20. THE EFFECTS OF STRESS RATIO, THICKNESS AND FREQUENCY ON FATIGUE CRACK GROWTH IN STRUCTURAL STEEL USED IN MARINE TECHNOLOGY

by

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SUMMARY

The influence of mean stress, thickness and loading frequency on fatigue crack growth rates in BS 4360-50C steel was investigated at 21°C.

Compact tension specimens (CTS) were manufactured from steel plates, as supplied in two thicknesses, 12 mm and 24 mm. Fatigue tests were performed at two stress ratios, R (0.08 and 0.7), and at two cyclic frequencies of 0.25 and 30 Hz. A limited number of tests were conducted at constant K_{mean} of 20 and 40 $MN/m^{3/2}$ and at 30 Hz.

The results showed that fatigue crack growth rates increased with increasing stress ratio, although this effect was more pronounced in thinner specimens. The growth rates increased with thickness at lower ΔK values; however, at higher ΔK, this behaviour was reversed. Cyclic frequency had only a negligible effect on crack growth rates at low stress ratios. At high stress ratios and lower frequencies, the growth rates increased substantially.

The parameter ΔK correlates the growth rates data adequately for the thicker specimens, but it fails to do so for the thinner material. It is suggested that, in this case, the ΔK_{eff} could be a more suitable variable.

INTRODUCTION

Studies of fatigue crack propagation have shown that the most suitable parameter for characterising the fatigue crack growth rate is the stress intensity factor, K. These studies have also confirmed that fatigue crack growth rate, da/dN, is primarily related to the stress intensity factor range, ΔK, through the Paris expression (1):

$$\frac{da}{dN} = C\,\Delta K^m \qquad \text{—— 1}$$

where C and m are constants depending on such variables as material, loading conditions, environment and temperature. This expression adequately describes fatigue behaviour for the mid-range of growth rates, typically 10^{-5} to 10^{-3} mm/cycle, but it over-estimates and under-estimates the respective lower and higher growth rates. Consequently, the variation of crack growth rates, da/dN, with the stress intensity factor range, ΔK, could be better described by a sigmoidal curve (Figure 1) (2).

This sigmoidal variation of growth rates with ΔK has recently (2) been rationalised in terms of primary crack growth mechanism, in order to explain the sensitivity of stress ratio, thickness, microstructure, environment, etc., on crack growth rates. It was shown that, in steels, for the mid-range of growth rates (regime II), failure generally occurred by a transgranular ductile striation mechanism (3), and the rate of crack growth was largely insensitive to stress ratio, thickness, frequency, microstructure, etc., (4-16). The large influence of stress ratio, thickness, microstructure, etc., may, however, predominate in the high and low growth rate regimes (regimes III and I respectively) (13-16). At high growth rates, the effects of the above factors could be ascribed to the occurrence of superimposed static modes of fracture, such as cleavage, intergranular and micro-void coalescence accompanying or replacing striation growth (4,5). The mechanism of growth in the low growth rates has been observed to be microstructurally sensitive and also sensitive to stress ratio, involving the occurrence of environmentally induced fracture modes, such as intergranular fracture in steels (4,5).

In addition to the mechanistic considerations outlined in the above paragraph, empirical growth models have been proposed to explain the effect of stress ratio on crack growth rates. One of the first models was that by Forman et al (17) and Roberts & Erdogan (18). In both cases, the Paris equation was modified to include the influence of K_{max}. Forman et al considered the consequences of K_{max} exceeding the fracture toughness of the test material and proposed the following growth rate expression:

$$\frac{da}{dN} = \frac{C\ (\Delta K)^{m_1}}{\left((1 - R)\ K_c - \Delta K\right)^{\beta}} \qquad —— 2$$

where β is unity, and R is the stress ratio. From considerations of crack tip plasticity, Roberts & Erdogan proposed:

$$\frac{da}{dN} = C\ (K_{max})^{m_2}\ (\Delta K)^{m_3} \qquad —— 3$$

The former of these two equations has been more widely adopted (6,19). Elber (20,21) advanced a complementary treatment of crack growth rates based on a consideration of crack tip conditions at minimum applied load. He detected physical crack closure in the specimens and proposed that the effective range of stress intensity factor at the crack tip, ΔK_{eff}, was not simply proportional to the applied dynamic load but, instead, was critically influenced by the degree of closure that occurred. He proposed a modification to the Paris equation of the form:

$$\frac{da}{dN} = C\ (\Delta K_{eff})^{m_4} = C\ (U\ \Delta K)^{m_4} \qquad —— 4$$

where $U = (K_{max} - K_{op})/(K_{max} - K_{min})$, and K_{op} is the stress intensity factor at which the crack opens, it being argued that damage does not occur when stress singularity is destroyed by closure.

Sullivan & Crooker (8) have proposed an effective stress intensity factor range given by:

$$\Delta K_{eff} = K_{max} - b\ K_{min}$$

which was rewritten as: $$\Delta K_{eff} = \left(\frac{1 - b\ R}{1 - R}\right) \Delta K \qquad —— 5$$

Walker (22) also proposed an effective stress intensity factor range of the form:

$$\Delta K_{eff} = (1 - R)^{m_5}\ K_{max} \qquad —— 6$$

which has successfully been applied by James (23). Each of these models does a satisfactory job of correlating fatigue crack growth data at various stress ratios and growth rate regimes.

The effect of specimen thickness on crack growth rates reported in the literature is conflicting. The earliest work by Frost & Denton (24) showed that some metals were influenced by thickness, whilst others were not. More recently (25), a faster crack growth was detected in thinner materials. However, in subsequent studies, Clark (26), Griffiths & Richards (10), and Sullivan & Crooker (11) reported no effect of thickness. Barsom et al (27) found that crack growth rate was accelerated by increasing thickness. This result was later confirmed by Heiser & Mortimer (28) and more recently by Dover & Boutle (12), who, however, noted reduced growth rates at lower growth regimes.

