Corrosion Fatigue Crack Initiation from Blunt Notches in Structural Steel Exposed to Seawater

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ABSTRACT

Fatigue experiments have been carried out using blunt notch compact tension specimens of BS 4360 Grade 50D steel with notch radii of 0.25, 1.0 and 4.0 mm. Both constant amplitude fatigue loading and variable amplitude loading using a wide frequency bandwidth spectrum have been used. Tests have been conducted in air, freely corroding in seawater and cathodically protected at −0.85V (SCE) in seawater to determine the number of stress cycles to initiate a 0.5 mm long crack.

Analysis of the results has utilized linear elastic and several elastic-plastic assessments of the notch tip strain amplitude. The linear elastic method, which is the simplest, has proved adequate for the long cyclic lives of interest here. A substantial detrimental effect of seawater corrosion and a beneficial effect of cathodic protection are clear at low stress ranges. Similar trends are observed under variable amplitude loading but the analysis of rms notch tip strains in this case does not give satisfactory agreement with known S-N curves for constant amplitude loading.

KEYWORDS

Corrosion fatigue; structural steels; crack initiation; seawater; cathodic protection.

INTRODUCTION

Considerable success has hitherto been achieved in the application of linear elastic fracture mechanics to the characterisation of fatigue crack propagation and in its application to tubular welded joints for offshore structures (Burns, 1987). Calculations on this basis assuming the presence of crack-like defects of the order of 0.1 to 0.5 mm at the start of life have been able to predict quite accurately cyclic lives up to about a million cycles. In addition, fracture mechanics analysis has allowed design guidelines to be derived for factors such as joint size, variable amplitude loading, corrosion and cathodic protection.

An outstanding issue is whether the presumption of the presence of crack-like defects in welds at start of life is unduly pessimistic and whether some benefit could be gained from an allowance for crack initiation, particularly at long lives in excess of one million cycles. This issue is important because comparatively small changes in S-N design curves at long cyclic lives can have a large influence on predicted fatigue lives. Since S-N testing beyond a few million cycles is impractical if the corrosion processes are to be correctly characterised by testing at a realistic wave frequency (c. 0.1 Hz), then some other analytical method is required to derive soundly based S-N curves. The programme described here was conceived as a contribution to that goal by providing an estimate of crack initiation life from blunt notches which could then be added to the crack propagation life to obtain the total fatigue life.

EXPERIMENTAL

Blunt notch compact tension specimens (Fig 1) with three different notch radii of 0.25 mm, 1.0 mm and 4.0 mm were manufactured from BS 4360 Grade 50D steel, the chemical analysis and mechanical properties of which are shown in Table 1.

Table 1. Chemical analysis and mechanical properties of BS 4360 grade 50D steel

Chemical Analysis	Specification %	Sample Plate %
C	0.18 max	0.120
Si	0.1-0.5	0.43
Mn	1.5 max	1.31
Nb	0.1 max	0.018
V	0.1 max	0.01
S	0.04 max	0.003
P	0.04 max	0.015
Ni	-	0.08
Cr	-	0.06
Mo	-	0.01
Cu	-	0.28
Al	-	0.029
N	-	0.008
Co	-	0.021

Mechanical Properties	Specification	Sample Plate
Yield Stress (MPa)	345 min	362
Ultimate Tensile Stress (MPa)	490-620	516
Elongation (%)	18 min	35
Charpy Impact values (J)	27 min at -30°C	147 at -40°C

Two channels of a four channel servo-hydraulic fatigue testing facility were used, each actuator capable of applying up to 50 KN force. Variable amplitude loading was controlled by a mini-computer according to a specified broad band power spectrum (Fig 2) and load range distribution (Fig. 3). The spectrum was stored in the mini-computer as a sequence of peaks and troughs.

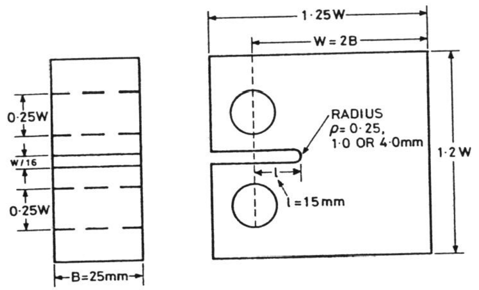

Fig 1 Blunt notch specimen geometries.

These were output with sine wave interpolation at a centre frequency around 0.167 Hz for tests in seawater and 1.0 Hz for tests in air. The mean stress was adjusted so that the stress ratio was always greater than 0.1. No clipping ratio was applied although the data processing from the original recording from an offshore platform to the series of stored peaks and troughs introduced an effective clipping ratio of about 5.

