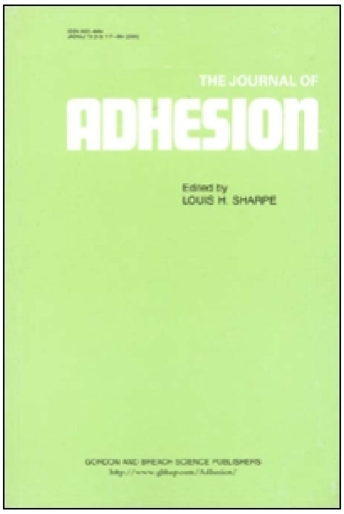

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Predicting the Fatigue Life of Adhesively-Bonded Joints

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The fatigue behaviour of adhesively-bonded joints, which consisted of an epoxy-film adhesive bonding fibre-composite substrates, has been studied. Using a double-cantilever beam specimen, the rate of crack growth per cycle has been measured as a function of the maximum strain-energy release rate, G_{max}. These data have then been modelled, and used to predict the fatigue lifetime of bonded single-lap joints. The agreement between the theoretical predictions and experimental results for the fatigue behaviour of the single-lap joints was found to be excellent.

KEY WORDS epoxy film adhesive; fiber reinforced composite; double cantilever beam specimen; crack growth; fracture mechanics; single lap joint; theory; experiment; adhesive fracture energy; life prediction; cyclic fatigue.

1. INTRODUCTION

Engineering adhesives are now widely used in many different industries where the adhesively-bonded component will experience cyclic fatigue loads. Thus, a knowledge of the fatigue behaviour of bonded joints is clearly an essential requirement. As with other materials, the fatigue behaviour of adhesives and adhesive joints has been successfully studied employing a continuum fracture mechanics approach.[1–8] The early work by Mostovoy and Ripling[1] clearly established the validity of using a linear-elastic fracture-mechanics (LEFM) approach for describing the fatigue crack growth behaviour when bonding aluminium-alloy substrates using a range of epoxy-based adhesives. They employed a tapered-double cantilever beam joint specimen and conducted the tests under nominally mode I (tensile-opening) cyclic loading and measured the rate of crack growth, da/dN, per cycle as a function of the range of strain-energy release-rate, ΔG, that was imposed; where:

$$\Delta G = G_{max} - G_{min} \tag{1}$$

and where G_{max} is the maximum and G_{min} is the minimum value of the strain-energy release-rate per cycle. Firstly, they observed that, as for many other materials, over much of the range of experimental data the crack growth rate may be expressed by:

$$\frac{da}{dN} = A_f \Delta G^q \tag{2}$$

where A_f and q are constants. Secondly, their studies revealed that the relationship between da/dN and ΔG was actually sigmoidal in shape. Crack growth rates were found to decrease to very low values as ΔG approached some limiting threshold value, ΔG_{th}, and to increase to very high values as ΔG approached the typical value, G_c, for crack growth under short-term monotonic loading (static) conditions. Subsequent work has, for example, studied the effects of the test frequency,[1] thickness of the adhesive layer,[7] the type of adhesive employed,[2,3] the possibility of crack closure[2] and the mode-mix[4,6] of the loading conditions. (The "mode-mix" being the ratio of mode I (tensile) to mode II (in-plane shear) loading.) However, virtually no work has been undertaken on using the results from such fracture mechanics studies to predict the fatigue lifetime of adhesively-bonded joints.

Therefore, the aim of the present work was to study the dynamic fatigue behaviour of joints which consisted of polymeric fibre-composite substrates bonded using an epoxy-based structural adhesive. The typical fracture mechanics data are firstly reported, and then the use of these data to predict the lifetime of single-overlap joints loaded in tension, a very common form of joint design, is discussed.

