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Modelling and predicting fatigue crack growth in structural adhesive joints

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Abstract

The present paper examines crack growth in a range of structural adhesive joints under cyclic-fatigue loadings. It is shown that cyclic-fatigue crack-growth in such materials can be modelled by a form of the Hartman and Schijve crack-growth equation which aims to give a unique and linear 'master' representation for the fatigue data points that have been experimentally obtained. This relationship is shown to capture the experimental data representing the effects of test conditions, such as the *R*-ratio ($=\sigma_{min}/\sigma_{max}$) present in the fatigue cycle and test temperature. It also captures the typical scatter often seen in such tests, especially at low values of the fatigue crack-growth rate. Furthermore, the methodology is shown to be applicable to, and to unify, the results from Mode I (opening tensile), Mode II (in-plane shear) and Mixed-Mode I/II fatigue tests. Finally, it is used to predict successfully the rate of fatigue crack-growth in two bonded-repair type joints where naturally-occurring disbonds have initiated and grown.

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Nomenclature

a	crack length
A	constant in the Hartman-Schijve crack-growth equation
da/dN	rate of crack growth per cycle
D	constant in the Hartman-Schijve crack-growth equation
G	strain-energy release-rate (SERR)
G_{max}	maximum value of the applied strain-energy release-rate in the fatigue cycle
G_{min}	minimum value of the applied strain-energy release-rate in the fatigue cycle
ΔG	range of the applied strain-energy release-rate in the fatigue cycle, as defined below
ΔG	$= G_{max} - G_{min}$
$\Delta\sqrt{G}$	range of the applied strain-energy release-rate in the fatigue cycle, as defined below
$\Delta\sqrt{G}$	$= \sqrt{G_{max}} - \sqrt{G_{min}}$
$\Delta\sqrt{G_{th}}$	value of $\Delta\sqrt{G_I}$ at a value of da/dN of 10^{-10} m/cycle
$\Delta\sqrt{G_{thr}}$	range of the fatigue threshold value of $\Delta\sqrt{G_I}$, as defined below
$\Delta\sqrt{G_{thr}}$	$= \sqrt{G_{thr.max}} - \sqrt{G_{thr.min}}$
m	exponent
n	exponent in the Hartman-Schijve crack-growth equation
N	number of fatigue cycles
R	displacement ratio ($=\delta_{min}/\delta_{max}$)
δ_{max}	maximum displacement applied during the fatigue test
δ_{min}	minimum displacement applied during the fatigue test

1.Introduction

Adhesively-bonded components and bonded repairs are widely used throughout the aerospace industry. However, given the central role that damage-tolerance assessment and analysis plays in the design and certification of modern aerospace structures and bonded repairs (Miedlar et al. 2003), it is imperative to understand their cyclic-fatigue behaviour. Further, it is important to have a sound, and validated, means for accounting for the effects of test conditions, such as the *R*-ratio, test temperature and type of loading, and the inherent variability, and hence scatter, seen in the fatigue performance of structural adhesives. The measurement and predictive methods developed so far (e.g. Ripling et al. 1963, Jethwa and Kinloch 1997, Curley et al. 2000, Pascoe et al. 2013, Azari et al. 2014) have been largely based upon the principles of linear-elastic fracture-mechanics (LEFM). Nevertheless, the use of fracture-mechanics methods for design and life-prediction studies for structural adhesives still represent relatively new areas of research and have yet to be adopted by design engineers. Current fracture-mechanics approaches to crack growth in structural adhesive joints are based on variants of the Paris crack-growth equation, where the rate of crack growth per cycle, *da/dN,* is assumed to be linearly related to either $(G_{max})^m$ or $(\Delta G)^m$. Here G_{max} is the maximum value of the applied strain-energy release-rate in the fatigue cycle and ΔG is the range of the applied strain-energy release-rate in the fatigue cycle ($=(G_{max} - G_{min})$). However, several major problems have been found to arise with this approach of using either ΔG or G_{max} as the 'crack driving force (CDF)'.

