THE USE OF THE PLASTIC CRACK TIP OPENING DISPLACEMENT TO CORRELATE FATIGUE CRACK GROWTH DATA FOR A STRUCTURAL STEEL

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ABSTRACT

A study has been conducted, on a low alloy steel, HY80, to show whether the crack tip opening displacement, δ, can be used to correlate the fatigue crack growth rate over a wide range of stress (strain) amplitudes. The results of this study have shown that the growth rate expression of the following form can be used for both COD and load control $\frac{da}{dN} = C\,\delta^n$

KEYWORDS

Crack growth, C.O.D. control, high strain fatigue crack growth.

INTRODUCTION

Large structures sometimes experience varying stresses in service of sufficient magnitude to cause fatigue damage. Provided these stresses are below a certain level linear elastic fracture mechanics can be used to estimate the fatigue life of the structure. However if the plastic zone at the tip of a crack is not small compared to the crack length, and general dimensions of the body, one cannot use LEFM. In this sort of situation the stress intensity factor range (ΔK) does not characterise the fatigue damage occurring at the crack tip. It has already been shown (1) that it is possible to correlate fatigue crack growth data under these elasto-plastic conditions using the crack tip opening displacement (δ). This offers the advantage over other possible parameters that it can be linked with the crack growth rate under either environmentally passive or aggressive conditions (2).

Several possibilities are available for providing test data in terms of crack tip opening displacement. One can test under load cycling conditions and either measure δ or interpret from measured load values. Alternatively one can test under clip gauge control conditions and measure δ or interpret from a prior calibration. For mainly elastic loading it is easier to monitor force, for elasto-plastic cycling it is easier to control the dispalcement. In the present work tests have been conducted using both forms of control.

These tests have been on a low alloy structural steel and have been correlated in terms of δ_p the plastic part of the crack tip opening displacement.

EXPERIMENTAL DETAILS

The material used in this investigation was Q1(N), a low alloy medium strength steel, with the mechanical properties and chemical composition shown in Tables 1 and 2. Specimens were edge notched bars 900mm long by 100mm wide by 37mm thick. These specimens were tested in a four point bending rig capable of fully reversed loading (± 30 KN). The rollers were positioned so that the major span was 861mm and the minor span 205mm. Chevron starter notches were machined into the specimens to ensure that fatigue cracks started quickly and the shape of the subsequent crack fronts were symmetrical. At the mouth of these chevron notches, integral knife edges were machined in order to provide positive and accurate location of a double cantilever beam clip gauge which was specially constructed for these tests. The crack opening displacement was measured at an intermediate point between the mouth of the notch and the tip of the crack using a Novatech LVDT (Linear Variable Differential Transformer) type R406. The LVDT was mounted in a small aluminium block which was secured to the specimen using a cyanoacrylate adhesive. A second aluminium block was fixed opposite the first, but on the far side of the crack. The spring loaded centre section of the LVDT then rested against the second block. Measurement of crack length was by means of a low power travelling microscope with a magnification factor of approximately twenty. Recordings of load versus clip gauge output were made frequently during all the tests on a Hewlett-Packard X-Y recorder type 7044A. Prior to the high strain fatigue crack growth tests all the initial cracking was conducted at a relatively low value of applied stress to ensure a regular crack front across the specimen. Details of the two high strain fatigue crack growth tests and the single stress cycling test are shown in Table 3.

RESULTS

Stress Cycling Results

Test A (see Table 3) was carried out under conditions of constant load cycling. The testing frequency used was predominantly 3 Hz but as the crack growth rate increased rapidly the frequency was reduced to 1 Hz, then 0.3 Hz and finally 0.1 Hz. The crack growth curve for this test is shown in Fig 1. Values of crack growth rate were deduced from the results shown in Fig 1 by means of a secant technique. Calculations of the stress intensity factor range (ΔK) were made using the boundary collocation results of Srawley and Gross (3) for conditions of pure bending applied to the specimen. No account of crack front curvature was taken in calculating these results since no continuous measure of this effect was available. The plot of log (da/dN) versus log (ΔK) is shown in Fig 2.