2. THEORETICAL

2.1 Determination of the Adhesive Fracture Energy, G_c

From LEFM the value of the adhesive fracture energy, G_c, may be calculated from a test conducted at a constant rate of displacement using the relationship:

$$G_c = \frac{P_c^2}{2B}\frac{dC}{da} \qquad (3)$$

where P_c is the load at the onset of crack propagation, C is the compliance of the specimen and is given by displacement/load (*i.e.* δ/P), a is the crack length and B is the width of the specimen. When crack propagation through the specimen is stable, the value of G_c at various values of the crack length, a, may be deduced and examined to discern whether any form of "R-curve" exists. (An "R-curve," or "resistance-curve," being where the plot G_c *versus* the length of the propagating crack reveals that the fracture energy increases as the crack grows stably through the material or joint. This is typically due to, for example, an increasing degree of plastic deformation occurring at the crack tip or the development of a bridging mechanism behind the crack tip as the crack propagates.)

In the present work a bonded double-cantilever beam (DCB) test specimen, Figure 1, was employed to determine the mode-I (*i.e.* tensile-opening mode) value of the adhesive fracture energy, G_c, as a function of the length of the propagating crack.

2.2 The Fracture Mechanics Data from the Fatigue Tests

Similarly, the maximum value of the strain-energy release-rate, G_{max}, applied during a fatigue cycle may be deduced using:

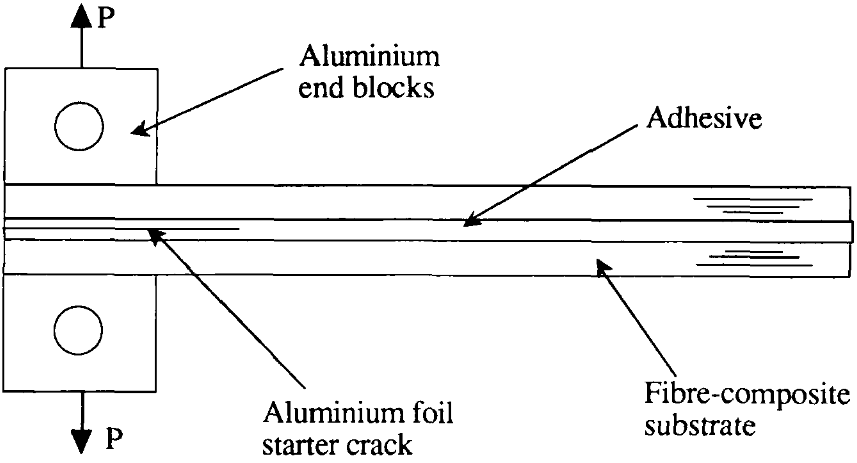

FIGURE 1 The adhesively-bonded double-cantilever beam (DCB) specimen.

$$G_{max} = \frac{P^2_{max}}{2B}\frac{dC}{da} \tag{4}$$

where P_{max} is the maximum load applied during the fatigue cycle. Again the DCB test geometry was employed.

If the fatigue data are plotted in the form of G_{max} *versus* da/dN, using logarithmic axes for both parameters, then a major portion of the relationship so obtained is often linear and this region may be described by a form of the Paris Equation, namely:

$$\frac{da}{dN} = DG^n_{max} \tag{5}$$

where D and n are material constants. Alternatively, the complete relationship between log G_{max} *versus* log da/dN is often of a sigmoidal form, which may be described by:

$$\frac{da}{dN} = DG^n_{max}\left\{\frac{1-\left(\frac{G_{th}}{G_{max}}\right)^{n_1}}{1-\left(\frac{G_{max}}{G_c}\right)^{n_2}}\right\} \tag{6}$$

where G_{th} is the minimum, or threshold, value of the adhesive fracture energy below which no fatigue crack growth is observed to occur, G_c is the value of the adhesive fracture energy from the constant rate of displacement tests (*i.e.* the "static" value) and D, n, n_1 and n_2 are material constants.

It should be noted that G_{max} has been employed, as opposed to ΔG, since during the unloading part of the fatigue cycle the debonded surfaces typically come into contact resulting in facial interference of the adhesive, or fibre-composite material, in which the crack is propagating. This leads to the generation of surface debris which prevents the crack from fully closing when it is unloaded, and hence may give an artificially high value of G_{min}. Thus, it has been suggested[9] that it is better to use G_{max}, instead of ΔG, and this convention has been followed in the present studies. However, the choice of this approach does not significantly affect the general form of the fatigue crack growth relationships, nor the results of the fatigue lifetime predictions for the lap joints.

