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Discussion of the Stress Ratio Effect on the Fatigue Delamination Growth Characterization in FRP Composite Structures

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Abstract

The strain energy release rate (SERR) is widely used to study delamination growth in composites and adhesively bonded structures. Both the maximum SERR (G_{max}) and the range of SERR (ΔG) are commonly used to characterize delamination growth rate. The present paper discusses the appropriateness of using the SERR range to characterize delamination growth in fibre reinforced plastic (FRP) composite structures, and several inconsistent results associated with fatigue tests reported in the open literature will be presented. To this end, the paper focuses on the question of 'similitude' and the potential for using the terms $\Delta G'$ and $\Delta\sqrt{G}$ as alternative methods for characterizing Mode I, Mode II and Mixed mode I/II delamination growth.

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1. Introduction

Since Paris, Gomez, & Anderson (1961) introduced the concept of using the range of stress intensity factor, ΔK, as the crack driving force (CDF) to characterize the cyclic fatigue crack growth rate per cycle, da/dN, for aluminium alloy, ΔK has become one of the most widely used parameters for characterizing the fatigue performance of metallic materials (Schutz, 1996). It is generally known that in a thin layer of polymeric matrix sandwiched between two

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relatively rigid layers of fibers in a composite laminate, the singularity region dominated by the r-1/2 of a crack is exceptionally small, where r is the distance ahead of the crack tip (Wang, Mandell, & McGarry, 1978; Hu, Jones, & Kinloch, 2016). As the result, the SERR, instead of the stress intensity factor, is widely used to study delamination growth in FRP composites.

Nomenclature

a	crack length
da/dN	crack growth rate per cycle
E	elastic modulus
G	strain energy release rate (SERR)
G_{max}	maximum value of the applied G in the fatigue cycle
G_{min}	minimum value of the applied G in the fatigue cycle
ΔG	G_{max} - G_{min}
$\Delta G'$	$(\Delta P)^2 G_{max}/(P_{max})^2$
$\Delta \sqrt{G}$	$\sqrt{G_{max}}$ - $\sqrt{G_{min}}$
K	stress intensity factor
K_{max}	maximum value of the applied K in the fatigue cycle
K_{min}	minimum value of the applied K in the fatigue cycle
ΔK	K_{max} - K_{min}
P_{max}	maximum applied load in the fatigue cycle
P_{min}	minimum applied load in the fatigue cycle
ΔP	P_{max} - P_{min}
r	the distance between the point to the crack tip in polar coordinate
R	load ratio, P_{min} / P_{max}
θ	the angle measured from the extension of the crack line in polar coordinate
s_{ij}	stress state around the crack tip
I, II	subscripts indicating Mode I (opening tensile) and Mode II (in-plane shear) loads
I/II	subscript indicating mixed mode I and II load
CDF	crack driving force
CLS	crack lap shear
DCB	double cantilever beam
ENF	end notched flexure
FRP	fibre reinforced plastic
SERR	strain energy release rate

The use of fracture mechanics based tools to assess fatigue crack growth in operational structures relies on the similitude principle, viz: 'Two different cracks growing in identical materials with the same stress intensity factor range ΔK, and the same K_{max}, will grow at the same rate' (Jones et al., 2007). For metals, it has been found that there is a corollary to this principle, viz: 'Two different cracks growing in identical materials with the same stress intensity factor range ΔK, then the crack in the specimen subjected to a higher R-ratio will grow at a faster da/dN value.' (Jones, Kinloch, & Hu, 2016). This phenomenon has been observed in many fatigue test results in metals (Hartman & Schijve, 1970; Boyce & Ritchie, 2001; Schonbauer, et al., 2014).

Thus, as most obvious parameter, the range of SERR, shown in Eq. (1), has been employed as the CDF to plot against the cyclic fatigue crack growth rate, da/dN, in fiber-composite materials:

$$\Delta G = G_{max} - G_{min} \tag{1}$$

where G_{max} and the G_{min} are the maximum and minimum values of the applied SERR in a fatigue cycle, respectively. The term ΔG is assumed to be capable of accounting for the R-ratio effect as its counterpart of the

metal parameter, ΔK. Now, for a constant ΔG, the value of da/dN should be faster for a higher R-ratio (or load ratio) in the cyclic fatigue test, as the mean stress increases with the increase in the R-ratio. However, Rans, Alderliesten, & Benedictus (2011) questioned the appropriateness of using ΔG to characterize delamination growth in composite structures, as they found that there are test results where a decrease of da/dN occurs with an increasing R-ratio, for a given value of ΔG.