Clip Gauge Cycling Results

The crack growth curves for Tests B and C are shown in Fig 3. These two tests were conducted under clip gauge opening control, the details of which are given in Table 3. The frequency of cycling was 0.1 Hz throughout these tests. During Test B the amplitude of the clip gauge opening was increased twice in order to obtain more data in the very high growth rate regime. In Test C the amplitude of the clip gauge opening was kept constant so that the crack growth rate would decrease until it reached a value equal to the maximum found during constant load cycling (Test A). For Tests B and C the plots of clip gauge versus LVDT output were not linear during a cycle, but formed a narrow hysteresis loop. When the plastic crack tip opening was large, this effect was at a maximum. At the very smallest values of δ the hysteresis effect was indiscernible. As a first approximation hysteresis effects were ignored and a rotational factor was calculated using the change in LVDT output between the zero and maximum values of clip gauge displacement on the tensile loading part of each cycle. The equation used to calculate the rotational factors was as follows:

$$r = \frac{a(B-A) + Ax}{(A-B)\ (W-a)} \tag{1}$$

where A = clip gauge opening between zero and maximum values on the tensile part of each cycle

B = LVDT displacement between zero and maximum values of clip gauge opening

x = distance of LVDT from mouth of notch

a = crack length

W = specimen width

During cycling values of plastic clip gauge displacement, V_p, (i.e. the residual clip gauge opening after the tensile part of the cycle) were recorded. These values of V_p were then used along with values of r to calculate δ_p at various stages in the test, by means of the following equation:

$$\delta_p = \frac{V_p}{1 + (a/r(W-a))} \tag{2}$$

Fig 4 shows a plot of δ_p versus r for Tests B and C. The results appear to fall into two groups, corresponding to the results for Test B or the results for Test C. The one point which belongs to Test B but falls in with the results for Test C was taken during the first part of Test B. This would be expected since the conditions for the first part of Test B were identical to those of Test C (see Table 3 for details). The difference between the two sets of results may be due to the fact that the loads experienced in Test C and the first part of Test B were less than limit load, whereas limit load was equalled and exceeded in the last two parts of Test B. Once limit load is exceeded plastic deformation reaches the far edge of the specimen and a plastic "hinge" is formed across the remaining ligament.

A log-log plot of crack growth rate versus crack tip opening displacement is shown in Fig 5. Also shown in this figure are the results of the stress cycling test interpreted in terms of δ_p by means of a theoretical relationship between δ_p and ΔK developed by Rice (4). The general relationship derived by Rice is as follows:

$$\delta_p = \tfrac{1}{4}(1-\nu^2)\sin^3\phi(1 + \cos\phi)\Delta K^2/E\tau_o \tag{3}$$

now if we use Von Mises criterion

$\sigma_y = \sqrt{3}\tau_o$ (where σ_y is the yield strength and τ_o the shear strength of the material)

Since we are dealing with cyclic crack growth it is necessary to replace σ_y with $2\sigma_y$ due to the reversed plastic zone created in the unloading part of the cycle. The slip band angle (ϕ) has been observed to be 45° in the case of fatigue crack growth in metals (5,6). Using this value of slip band angle at the crack tip, the above equation becomes

$$\delta_p = \frac{0.12\ \Delta K^2}{E\ \sigma_y} \tag{4}$$

A least squares fit to the points in Fig 5 yields the relationship

$$\frac{da}{dN} = 66.7\ (\delta_p)^{1.47} \tag{5}$$

It was observed during the clip gauge cycling tests that in many instances significant crack closure occurred during a cycle. This was inferred from the shape of the plots of clip gauge output versus force taken throughout these tests. The results as presented have not been modified to try and take account of the crack closure.

