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Crack Initiation and Propagation of Bonded Metallic Joints under Mixed-Mode Cyclic Loading

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***Abstract* – Double Cantilever Beam (DCB) specimens have been used to carry out Fatigue tests to investigate mixed mode crack growth behaviour in bonded joints. Equal thickness mild steel DCB substrates bonded with FM73 adhesive were used. The bonded joints were tested under pure mode I and a range of fatigue mixed-mode conditions using a relatively simple, variable-mode loading fixture as described in [1and 2]. The fatigue testing was carried out at a load ratio (*R*) of 0.1, in displacement control such that the initial maximum fatigue load was 70% of the corresponding quasi-static fracture load. The fatigue load decreased as the fatigue crack grew and this load was recorded. Crack growth was monitored and measured using a video microscope. The strain energy release rate components were determined using corresponding values of fatigue crack length and fatigue load. The fatigue crack growth rates were characterised using a Paris Law approach and a significant influence of mode II component on the crack growth rate has been observed.**

***Keywords* – Mixed-Mode Loading, Fatigue Characterisation, Crack Growth, Paris Law, Strain Energy Release Rate (SERR), Linear Elastic Fracture Mechanics (LEFM).**

I. Introduction

The use of adhesive bonding is becoming much more widespread in recent decades. However, the presence of flaws/ defects (at least microscopically) cannot be avoided at all. Hence better understanding of cracks/defects behaviour is very important [1]. Interestingly, Most of adhesively bonded joint geometries used in practice are characterised by the combined presence of peel and shear stresses, hence experiencing mixed mode loading conditions at the crack tip. To perform reliable predictions of fatigue lifetime and endurance limit, it is, therefore, desirable to have crack propagation data for a range of mixed mode loadings [2]. It is for this purpose the present study is conducted. The term "Fatigue failure" refers to failure after the application of a load regime comprising multiple cycles (normally many), none of which would have led to failure if applied individually. The fatigue process can be considered to involve two stages; crack initiation and crack propagation. It is the latter that will be considered in detail in the present work, in the context of bonded joints under mixed mode loading. The main purpose of this work is to summarize the set-up and procedures used during the fatigue testing and then to report the experimental results.

The structure of thearticle is divided into five main sections and a set of concluding remarks at the end. Following this introductory section, the main sections cover mechanical testing methodology, results and discussion. The fatigue test methods used evolved after a number of trials - as fatigue is a phenomenon that often has considerable associated scatter, it was essential to adopt a consistent methodology so as to minimise any effects of variability. Fatigue tests were carried out using the loading jig described in previous work [1], employing test geometries with a range of mode mixities (pure mode I and mode mixity ratios of 0.22, 0.72, 1.29 and 6.62). Paris-type plot is presented with associated discussion.

II. Testing Methodology

2.1 Introduction

This section is divided in sub-sections. These consider the fatigue test parameters used, details of the sample preparation and test method, the mode of loading used during the tests, the crack growth monitoring technique and the generation of Paris law plots from the crack growth data.

2.2 Fatigue Test Parameters

Tests were carried out using constant (displacement) amplitude loading. The main parameters are indicated below and are shown in Fig.1.

Maximum displacement=δ_{max}

Minimum displacement= δ_{min}

Displacement range= $\Delta\delta=\delta_{max}-\delta_{min}$

Mean displacement =$\delta_{mean}=(\delta_{max}+\delta_{min})/2$

Displacement amplitude=$\delta_a=\Delta\delta/2$

$$\text{Frequency} = f = \frac{1}{cycles\,(\text{second})}\,Hz$$

Several fatigue test parameters were considered and trialled before finalising the approach used in the present work. These included the cycle shape and frequency and the appropriate maximum and minimum load/displacement (and corresponding load/displacement ratio *R*). Eventually a test frequency of 3 Hz was chosen, as this was well within the capabilities of the loading jig, while not being likely to cause significant heating effects in the adhesive. It is generally accepted that the effect of frequency on Fatigue Crack Growth (FCG) is limited in thermosetting adhesives significantly below the glass transition temperature T_G, [3-5]. The load ratio, *R*, was kept constant at 0.1, which is a value used widely in aerospace component testing [6]; this also ensures that compression of the parts of the pin-jointed loading jig is avoided. The maximum load applied was determined from the static failure load. Eventually it was decided to carry