Firstly, unfortunately, the value of the exponent, *m*, in this relationship tends to be relatively large for structural adhesives (and fibre-composite materials). Secondly, fatigue crack growth may be initiated from relatively small naturally-occurring material discontinuities, and be more rapid than predicted from experimental data obtained from relatively 'long-crack' tests. Thirdly, how to account for typical scatter that is observed in the experimental fatigue tests is a challenge. Fourthly, how to account for, and model, the effects of the particular test conditions, such as the *R*-ratio employed, the test temperature and the mode of loading, has yet to be resolved. The present paper presents a study of the use of the Hartman-Schijve approach to model and predict fatigue crack-growth in structural adhesives in order to overcome the aforementioned problems.

2. Theoretical background

More recently, work has shown (Rans et al. 2011, Jones et al. 2012, Jones et al. 2014, Jones et al. 2014a, Jones et al. 2015, Jones et al. 2016) that, to describe the Mode I cyclic-fatigue behaviour of adhesive joints and polymeric fibre-composites, the term $\Delta\sqrt{G_I}$ should be employed as the CDF. Thus, the form of the Hartman and Schijve equation (Hartman and Schijve 1970) becomes, for Mode I (tensile-opening) loading:

$$\frac{da}{dN} = D\left[\frac{\Delta\sqrt{G_I} - \Delta\sqrt{G_{Ithr}}}{\sqrt{\{1 - \sqrt{G_{Imax}}/\sqrt{A}\}}}\right]^n \quad (1)$$

where D, n and A are constants and where the term $\Delta\sqrt{G_I}$ is defined by:

$$\Delta\sqrt{G_I} = \sqrt{G_{Imax}} - \sqrt{G_{Imin}} \quad (2)$$

$$\Delta\sqrt{G_{Ithr}} = \sqrt{G_{Ithr.max}} - \sqrt{G_{Ithr.min}} \quad (3)$$

and the subscript '*thr*' in Equations (1) and (3) refers to the values at threshold, such that $\Delta\sqrt{G_{Ithr}}$ represents the range of the fatigue threshold value as defined by Eqn. (3). Now, for structural adhesives, it is often found from experimental tests (Jethwa and Kinloch 1997, Curley et al. 2000, Kinloch et al. 2000, Ashcroft and Shaw 2002, Azari et al., 2010) that a clearly defined threshold value exists, below which little fatigue crack-growth occurs. In this case the value of the threshold, $\Delta\sqrt{G_{Ithr}}$ is taken to be the experimentally-determined value. If this is not the case, then the concepts described in the ASTM standard (ASTM 2013), which are widely used by the metals community, may be employed. This standard defines a threshold value which, in the above terminology, may be taken to be the value of $\Delta\sqrt{G_I}$ at a value of da/dN of 10^{-10} m/cycle. This is termed $\Delta\sqrt{G_{Ith}}$ and hence, by rearrangement of Eqn. (1), the value of $\Delta\sqrt{G_{Ithr}}$ is given by:

$$\Delta\sqrt{G_{Ithr}} = \Delta\sqrt{G_{Ith}} - \sqrt{\{1 - \sqrt{G_{Imax}}/\sqrt{A}\}}\left[\frac{10^{-10}}{D}\right]^{1/n} \quad (4)$$

Considering the parameters in the above equations then the value of $\Delta\sqrt{G_{Ithr}}$ is experimentally measured for those adhesives where a clearly defined threshold value exists, below which little fatigue crack growth occurs. If this is not the case, then it is calculated via Eqn. (4) above. As previously discussed (Jones, 2014a), the value of A is best interpreted as a parameter chosen so as to fit the experimentally-measured da/dN versus ΔG_I (or G_{Imax}) data. Finally, it should be noted that adhesive joints can also undergo fatigue crack-growth under Mode II (in-plane shear) loading and Mixed-Mode I/II loading, and then the strain-energy release-rate, G, carries the appropriate subscript.