Evidence available at present suggests that the speed of cyclic loading has little effect on the fatigue crack growth rate in a material over the range of 0.25 to 100 Hz in a mild environment. However, it has been reported that the growth rate is generally slightly higher at lower frequency than at higher frequency ranges. Early tests by Schijve (29) showed that growth rates were about 30% faster at 0.33 Hz than at 33 Hz. Later, Hertzberg & Paris (30) reported that growth rates at higher frequencies tended to be slightly slower than at lower frequencies. Subsequent results by Christensen & Harman (31) showed only a little influence of frequency on growth rates. Recently, Yokobori & Sato (15) reported decreased growth rates with increasing frequency, and proposed an empirical formula to correlate their data in the form:

$$\frac{da}{dN} = C\ (\Delta K)^{m_6}\ f^{-\lambda} \qquad —— 7$$

where $\lambda = 0.08 \simeq 0.09$ for the steel investigated.

From the above, it is seen that the effect of stress ratio, thickness and frequency is varied.

The work reported in this paper is part of a major work being undertaken to study the fatigue crack behaviour of a structural steel currently being used for construction of Offshore structures in the North Sea area. The effects of stress ratio, thickness and frequency have been studied in the mid-range growth rates.

EXPERIMENTAL PROCEDURE

The steel investigated is a low alloy structural steel, BS 4360-50C, of chemical composition and mechanical properties as given in Tables I and II. The material was available in two plate thicknesses, 12 mm and 24 mm. No heat treatment was performed on either the plates or the machined specimens.

Fatigue crack growth tests were performed using compact tension specimens (CTS) of dimensions as shown in Figure 2. In all the specimens, the fatigue crack was grown perpendicular to the rolling direction of the plate. The CTS geometry was found to be satisfactory for the testing machines used and the results obtained were sufficiently repeatable.

All tests were performed in laboratory air at ambient conditions. For the fast tests at 30 Hz, the Dowty Rotol Fatigue machine, of 60 kN (6 tonf) maximum capacity, was used. For the slow tests at 0.25 Hz cyclic frequency, the Avery Fatigue machine, of 50 kN (5 tonf) maximum capacity, was used.

The tests for both specimen thicknesses were performed at two stress ratios, R , of 0.08 and 0.7, and two cyclic frequencies of 30 Hz and 0.25 Hz. Some additional tests for the 24 mm thick specimens at R = 0.5 and 30 Hz were also included. A few tests* at constant K_{mean} of 20 $MN/m^{3/2}$ and 40 $MN/m^{3/2}$ were performed at 30 Hz to illustrate the effect of K_{mean}. However, in these tests, a continuous readjustment of the machine load to maintain constant K_{mean} was necessary, and this could have some effect on the results.

In all the tests, the specimen was provided with a sharp notch and the surface of one side polished to facilitate viewing of the crack tip. The specimen was then pre-cracked at an appropriately higher frequency and a lower load, and subsequently the fatigue crack propagated at the required load limits and frequency for some 2 mm to 3 mm before starting the actual test readings. This process ensured stable growth at the particular load limits, thus avoiding the influence of short cracks or loading histories on the crack growth rate. Measurements of the crack length were made optically using microscopes mounted

* Again, only 24 mm thick plate.

on travelling micrometric stages. These microscopes could measure the crack growth up to 0.02 mm. All the tests were conducted at fixed load limits, i.e. constant R ratio, and the crack allowed to grow from the original notch (after pre-cracking) to the maximum allowable crack length before the test was stopped. A typical record of a versus N is shown in Figure 3.

The experimental readings of the number of cycles, N, and the corresponding crack length, a, were used to calculate the growth rate, da/dN, applying the secant method, i.e. slope of line joining two successive points. The stress intensity factor was then calculated using the standard formula recommended for this specimen geometry, i.e.

$$K = \frac{P}{B\,W^{\frac{1}{2}}} f(a/W) \qquad \text{—— } 8$$

where $f(a/W)$ is a geometry function of the specimen and, for this CTS type, is given by:

$$f(\tfrac{a}{W}) = 29.6\,(\tfrac{a}{W})^{1/2} - 185.5\,(\tfrac{a}{W})^{3/2} + 655.7\,(\tfrac{a}{W})^{5/2} - 1017\,(\tfrac{a}{W})^{7/2} + 638.9\,(\tfrac{a}{W})^{9/2} \quad \text{—}$$

for $0.3 < (a/W) < 0.7$, and the crack length was the average of the two successive points used to calculate the corresponding da/dN.

RESULTS AND DISCUSSION

Effects of Stress Ratio (Mean Stress)

Stress ratio, R, has been used by most researchers (8,14,17,24) to investigate the effects of mean stress on fatigue crack propagation. However, K_{mean} has also been used (13,33,34) for the same purpose. Data from one form (constant R ratio) can easily be transformed into the other (constant K_{mean}), provided enough data is available*. The constant R ratio tests are easier to perform and are more appropriate for application in the life calculation of non-redundant structures where the load ratio, R, remains constant. Both the constant R ratio and K_{mean} data are shown in the results in Figures 4 to 7.

The data for the 24 mm thick specimens are shown in Figures 4 and 5. It

* This is accomplished by the expression: $K_{mean} = \frac{1}{2}\,(1+R)/(1-R)\ \Delta K$.

is seen that the data lie in a very narrow band for most of the growth rates tested. This shows very small effect of mean stress except towards lower growth rates where the band seems to widen. A close look at the results shows that growth rates are generally higher for the larger R ratio or K_{mean} than for the smaller ones. The data fits well into the Paris expression with the best fit straight line having a slope of about 3.0. The constant C in the Paris expression was evaluated to be 6.71×10^{-9}. Thus, it can be said that ΔK is the controlling parameter for the crack growth rate and the mean stress has very little influence on da/dN. The data fits in the expression:

$$\frac{da}{dN} = 6.71 \times 10^{-9} \Delta K^3 \qquad \text{—— 10}$$

for $0.08 < R < 0.7$.