2.3 The Life-Prediction Model

2.3.1 Introduction A major aim of the current work was to use the fracture mechanics data to predict the fatigue lifetime of adhesive joints of a type commonly used in industrial applications. Such a design of adhesive joint is the single-overlap joint loaded in tension, as shown in Figure 2. Obviously, to employ the fracture mechanics data generated from the above studies, the strain-energy release-rate in a single lap-joint during cyclic fatigue loading needs to be deduced.

2.3.2 The strain-energy release rate in a single-lap joint It is well documented[10] that single-overlap joints loaded in tension fail due to the transverse (out-of-plane) tensile, or cleavage, stresses, σ_{11}, which act at right angles to the direction of the applied load. These stresses are mainly introduced by the eccentricity of the loading path.

Now the maximum value of the transverse tensile stress, σ_{11}, in a lap joint is given by Hart-Smith's[11] analysis to be:

$$\sigma_{11} = M_e \left(\frac{E_a}{2t_aX}\right)^{1/2} \tag{7}$$

where E_a and t_a are the modulus and thickness of the adhesive layer, respectively. The bending stiffness, X, and the bending moment, M_e, are given by:

$$X = \frac{E_sh^3}{12(1-\nu^2)} \tag{8}$$

and

$$M_e = 0.5KT(h + t_a) \tag{9}$$

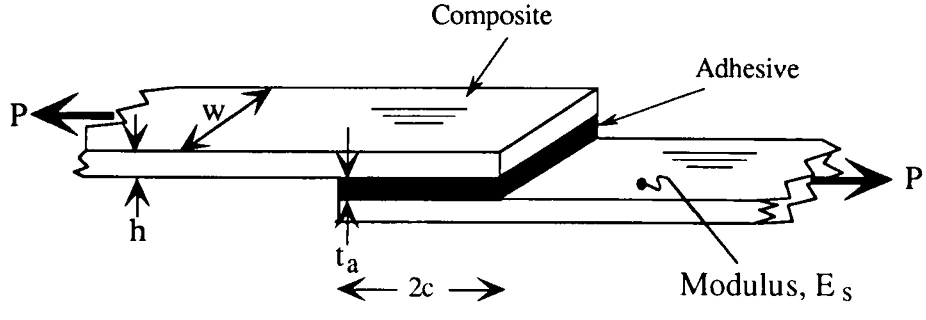

FIGURE 2 The single-overlap joint loaded in tension.

where the bending moment factor, K, is given by:[12]

$$K=\frac{1}{1+\epsilon c} \tag{10}$$

where

$$\epsilon=\left(\frac{T}{X}\right)^{1/2} \tag{11}$$

and where E_s, h and ν are the modulus, thickness and Poisson's ratio of the substrate material, c is one-half of the bonded overlap length and T is the load per unit width applied to the lap joint.

Now, Williams[13] has proposed a very powerful method for deducing the strain-energy release-rate acting in a cracked beam from a knowledge of the bending moments at the crack tip. For symmetrical loading, the mode I strain-energy release-rate, G, is given by:

$$G=\frac{12M_e^2}{B^2E_sh^3} \tag{12}$$

Combining equations (9), (10) and (12), then the value of G_{max} may be expressed by:

$$G_{max}=\frac{12}{E_sh^3}\left(\frac{T_{max}(h+t_a)}{2}\right)^2\left(\frac{1}{(1+\epsilon c)^2}\right) \tag{13}$$

where T_{max} is the maximum applied load per unit width during a fatigue cycle.

If it is assumed that a crack grows through the adhesive layer in the single lap joint in a plane parallel to the loading direction, then the growth of the crack by a length, a, from either end will change the effective overlap length from 2c to (2c − 2a). Thus, equation (13) will become:

$$G_{max}=\frac{12}{E_sh^3}\left(\frac{T_{max}(h+t_a)}{2}\right)^2\left(\frac{1}{(1+\epsilon[c-a])^2}\right) \tag{14}$$