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out all tests under sinusoidal displacement control such that the initial maximum fatigue load was 70% of the corresponding quasi-static fracture load shown in Fig.1. Choosing 70% of the fracture load enabled data to be recorded over a representative range of crack growth rates, while at the same time reducing the likelihood of specimen failure during the first load cycle.

2.3 Sample Preparation and TESTING

The bonded joint manufacturing process followed the procedure and the quasi-static failure loads (as a function of mode mixity) were known from the test programme andFatigue testing of the joints were carried out using the jig described in [1], mounted on an Instron 8511 testing machine, Fig. 2, which has a maximum load capacity of 20 kN.

In addition to the pure Mode I test configuration, tests were carried out over a range of mode mixities G_{II}/G_I, based on Eqs. 1 and 2 below (for further details see [1 and 2]). The geometries used give initial mode mixity ratios of 0.22, 0.72, 1.29 and 6.62. The values are a function of crack length and they increase (slightly) as the crack grows during a fatigue test to final values of 0.24, 0.74, 1.32 and 6.68. These changes were viewed as sufficiently small to ignore during the analysis of the data.

$$G_I = \frac{12M_I^2}{B^2Eh^3}\left(1+\frac{(1+\upsilon)}{5}\left(\frac{h}{a}\right)^2\right)\left(1+\frac{1}{\lambda_\sigma a}\right)^2 \quad 1 \qquad [1]$$

$$G_{II} = \frac{9M_{II}^2}{B^2Eh^3}\left(1+\frac{1}{\lambda_\sigma a}\right)^2 2 \qquad [2]$$

2.4 Mode of Loading

In the current work fatigue tests were carried out initially under load control. Under this test condition, crack growth rates were low initially, but then accelerated until the sample fractured. It was found that very few data points for crack length as a function of number of cycles could be recorded before fracture. It was therefore decided to investigate behaviour under displacement-controlled fatigue testing. Crack growth behaviour is independent of the mode of control during constant amplitude fatigue testing - published results from Mall et al (1987) show that the relationship between crack growth rate and applied strain energy release rate is not affected by whether a sample is tested in displacement or load control. However, in displacement controlled experiments, the load drops and the crack growth rate decreases as the crack grows during the fatigue test and for some specimen geometries the crack arrested before complete failure. While few data points were recorded for crack growth against number of cycles under load control, in displacement control it was possible to obtain sufficient data for analysis. For this reason displacement controlled tests were preferred and the results presented in the remainder of this chapter are derived from such tests.

Similar trends for the reduction in maximum load with fatigue cycles were observed for each specimen configuration and mode ratio tested, albeit with some variation, in particular in respect of the number of cycles before the onset of crack propagation was observed. It was apparent that the peak load remains essentially constant prior to the onset of crack growth. The point where the load starts to drop was recorded for each specimen as a measure of the number of cycles for crack initiation. Once the crack starts to propagate there is a corresponding rapid decrease in maximum load.

It was observed that initial crack growth is rapid but subsequently it reduces while the corresponding load value falls steeply before levelling off. This is not surprising as under displacement control a reduced maximum load is required to keep the displacement constant because the compliance of double cantilever beam (DCB) increases with crack length. Similar trend for increase in crack length and decrease in maximum load in DCB bonded joint were observed in [7].

