FATIGUE CRACK GROWTH IN A GLASS FIBRE REINFORCED PLASTIC

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ABSTRACT

Low cycle fatigue crack growth tests under constant load were carried out on centre-notched specimens in order to measure the influence of load biaxiality in air and also in a 5% sulphuric acid. The effect of biaxiality on the crack growth rate and on the toughness K is of considerable interest. In the present tests the Paris law relationship $da/dN = const. \Delta K^m$ was found to be applicable in the region II; however, some differences observed in the values of the exponent m will require further study as the available results indicate a decrease of m with increasing biaxiality. A further reduction in the propagation rate was noted in similar tests carried out in an acidic environment. The fracture surface morphology in the acidic tests was found to be very different from the laminates fractured in air which showed an extensive pull-out. A similar difference was observed in biaxial fatigue tests where the surface was very smooth with glass fibres fractured cleanly and at the level of the crack plane. A compliance calibration and the Moire fringe technique were used to determine the effective crack length so as to overcome difficulties connected with visual measurement and to present the fatigue results on a fracture mechanics basis when using conventional stress intensity factors.

KEYWORDS

Biaxial fatigue, glass reinforced plastics, environmental crack growth.

INTRODUCTION

A detailed understanding of the deformation process at the crack tip is one of the basic requirements for the prediction of fatigue crack propagation. It is known that plastic deformation occurring in the vicinity of a fatigue crack tip may form a field of high residual stresses, reversed plasticity and may also frequently cause crack tip renucleation or closure. These concepts are familiar factors in yielding fracture mechanics and also in metallurgical considerations.

Real materials do not exhibit linear elastic behaviour near the tip of a flaw. A plastic zone develops at the crack tip to accommodate the crack tip opening. This form of yielding at the crack tip, for example plastic flow in metals, has the function of partially relaxing the high local stresses and partially absorbing the fracture energy. The glass reinforced plastic material investigated in the present work showed a small capacity for plastic flow, and the yielding at the crack tip was observed to take the form of a damage zone. This damage zone is a region of crack growth extending from the tips of a precut centre notch and consisting of sub-critical secondary cracks orientated along the interface between glass fibres and matrix all around the main crack. This makes the direct measurement of crack length very difficult because it is not always clear whether the aligned fibres within the damage zone have either broken or pulled out, or where the crack tip can be located within the thickness of the specimen. Thus substantial variations in the physical crack length may be recorded.

Two methods were used for making crack measurements; one, compliance; and the other a moire fringe technique to circumvent difficulties observed in the direct measurement of crack lengths in composite materials. A compliance technique has been developed to determine an equivalent crack length which includes a plastic zone correction, using expressions derived from fracture mechanics. The moire fringe method provides a precise location of the crack tip so that an accurate crack length measurement can be made. No plastic zone correction was made for the moire technique as plastic flow ahead of the crack tip would have been observed as distortion in the fringe pattern.

EXPERIMENTAL PROCEDURE

The cruciform specimens of 3.5 mm nominal thickness (1), were individually moulded, the polyester laminates being impregnated with a powder bound E-glass fibre in a chopped strand mat reinforcement configuration. A horizontal testing machine of an electro-hydraulic type (2), cycling from zero to a maximum load amplitude of 30 kN at a cyclic frequency range of 0.1 to 1 Hz, was used to perform the fatigue tests.

Fatigue tests were carried out at a constant load range ΔP and biaxiality factor B until fracture in two different environments, air at 20°C and 50% relative humidity, and 5% sulphuric acid solution at 20°C, for B = 0 and 1 in each environment. The stress ratio equivalent to K_{min}/K_{max} and the constant load range rate dP/dt was maintained at 0.1 and 5 kN/sec. The cyclic frequency f was related to the load range rate by f = 2.5/dP Hz. For the acidic environment fatigue tests a chamber was constructed using a rubber 'O' ring and polyethylene terephthalate film sealed together with silicone rubber to both sides of the specimen. The compliance method was used to determine the effective crack length, 2a, in relation to the biaxial CN specimen compliance. Calibration curves for biaxiality ratios B = 0, 1 and 2 are shown in Fig. 1, where the compliance, ϕ, is defined as the result of crack opening displacement multiplied by specimen thickness and divided by a corresponding load increment. The crack length was calculated and plotted as a function of the number of cycles, N, from which the crack growth rate was determined by graphical differentiation.

The plastic zone at the crack tip was originally developed by Irwin for conditions of plane stress having a radius (a length) $r = K_I^2/2\pi\sigma_{ys}^2$. The stress, σ_{ys} = 52.7 MPa, is the off-set stress obtained from the stress-strain curve of the composite material, and corresponds to the stress at which the resin cracking becomes a maximum. The modified half crack length $a_m = a + r$ was plotted against the number of cycles, N, and subsequently used in further calculations of da/dN and ΔK. An example of the plot of the crack length vs. cycles is shown in Fig. 2.

