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PREDICTING THE FATIGUE-LIFE OF STRUCTURAL ADHESIVE JOINTS

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ABSTRACT

A fracture-mechanics approach has been used to predict the cyclic-fatigue performance of the adhesively-bonded single-lap joint and a typical bonded component, represented by an adhesively-bonded 'top-hat' box-beam joint. The joints were tested under cyclic-fatigue loading in either a 'wet' or 'dry' environment, respectively. Several steps were needed to predict the cyclic-fatigue lifetime of these joints. Firstly, fracture-mechanics tests were used to obtain the relationship between the rate of fatigue crack growth per cycle, da/dN, and the maximum strain-energy release-rate, G_{max}, applied during the fatigue cycle for the adhesive/substrate system under investigation, in both a 'dry' and a 'wet' test environment. Secondly, analytical and finite-element theoretical models were developed to describe the variation of the strain-energy release-rate, G, with crack length, a, as a function of the applied fatigue loads, for the single-lap joint and the 'top-hat' box-beam joint. Thirdly, the experimental results from the short-term fracture-mechanics tests, obtained under similar test conditions and in the same environment as were used for the single-lap or bonded box-beam joints, were combined with the modelling results from the theoretical studies. This enabled the cyclic-fatigue performance of the single-lap or bonded box-beam joints to be predicted over relatively long time-periods. The agreement between the theoretical predictions and the experimentally-measured cyclic-fatigue behaviour for the joints was found to be very good.

KEYWORDS

Adhesives, Fatigue, Finite-element analysis, Fracture mechanics, Lifetime predictions.

INTRODUCTION

The use of adhesive bonding in industry has greatly increased in recent years. However, its use in truly structural applications is still often limited. This is mainly due to a lack of confidence in the performance of adhesive joints, since the mechanical performance of the joints may deteriorate upon being subjected to cyclic-fatigue loading, especially if the joints are also exposed to a moist environment [1-4]. Thus, the ability to quantitatively describe this reduction in performance and to predict the lifetime of bonded joints would be a powerful tool, enabling manufacturers to make wider and more efficient use of adhesive bonding. In the present paper, mild-steel substrates have been employed which have been bonded using a rubber-toughened hot-curing epoxy adhesive.

Firstly, fracture-mechanics tests are undertaken to identify the relationship between the rate of fatigue crack growth per cycle, da/dN, as a function of the maximum strain-energy release-rate, G_{max}, applied during a fatigue cycle. These cyclic-fatigue tests are conducted in both a 'dry' environment of 23±1°C and 55 % relative humidity, and a 'wet' environment of immersion in distilled water at 28±1°C.

Secondly, the cyclic fatigue of bonded (uncracked) single-lap joints in the ‘wet’ environment is studied. Analytical and finite-element models are developed to describe the variation of the maximum strain-energy release-rate, G_{max}, with the length, a, of the growing fatigue crack in the adhesively-bonded single-lap joints. These models are then combined with the results from the above experimental fracture-mechanics data, which have also been conducted under cyclic-fatigue loading in the appropriate environment. These combined expressions are integrated between the initial (i.e. intrinsic or Griffith) flaw size, a_o, and the crack length at final failure. Hence, the predicted number of cycles to failure for the lap joints may be deduced as a function of the cyclically-applied load. These predictions are compared with the experimental results, and the accuracy of the two approaches (i.e. via the analytical and the finite-element modelling studies) assessed. The sensitivity of the predictions to the boundary conditions employed, for example to the initial flaw size, is also discussed. The fracture-mechanics approach to lifetime prediction described above assumes that the cyclic-fatigue life of the lap joints is dominated by the propagation of cracks, rather than the initiation of such cracks. Thus, it is of some importance to establish whether this assumption is indeed correct, and therefore a backface-strain technique [3,5,6] is used to investigate crack growth in the lap joints during the fatigue tests.

Thirdly, a finite-element model is used to predict the rate of crack growth in a typical adhesively-bonded component subjected to cyclic-fatigue loading, but in this case in a ‘dry’ environment. The component selected is a bonded ‘top-hat’ box-beam, loaded from one end of the bonded ‘top-hat’ section in a cantilever-bending mode. The predictions of the expected cyclic-fatigue life are again compared with the experimental results.

RESULTS AND DISCUSSION

Fracture-mechanics data

The fracture-mechanics data were obtained using tapered double-cantilever beam (TDCB) adhesive-joint specimens and the experimental results obtained relate the rate of cyclic-fatigue crack growth, da/dN, to the maximum strain-energy release-rate, G_{max}, applied during a fatigue cycle, see Figure 1 for example. Obviously, the fracture-mechanics tests need to be conducted under similar test conditions as the joints, or components, whose service-life is to be predicted. It is also important to ensure that the TDCB fatigue test specimens do indeed exhibit a similar locus of failure as observed in the joints, or components, whose lifetime is to be predicted. The locus of failure of the different joints was therefore studied to ensure that this was indeed the case.