2.3.3 Number of fatigue cycles, N_f, for failure The number of cycles to failure, N_f, of the single lap joint subjected to cyclic loading may be estimated by combining equations (6) and (14), to eliminate G_{max}, and then by integrating between the limits of the initial flaw size, a_o, and the crack length, a_f, at which rapid fracture of the joint occurs, This gives:

$$N_f=\int_{a_o}^{a_f}\frac{DG_c^{n_2}[E_sh^3(1+\epsilon[c-a])^2]^{n-n_2}}{[3(T_{max}\{h+t_a\})^2]^{n-n_1}}\cdot\frac{[G_cE_sh^3(1+\epsilon[c-a])^2-(3(T_{max}\{h+t_a\})^2]^{n_2}}{[3(T_{max}\{h+t_a\})^2-G_{th}E_sh^3(1+\epsilon[c-a])^2]^{n_1}}\cdot da \tag{15}$$

In this equation the values of the fracture mechanics parameters (*i.e.* D, n, n_1, n_2, G_{th} and G_c) may be deduced from the fatigue data obtained from the fracture mechanics specimens. Further, the geometry of the single lap joint, whose fatigue behaviour is to be predicted, is known; so the values of the parameters ϵ, h, t_a and c are known, as is the modulus, E_s, of the substrate materials forming the lap joint.

So, if the values of the integration limits could be identified, then the number of cycles to failure, N_f, of the single lap joint may be predicted as a function of the maximum load per unit width, T_{max}, of the joint applied during a fatigue cycle.

The integration limits, a_o and a_f, represent the initial (Griffith) flaw size and the length of the fatigue crack when fast fracture occurs, respectively. The value of a_o may be readily deduced from the Griffith equation:

$$a_o = \frac{E_a G_c}{\pi \sigma_a^2} \tag{16}$$

where σ_a is the tensile strength of the adhesive. The length of the fatigue crack when fast, catastrophic, failure results may be determined by re-arranging equation (14) and letting $G_{max} = G_c$. Hence:

$$a_f = c - \left(\frac{\left(\frac{3(T_{max}[h + t_a])^2}{E_s h^3 G_c} \right)^{1/2} - 1}{\epsilon} \right) \tag{17}$$

where, obviously, $a_f \leq c$.

3. EXPERIMENTAL

3.1 Materials and Joint Preparation

The adhesive employed was a hot-cured epoxy-film adhesive ("FM73M," supplied by Cyanamid, USA). The fibre-composite substrates consisted of an epoxy-based unidirectional carbon-fibre material ("913C XAS-5-47," supplied by Ciba Giegy, UK). Prior to joint preparation the fibre-composite substrates were lightly abraded and then degreased using methylethyl ketone. The axial modulus, E_s, of the composite substrate was measured, and was 126 GPa, and its Poisson's ratio, ν, was taken to be 0.4.

Double-cantilever beam (DCB) test specimens, schematically shown in Figure 1, were prepared. The width of the test specimen was 25 mm and the length was about 150 mm. The nominal thickness of the fibre-composites substrates was 6.0 mm. The DCB joints were prepared by placing a rectangular length of the film adhesive onto each strip of fibre-composite and then laying a release-coated aluminium foil, about 50 mm in length, between the adhesive films before bringing the adhesive films into contact. The assembled joint was then heated from room temperature to 120°C over a period of about 30 minutes. A pressure of 28 kPa was then applied to the joint and it was heated at 120±3°C for 60 minutes to cure the adhesive. The thickness of the adhesive layer was typically about 0.4 mm. When the joint was cool, aluminium-alloy loading-blocks were bonded at the end of the DCB joint where the release-coated aluminium-alloy foil had been placed. These were bonded onto the fibre-composite substrates using a cold-cured epoxy-paste adhesive ("Permabond E38" from Permabond, UK). To help monitor the position of the crack front, the side of the specimen was painted using typewriter correction fluid, and marked at 5 mm intervals. It was important to apply only a thin coating, so that the crack length recorded was the actual crack length in the specimen, and was not simply the cracking of the correction fluid either ahead or behind the actual crack tip.

Single-lap joints, to be tested in tension, were also prepared using the same grades of fibre-composite substrate and epoxy-film adhesive. The same preparation conditions were employed as for the DCB joints, but in the single-lap joints no aluminium-foil starter-crack was used. The dimensions of the lap joint were in accordance with ASTM 1002[14] and typically three specimen replicates were employed for each test. The thickness of the substrates was 1.5 mm, the width was 25.4 mm and the bonded overlap length was 12.7 mm. The thickness of the adhesive layer, t_a, was typically about 0.4 mm. The tensile modulus, E_a, of the adhesive was 2.45 GPa and its uniaxial tensile strength, σ_a, was 63.5 MPa.