The data for the 12 mm thick specimens, shown in Figures 6 and 7, show more pronounced effect of mean stress. The effect is large for growth rates below 10^{-4} mm/cycle; above this value, the effect is minimised, but increases again for higher growth rates. Thus, for a given value of ΔK, growth rates increase with mean stress significantly. It will be seen that ΔK is not the only suitable parameter to correlate the data for this thickness of the material (33). None of the empirical expressions discussed earlier was found suitable to correlate the data for the whole growth range tested, although the Sullivan & Crooker (8) model was found fairly suitable for correlating the data for the growth rates between 2×10^{-4} mm/cycle and 5×10^{-6} mm/cycle (Figure 6). Note that the data obtained in the present tests at constant values of R (Figure 6) were recalculated as indicated above and plotted in Figure 7, together with those for $R = 0.08$.

This effect of mean stress could adequately be explained in terms of state of strain and stress at the crack tip due to K_{max} as well as crack closure effects and other interacting factors (residual stress, etc.).

Effects of Thickness

The best fit lines through the data in Figures 4 and 6 for the stress ratios 0.08 and 0.7 are shown in Figures 8 and 9, respectively, to illustrate the effect of thickness on growth rates. It may be noted that, for a given value of ΔK, the fatigue crack growth rates are greater for the thicker specimen than for the thinner one for growth rates below 2×10^{-4} mm/cycle. However, at higher growth rates above 10^{-3} mm/cycle for the 0.08, the situation is reversed. Between the

growth rates of 2×10^{4} mm/cycle and 10^{3} mm/cycle, the effect of thickness is small*. It can be noted that this effect of thickness is less pronounced for the higher stress ratio of 0.7. It was not possible to obtain results for $R = 0.7$ at higher growth rates because of the large plastic zone developed in the specimen at these values and causing a sudden fracture.

It has been noted by Kang & Liu (34) that calculations based on linear elastic fracture mechanics adequately predict the strain when plane strain conditions exist. However, as soon as a particular value of K_{max} is exceeded, conditions at the crack tip change to plane stress and the calculations underestimate the actual strain at the crack tip. Consequently, a local thinning, due to mixed mode condition, will occur at the surface and this will result in accelerated fatigue damage. This transition from plane strain to plane stress may adequately explain the growth behaviour observed at growth rates above 2×10^{4} mm/cycle, but does not explain the behaviour at low growth rates.

Fatigue damage has also been found to depend on the reversed plastic strain range. For a given stress intensity range, applied to the specimen, the plastic strain range will depend on the degree of plane strain existing at the crack tip as well as on material properties. It should then be reasonable to conclude that the fatigue crack growth rate will depend on specimen thickness over a certain range of thicknesses, eventually becoming independent. This may confirm the disagreement in the literature regarding the effect of thickness, and also the need to perform tests over a wide range of growth rates and stress ratios.

Effects of Frequency

The results of tests on the 24 mm thick specimens at stress ratio of 0.08 and cyclic frequencies of 0.25 Hz and 30 Hz are shown in Figure 10. The results show only a very small effect of cyclic frequency on growth rate. Close examination of these results indicates slightly higher growth rates for the lower frequency, especially for growth rates below 3×10^{4} mm/cycle.

The results for the 12 mm thick specimens at a higher load ratio of 0.7 and cyclic frequencies of 0.25 Hz and 30 Hz are shown in Figure 11. These results show increased influence of frequency than those for the 24 mm thick specimens tested at $R = 0.08$. It should be noted that the results for the 24 mm thick specimens tested at $R = 0.7$ showed similar increased influence of frequency as those for the 12 mm thick specimens.

The possibility of crack tip heating, and thus stress relaxation at the

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* These results differ from those reported by Dover & Boutle (12).

crack tip, at high frequency could explain the observed reduced growth rate with increase in frequency. However, no appreciable change in temperature was observed on the specimens during the tests. Monotonic crack extensions, especially at high stress ratios and thus higher K_{max}, could also account for the observed growth rate increase of the lower frequency. This occurs at K_{max} and since the "hold-up" period at K_{max} during one cycle is longer at the lower frequency, the monotonic crack extensions/cycle could be higher at the lower frequency. Environmental effects at lower frequncies could also influence the growth rates.

CONCLUSIONS

Linear elastic fracture mechanics methods were used to characterise the effects of mean stress, thickness and frequency upon fatigue crack growth rates in BS 4360-50C steel tested in air and at 21°C.

1. Stress ratio, thickness and frequency may substantially affect crack growth rates in tensile fatigue cycling. However, these effects are not of a cumulative nature.

2. In general, fatigue crack growth rate increases with the increase in mean stress at a given value of ΔK. This effect is more pronounced in thinner specimens (12 mm thick plate).

3. For the 24 mm thick specimens, the fatigue crack growth rate, da/dN, is adequately correlated with the stress intensity factor range, ΔK, through the Paris expression in the form:

$$\frac{da}{dN} = 6.71 \times 10^{-9} \, \Delta K^3$$

4. The stress intensity factor range, ΔK, may not be the best parameter to correlate growth rates for the 12 mm thick specimens. The effective stress intensity factor range, ΔK_{eff}, could be more appropriate in the range between 5×10^{-6} and 2×10^{-4} mm/cycle, although not for higher values.

5. For the range of thickness tested, i.e. 12 mm and 24 mm, growth rates increase with thickness at given values of ΔK provided plane strain conditions are maintained at the crack tip. When transition from plane strain to plane stress occurs, crack growth rates decrease with thickness for given values of ΔK. This transition was found to occur between growth rates of 2×10^{-4} and 8×10^{-4} mm/cycle for both thicknesses tested.