2.5 Crack Growth Monitoring During Fatigue Cycling

After curing of the DCB bonded joints, the extra adhesive was removed from the joint with sand paper and the bond-line was highlighted using diluted “Tip-Ex” to enable the crack tip to be identified more easily. The crack length was measured using a scale attached to the edge of the joint. A digital microscope, as shown in Fig. 3, enabled the crack length to be monitored. The scale was sub-divided into intervals of 0.15 mm. The digital microscope camera enables objects to be displayed in "live view" with up to 200x magnification on the computer screen as shown in Fig. 4. At the end of the test, the load and the number of cycles from the wave-matrix software and the corresponding measured crack lengths were transferred into a spreadsheet for analysis.

A three-parameter exponential function was selected for curve fitting and the three coefficients namely a, b and c were determined using origin 8 software.

2.6 Generation of Paris Law Plots

It is conventional to seek to represent fatigue crack growth data using the Paris relationship, which is well known to be applicable to metals and polymers [8]:

$$\frac{da}{dN} = C(G_{\max})^m \qquad [3]$$

The question is what form of the strain energy release rate parameter should be used to correlate data under mixed mode loading? In the present work the crack growth data for each of the test geometries investigated are correlated with maximummode I component of the strain energy release rate ($G_{I\max}$). This is a convenient way of viewing the data to check for consistency between individual tests.

III. Results and Discussions

3.1. Introduction

In this section the results from the fatigue tests are presented. The main focus of the results and the subsequent analysis are the fatigue crack growth data. Before considering these, the data relating to fatigue crack initiation, i.e. the number of cycles before the onset of crack propagation within the as-manufactured joint is presented.

3.2 Fatigue Crack Initiation

It was noted that there was an "initiation" period for each test specimen – a number of cycles of fatigue loading were applied before the onset of crack growth and the associated load drop were observed. In this section these crack initiation data are presented. Fig. 5 shows the data relating to the number of cycles for crack initiation in the fatigue specimens covering the range of geometries investigated. Nine specimens are shown at a mode mixity of 0.72, which arise from testing three specimens at each of the three testing jig arrangements giving rise to this level of mode mixity (see[1]). Three or four specimens were tested at each of the other mode mixities. It should be recalled that each of these test specimens was tested at 70% of the corresponding mean quasi-static strength, which correspond to different strain energy release rate component (and total) values. There are no clear trends apparent from the data shown in Fig. 5, although it appears that there is a reasonable consistency of behaviour within a given test arrangement. Fig. 6 shows the mean values of the number of cycles for crack initiation, while Fig. 7 and 8 show the corresponding value of the strain energy release rates, Fig. 7 showing the total strain energy release rate and Fig. 8 the mode I component. It is apparent from Fig. 7 that the number of cycles for crack initiation actually increases slightly with increasing total strain energy release rate, which does not seem physically reasonable. Looking at Fig. 8, however, it becomes apparent that while the total strain energy release rate is increasing the absolute level of the mode I component is decreasing. Plotting the data from Figs 7 and 8 in Fig. 9 gives a trend that suggests for these specimens the number of cycles for crack initiation correlates with the mode I component of the strain energy release rate: as the mode I value decreases, there is a greater number of cycles required for propagation of the crack in the as manufactured specimen.

3.3 Fatigue Crack Propagation

The logarithmic plot of the cyclic crack growth rate da/dN against log $G_{I\ max}$ (maximum mode I strain energy release rate) is used to present the results for each mode mixity considered [Following Pirondi and Nicoletto (2004), the maximum strain energy release rate (SERR)is preferred to strain energy release rate amplitude, i.e. $\Delta G= (G_{max} - G_{min})$, as any surface debris that accumulates on the crack face may prevent the crack from fully closing, giving a higher value of G_{min} and hence a lower value of ΔG than would be expected from the loading].

There is reasonable consistency between the FCG results for the tests carried out under pure mode I loading as a plot of log da/dN against log G_{Imax}. All of the samples showed adhesive on each fracture surface suggesting cohesive fatigue crack growth. The specimens named Mode I_1 and Mode I_2 showed some evidence of interfacial failure, but the crack growth data do not obviously differ from the other two specimens tested.