3.2 Constant Rate of Displacement Tests

Tests were conducted at a constant rate of displacement of the crosshead of the tensile testing machine in order to ascertain the value of the adhesive fracture energy, G_c, of the adhesive and the static failure load of the single-lap joints. The rate of displacement used for the DCB test specimens was 2.0 mm/min and for the single-lap joints was 0.5 mm/min.

3.3 Cyclic Fatigue Tests

3.3.1 Fracture mechanics tests The DCB test specimen was used to obtain the values of da/dN as a function of G_{max} and a sine-wave form of loading was employed at a frequency of 5 Hz. The displacement ratio ($\delta_{ratio} = \delta_{min}/\delta_{max}$) was 0.5 and the mean displacement was 1.5 mm. The test temperature was 23°C.

The method employed for obtaining values of the crack growth rate per cycle, da/dN, was that described as the "incremental polynomial method" in ASTM E647-88.[15] Several methods were investigated[16] for deducing the value of da/dN associated with a given crack length from the experimental measurements of crack length, a, *versus* number of cycles, N. The "incremental polynomial method" was found to be the most accurate, and the one that gave the lowest scatter. The value of G_{max} was determined using equation (4).

3.3.2 Single-lap joint tests The single-lap joints were also subjected to a sine-wave form of loading at a frequency of 5 Hz. The load ratio was 0.5 and the test temperature was 23°C. The number, N_f, of cycles needed for the lap joint to fracture was measured as a function of the maximum applied load per unit width, T_{max}, imposed on the lap joints in each cycle.

4. RESULTS AND DISCUSSION

4.1 Value of G_c of the Adhesive

The adhesive fracture energy, G_c, as a function of the length of the propagating crack is shown in Figure 3. The crack propagated cohesively through the adhesive

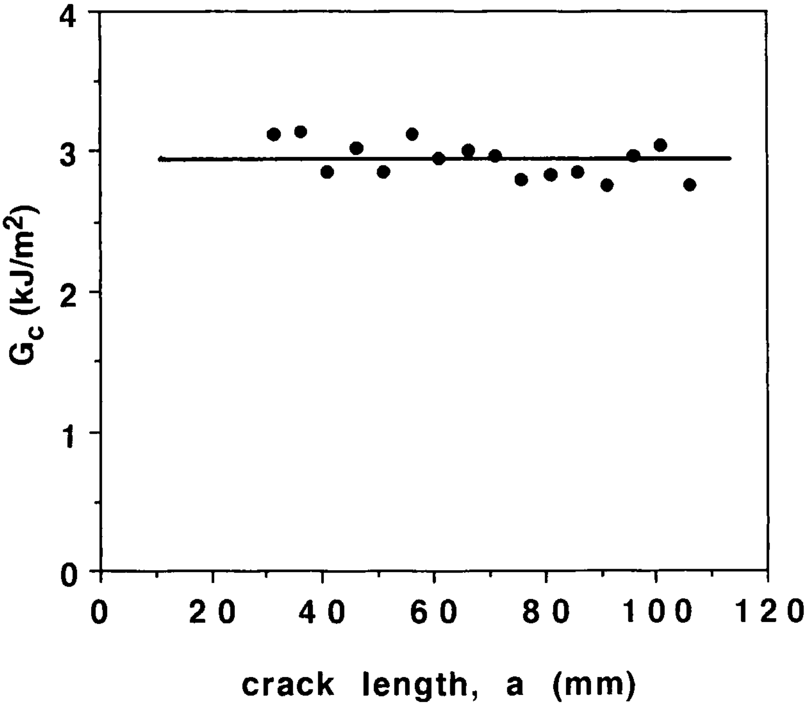

FIGURE 3 The adhesive fracture energy, G_c, as a function of the length of the propagating crack. Data are from a static test.

layer in a stable manner, and there is no dependence of the value of G_c upon the length of the propagating crack, *i.e.* no "R-curve" is observed for this adhesive. The value of G_c is 2.93 kJ/m^2.