6. Frequency has little influence on crack growth rates, especially for the thicker specimens and at low stress ratios. However, growth rates were found to increase significantly with decreasing frequency for tests at higher stress ratios. This increased effect could be associated with monotonic crack growth superimposed on the fatigue process, as well as with the environmental influence.

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STEEL BS 4360-50C

TABLE I

Chemical Composition (Weight %)

Element	C	Mn	S	P
%	0.24	1.6	0.06	0.06

TABLE II

Mechanical Properties

Tensile Strength = 494-618 MN/m^2 (32-40 $tonf/in^2$)

Yield Strength = 350 MN/m^2 (22.5 $tonf/in^2$)

% Elongation = 18%

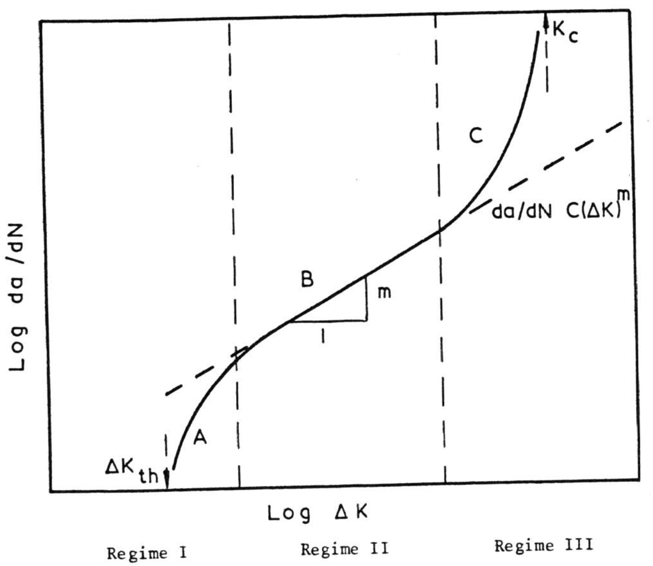
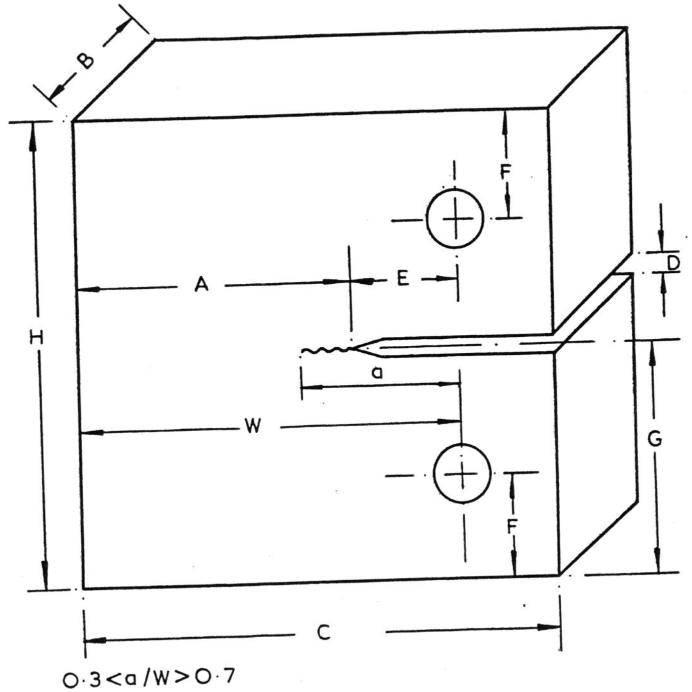


Figure 1: Fatigue crack growth rate *da/dN* versus *ΔK*. Schematic. (Ref. 4).



Dimension	A	B	C	D	E	F	G	H	R	W
Size (mm)	59.5	12 or 24	98.6	3.0	20.0	21.8	47.7	95.4	6.35	79.5

Figure 2: CTS specimen (all dimensions in mm)