Each specimen was tested either in air or exposed to seawater at ~ 10°C flowing through a plastic cell at about 1 litre/min. When required, cathodic protection was applied using a potentiostat, saturated calomel reference electrode and platinum counter electrode. Only the portion of the specimen containing the crack was immersed in seawater and, due to the creep of salt deposits over surfaces above the water level, accurate current densities could not be calculated.

Crack monitoring was carried out by visual observation with a travelling microscope in air or by a DC potential drop method when the specimens were immersed in seawater. Experiments were carried out to verify that the crack detection system did not introduce any unwanted electrochemical effects on corrosion fatigue crack initiation and propagation. For a DC current of 50 amps, the resolution of the crack detection system was about 50 µm. This system avoided any problems with corrosion products and calcareous cathodic protection scales which complicate compliance based techniques (Maahn et al, 1987, 1988). The definition of crack initiation adopted was the number of cycles required to grow a crack to 0.5 mm depth from the notch root and was determined using a computer to examine the crack versus cycles records in order to eliminate any subjective judgement.

RESULTS

In order to compare results from different notch radii and specimen geometries and to extrapolate to other stress concentrations such as minor surface defects in welds, some estimation of a parameter describing the elastic-plastic strain field at the tip of the notch is required. This problem is addressed first by concentrating on analysis of the air data as a

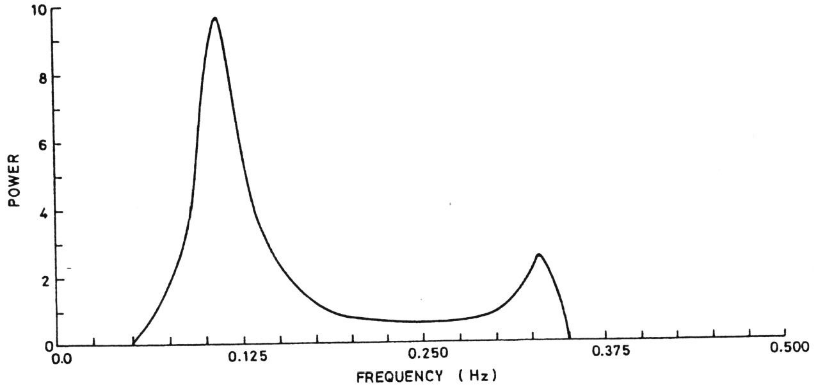

Fig 2 Variable amplitude loading sequence - power spectrum

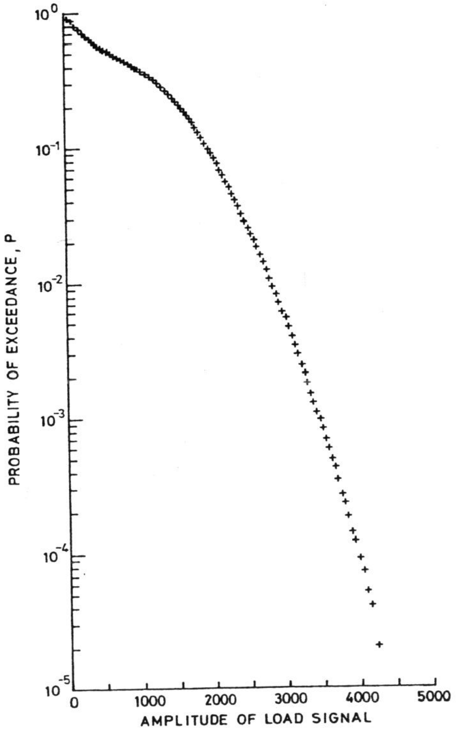

Fig 3 Variable amplitude loading sequence - stress range distribution

basis for the Discussion section on the effects of seawater and cathodic protection. However, no attempt has been made to measure or calculate microstructurally short crack growth kinetics, (Miller, 1987).

The most straightforward and simplest approach to calculating notch tip stresses is provided by the work of Wilson (1974). He showed that the notch tip elastic stress range, ΔS_t, may be estimated with a high degree of accuracy from the nominal value of the cyclic stress intensity factor, ΔK, for a crack of equivalent length to the notch depth:

$$\Delta S_t = \frac{2\Delta K}{\sqrt{\pi\rho}} \tag{1}$$

where ρ is the notch radius. The cyclic stress intensity factor, ΔK, is easily estimated from standard formulae for the specimen shown in Fig 1. From finite element studies, Wilson showed that even for the largest radius notch of 4 mm considered here, the error in the calculated notch tip elastic stress would be less than 4%. As a first approximation, ΔS_t can be regarded as a pseudo-elastic stress range equivalent to the strain range, $\Delta\varepsilon_t$, multiplied by the elastic modulus, E.