3. Results

As an example, the experimental Mode I and Mode II data (Ripling et al. 1988, Russell 1988) for a structural epoxy-film adhesive (i.e. FM-300K from Cytec, USA) are shown plotted in Fig. 1 according to Eqn. (1). Here log (da/dN) through the adhesive layer is plotted against log $\left[\frac{\Delta\sqrt{G} - \Delta\sqrt{G_{thr}}}{\sqrt{\{1 - \sqrt{G_{max}}/\sqrt{A}\}}}\right]$, where the corresponding Mode I and Mode II values are employed as appropriate. The values of A and $\Delta\sqrt{G_{thr}}$ have been calculated, as described above, from the individual experimental data. It should be noted that, for each mode of loading, the values for the constants D and n in Eqn. (1) have been taken to be the same for all the tests, as shown in Tables 1 and 2. Now, Fig. 1 reveals that, for both Mode I and Mode II loading, the various effects of mode of loading, R-ratio and temperature-dependence essentially collapse onto a single 'master' linear plot when Eqn. (1) is employed to represent the fatigue data. Further, the slope, n, of the 'master' linear relationship has a relatively low value of about two, and the associated scatter of the data is also relatively low. Furthermore, these results may be coupled with a finite-element analysis (Hu et al. 2016) of an adhesively-bonded component or structure (using the appropriate adhesive) and so be used to

model and predict the rate of fatigue crack-growth in the adhesive layer. In the present paper, two examples have been selected which consist of different designs of adhesively-bonded joints where naturally-occurring disbonds have been allowed to initiate and grow under cyclic-fatigue loading in: (i) a symmetrical double over-lap adhesively-bonded specimen (Cheuk et al. 2005) and (ii) an asymmetrical adhesively-bonded doubler joint. Both designs are typical of adhesively-bonded repairs (Pascoe et al. 2013a). It has been found that, in both cases, the use of the Hartman-Schijve equation, coupled with the finite-element analysis, gives rise to computed crack length, *a*, versus number, *N*, of fatigue-cycle histories that are in very good agreement with the experimental measurements, as shown for example in Fig. 2.

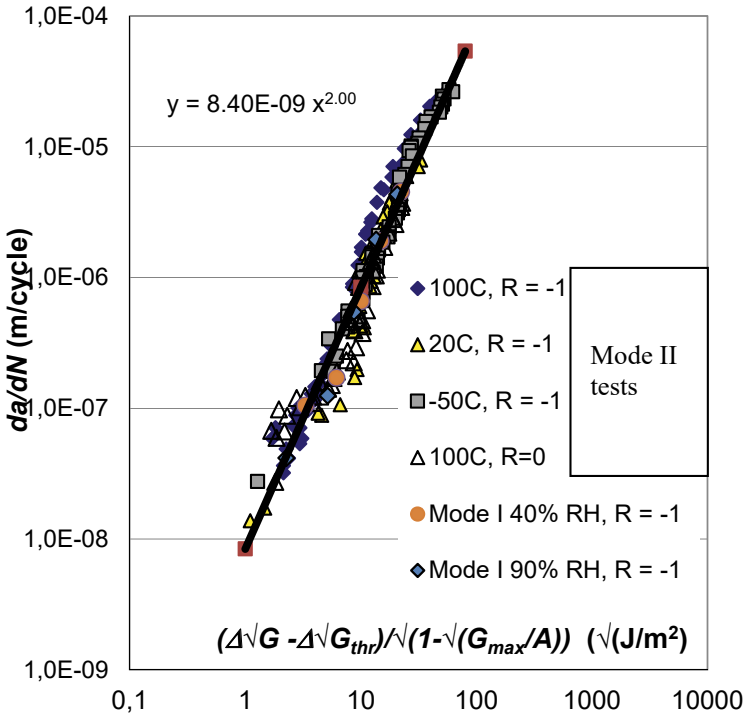

Fig. 1. The Hartman-Schijve representation of the Mode I and Mode II fatigue behaviour for the epoxy-film adhesive 'FM300K'.

Table 1. Values of the parameters employed in the Hartman and Schijve Eqn. (1) for Mode I crack growth in the 'FM300K' adhesive.

Test	***D* (m/cycle)**	***n***	***A* (J/m²)**	$\Delta\sqrt{G_{Ithr}}$ **(√(J/m²))**
40% RH	8.40 x 10^{-9}	2.00	630	9.8
80-90% RH	8.40 x 10^{-9}	2.00	630	10.5

Table 2. Values of the parameters employed in the Hartman and Schijve Eqn. (1) for Mode II crack growth in the 'FM300K' adhesive.