The FCG results for an initial mode-mixity ratio of 0.22, again as a plot of log da/dN against log G_{Imax}showed a reasonable agreement. The data for specimens with mode_mixity=0.22_1 and mode_mixity=0.22_3 are very similar with the data from specimen mode_mixity=0.22_2 displaced to the left, meaning that for a given strain energy release rate the crack growth rate is higher in this specimen. Interestingly specimen mode_mixity=0.22_2 was the one for which there is perhaps most evidence of interfacial failure and it seemed plausible (if there is an associated plane of weakness) that this would give rise to a higher crack growth rate.

Three different configurations are available in the jig to achieve a mode ratio of 0.72. This feature was kept in mind during designing of the jig so that results could be compared and checked accordingly. The FCG results for mode-mixity ratio of 0.72 plotting log da/dN against log G_{Imax} when S_1=0 and S_2=200 and pinning the support at point C (see [1] for details)– samples from mode_mixity=0.72_1 to mode_mixity=0.72_3. The FCG results for mode-mixity ratio of 0.72, plotting log *da/dN* against log G_{Imax} when S_1=200 and S_2=0 and pinning the support at point C (see [1] for details) – samples from mode_mixity=0.72_4 to mode_mixity=0.72_6. Finally, The FCG results for mode-mixity ratio of 0.72, plotting log *da/dN* against log G_{Imax} when S_1=0 and S_2=200 and pinning the support at point D (see[1]) – samples from mode_mixity=0.72_7 to mode_mixity=0.72_9.While there is some variation from sample to sample, it is noted that the data are reasonably consistent and most of the failure surfaces appear predominantly cohesive. Not only do the data more or less appear to superpose, which builds confidence in the use of the jig for fatigue testing, but the overall scatter in the fatigue crack growth rate of about one decade in crack growth rate at any strain energy release rate is reasonable when testing polymers [8], such as an adhesive, in fatigue.

The FCG results for mode-mixity ratio of 1.29, plotting log *da/dN* against log G_{Imax} showed reasonable consistency although the results from the first test namely mode_mixity=1.29_1 are perhaps different from the others – note that the failure surface from this specimen shows evidence of interfacial failure.The FCG results for mode-mixity ratio of 6.62, plotting log *da/dN* against log G_{Imax} showed good consistency and the failure mode of the specimens is predominantly cohesive in each case.To conclude, Fig. 10 shows the FCG results for the full range of mode-mixities tested as a plot of log *da/dN* against log G_{Imax}. It is clear that as the mode II contribution is increasing (or mode I contribution decreasing) the data move consistently to the left. This suggests that mode II component has a significant influence on the crack growth rate which seems entirely reasonable.

IV. Concluding Remarks

Crack growth in bonded joints under mixed mode fatigue loading has been studied using the loading jig developed and applied already to investigate fracture under quasi-static loading[]. Fatigue crack growth data for any particular geometry/test condition are reproducible and where there are discrepancies, these seem to be associated with the crack following an interfacial (as opposed to cohesive) crack path. The fatigue crack growth data have been shown to be consistent.

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Author Profile

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completed his B.Sc. with Honours in Indurstrial and Manufacturing Engineering (IME) from University of Engineering and Technology (UET) Lahore, Pakistan in 2004. He then secured M.Sc. with Merit in Advance Manufacturing Management and Technology (AMMT) from University of Surrey, UK in 2006 and PhD in 2011 from the same University.

Hafiz is currently working on an EU funded consortium involving developing nonlinear ultrasonic techniques to allow the determination of bond strength in composite structures. The key research challenges are interpreting the complex nature of the transmitted nonlinear signal and optimizing the operating point selection for thin specimens. Main challenges include: Experimental demonstration of various nonlinear ultrasonic techniques in thin specimens, Development of models to allow easy selection of a guided wave operating point for inspection of thin components and Usage of nonlinear guided wave inspection techniques to investigate the levels of nonlinearity present in thin composite specimens of varying bond strength.