From examination of the fracture surfaces after the completion of the tests, the crack fronts at the centre of the specimens were seen to be as much as 5mm in advance of the crack length that was measured at the sides of the specimens. The crack lengths used to calculate δ_p and da/dN were those measured optically on the surface of the specimen.

DISCUSSION

Fatigue crack growth over four orders of magnitude appears to be well correlated using δ_p as the characterising parameter. Further, the theoretical formula derived by Rice (4) yields a good estimate of δ_p in the plane strain small scale yielding situation. Similar evidence, supporting the use of δ_p as a parameter capable of characterising fatigue crack growth, comes from the work of Dover (1). From stress cycling results on EN1 mild steel, Dover quotes the result:

$$\frac{da}{dN} = 2.36 \times 10^{-12} (\Delta K)^{3.3} \tag{6}$$

for

$$2.5 \times 10^{-9} \leq \frac{da}{dN} \leq 2.5 \times 10^{-7}\ \text{m/cycle}$$

In terms of the Rice equation the above equation becomes:

$$\frac{da}{dN} = 1.23 \times 10^{3} (\delta_p)^{1.65} \tag{7}$$

The result Dover quotes for clip gauge cycling of EN1 specimens

$$\frac{da}{dN} = 1.32 \times 10^{3} (\delta_p)^{1.72} \tag{8}$$

for

$$5.0 \times 10^{-5} \leq \frac{da}{dN} \leq 2.5 \times 10^{-3}\ \text{m/cycle}$$

Again it appears that stress cycling and clip gauge cycling results taken at grossly different crack growth rates can be correlated using δ_p as the characterising parameter. It should be noted that in Fig 5 the stress cycling data and clip gauge cycling data overlap at intermediate growth rates. For this region the data from both tests correlates well using δ_p. It would appear that the use of Eqs 2 and 4 to correlate the data is justified.

It has been suggested (7) that under non aggressive environmental conditions the upper limit to fatigue crack growth rate by a slip mechanism is $\delta/2$. This argument is purely on the grounds of geometrical considerations. At low crack growth rates $da/dN << \delta/2$, a possible explanation for this being given by Tomkins (2). As can be seen from Fig 5, the line representing the crack growth data for Q1(N) intersects with the line $da/dN = \delta/2$ at $\delta \simeq 3 \times 10^{-5}$, whilst for Dover's EN1 data this intersection occurs at $\delta \simeq 2 \times 10^{-5}$m. If the maximum possible crack growth rate by a slip mechanism is $\delta/2$, then growth rates greater than this must be attributed to some other mechanism of crack extension. Ductile crack tearing has been seen in these steels under non-cyclic test conditions (8,9), but this occurred at larger values of δ_p($\sim 2 \times 10^{-4}$m for EN1, $\sim 1.2 \times 10^{-4}$m for Q1(N)). Therefore it is possible that ductile crack tearing occurs at much lower values of δ_p under fatigue conditions, than under conditions of ¼ cycle to failure. Indeed one would not expect the conditions at the crack tip to be similar under fatigue and tensile only loading, since in fatigue crack growth, reversed plastic deformation occurs at the crack tip on each cycle.

The initiation of ductile tearing under fatigue conditions at lower values of δ_p than found with monotonic loading points out a danger that might have been overlooked previously. In service the fracture condition, eventually reached, often follows a fatigue crack growth period. It could be that in service fracture occurs at lower values of C.O.D. than those predicted from monotonic loading tests. Indeed the last few cycles prior to fracture could be crucial in determining the fracture conditions. It would also be of interest to see whether the initiation of tearing under C.A. cycling conditions differs from that under variable amplitude loading. Currently our understanding of the influence of load sequence on cracking modes is not extensive. It is hoped that further tests based on C.O.D. cycling will increase our understanding of these problems.

CONCLUSIONS

1. Crack tip opening displacement can be used to correlate fatigue crack growth under conditions of both large and small scale yielding at the crack tip.
2. The theoretical model proposed by Rice for predicting crack tip opening displacement under conditions of small scale yielding agrees well with experiment.

