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Procedia Structural Integrity 2 (2016) 080–087

Structural Integrity Procedia

www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Characterising resistance to fatigue crack growth in adhesive bonds by measuring release of strain energy

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Abstract

Measurement of the energy dissipation during fatigue crack growth is used as a technique to gain more insight into the physics of the crack growth process. It is shown that the amount of energy dissipation required per unit of crack growth is determined by G_{max}, whereas the total amount of energy available for crack growth in a single cycle is determined by $\left(\Delta\sqrt{G}\right)^2$.

Keywords: Adhesive Bonds; Fatigue Crack Growth; Strain Energy Dissipation

Nomenclature

a	Crack length	n	Calibration parameter
A	Fit parameter in the Jones model	P	Force
C	Curve fit parameter	R	Load ratio
d	Displacement	U	Strain energy
G	Strain energy release rate	w	Width
G_{th}	Threshold strain energy release rate	ΔG	Strain energy release rate range
K	Stress intensity factor	ΔK	Stress intensity factor range
N	Cycle number	γ	Mean stress sensitivity
n	Curve fit parameter		

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10.1016/j.prostr.2016.06.011

1. Introduction

Since the pioneering work of Roderick et al. (1974) and Mostovoy and Ripling (1975), there have been many attempts to model fatigue crack growth (FCG) in composites and adhesive bonds. However these models are invariably based purely on empirical correlations (Pascoe et al., 2013). This is most likely because most research in this area has been focused on predicting crack growth, rather than gaining more understanding of the underlying physics.

The basis for most models dealing with FCG in composites and adhesives is the equation proposed in Paris (1964), but modified to depend on the strain energy release rate (SERR), G, rather than the stress intensity factor (SIF), K, i.e:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\Delta K^n \quad \text{or} \quad \frac{\mathrm{d}a}{\mathrm{d}N} = CG^n_{\max} \quad \text{or} \quad \frac{\mathrm{d}a}{\mathrm{d}N} = C\Delta G^n \tag{1}$$

where a is the crack length, N is the cycle number, and C and n are empirically determined curve fit parameters.

In the work of Paris et al. (1961) and Paris (1964) it was already noted that the crack growth rate depended not only on SIF range ΔK, but also on the ratio of minimum to maximum stress, R. Paris (1964) suggested that this could be accounted for by varying the coefficient C in equation 1 as a function of R.

Later researchers have suggested different ways of accounting for the R-ratio (or for the mean stress effect, which is equivalent). Hojo et al. (1987, 1994), Atodaria et al. (1997, 1999a,b), and Khan (2013) all proposed variations of the Paris equation, but with $\mathrm{d}a/\mathrm{d}N$ as a function of both $G_{\max}$ and ΔG simultaneously. Allegri et al. (2011) proposed a power-law dependence of $\mathrm{d}a/\mathrm{d}N$ on $G_{\max}$, including R in the exponent. Andersons et al. (2004) and Jones et al. (2012, 2014a,b, 2016) have proposed modifications of the equation suggested by Priddle (1976) and Hartman and Schijve (1970).

A characteristic of all these models is that they are phenomenological. The form of the equations was not chosen based on principles of the physical behaviour of the material, but solely based on the shape of the graph of $\mathrm{d}a/\mathrm{d}N$ vs a chosen similitude parameter. Although this approach can result in good predictions, as long as there is sufficient experimental data available to calibrate the models, an actual understanding of fatigue crack growth remains lacking. This means very large tests campaigns are necessary to generate sufficient data, and that it is sometimes unclear what the limits of validity of the found correlations are.

The research presented in this paper aims to increase the understanding of FCG in adhesive bonds, rather than just creating yet another prediction model. To that end the strain energy dissipation during FCG in an adhesive joint was characterised, following the methodology established by Pascoe et al. (2014b, 2015).

2. Test set-up and data processing

FCG tests were performed on double cantilever beam (DCB) specimens, consisting of two aluminium 2024-T3 arms bonded with FM94 epoxy adhesive, cured according to the manufacturer's instructions. Adhesive tape was applied between the adhesive and the adherents to act as a crack starter. The nominal specimen width was 25 mm. For more details on specimen preparation see Pascoe et al. (2015). Actual dimensions for each specimen are available from the online dataset (Pascoe et al., 2014a).

Tests were performed on an MTS 10 kN fatigue machine under displacement control, at a frequency of 5 Hz. Before each fatigue test the specimens were loaded quasi-statically until onset of crack growth was determined visually. Table 1 shows the applied load ratios for the experiments discussed here. For convenience of presentation the experiments have been collected into 4 groups according to applied R-ratio, as is also shown in table 1.

The crack length was measured by means of a camera aimed at the side of the specimen. Photographs were taken at regular intervals (once every 100 cycles at the start of the test, after approximately 10,000 cycles this was increased to once every 1,000 cycles) while the specimen was held at the maximum displacement. After completion of the test, an image recognition algorithm was used to automatically determine the crack length in each picture. A power-law curve was then fit through the crack length vs cycle number data. The crack growth rate was determined by taking the derivative of this power-law.