For the moire fringe method orthogonal gratings of 500 lines per inch were used, in the form of a film deposited on an acetate base. The gratings were cut to an appropriate size and then attached to the specimen. A second grating of the same pitch was superimposed on the fixed grating producing an interference pattern due to the misalignment of the gratings. During a fatigue test the development of a crack disrupts the fringe patterns causing local kinks because displacement is not single valued at the crack tip. Location of the crack tip using moire fringes and the grid attached to the specimen surface below the crack line, Fig. 3, was judged to be accurate to ±0.1 mm or better. Fracture mechanics concepts were applied in analysing the crack propagation data obtained from the fatigue tests in the usual way (3).

RESULTS AND DISCUSSION

In these constant load fatigue tests a cyclic plastic zone was created ahead of the crack tip. The boundary of this zone is usually expressed as a function of the angle Θ and the length r_c, which is the radial distance from the crack tip,

$$r_c^{\Theta} = \alpha^{\Theta} \left(\frac{K_{max}}{\sigma_{cy}}\right)^2 \qquad \text{..... (1)}$$

where σ_{cy} is the cyclic yield stress, which depends in particular on the environment and strain rate. As the yield stress usually increases with strain rate, the size of the plastic zone will decrease accordingly. Theoretically, the cyclic plastic zone will be a quarter of the monotonic plastic zone, as discussed in (4). Because the composite investigated here did not exhibit a sudden yield point, the off-set yield stress was used for the calculation of the corrected crack length.

The plastically deformed material, Fig. 4, was surrounded by the elastic field, where the stress and strain are proportional to $\frac{1}{\sqrt{r}}$. It can be divided into three zones:

(1) a monotonic plastic zone, experiencing low strain cycles of ε_p less than 10^{-3},

(2) a cyclic plastic zone, nearer to the fatigue crack tip, subjected to a higher strain of 10^{-1},

(3) an intensely deformed process zone, subjected to a very high strain of the order of 10^0 at the tip of the crack, where the fracture took place. Fig. 4 shows the crack directly extending from the crack tip opening CTOD. The strain, proportional to $\frac{1}{r}$, is accommodated in local slip bands. The blunting of the crack tip, proportional to $K^2/\sigma_{cy}E$, leads firstly to the formation of local intense slip bands and secondly to the extension of the crack at each consecutive cycle. At the same time secondary cracks form parallel with the main crack, but mostly in the surface layer. This discontinuous movement of the crack tip at each cycle corresponds to the formation of striations as observed on the fracture surface in the region II of the crack propagation curve. The one-to-one correspondence with the fatigue