ACKNOWLEDGEMENT

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TABLE 1 Typical Composition of Q1(N)

Chemical	% by weight
C	0.15
Si	0.28
Mn	0.35
P	0.007
S	0.009
Ni	2.63
Cr	1.2
Mo	0.40

Table 2 Measured Mechanical Properties of Q1(N)

Plate orientation	Longitudinal
0.2% offset yield strength MNm^{-2}	633
U.T.S. Mnm^{-2}	743
Young's Modulus MNm^{-2}	1.96×10^{5}
Percentage elongation (50.8mm Gauge Length)	23%
Reduction of Area	71%

TABLE 3 Details of Fatigue Crack Propagation Tests

Test	Control Parameter	Control Limits	Test Frequency	Comments
A	Force	$+4.32 \times 10^{-3}$ MN 0.00 MN	0.1 → 3 Hz	Tension only stress cycling. Crack closure negligible.
B	Clip gauge opening	1.5×10^{-3}m 0.0m 2.5×10^{-3}m 0.0m 5.0×10^{-3}m 1.0×10^{-3}m	0.1 Hz	Test consisted of three parts, all under constant amplitude clip gauge cycling.
C	Clip gauge opening	1.5×10^{-3}m 0.0m	0.1 Hz	

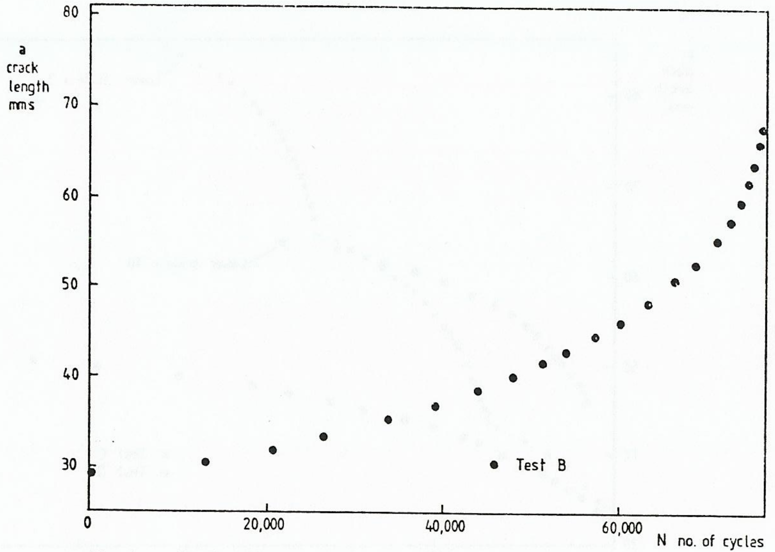

Fig. 1 Crack growth plots for test B Q1(N) - stress cycling

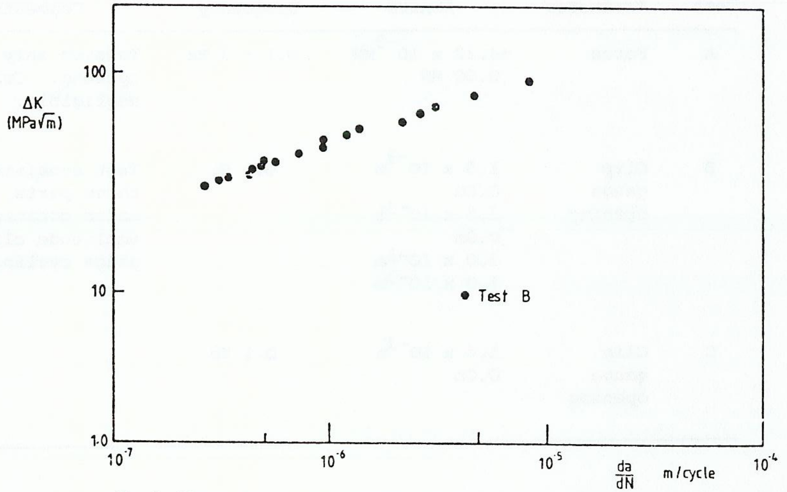

Fig. 2. Plot of ΔK against crack growth rate, Q1(N) - strss cycling

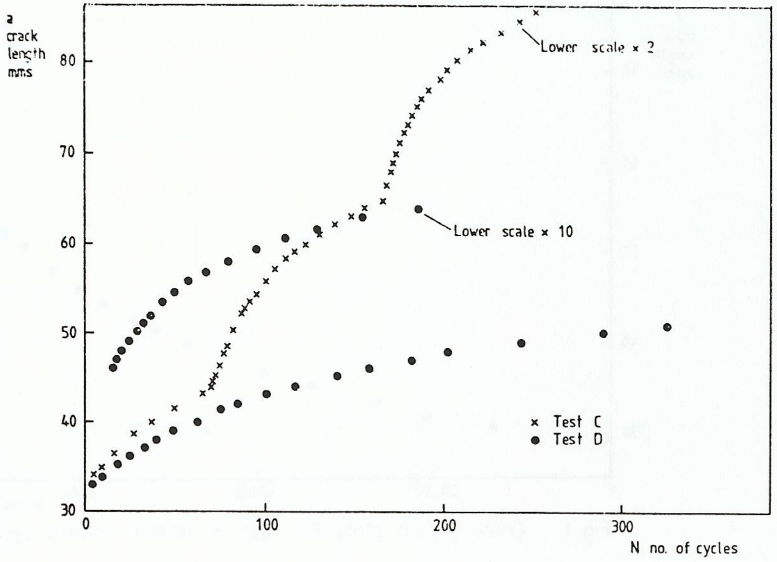

Fig. 3 Crack growth plots for tests C and D

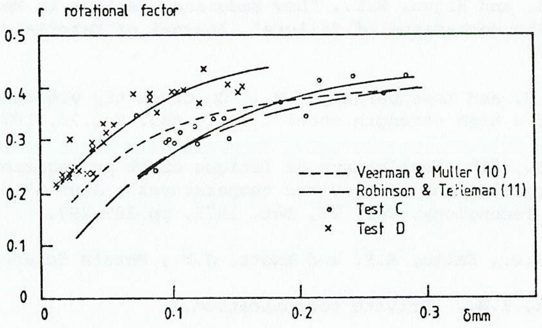

Fig. 4 Plots of rotational factors versus crack opening displacements for tests C and D

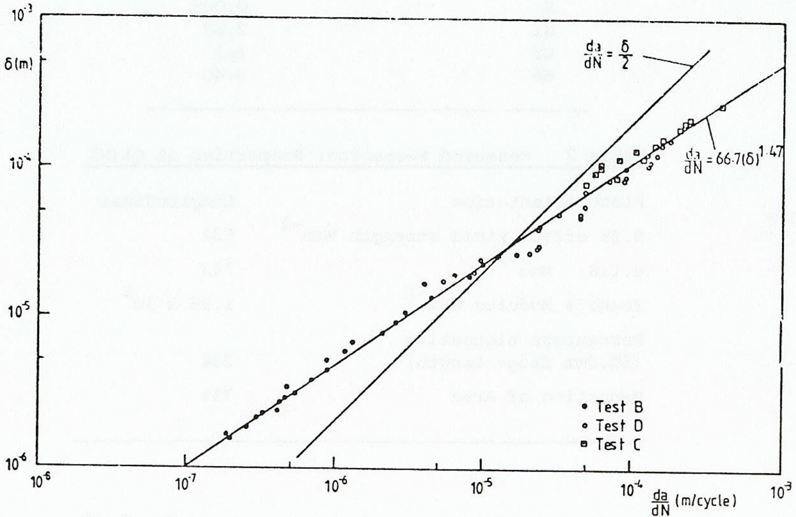

Fig. 5 Plot of δ versus crack growth rates for tests B, C & D