4.2 Fatigue Data from the DCB Tests

As was observed for the static tests, during the fatigue tests the crack propagated cohesively through the adhesive layer. The graph of da/dN *versus* G_{max}, where the value of G_{max} was determined using equation (4), is shown in Figure 4. The fatigue data, taken together with the value of G_c, reveal a curve which is sigmoidal in shape with three clearly distinguishable regions: "region I," which is a threshold region and which is associated with very low values of da/dN and G_{max}; "region II," which is the linear portion; and "region III," where the value of G_{max} approaches that of G_c. The presence of a threshold, below which no significant fatigue crack growth occurs, is clearly visible. Indeed, the data in this "region I" part of the curve show that the values for fatigue crack growth rate, da/dN, are less than 10^{-10} m/cycle and this meets the ASTM[15] requirement for the value of da/dN to be considered to be negligible. The value of G_{th} is 0.28 kJ/m^2. It should be noted that this value of G_{th} is an order of magnitude lower than the adhesive fracture energy, G_c, measured under static test conditions.

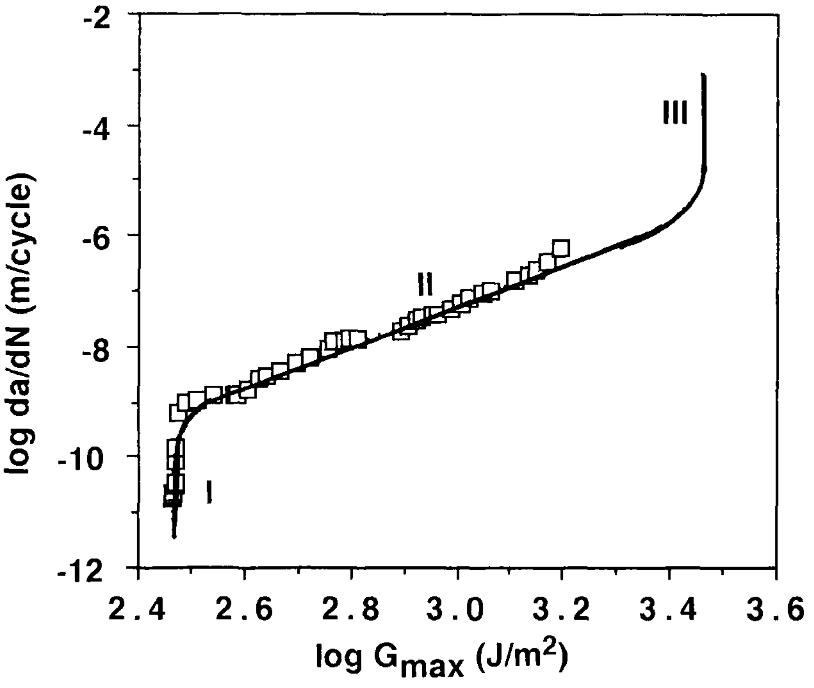

FIGURE 4 Fatigue crack growth data obtained using the DCB test where da/dN is plotted *versus* G_{max}. The solid line is from equation (6), using the values of the parameters given in Table I.

4.3 Single-Lap Joint Studies

The strength of the single-lap joints was determined at a constant displacement rate of 0.5 mm/min. The measured (static) strength was 9.75 ± 0.25 kN, and the joints failed by fracture through the adhesive layer.

The experimental fatigue results are shown in Figure 5, and in these studies the number, N_f, of cycles needed for the lap joint to fracture was measured as a function of the maximum load per unit width, T_{max}, imposed on the joint during the fatigue cycle. Again the locus of joint failure was by crack growth through the adhesive layer.