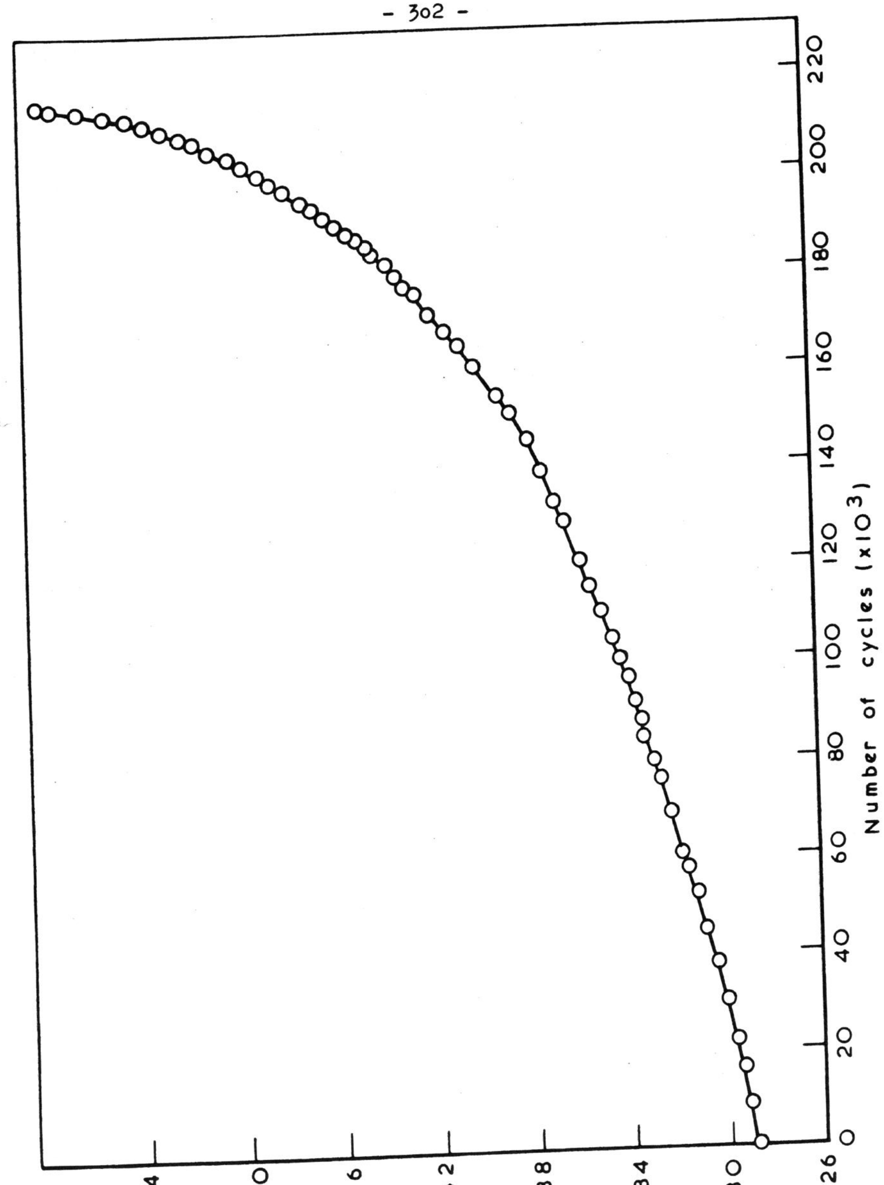


Figure 3: BS 4360-50C. Crack length, a, versus number of cycles, N, for constant stress ratio R = 0.08 at 0.25 Hz

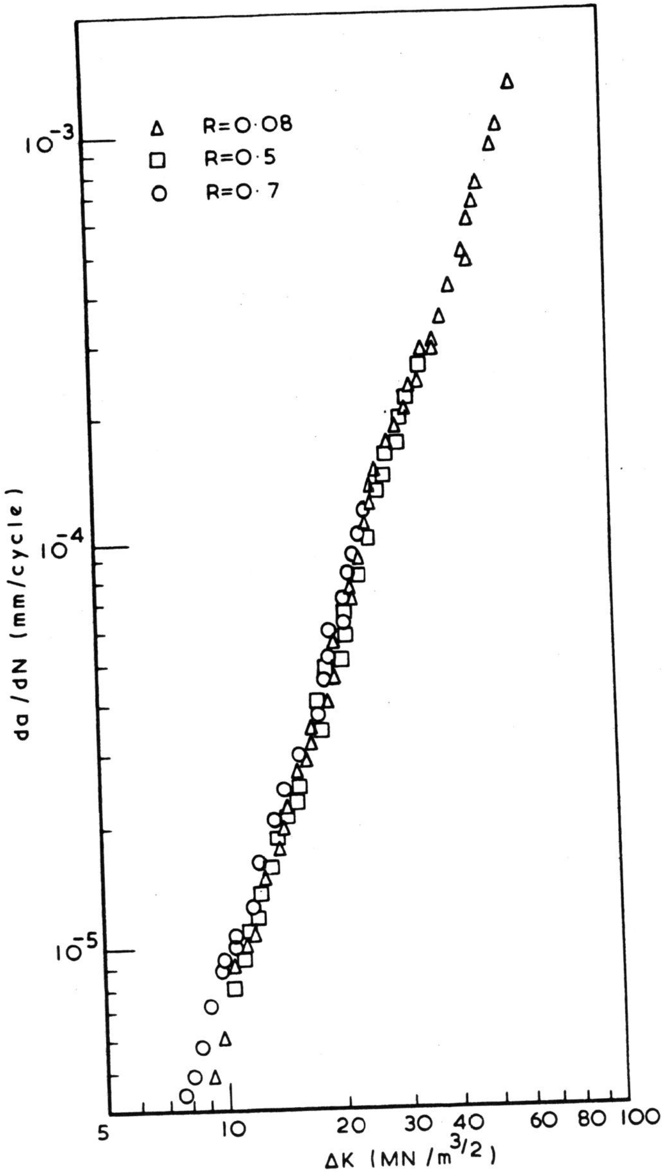


Figure 4: BS 4360-50C. Fatigue crack growth rate for the 24 mm thick specimen at three different stress ratios and 30 Hz

