20th European Conference on Fracture (ECF20)

Towards Understanding Fatigue Disbond Growth via Cyclic Strain Energy

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Abstract

The concept of relating fatigue disbond growth to the strain energy release rate (SERR) is critically examined. It is highlighted that the common practise of using only the maximum SERR or only the SERR range is insufficient to correctly characterize a load cycle. As crack growth requires energy, it is argued that growth should be related to the total amount of energy released during a fatigue cycle, and not to the amount of energy that would be released by a crack growth increment under the instantaneous load conditions at one point in the load cycle. This argument is supported by experimental evidence, showing that the relationship between fatigue disbond growth (FDG) rate and either maximum SERR or SERR range is R-ratio dependent, whereas the relationship between FDG rate and the loss of strain energy is not.

Keywords: Adhesive Bonding; Fatigue; Disbond Growth; Energy Method

1. Introduction

Compared to the traditional mechanical joining methods in use in the aerospace sector, adhesive bonding holds the tantalising promise of more efficient (i.e. lighter) structural designs. Lighter structures will result in reduced fuel use, lowering both the environmental impact and the operating costs of air travel. However, before this promise can be fulfilled a better understanding of the phenomenon of fatigue disbond growth (FDG) is imperative. Application of adhesive bonding to primary (i.e. safety critical) structure requires the ability to confidently predict the rate of disbond growth for a given load history.

As discussed in a recent review of the literature (Pascoe et al. (2013b)), FDG has been studied for approximately 40 years. Researchers have focussed on the link between the strain energy release rate (SERR) and the FDG rate. This paper highlights some of the issues with this approach and suggests an alternative perspective, based on the energy balance. Experiment data will be presented to support this new approach.

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Nomenclature

a   Crack length (mm)
b   Specimen width (mm)
C   Fit parameter
d   Displacement (mm)
G   Strain energy release rate (N/mm)
K   Stress Intensity Factor (MPa $\sqrt{\text{mm}}$)
N   Number of cycles
n   Fit parameter
n   Compliance calibration parameter
P   Load (N)
R   Load ratio, $P_{\min}/P_{\max}$
U   Strain energy (mJ)

2. A Brief Examination of Current Approaches

The currently accepted approaches to predicting FDG are ultimately based on the work of Paris and co-workers, as described in Paris et al. (1961); Paris and Erdogan (1963); Paris (1964). In these works the Paris relationship was proposed, linking crack growth in metals to the range of the stress intensity factor (SIF), K:

$$\frac{da}{dN} = C\Delta K^n \tag{1}$$

In this equation a is the crack length and C and n are empirical constants found by curve fitting. Eqn. 1 was modified and applied to fatigue delamination and disbonding problems by Roderick et al. (1974), using $G_{\max}$, and Mostovoy and Ripling (1975), using ΔG, to give:

$$\frac{da}{dN} = CG_{\max}^n \qquad \text{or} \qquad \frac{da}{dN} = C\Delta G^n \tag{2}$$

where $G_{\max}$ is the maximum value of the SERR attained during the load cycle and $\Delta G = G_{\max} - G_{\min}$.

There equations are both based on eqn. 1, making use of the fact that SIF and SERR are equivalent, as demonstrated in Irwin (1957). Both equations soon turned out to be insufficient to describe all cases of disbond growth. In particular it became apparent that the relationships found between the SERR (range) and disbond growth rate were not only material dependant, but also depended on the R-ratio or mean stress, as had in fact already been noted in Paris et al. (1961) and Paris (1964). This is of course a consequence of the fact that either $G_{\max}$ or ΔG by themselves do not provide sufficient information to uniquely characterize a stress cycle.

A number of models have been developed in order to deal with the R-ratio / mean stress dependence. Roughly these can be grouped into models that include the R-ratio in the equations and models that combine both $G_{\max}$ and ΔG in the equations. Models from the first category include Poursartip and Chinatambi (1989); Andersons et al. (2001) and Allegri et al. (2011, 2013). Models from the second category include Hojo et al. (1987, 1994); Andersons et al. (2004); Atodaria et al. (1997, 1999a,b) and Jones et al. (2012). However, as discussed more fully in Pascoe et al. (2013b), all these models are based on empirical correlations, rather than on a consideration of the underlying physics.

To come to a more physics-based understanding of disbond growth, the following line of reasoning is proposed: The fundamental principle of fracture mechanics is that energy is required to create new (fracture) surfaces, as outlined in Griffith (1921). In Irwin (1957) it was proposed that for *fixed-grip* crack growth the amount of energy that is consumed per increment of crack growth must equal to amount of strain energy released by that same increment of crack growth, i.e. must equal the strain energy release rate. The SERR is a function of both geometry and applied load. Thus, during a fatigue cycle, where the load constantly varies and as a consequence the fixed-grip assumption is questionable, the SERR will also constantly vary. Furthermore, the SERR is an energy release *rate*. The SERR does

not tell one the total amount of energy that is released, only the amount released for a certain amount of crack growth. Why then should the disbond growth rate be related to the SERR at only one (G_{max}) or two (ΔG) points in the load cycle? Instead, it is proposed to consider the energy released during the *entire* load cycle. The tests used to measure this energy and the results will be presented below.