In the present paper, Mode I, Mode II and Mixed mode I/II fatigue test data from the literature are analysed. The results of this analysis indicate that ΔG is not a suitable term to be used as a CDF for the delamination in composites under fatigue loadings. Two CDFs other than ΔG are discussed in the paper that are consistent with the corollary.

2. The R-ratio effect and ΔG

In linear elastic fracture mechanics (LEFM), the stress intensity factor, K, is used to characterize the stress state around the crack tip and is formulated as Eq. (2):

$$\sigma_{ij} = \frac{K}{\sqrt{2r}} f_{ij}(\theta) + \cdots \tag{2}$$

where r is the distance between the point to the crack tip, θ is the angle measured from the extension of the crack line and the higher order terms are ignored. This equation also demonstrates that the stress state at the crack tip is dominated by the $r^{-1/2}$ singularity. In LEFM, the stress and K are linearly proportional as shown in Eq. (2) and the term ΔK can be expressed as Eq. (3):

$$\Delta K = K_{max} - K_{min} = (1 - R)K_{max} \tag{3}$$

where K_{max} and K_{min} are the maximum and minimum stress intensity factor in one fatigue cycle and R is the ratio of the minimum applied load to the maximum applied load in one fatigue cycle.

Unlike metals, the stress intensity factor cannot represent the stress state of the delamination growing in the polymeric matrix, or at an interface, between the plies of the fibers. Thus, the SERR is the dominant measurement to evaluate the delamination in LEFM and it has the relationship to the stress intensity factor, K, as shown in Eq. (4):

$$G = \frac{\mathrm{K}^2}{E} \tag{4}$$

where E is the elastic modulus . Hence, Eq. (3) can be re-written with respect to the R-ratio as:

$$\Delta G = (1 - R^2)G_{max} \tag{5}$$

It is often assumed that the term ΔG can show R-ratio effects in a similar manner to the term ΔK. For a given value of ΔG, an increase in the R-ratio would increase both the maximum and minimum SERR, and hence increase the mean stress. As a consequence, for a given carbon fiber epoxy Toray P305 prepreg of Toray T300/#2500. The double cantilever beam (DCB) specimen geometry consisted of 32 plies of laminates which is 125 mm long and 20 mm wide. The initial delamination length was 20 mm. The resultant da/dN versus ΔG curves associated with R = 0.2, 0.5 and 0.7 are shown in Fig. 1 which reveals that, when plotted in this fashion, the curves of da/dN versus ΔG shift to the right, with increasing R-ratio. This means that for a given value of ΔG, the DCB specimens tested using higher R-ratio values would have slower delamination rates. This is contrary to the metal results (Hartman & Schijve, 1970; Boyce & Ritchie, 2001; Schonbauer, et al., 2014), as well as the expectation associated with a valid CDF.

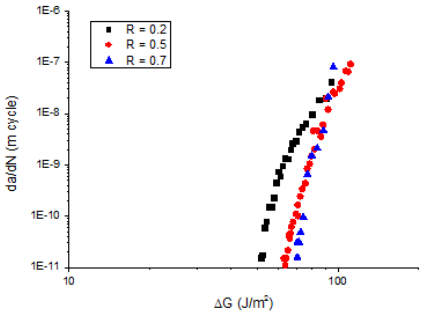
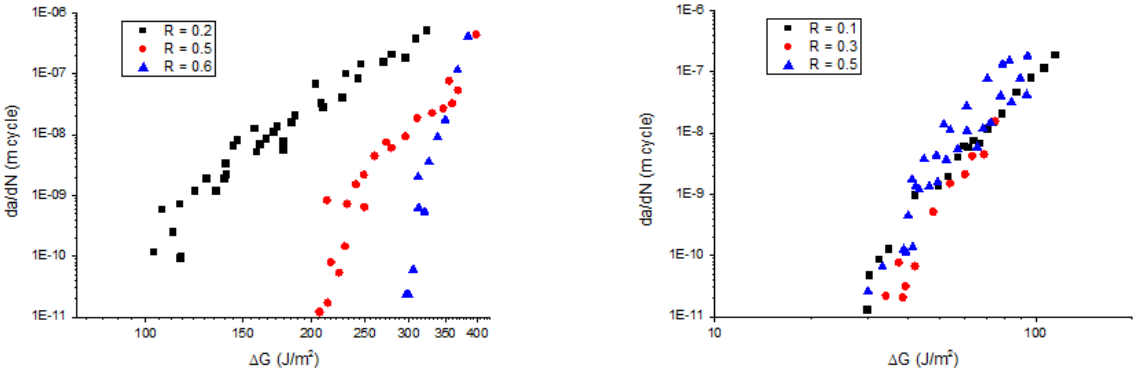


Figure 1 Plot of da/dN vs. ΔG in Mode I (Hojo et al., 1987).