4.4 Life-Predictions

As was mentioned previously, the fatigue data from the fracture mechanics tests, shown in Figure 4, consists of three regions, and the general shape of the curve can be described by equation (6). The values of the various parameters which are needed in equation (6) are given in Table I. To obtain these values, the values of G_c and G_{th} were taken directly from Figures 3 and 4. The values of D and n were deduced by fitting equation (5) to the experimental data for the linear "region II" part of the fatigue curve shown in Figure 4. In the present study this linear region extends from da/dN values from about 10^{-5} to 10^{-9} m/cycle. Finally, using these

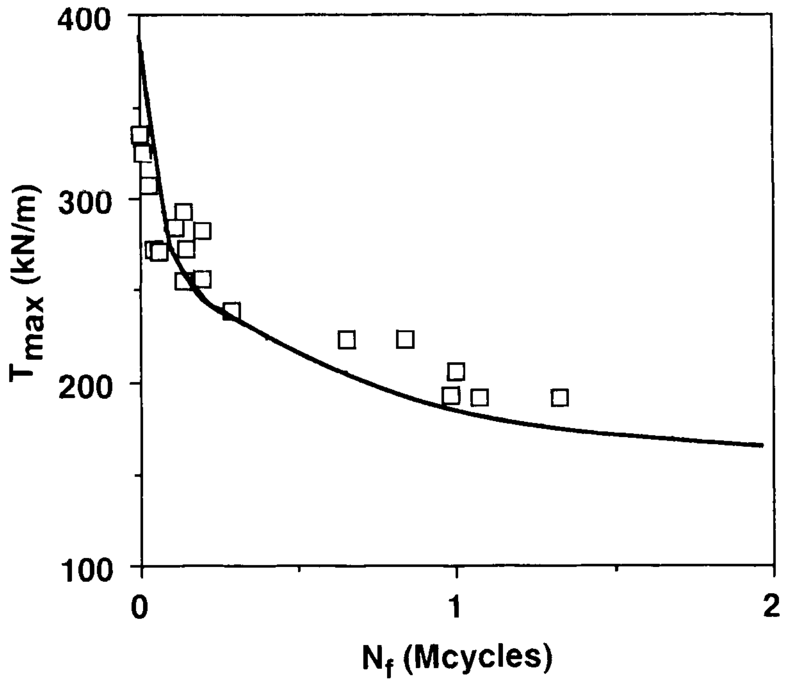

FIGURE 5 Experimental values of the maximum load per unit width, T_{max}, applied during a fatigue cycle *versus* the number, N_f, of cycles to failure for the single-overlap joints. The solid line shows the theoretical predictions from using equation (15).

values of G_{th}, G_c, D and n, the values of n_1 and n_2 were obtained by fitting equation (6) to all the experimental values of da/dN *versus* G_{max} shown in Figure 4. The fit of equation (6), using the values given in Table I, is shown in Figure 4. As may be seen, equation (6) yields an excellent representation of the fatigue data.

In order to predict the fatigue properties of the single-lap joints, equation (15) may be integrated numerically, using Simpson's rule, to determine the number, N_f, of cycles to failure as a function of the maximum applied load per unit width, T_{max}, during the fatigue cycle. All the values of the various parameters needed in equation (15) are now known, and the integration limits, a_o and a_f, may be determined using equations (16) and (17).

The theoretical predictions of T_{max} *versus* N_f are shown in Figure 5, together with

TABLE I
Values of the parameters in equation (6) needed to describe the fatigue data shown in Figure 4

G_{th} (J/m^2)	G_c (J/m^2)	D	n	n_1	n_2
280	2930	1.903×10^{-18}	3.59	10	10

(Note: values for D and n are given for when G_{max} is in J/m^2 and da/dN is in m/cycle.)

the experimental results for the fatigue behaviour of the single-lap joint. As may be seen, the agreement between the theoretical predictions and the experimental results is excellent.

Equation (15) may obviously be used to predict the effects of changing the geometry of the single-lap joint on the fatigue behaviour of the joint. For example, the effect of changing the length, 2c, of the bonded overlap on the fatigue behaviour may be analysed. The influence of the length of the bonded overlap on the predicted fatigue behaviour is shown in Figure 6. As may be seen, it is predicted that increasing the length of the bonded overlap will improve the fatigue resistance of the bonded joint. Indeed, Althof[17] has reported the effect of overlap length on the fatigue behaviour of single-lap joints which consisted of stainless-steel substrates bonded using an epoxy-phenolic adhesive. His experimental results follow a very similar pattern to the predictions shown in Figure 6.