3. Test set-up

Double cantilever beam (DCB) specimens were manufactured following the design given in ASTM D5528-01, consisting of AL2024-T3 beams, bonded with Cytec FM94 epoxy adhesive. Teflon tape was applied to parts of both beams to prevent adhesion of the epoxy, creating a pre-crack. The nominal dimensions were: length 300 mm, width 25 mm and thickness 12.15 mm (2x6 mm aluminium, plus 0.15 mm adhesive). Detailed measurements of the specimens after manufacturing, as well as further manufacturing details, can be found in the public dataset Pascoe et al. (2013a). One side of each specimen was coated with thinned correction fluid to enhance visibility of the crack.

The specimens were cycled in an MTS 10 kN fatigue testing machine under displacement control. The crack length was measured from pictures taken with a CCD camera. These pictures were analysed in Matlab using a simple image recognition algorithm to detect the crack length. Before fatigue cycling the specimens were loaded monotonically until visual onset of disbonding was observed, in order to generate a pre-crack. On specimen B-002 two fatigue experiments were performed, denoted B-002-I and B-002-II. In between these experiments again a monotonic loading until onset of visual disbonding was performed in order to generate a 'fresh' crack. Two experiments were also performed on specimen B-001, but it was later determined that the load measurement was not properly calibrated during the first test, thus data is only shown for B-001-II. The applied displacments were chosen somewhat arbitrarily based on achieving desired nominal values of $\Delta G/G_c$, they are shown in table 1.

Table 1. Test matrix indicating the applied minimum and maximum displacement. Two independent experiments were performed on specimen B-002. Specimen codes match those of the dataset Pascoe et al. (2013a). The listed R ratios are the mean values of P_{min}/P_{max} achieved during the test. As the extrapolated P-d curve did not pass through the origin, this does not equal d_{min}/d_{max}.

Specimen & Crack	d_{max} (mm)	d_{min} (mm)	R (-)
C-001-I	2.85	0.95	0.29
C-002-D	2.85	1.90	0.61
B-001-II	7.50	0.75	0.036
B-002-I	3.16	2.78	0.86
B-002-II	3.79	2.82	0.61

3.1. Data analysis

As mentioned above, crack length was measured optically. Displacement and load were recorded by the fatigue test machine. Depending on the disbond growth speed measurements were performed once every 100 or once every 1000 cycles. The crack length was measured at maximum displacement. At each measurement point both maximum and minimum load and displacement were recorded. Following ASTM D5528-01, displacement is defined as the change in distance between the test machine grips (assumed to equal the displacement of the load points) and crack length is defined as starting from the load application line. The full test data, as well as the full results of the analysis discussed below, are available from the 3TU data centre, in the dataset Pascoe et al. (2013a).

From these measurements the crack growth rate da/dN was derived by taking the derivative of a power-law fit of the a vs N curve. G_{max} and G_{min} were calculated using the compliance calibration method given in ASTM D5528-01, i.e:

$$G_I = \frac{nPd}{2ba} \tag{3}$$

where a is the crack length, n is the slope of the $\log(d/P)$ vs $\log(a)$ line, and b is the specimen width.

The strain energy input into the specimen can be divided into the monotonic energy U_{mono}, which is input at the start of the test and not recovered until testing is ceased, and the cyclic energy U_{cyc}, which is supplied and recovered
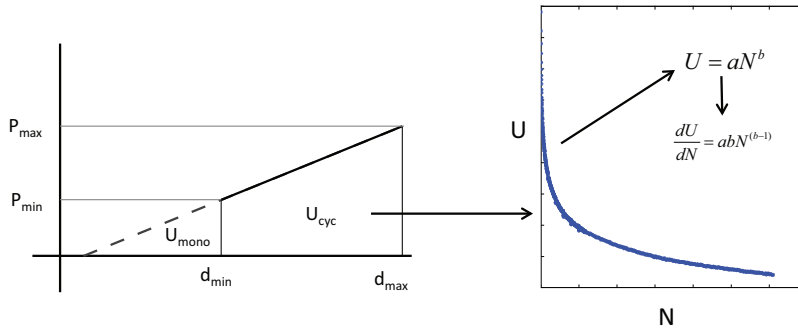
Fig. 1. The definition of U_{mono} and U_{cyc} and the deriviation of dU/dN. Note that the *P-d* curve does not pass through the origin.

again (minus losses) every cycle. This division is shown in Figure 1. Both U_{mono} and U_{cyc} can be calculated from the measured values of $d_{\mathrm{min}}, d_{\mathrm{max}}, P_{\mathrm{min}}$ and P_{max}. To calculate U_{mono} it was assumed that the *P-d* behaviour was linear between d_{min} and d_{max} (this was also experimentally confirmed) and this line was extrapolated to find the intersection with the abscissa.