Test	D (m/cycle)	n	A (J/m^2)	$\Delta\sqrt{G_{IIthr}}$ (√(J/m^2))
100ºC & R = -1	8.40 x 10^{-9}	2.00	975	12.5
20ºC & R = -1	8.40 x 10^{-9}	2.00	1200	14.1
-50ºC & R = -1	8.40 x 10^{-9}	2.00	1500	15.5
100ºC & R = 0	8.40 x10^{-9}	2.00	2700	10.0

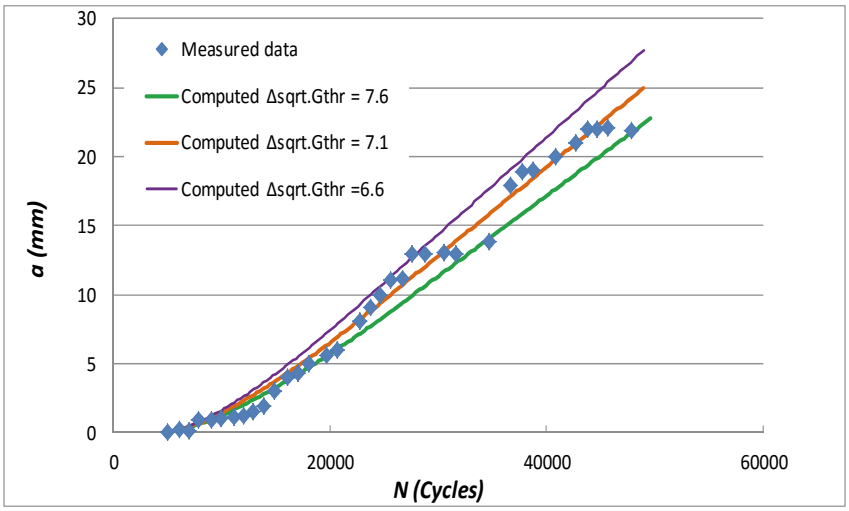

Fig. 2. The measured and predicted crack growth, a, histories for the initial naturally-occurring defects growing in the adhesive layer under cyclic-fatigue loading in the symmetrical double over-lap adhesively-bonded specimens. (The values of $\Delta\sqrt{G_{Ithr}}$ (√(J/m^2)) used to represent the mean and the standard deviation values were measured experimentally.)

4. Conclusions

The exciting potential for the Hartman-Schijve approach to unify many aspects of the cyclic-fatigue crack-growth behaviour that have been observed in structural adhesive joints have been described. In particular:

- A 'master' linear representation has been observed for each adhesive studied when such data are replotted according to the Hartman-Schijve approach, i.e. Eqn. (1). The slope, n, of this 'master' linear relationship has a relatively low value of about two. This will greatly assist a designer to allow for some fatigue crack growth to occur but still provide a safe-life for the adhesively-bonded structure.
- The variability, and hence the scatter, which was sometimes observed in the typical plot of log da/dN versus log ΔG_I (or G_{Imax}) from testing replicate specimens, has been captured by varying only the fatigue threshold term, $\Delta\sqrt{G_{Ithr}}$, in the Hartman-Schijve equation; with the value of $\Delta\sqrt{G_{Ithr}}$ being ascertained either via direct measurement or as calculated from Eqn. (4). Indeed, the degree of scatter associated with the Hartman-Schijve 'master' linear relationships was always found to be relatively low, as observed by the relatively high values of the correlation coefficients that were deduced.

- Having ascertained the constants in the Hartman-Schijve equation, it has been found that the complete curve for the experimentally-measured results (i.e. typically of the form da/dN versus G_{max} or ΔG) could be computed with a relatively high degree of accuracy.
- The Hartman-Schijve approach may account for both R-ratio and test temperature effects, again yielding a unique 'master' linear relationship which captures these effects.
- The Hartman-Schijve approach was found to be applicable to Mode I, Mode II and Mixed-Mode I/II types of fatigue loading. Indeed, it has been demonstrated that both the Mode I and the Mode II fatigue behavior for an adhesive may be conveniently described by a single, unique, 'master' linear relationship via the Hartman-Schijve approach.
- Finally, the Hartman-Schijve approach has been used to predict the crack-growth histories under cyclic-fatigue loading in two bonded-repair type joints, where naturally-occurring disbonds have been allowed to initiate and grow. The agreement with the experimental results was very good, and the typical scatter that is observed in the experimental fatigue tests was also predicted.

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