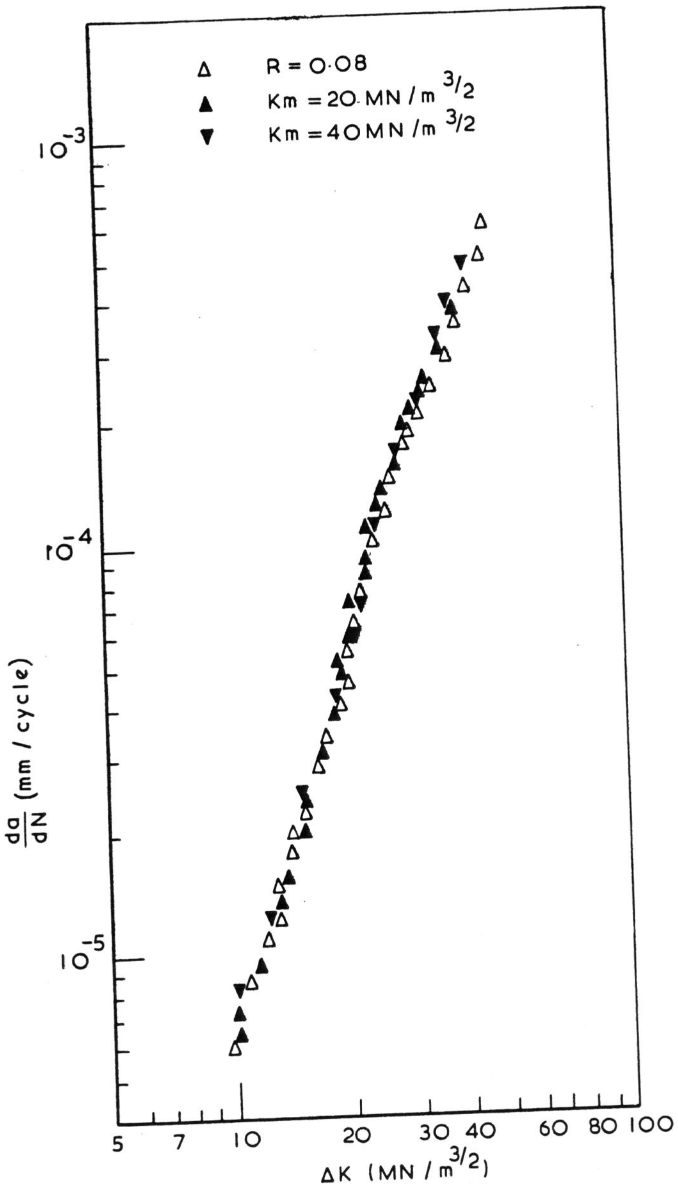


Figure 5: BS 4360-50C. Effect of K_{mean} on growth rate at 30 Hz for the 24 mm thick specimen

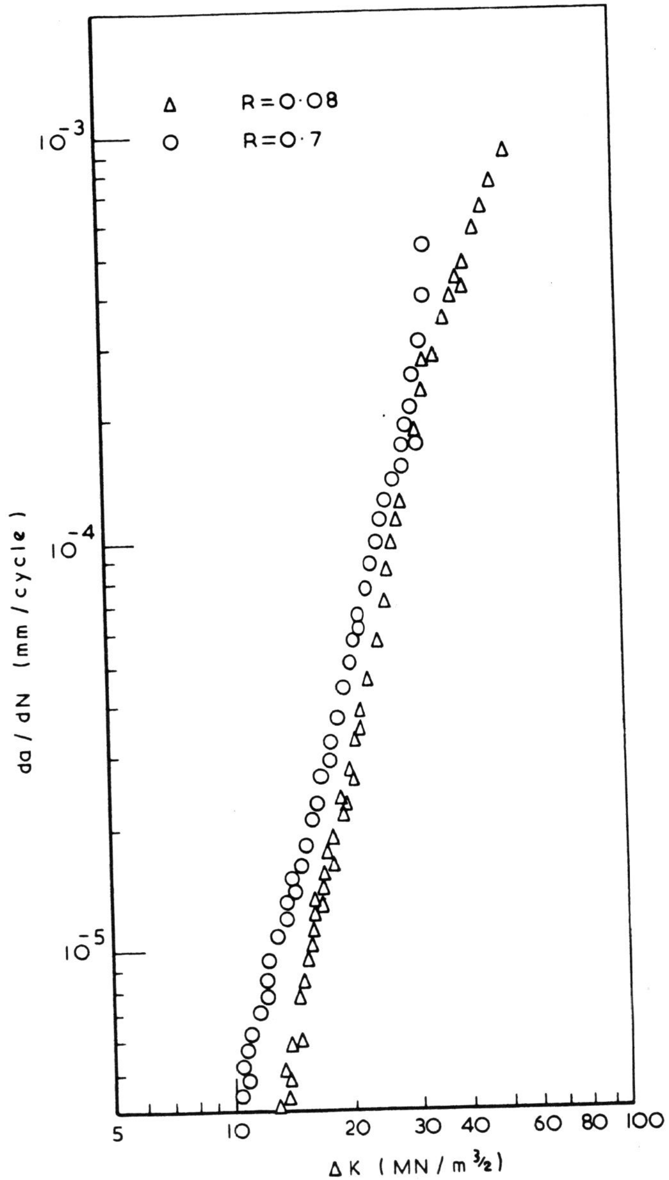


Figure 6: BS 4360-50C. Fatigue crack growth rate for the 12 mm thick specimen at two different stress ratios and 30 Hz