Fig 4 shows the available crack initiation results, in air, freely corroding in seawater and cathodically protected to between -800 and -900 mV as S-N data for crack initiation. However, the pseudo-stress amplitude $S_a = \Delta S_t/2 = \varepsilon_a E$ is used rather than the full range on the stress axis of Fig 4. Comparable constant amplitude data from a parallel coordinated programme on the same steel at the Danish Korrosionscentralen obtained using a cantilever bend specimen with a notch radius of 0.25 mm (Maahn et al , 1987, 1988) are also included in Fig 4. Two S-N curves (R = -1.0) are given in Fig 4 for comparison with the experimental results. One with a high mean stress modification is taken from the strain controlled fatigue data base for low alloy steels of medium strength given in the ASME Boiler and Pressure Vessel Code, Section III. The second is from work on directly comparable offshore structural steel by Bignonnet et al (1987). Since little material sensitivity is anticipated for such S-N curves, the agreement between the air environment data and the curve shown in Fig 4 is very satisfactory.

Comparable analysis of the variable amplitude data has been confined to correlations with root mean square stress amplitudes. The effective elastic rms stress amplitude at the notch tip was determined from the applied rms stress range in the same manner as for the constant amplitude tests. An S-N plot showing rms notch tip, pseudo stress amplitude versus crack initiation life is shown in Fig 5. In this case the agreement between the experimental data and the ASME Section III and Bignonnet et al S-N curves (corrected for the rms of a sine wave) is less satisfactory although there are rather few data points to make a good judgement.

Since elastic-plastic conditions exist in fact at the notch tip, it is well known that once yield is exceeded, the stress concentration decreases and the strain concentration increases (Wilson, 1974). Once non-linear plasticity becomes appreciable at the notch tip with increasing applied stress or notch acuity, problems then arise with the assumption that the pseudo-elastic notch tip stress range, ΔS_t, represents adequately the notch tip strain range. To overcome this difficulty further refinement is needed and various methods have been proposed (Prater and Coffin, 1981; Lawrence et al, 1978; Dowling et al, 1979; Glinka, 1985). Each of these methods has been applied to the present results but with only marginal effect on the

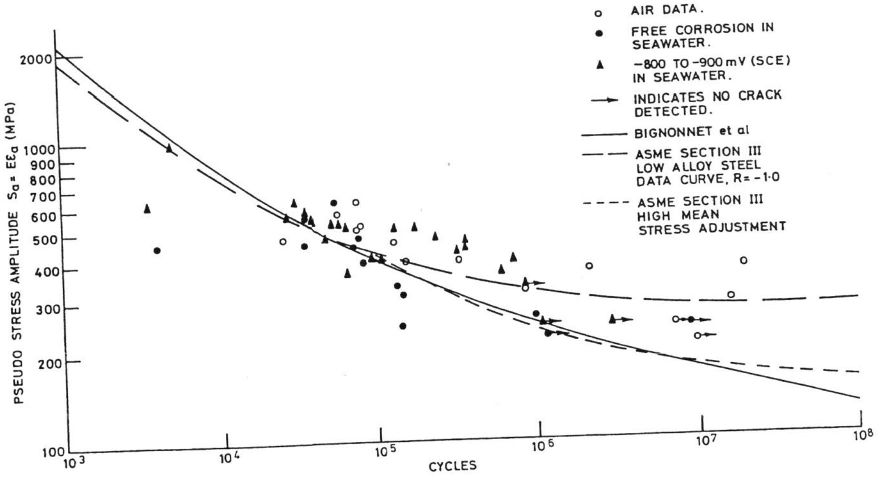

Fig 4 S-N curve for crack initiation from blunt notches under constant amplitude loading - linear elastic analysis of notch tip stress amplitudes