This phenomenon is also seen in Mode II and Mixed Mode I/II fatigue tests. Tanaka and Tanaka (1997) presented Mode II fatigue tests which were performed using End Notched Flexure (ENF) test specimens. The ENF specimen was a 44-ply unidirectional graphite fiber epoxy prepreg of Toray T800H/#3631 with a nominal thickness of 6.2 mm. The initial delamination length of 30 mm was introduced by a 12 μm thick Kapton film. The specimen was 120 mm long and 20 mm wide. The force was applied at the center of the specimen, which was 60 mm from both ends. Gustafson and Hojo (1987) performed a Mixed Mode I/II fatigue test using 22 mm wide unidirectional T300/914C (Ciba Geigy) prepregs. The specimen configuration was the cracked lap shear (CLS) specimen, as shown in Gustafson & Hojo, 1987.

The results of the ENF and CLS tests are shown in Fig. 2. These figures reveal that for a constant ΔG, increasing the mean stress (i.e. an increasing R-ratio) would appear to either slow down or not to change the delamination growth rate. It is thus clear that using ΔG to characterize da/dN can lead to an incorrect interpretation associated with Mode I, Mode II and Mixed Mode I/II fatigue delamination data for FRP composite structures. As a consequence, the applicability of ΔG as a valid CDF is questionable.



(a) (b)

Figure 2 Plot of da/dN vs. ΔG (a) in Mode II (Tanaka & Tanaka, 1997); (b) in Mixed Mode I/II (Gustafson & Hojo, 1987).

3. Potential solutions for the R-ratio anomaly

Matsubara, Ono, & Tanaka (2006) and Azari, Jhin, Papini, & Spelt (2014) suggested to use Eq. (6) below as the CDF whilst Rans, Alderliesten, & Benedictus (2011) and Jones, Pitt, Bunner, & Hui (2012) suggested that Eq. (7) would be a more appropriate means for characterizing da/dN:

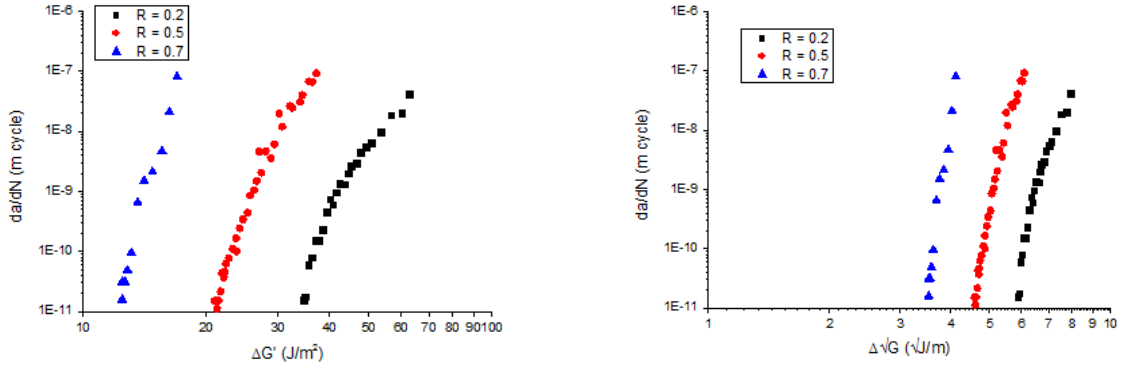
$$\Delta G' = (\Delta P)^2 \frac{G_{max}}{P_{max}^2} \tag{6}$$

$$\Delta\sqrt{G} = \sqrt{G_{max}} - \sqrt{G_{min}} \tag{7}$$

where P_{max} is the maximum applied force in the fatigue cycle and ΔP is the range of the applied load in the fatigue cycle. To evaluate these concepts, the data (Hojo, Tanaka, Gustafson, & Hayashi, 1987; Tanaka & Tanaka, 1997; Gustafson & Hojo, 1987) are re-plotted in terms of da/dN versus $\Delta G'$, or $\Delta\sqrt{G}$, respectively, and the results are shown in Figs. 3-5. These results show that both approaches are capable of eliminating the anomaly which arises from using ΔG as the CDF in FRP composite structures. Although, at first glance the two approaches would appear to be different, inspection of Eq. (8) and Eq. (9) reveals that $\Delta G' = (\Delta\sqrt{G})^2$, via:

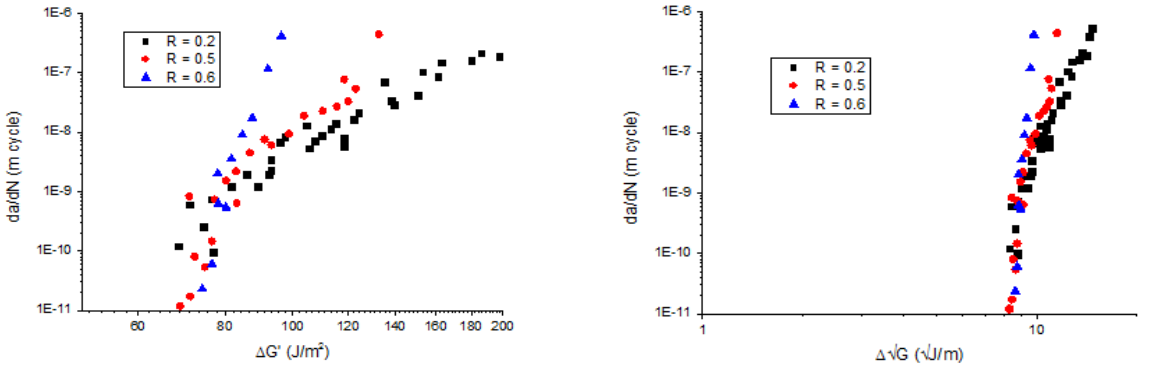
$$\Delta G' = (1-R)^2 G \tag{8}$$

$$\Delta\sqrt{G} = (1-R)\sqrt{G} \tag{9}$$



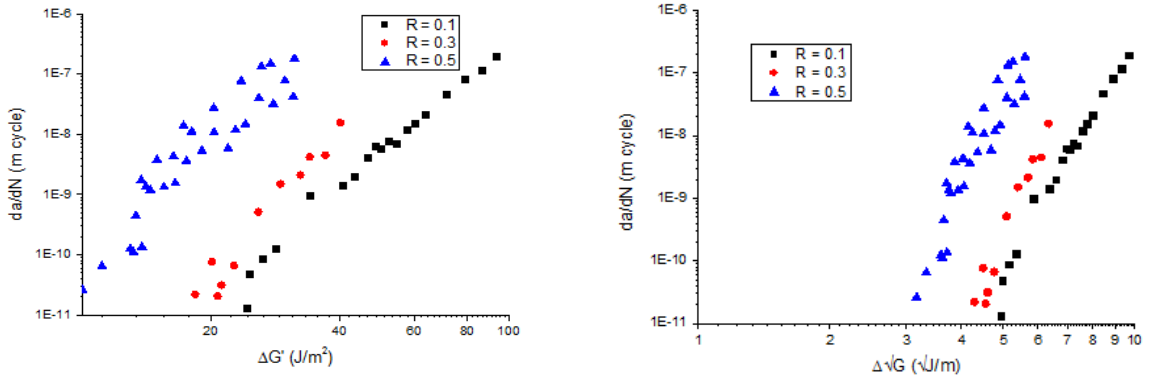
(a) (b)

Figure 3 Mode I delamination growth rate characterized by the two different CDF terms. (a) $\Delta G'$; (b) $\Delta\sqrt{G}$.



(a) (b)

Figure 4 Mode II delamination growth rate characterized by the two different CDF terms. (a) $\Delta G'$; (b) $\Delta\sqrt{G}$.



(a) (b)

Figure 5 Mixed Mode I/II delamination growth rate characterized by the two different CDF terms. (a) $\Delta G'$; (b) $\Delta\sqrt{G}$.

4. Conclusions

The parameter ΔG is widely used as a CDF to characterize the delamination growth rate in FRP composite structures. However, it is found that for the same value of ΔG, the da/dN versus ΔG curves appear to suggest that increasing the mean stress would result in a slower delamination growth rate. This anomaly raises the question of whether ΔG is a valid CDF. Fortunately, when expressing da/dN as a function of ΔG', or Δ√G, this anomaly does not occur. Further, it has been shown that these two terms are directly related.

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