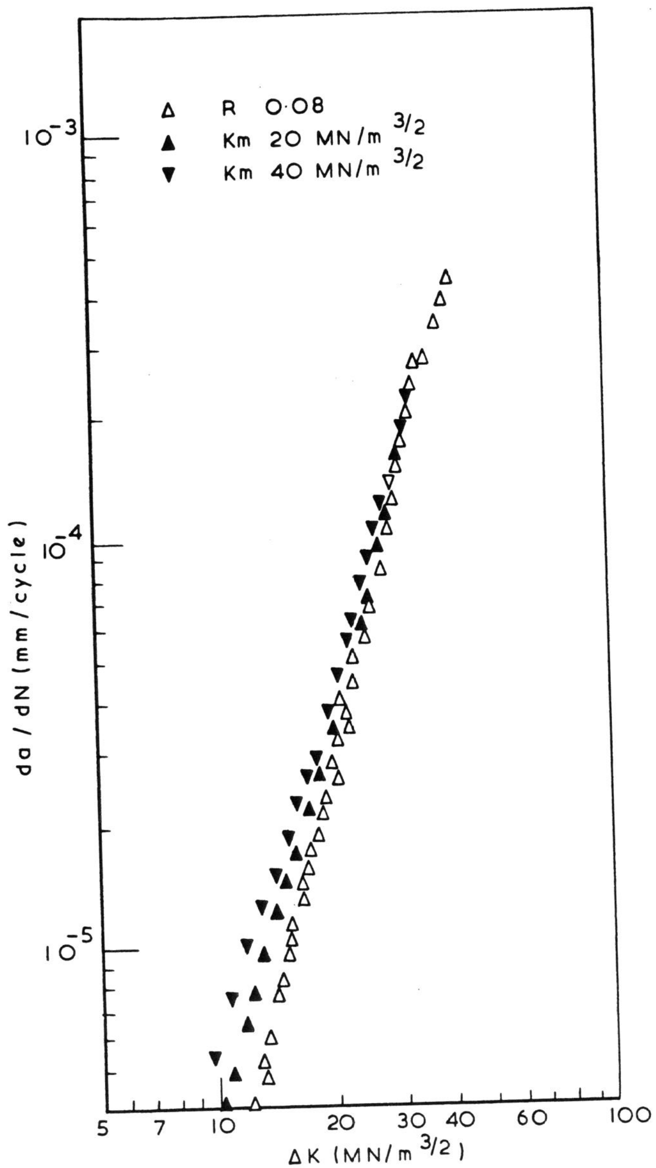


Figure 7: BS 4360-50C. Effect of K_{mean} on growth rate at 30 Hz for the 12 mm thick specimen

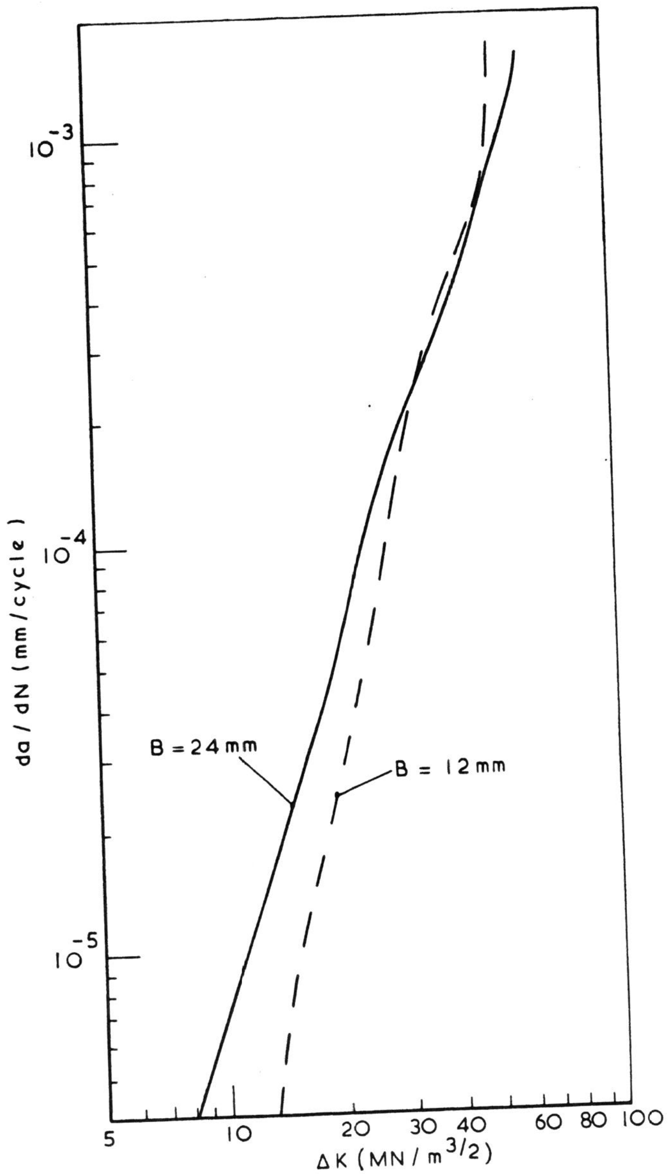


Figure 8: BS 4360-50C. Effect of thickness on fatigue crack growth rate at a stress ratio R of 0.08 and 30 Hz

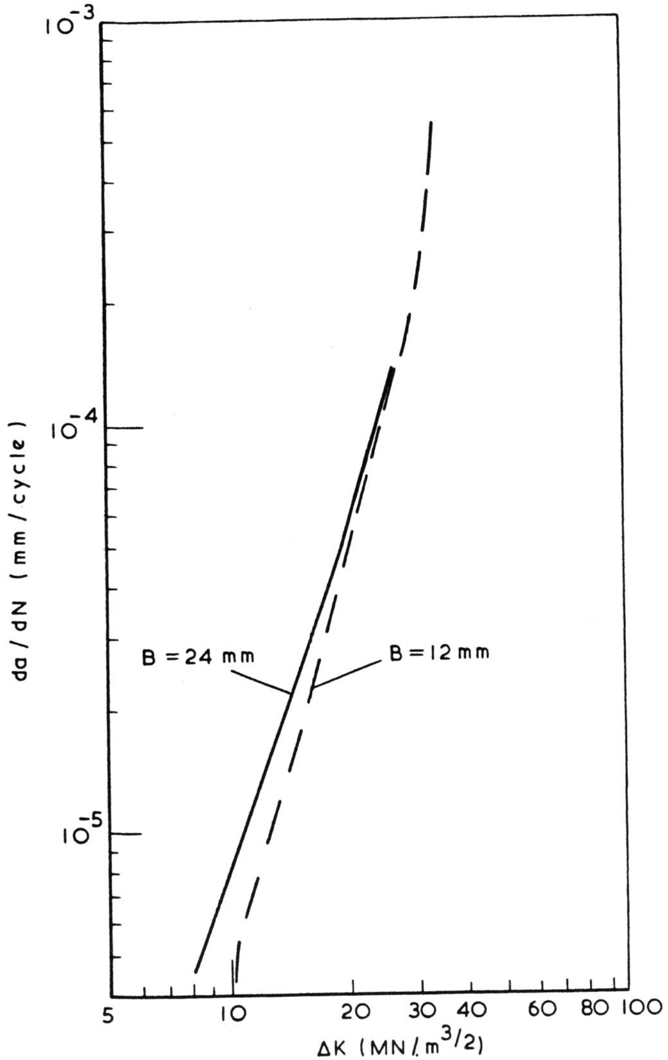


Figure 9: BS 4360-50C. Effect of thickness on fatigue crack growth rate at a stress ratio, R, of 0.7 and 30 Hz