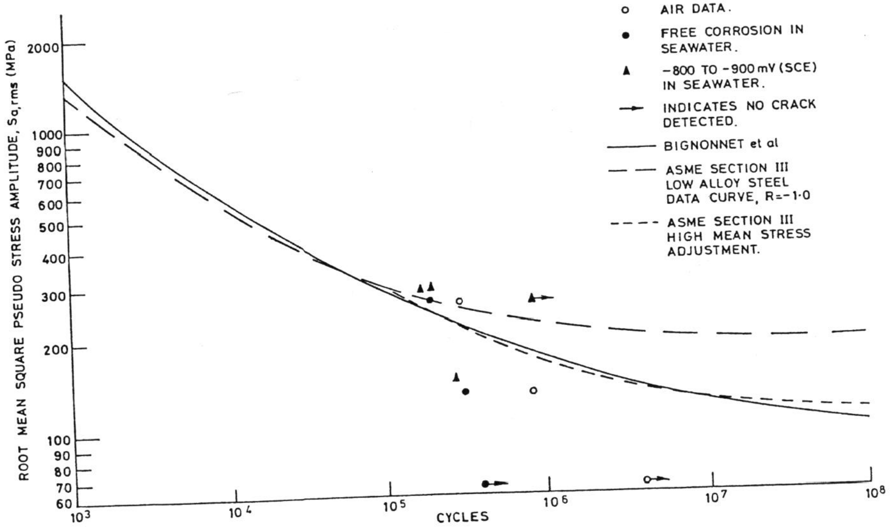

Fig 5 S-N curve for crack initiation from blunt notches under variable amplitude loading - linear elastic analysis of root mean square notch tip stress amplitudes

calculated pseudo-elastic notch tip stress ranges relevant to the cyclic lives of interest here of > 10^4 cycles. Therefore, we have concluded that a linear elastic analysis is sufficient and $S_a = \Delta S_t/2$ at the notch tip can be satisfactorily estimated from equation 1.

DISCUSSION

It is evident that to achieve a more precise definition of design S-N curves in the long life regime for welded steel tubular connections and the effects of the marine environment requires a careful examination of the contribution from crack initiation as well as from crack propagation.

Inspection of both Figs 4 and 5 for crack initiation lives under constant amplitude and variable amplitude loading respectively reveal a significant detrimental effect, occasionally up to a factor of 10, of seawater corrosion on fatigue initiation lives. It is also plain that with one exception at a very short cyclic life there is a major beneficial influence of cathodic protection in extending crack initiation life from notches in these experiments. The reasons for the beneficial effect of cathodic protection have been extensively analysed (Maahn et al, 1987, 1988). In addition to the elimination of corrosion by cathodic protection, calcareous scales appear to inhibit the early stages of crack nucleation and growth by inducing premature crack closure. Although in some cases the net effect of these precipitates is to give an even better fatigue initiation life than in air, it seems unwise to try to take advantage of this in design or structural integrity assessment since such scales could be disrupted by intermittent compressive stress cycles or torsional moments, for example. Nevertheless, the restoration of at least in-air fatigue initation lives by cathodic protection has been demonstrated. Note, however, that crack propagation rates are not reduced to in-air rates by cathodic protection in seawater (Austen, 1987) and therefore the overall cyclic life of a welded joint which incorporates both crack initiation and propagation phases will not necessarily be totally restored by cathodic protection.

Some additional justification for not claiming too much advantage from cathodic protection is indicated by the results for variable amplitude loading shown in Fig 5. Not only are the crack initiation lives in all cases lower than anticipated in the long life regime, but the benefit to be gained from cathodic protection is also seen not to be as great. There is clearly a need for further work and analysis in this important area of variable amplitude loading in combination with time dependent corrosion effects.

CONCLUSIONS

1. Seawater corrosion significantly reduces crack initiation lives (defined as the cyclic life to develop a 0.5 mm deep crack), from blunt notches in BS 4360 Grade 50D steel when tested at 0.167 Hz.

2. Cathodic protection can restore and even improve on in-air crack initiation lives. However, because any improvement on in-air performance depends on calcareous scales blocking propagating cracks and impeding crack closure, it is not recommended that any longer cyclic life than that achievable in air should be assumed in structural analysis.

3. Crack initiation lives under constant amplitude loading from notches of various radii from 0.25 mm to 4.0 mm have been successfully correlated with the notch tip cyclic strain amplitude (or pseudo-stress amplitude obtained by multiplying the strain amplitude by the elastic modulus) calculated on the basis of a linear elastic analysis of notch tip strains (equation 1). It has not proved necessary to incorporate more sophisticated elastic-plastic analytical methods for the notch stress amplitude for the range of long cyclic lives of interest here.

4. Variable amplitude loading has not been so successfully correlated with the rms of the notch root strain amplitude and the errors appear worst at longer lives. More work is required to resolve the problem.

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