It was found that the threshold strain-energy release-rate, G_{th}, below which no cyclic-fatigue crack growth occurred, as measured in the 'dry' environment, was significantly lower than the value of the adhesive fracture energy, G_c, determined under monotonic loading. Further, the value of G_{th}, was often further reduced if the cyclic-fatigue tests were conducted in water, as opposed to the 'dry' environment. Since the time-scales of such 'wet' cyclic-fatigue tests are relatively short, they act as a very effective accelerated test technique and may readily be used to 'rank' the durability of adhesive joints. For example, 'wet' fatigue tests may be employed to compare, and develop, different and novel types of surface treatments for polymeric and metallic substrates - this is of particular importance since the surface treatment employed may have a major effect on the durability of the bonded joint.

Now, it is well established that the linear, central, region (labelled 'Region II' in Figure 1) of the plot of the relationship between logarithmic da/dN and G_{max} may be modelled by using an expression based upon the Paris Law [7]:

$$\frac{da}{dN} = DG_{\max}^{n} \qquad (1)$$

where D and n are obtained by fitting the above equation to the experimental data. However, as may be seen in Figure 1, the complete relationship between logarithmic da/dN and G_{max} is of a sigmoidal form. A lower-bound occurs at the fatigue threshold, G_{th}, where the crack growth rate is negligible ('Region I' in Figure 1) and an upper-bound occurs which is equivalent to the adhesive fracture energy, G_c, measured at a constant displacement-rate ('Region III' in Figure 1). Thus, the relationship between logarithmic da/dN and G_{max} may be better expressed by a modified form of the Paris Law, namely [8,9]:

$$\frac{da}{dN} = DG_{\max}^{n}\left[\frac{1-\left(\dfrac{G_{th}}{G_{\max}}\right)^{n_1}}{1-\left(\dfrac{G_{\max}}{G_c}\right)^{n_2}}\right] \qquad (2)$$

where G_{th} and G_c are the values of the cyclic-fatigue threshold and constant displacement-rate adhesive fracture energies respectively. The empirical constants n_1 and n_2 may again be obtained by fitting the above expression to the experimental data.

For example, the data obtained from the 'wet' cyclic-fatigue tests on steel TDCB specimens bonded with the epoxy adhesive give D and n values of 1.37 x 10^{-13} m^2/N.cycle and 3.64 respectively. The relationship based upon Eqn. 1 is shown in Figure 1, together with the experimental data. The modified relationship, Eqn. 2, is also shown in Figure 1, and the values of n_1 and n_2 were found by fitting Eqn. 2 to the experimental data.

Modelling

The first step in modelling the cyclic-fatigue lifetime of the bonded joints and components is to obtain an expression to describe the experimentally-measured fracture-mechanics data, i.e. the relationships between the rate of crack growth per cycle, da/dN, and the maximum strain-energy release-rate, G_{max}, in a fatigue cycle as given in Eqns. 1 or 2, see above. Secondly, the variation of G_{max} with crack length in the joint is theoretically modelled, using either an analytical or a finite-element approach. In the present work, both analytical and finite-element approaches were used for the single-lap joints, though only the finite-element approach was used for the bonded component. Finally, these data are combined and the resulting expression is integrated and, hence, the long-term cyclic-fatigue life of the joint may be predicted.

Predictions: Lap joints

The cyclic-fatigue lifetimes in the 'wet' environment for the single-lap joints predicted using the finite-element model are compared with the experimental results in Figure 2. The overall agreement between this numerical method, as well as via the analytical method, and the experimental results is relatively good, bearing in mind that the fatigue life has been predicted from first principles with no empirical 'fitting factors' being employed. For example, the finite-element modelling studies give a threshold value of the maximum load, T_{max}, per unit width in a fatigue cycle which could be applied to the lap joint of approximately 75 kN/m. This is equivalent to about 25% of the initial failure load, or fracture stress, of the lap joints. This predicted value of 75 kN/m may be compared with the measured value of 90 kN/m, which equivalent to 30% of the initial fracture strength of the lap joints.