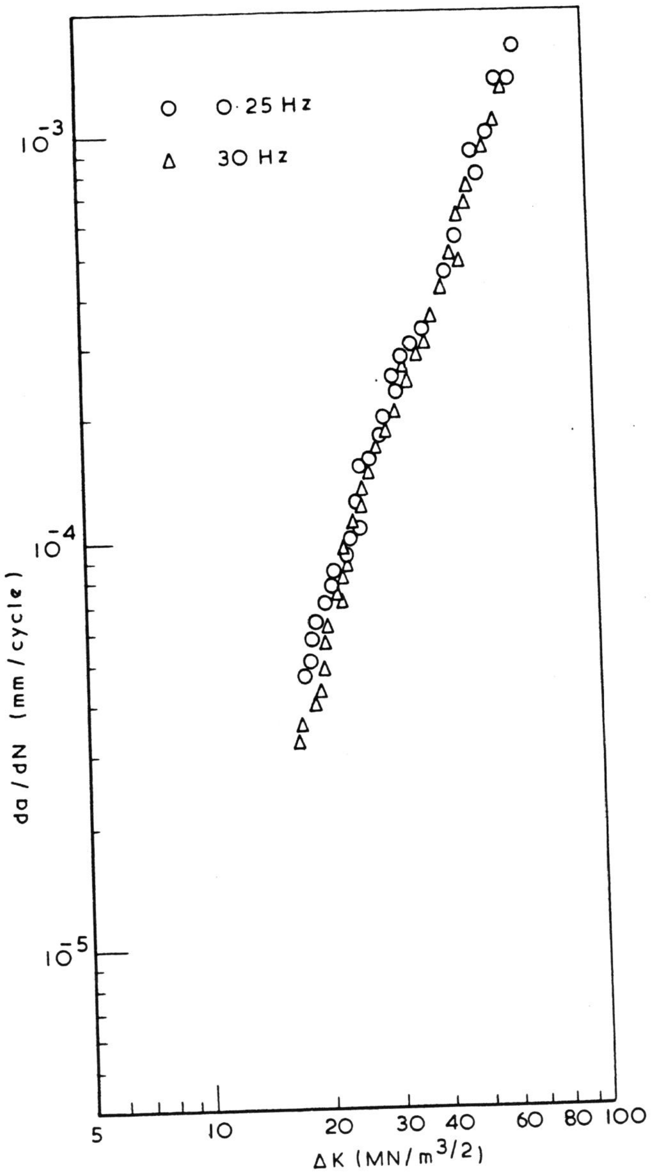


Figure 10: BS 4360-50C. Effect of frequency on fatigue crack growth rate at a stress ratio, R, of 0.08 for the 24 mm thick specimen

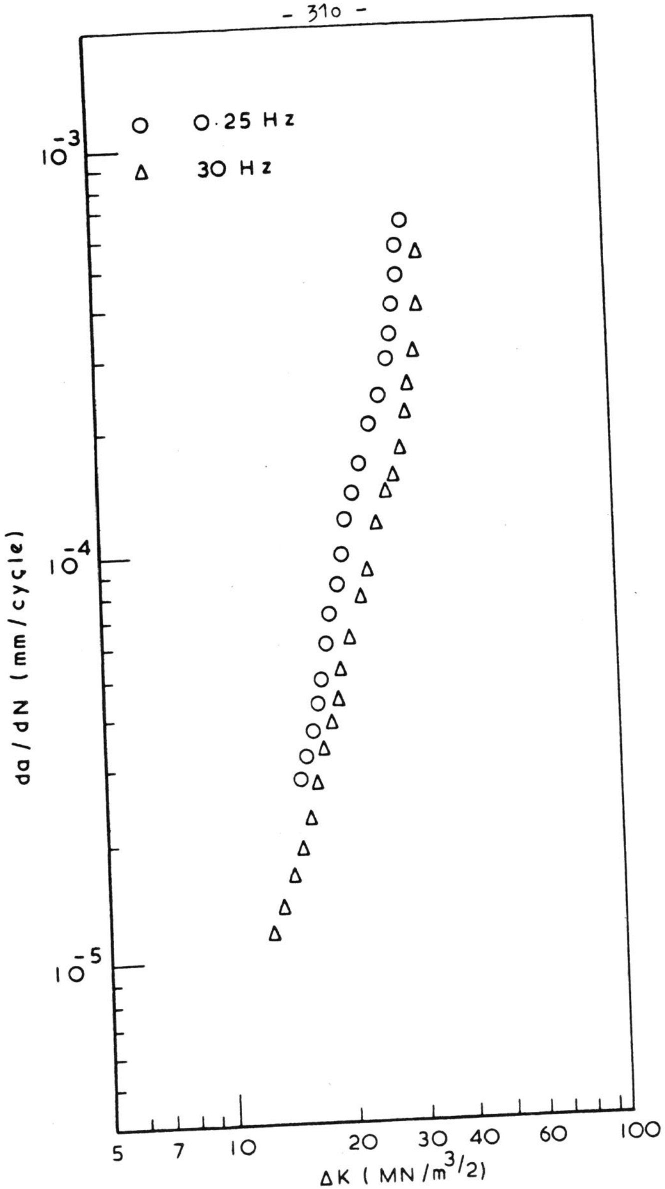


Figure 11: BS 4360-50C. Effect of frequency on fatigue crack growth rate at a stress ratio, R, of 0.7 for the 12 mm thick specimen