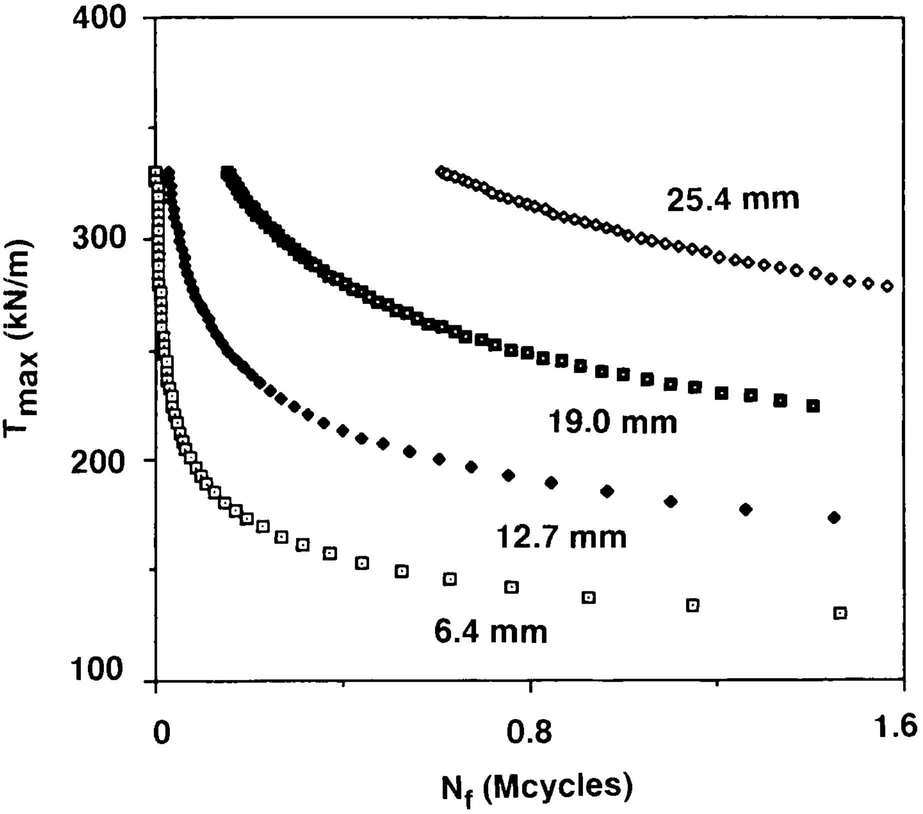

FIGURE 6 Theoretical predictions of the maximum load per unit width, T_{max}, applied during a fatigue cycle *versus* the number, N_f, of cycles to failure for single-overlap joints prepared with various lengths of bonded overlap.

5. CONCLUSIONS

The fatigue behaviour of adhesively-bonded joints has been studied. The joints consisted of an epoxy-film adhesive bonding together unidirectional carbon-fibre/epoxy composites. Using a double-cantilever beam (DCB) specimen, the rate of crack growth per cycle, da/dN, has been measured as a function of the maximum strain-energy release rate, G_{max}, imposed in a fatigue cycle. The results show that there does exist a threshold value, G_{th}, below which no significant fatigue crack growth will occur. The value of G_{th} is 0.28 kJ/m^2, and this value of G_{th} is about an order of magnitude lower than the adhesive fracture energy, G_c, measured under static test conditions. Obviously, one could employ the value of G_{th} as a very conservative design parameter and estimate the maximum fatigue loads which could be imposed on a structure without causing fatigue crack growth.

However, in the present work, the complete da/dN *versus* G_{max} relationship has been described by an empirical equation and the data then used to predict the fatigue lifetime of bonded single-lap joints. The predictive model developed assumes that the fatigue lifetime of the single-lap joints is governed by the growth of a fatigue crack which eventually reaches a critical length when rapid, catastrophic failure of the lap joint occurs. The agreement between the theoretical predictions and experimental results for the fatigue lifetime of the single-lap joints is excellent.

Therefore, the present work has demonstrated that it is possible to predict the long-term fatigue behaviour of common, and industrially important, designs of adhesive joints from relatively short-term fracture-mechanics tests.

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