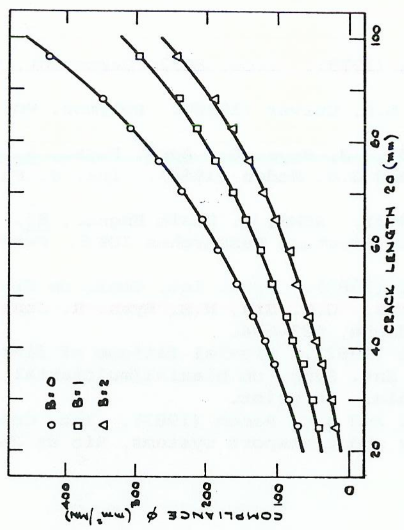

Fig. 1 Compliance calibration curves

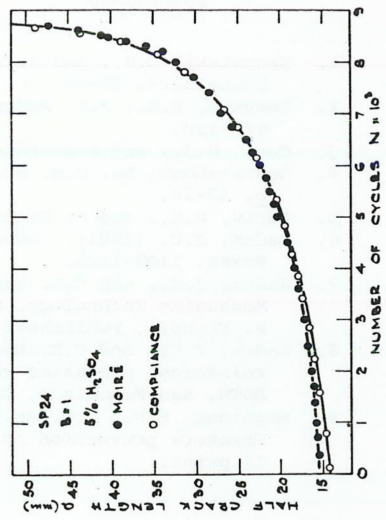

Fig. 2 Crack growth for B = 1 in acid

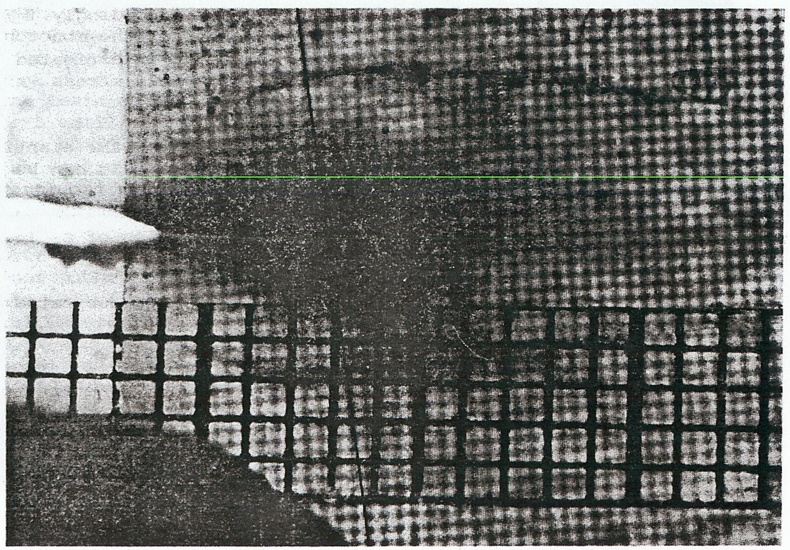

Fig. 3 Moire fringe pattern for B = 1 in acid. Millimetre scale.

striations does not take place in the region I. A gradual transition between these two regions was observed at the K_{max} values of 2.8 MPa $m^{\frac{1}{2}}$ for the biaxiality B equal to 0 and less than 2.2 for B = 1.

The fatigue crack growth in region II is usually expressed in the form of a da/dN versus ΔK curve using the Paris relationship (5),

$$\frac{da}{dN} = C\ (\Delta K)^m \quad \ldots\ldots (2)$$

The constants C and m are determined from constant crack growth data of specimens cycled at a constant load range in steady state fatigue growth. The fatigue cycle was here described by $\Delta K = (K_{max} - K_{min})$; K_{max} and K_{min} represented the opening mode stress intensity factors calculated from the maximum and minimum stresses measured during the fatigue cycle for an appropriate stress ratio R. Because of the experimental limitations (2) it was advisable not to use a value of K_{min} below 10% of K_{max}. It is interesting to note that for this GRP material the values of the exponent m were much higher than expected. In all the tests performed in air the value of m was 15 for B = 0 and decreased only slightly with increasing biaxiality (7). In the acidic environment this value changed to 5. It is well known from the literature that the respective values for metals are of the order of 2 to 4 and for polymers 3 to 8 (6).

The environmental fatigue crack growth results under biaxial stress B equal to 0 and 1 are shown in Figs. 5 and 6, and analysis of the data shows a unique relationship existing between da/dN and ΔK for the two tests in air and in the acidic environment. The results also show fairly good agreement between moire and compliance data for the conditions tested.

The analysis of the fatigue data has been discussed elsewhere in terms of enviromental (7) and biaxiality (8) effects. The appearance of the fracture surfaces of the specimens from the dilute acid and air tests were found to be different; those tested in air displayed significant fibre pull-out over the whole surface whereas the surface of the slow crack growth region of specimens fatigued in the acid environment showed little sign of fibre pull-out, giving a glassy appearance to the fracture surface. This lack of fibre pull-out is attributed to chemical attack of the fibres by acid, in conjunction with the mechanically applied cyclic stress, causing the fibres to fail along their length and effectively eliminating their reinforcing properties.

The damage zone in the context of this paper represents the crack and the debonded fibres around it, the consequence of environmental fatigue is the reduction in volume of that damage zone. The energy that would have been dissipated in the fibre pull-out mechanism was channelled into propagating the crack even further. The difference in crack growth data for acid and air tests is shown dramatically in Figs. 5 and 6, for comparative crack growth rates there is a reduction by a factor of two in the applied stress cycle, for the acid tests with a corresponding reduction in the volume of the damage zone.

The trajectories of fatigue cracks, particularly those in the region II, were reasonably straight. However, they showed a large amount of bifurcation and debris, the volume of which increased with the decreasing stress intensities. The degree of debonding appeared to be larger in air for all types of dynamic fractures, followed by an extensive pull-out of fibres. On the other hand, in the acidic environment the amount of debonding was much smaller and this was due to a large reduction in fibre strength. The crack initiated on the surface of the fibre immediately after the protective layer of PVA was leached away. Subsequently the crack propagated in the transverse direction of the fibre under the action of pure corrosive fatigue. With increasing ΔK the crack growth rate increased very slowly and it is expected that the growth rate in the region III would not differ greatly from that in air. A similar relative decrease in the rate was observed with increasing biaxiality B, Figs. 5 and 6. However, tests at much lower ΔK values are needed in order to evaluate the influence of environment on the fatigue behaviour of GRP. In the parallel fatigue tests on a low-alloy steel in NaCl solution (9) the crack growth rate decreased below that observed in a laboratory air environment at very low values of ΔK, thus showing that other factors, apart from the environmental attack may play an important role under cyclic loading.