U_{mono} and U_{cyc} as well as $U_{\mathrm{tot}} = U_{\mathrm{mono}} + U_{\mathrm{cyc}}$ were plotted against the number of cycles, which showed a power-law behaviour. Thus power-laws were fit for each specimen for U_{mono}, U_{cyc}, and U_{tot} as a function of N. The derivatives of these relationships were used to find dU/dN. This process is shown schematically in fig.1.

4. Test Results and Discussion

Figure 2 shows the results of the traditional approach of plotting da/dN vs G_{max} or $\Delta \sqrt{G}$. Note that here $\Delta \sqrt{G} = \left(\sqrt{G_{\mathrm{max}}} - \sqrt{G_{\mathrm{min}}} \right)^2$ was used, rather than $\Delta G = G_{\mathrm{max}} - G_{\mathrm{min}}$. This is because $\Delta \sqrt{G}$ preserves the similarity principle underlying the Paris relationship (eqn. 1), whereas ΔG does not (see also: Rans et al. (2011) and Azari et al. (2014)). As expected, different R-ratios result in different relationships between da/dN and either G_{max} or $\Delta \sqrt{G}$.

A very different picture emerges if one plots da/dN against the loss of strain energy per cycle dU/dN, as done in fig 3. In this case all the curves overlap and the relationship between crack growth rate and loss of strain energy appears to be the same, regardless of R-ratio (or, equivalently, mean stress). Based on this data one can write:

$$\frac{da}{dN} = C \left(\frac{dU}{dN} \right)^{n} \tag{4}$$

with $C = 0.0273$ and $n = 0.8232$ for U_{cyc} ($R^2 = 0.9999$) or $C = 0.01315$ and $n = 0.759$ for U_{tot} ($R^2 = 0.9995$).

These results can readily be understood in light of the fundamental principle proposed in Griffith (1921), i.e. that crack growth requires energy. The SERR is the amount of energy that is released by an increment of crack growth *under given loading conditions*. However during a fatigue cycle, the loading condition is continually changing. Thus the amount of energy that is released by an increment of crack growth occurring at the maximum fatigue load (G_{max}) is not equal to the amount of energy that is released by an increment of crack growth occuring at the minimum fatigue load (G_{min}). To understand the amount of crack growth occurring within one complete fatigue cycle, one should therefore consider the amount of energy that is released during that entire cycle; i.e. dU/dN. Fig. 3 shows that the amount of strain energy lost per cycle is indeed very strongly correlated to the FDG rate and independent of R-ratio or the mean stress level.