However, as may be seen from Figure 2, whilst the agreement from the finite-element models around the threshold portion of the T_{max} versus N_f plots is good, the agreement is clearly poorer as one moves to higher values of T_{max}; i.e. to lower values of N_f. Nevertheless, it may be argued that predicting a lower limit, threshold, load (below which cyclic-fatigue crack growth will not be observed) is the appropriate design philosophy in the case of adhesively-bonded joints. The present models are clearly capable of achieving very good predictions in this respect. It should also be noted that, as discussed above, an upper- and a lower-bound value of the initial flaw size, a_o, may be calculated. However, as may be seen from Figure 2, the sensitivity of the predictions of the fatigue life upon the value of the initial flaw size via any of the above models and expressions is negligible.

Predictions: Bonded component

The adhesively-bonded 'top-hat' box-beam joint was tested under cyclic-fatigue loading in the 'dry' environment, and the predicted rate of crack growth per cycle, da/dN, for a given crack length, a, was calculated using Equation 1. For these predictions, the values of the strain-energy release-rate, G_{max}, as a function of the length, a, of the propagating cyclic-fatigue crack were calculated from the finite-element model of the bonded component. The values of D and n, that are also needed, were obtained from the experimental fracture-mechanics data (see above), from tests conducted of course in the 'dry' environment. The experimental results and the predictions are shown in Figure 3 and, as may be seen, the agreement between the predicted values and the experimental data is very good.

CONCLUSIONS

The main aim of the work described in the present paper has been to predict the service-life of bonded joints and components when they are exposed to cyclic-fatigue loading. The basic idea derives from the fact that the cyclic-fatigue fracture-mechanics data may be gathered in a relatively short time-period, but may be applied to other designs of bonded joints and components, whose service-life may then be predicted over a far longer time-span. Thus, cyclic-fatigue fracture mechanics test have been conducted, and the results then combined with analytical and finite-element models, to predict the fatigue performance of bonded single-lap joints and a bonded 'top-hat' box-beam joint. The theoretical predictions were compared with the experimental results and the agreement was found to be very good.

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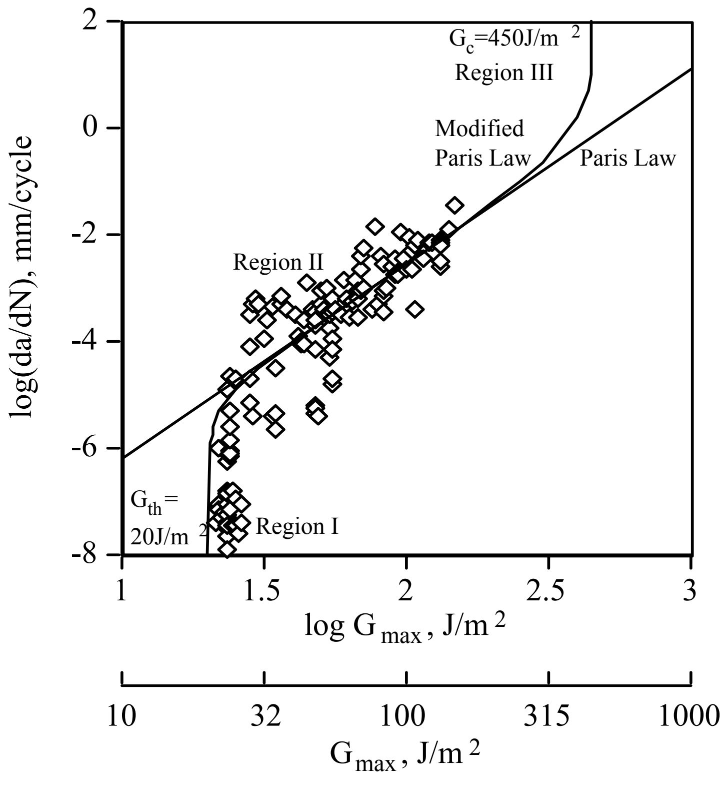

Figure 1: Logarithmic crack growth rate per cycle, *da/dN*, versus logarithmic, and linear, G_{max}, for the cyclic-fatigue fracture-mechanics tests performed in the 'wet' environment of 28^{o}C and water immersion. The relationships for Eqns. 1 and 2 are shown by the solid lines.