The tests in an air environment so far completed, suggest that the Paris's regime (region II) begins at ΔK equal to 4.5 MPa $m^{\frac{1}{2}}$ and slightly lower for increasing biaxiality B. However, the results obtained in the acidic environment show much lower values, such as 2.5 MPa $m^{\frac{1}{2}}$ or less. This premature fibre damage indicates that the acidic environment enables an early initiation of numerous microcracks with a consequent decrease in fibre strength and cyclic life.

The interesting difference between the two methods of crack measurement is the discrepancy in the magnitude of the crack length. The underestimation of crack length by the compliance technique can be partly explained by the mechanisms of fibre bridging and fibre pull-out, thus holding the crack faces together, reducing the compliance, and therefore the crack length. However, the biaxiality effect is not explained unless stress biaxiality reduces the plastic zone size, on the assumption that the applied biaxial stresses simply modify the uniaxial yield strength of the composite.

CONCLUSIONS

Low cycle biaxial fatigue of GRP in chemical environments is of considerable interest in structural engineering. The following conclusions were arrived at:

(1) The crack growth rate was investigated in air and acidic environments using two different methods of crack measurement. Despite the variation in crack length magnitude between the moire and compliance methods, the fatigue crack growth data showed good agreement.

(2) A very high value of the exponent m = 15 in the Paris's crack growth law da/dN = const. ΔK^m suggests a fast crack propagation in air.

(3) However, relative to the results in air, a much slower crack propagation was observed in the 5% H_2SO_4 environment, where the exponent m decreased to 5.

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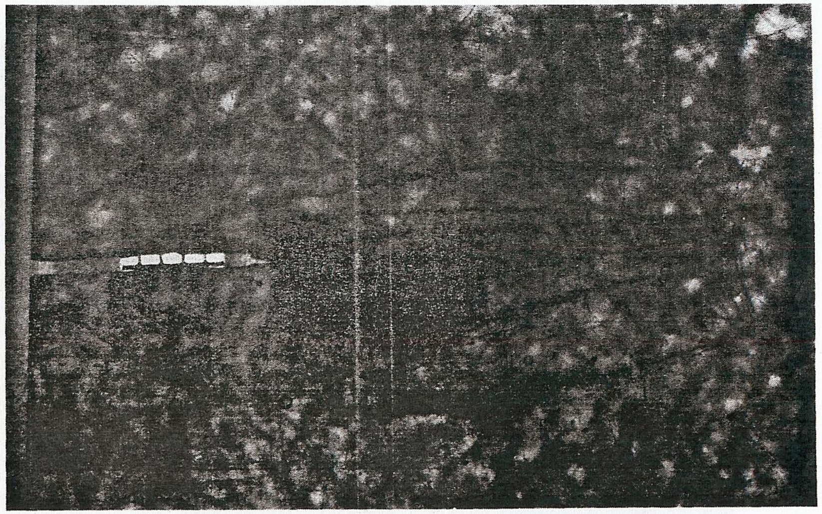

Fig. 4 Damage zone

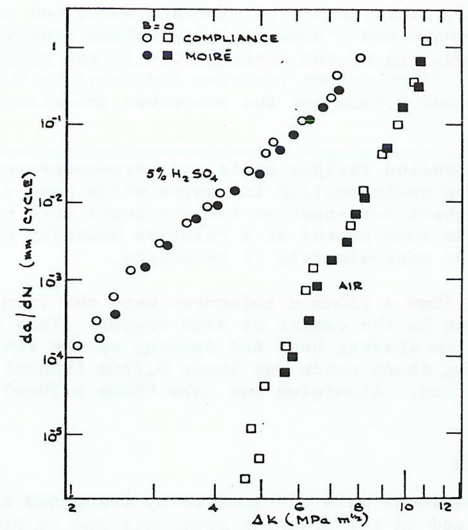

Fig. 5   da/dN vs. ΔK   for B = O

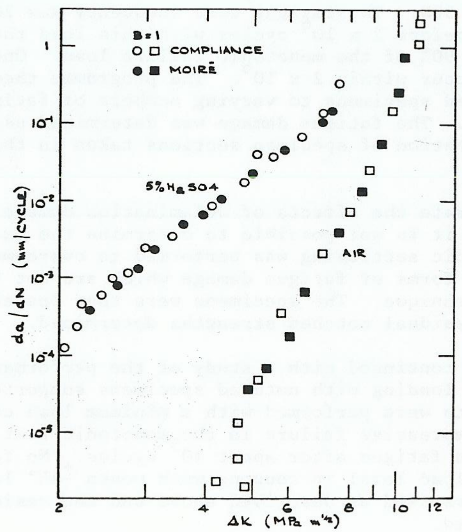

Fig. 6   da/dN vs. ΔK   for B = 1