It is important to acknowledge at this point that the argument made in Griffith (1921) applies only to perfectly brittle materials. In non-brittle materials energy will not only be consumed by the pure crack growth mechanisms, i.e. formation of new surfaces; but also by other attendant mechanisms such as plasticity. Thus it is the totality of processes, including not only the pure crack growth, but also the attendant processes, that is related to the loss of strain energy. This does not diminish the core argument of this paper, i.e. that to understand crack growth one should consider the total amount of energy released during the fatigue cycle.
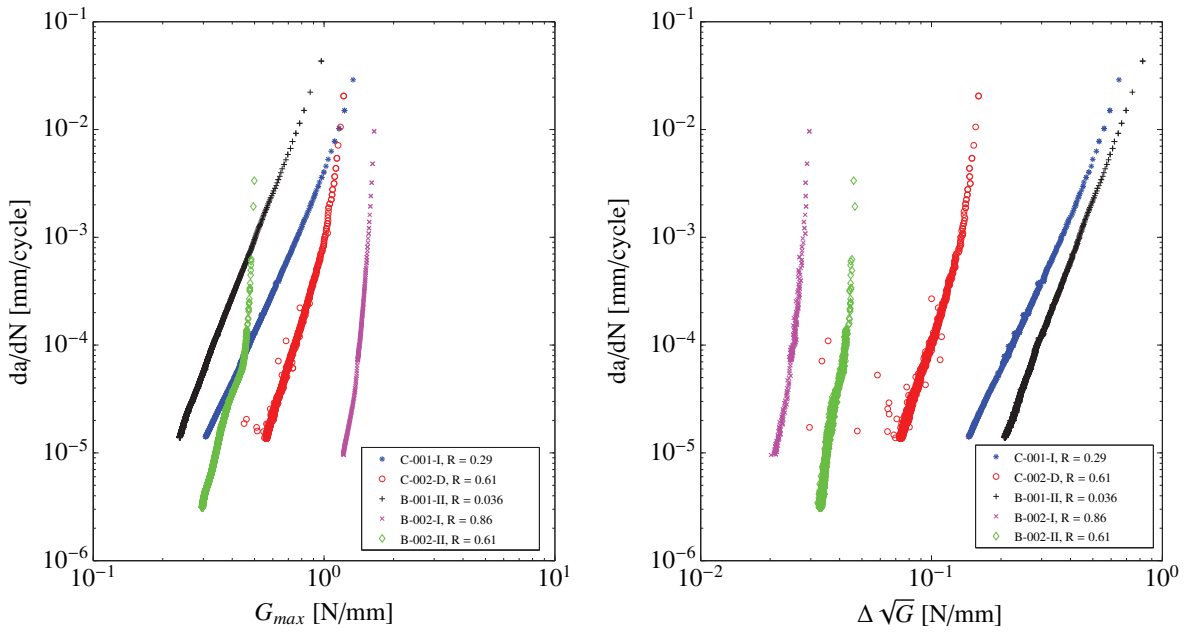
Fig. 2. Disbond growth rate versus SERR at maximum load (G_{max}) and SERR range ($\Delta \sqrt{G}$). The relationship between SERR and growth rate is dependent on the R-ratio.
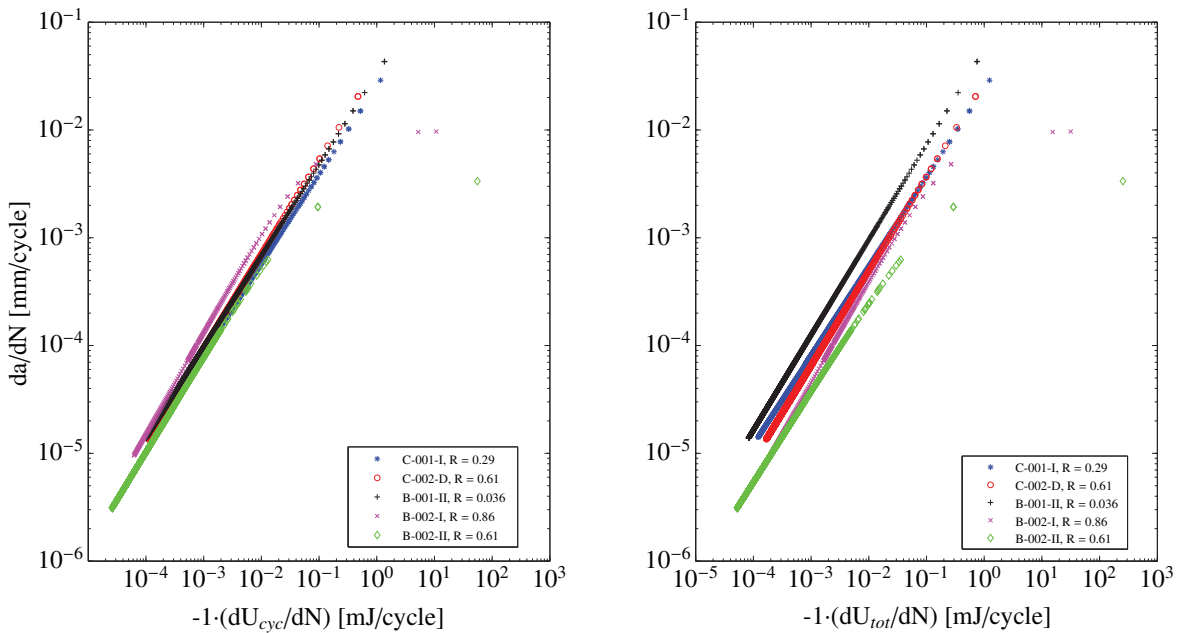

Fig. 3. Disbond growth versus loss of cyclic energy (dU_{cyc}/dN) and loss of total energy (dU_{tot}/dN). The best correlation is achieved for cyclic strain energy. The two outliers each for B-002-I and B-002-II are thought to be caused by the high sensitivity of the U vs N curve fit in the low N / high dU/dN region, as U increases asymptotically as N decreases.

5. Conclusion and Future Work

Using only the maximum SERR occurring during a stress cycle, or only the range of the SERR during a stress cycle, does not provide sufficient information to properly characterize the driving force for FDG. Instead FDG is related to the total amount of energy released during the fatigue cycle. Future work will aim to further explore the consequences of this finding, and to uncover the causal relationship underlying this empirical correlation. In particular, an important question is whether the loss of strain energy provides the driving force for FDG or if it is in fact a consequence of the disbond growth.

Acknowledgements

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