Appendix

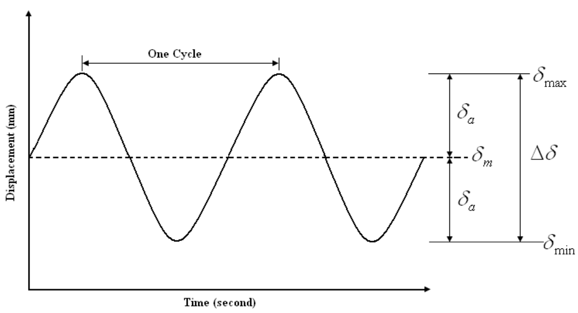

Fig.1. Constant displacement amplitude sinusoidal waveform used for fatigue testing

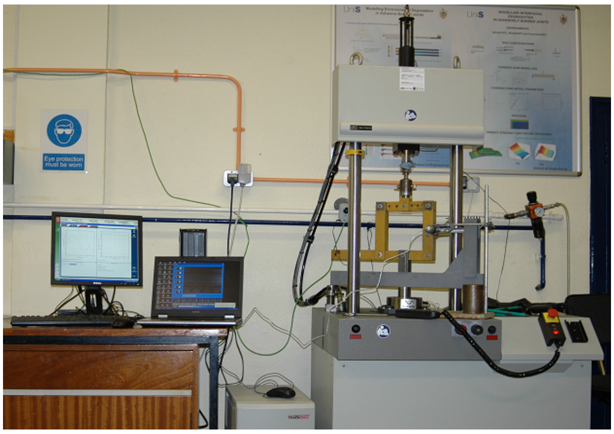

Fig.2. Experimental set-up [2]

Fig.3. Digital microscope used to monitor crack during fatigue tests

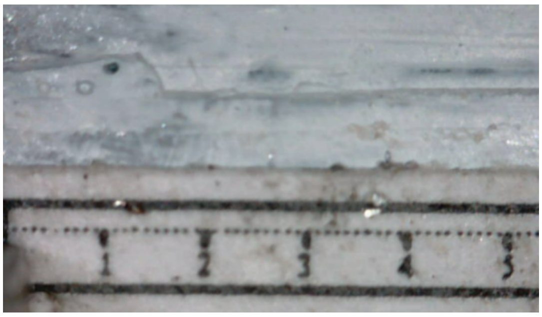

Fig.4. The scale used to monitor crack length during fatigue tests under digital microscope

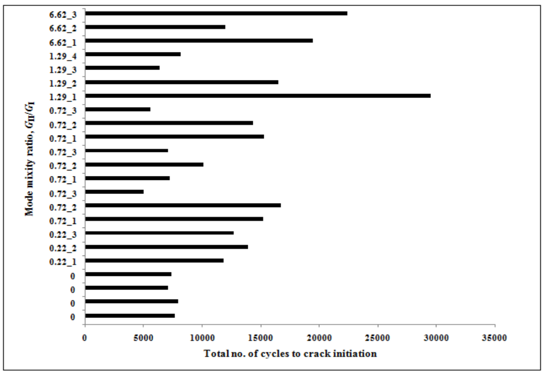

Fig.5. Data from 23 fatigue test specimens showing the number of cycles for crack initiation for the various test geometries. All specimens fatigued at an initial displacement/load level corresponding to 70% of the quasi-static strength.

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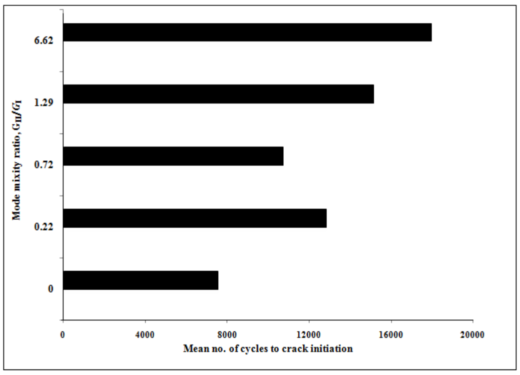

Fig.6. Average numbers of cycles for crack initiation for the various test geometries. All specimens fatigued at an initial displacement/load level corresponding to 70% of the quasi-static strength.