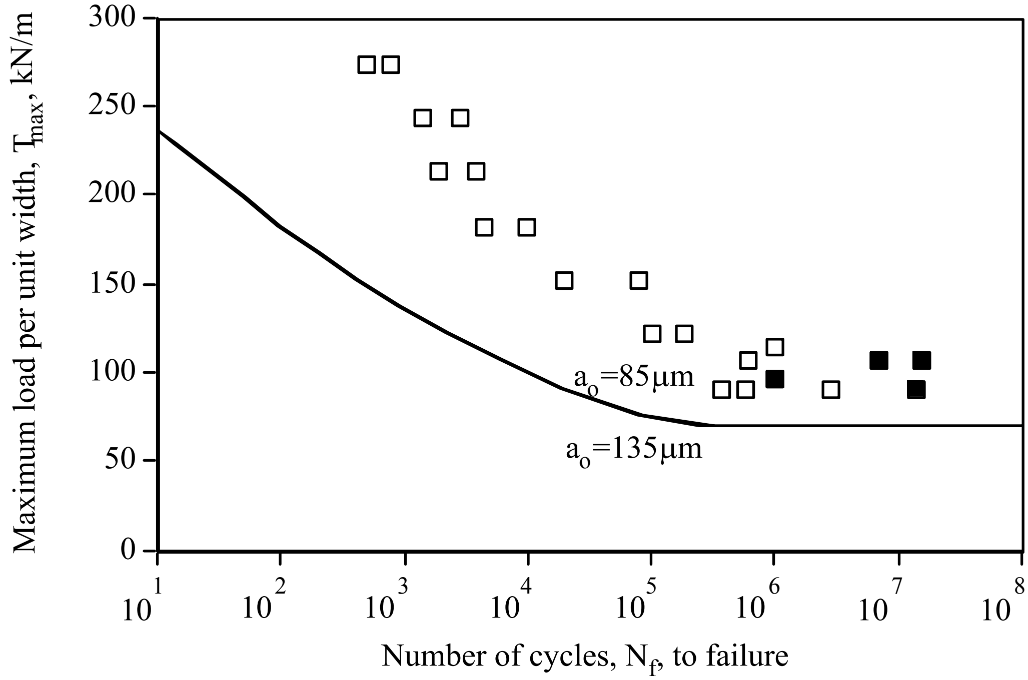

Figure 2: The number, N_f, of cycles to failure in a 'wet' environment for the single lap joints as a function of the maximum load, T_{max}, per unit width applied in a fatigue cycle. The points represent the experimental data whilst the lines are the predicted lifetimes using the finite-element model. Theoretical results are given for a_o values of 85 or 135μm by the solid and dashed lines, respectively.

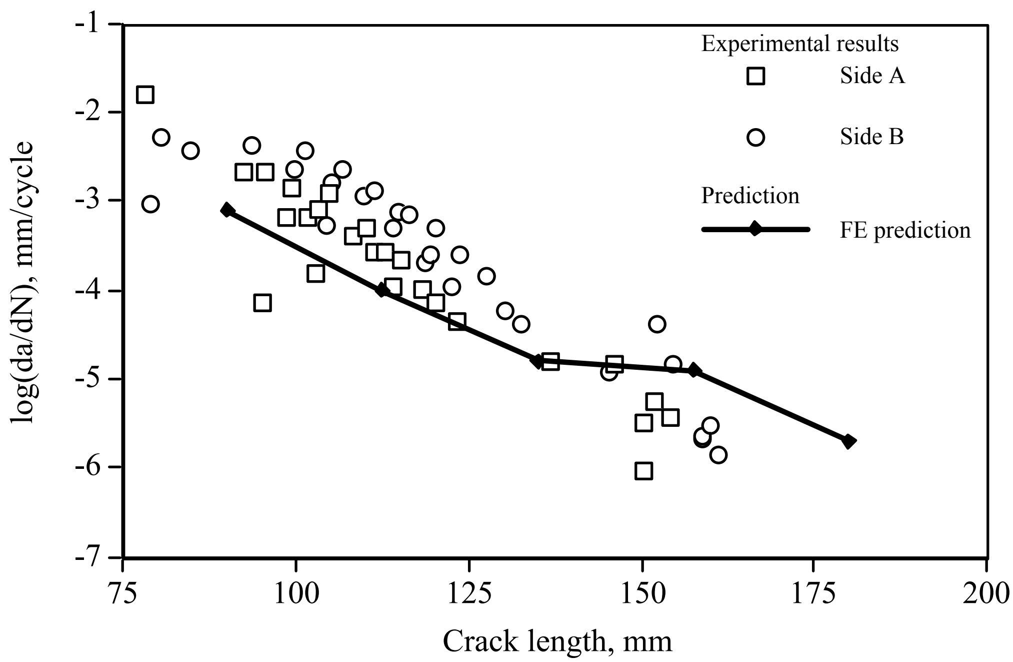

Figure 3: Logarithmic rate of crack growth per cycle, *da/dN*, versus the length, *a*, of the propagating cyclic-fatigue crack for the bonded 'top-hat' component tested in a 'dry' environment. The open points represent the experimental data, whilst the solid line is the predicted crack growth rate from using the finite-element model.