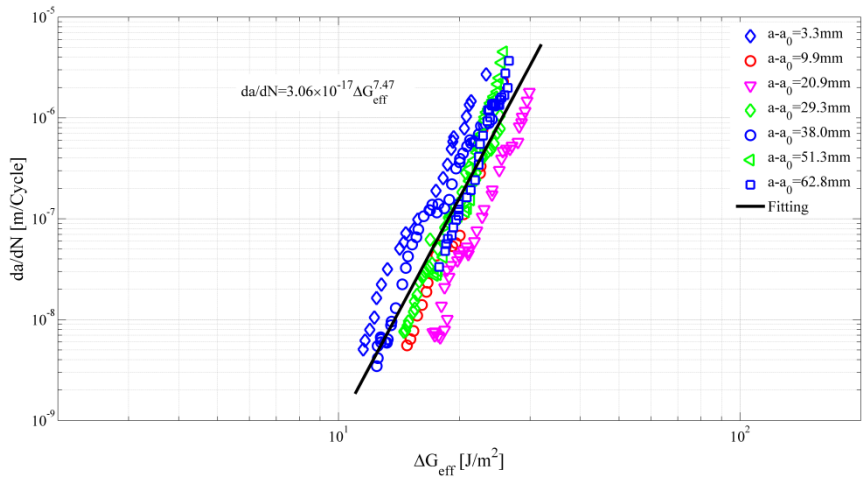


Figure 4: The modified Paris representation of fatigue delamination with fibre bridging

The obtained master resistance curve shown in Fig.4 was finally applied to predict fatigue delamination with different amounts of fibre bridging. Really good agreements between predictions and experiments were achieved as shown in Fig.5, demonstrating the validation of the modified Paris relation. One can therefore make conclusions that ΔG_{eff} is a reasonable similitude parameter to correlate fatigue crack growth and the modified Paris relation is valid for fatigue delamination with fibre bridging.

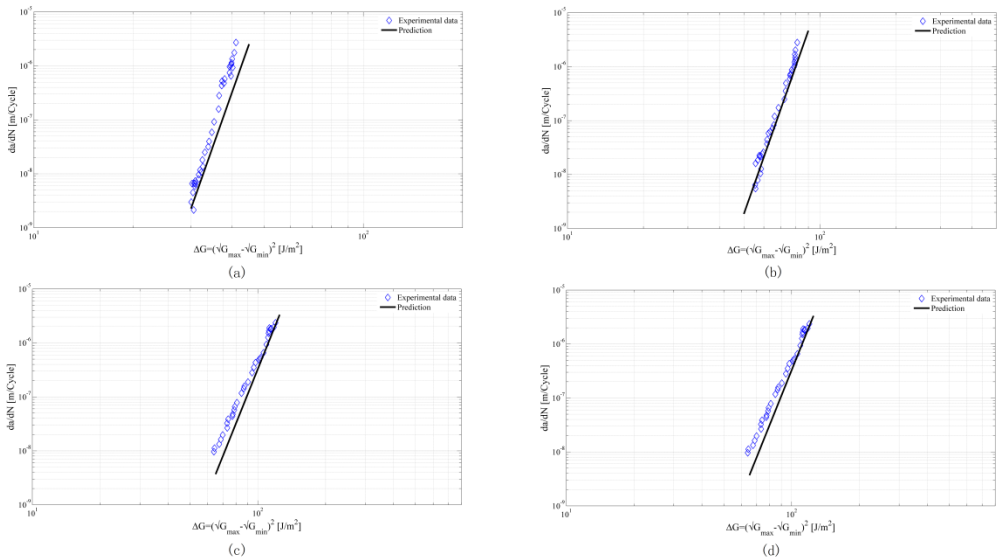


Figure 5: Fatigue delamination predictions with the modified Paris relation

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

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