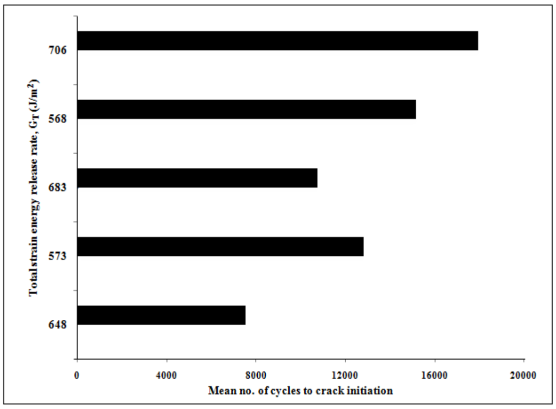

Fig.7. Values of maximum total SERR and number of cycles for crack initiation in the test geometries investigated. All specimens fatigued at an initial displacement/load level corresponding to 70% of the quasi-static strength

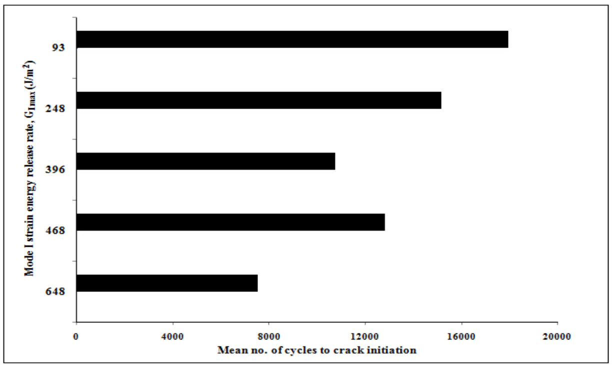

Fig.8. Values of maximum mode I SERR and number of cycles for crack initiation in the test geometries at an initial displacement/load level corresponding to 70% of the quasi-static strength.

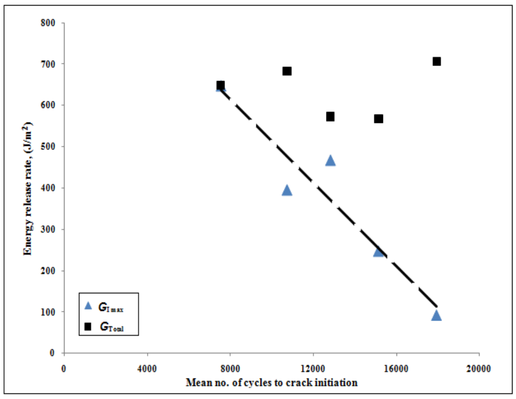

Fig.9. Plot of SERR against number of cycles to crack initiation in various bonded joint geometries subject to fatigue at an initial displacement/load level corresponding to 70% of the quasi-static strength [2].

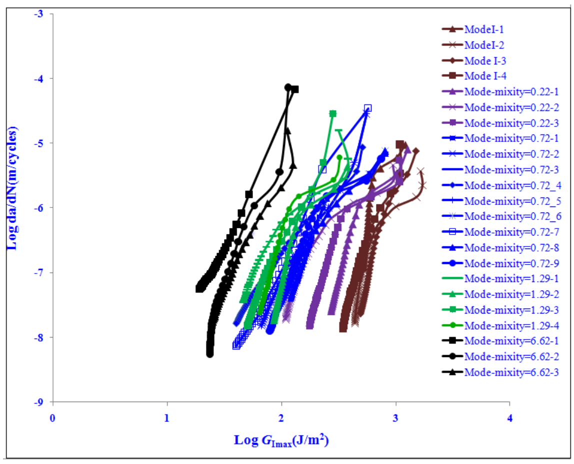

Fig.10. Plot of log (crack growth rate) against log (G_I max) for the range of mode mixity values used in the present study