CORROSION FATIGUE OF TUBULAR WELDED JOINTS

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ABSTRACT

A series of random load fatigue tests have been conducted on Tubular Welded T-joints in air and simulated sea water. These tests have provided data on crack shape evolution and shown that the crack depth growth rate in seawater can increase by from 2 to 6 times the equivalent air crack growth rates. These results confirm the prediction made from earlier precracked plate specimen test results.

KEYWORDS

Corrosion fatigue; seawater; tubular welded T-joints; fracture mechanics; crack shape; random loading.

INTRODUCTION

During the last seven years a large fatigue test programme has been conducted in the UK with the aim of providing information for designers concerned with the design of offshore platforms for the Northern North Sea. One of the areas studied was the problem of corrosion fatigue and this work included the effect of cathodic protection level, oxygen content, temperature, frequency, periodic immersion and pH. This work has been fully reported (1981) and has formed the basis for the New Fatigue Design Guidance notes to be issued by the Department of Energy (1983). The experimental work conducted in this programme was mainly based on precracked plate specimens and also welded cruciform specimens all manufactured from BS 4360:50D. The precracked specimens were used to provide data on fatigue crack growth rates in this material, the cruciform specimens were used to provide S/N curves. In general these tests showed that for fatigue crack growth tests the growth rate was influenced by the level of cathodic protection (enhanced growth rates of between 2 and 6 for CP in the range -0.85 to -1.1V) but that for fatigue life tests (the cruciform specimens) the CP level had little effect. The Guidance Notes appear to have been more influenced by the results from fatigue life tests and recommend for the free corrosion conditions for tubular joints, the basic S-N curve should be reduced by a factor of two on life whereas for adequately protected tubular joints (corrosion protection) the unmodified air S-N curve can be used.

The explanation for this choice rests on the belief that for the fatigue life calculation crack initiation and early growth are important and that for these two periods corrosion protection is beneficial. However large scale tubular joint tests in air (Dover, 1979) have shown that these two periods do not form a major part of the total fatigue life. Unlike the cruciform specimen a tubular joint test has an almost constant crack growth rate after crack initiation and consequently a major part of the total fatigue life for the tubulars consist of deep surface crack growth. This would mean that in a North Sea platform, designed for a safe life of 25 years, there could be fatigue cracks growing at about 10^{-8} m/cycle. The reason for this behaviour in the tubular joints is that the initial cracking leads to local load redistribution. This does not occur in the load control tests on cruciform specimens.

It can be seen from this that the behaviour of tubular joints in corrosion fatigue should be more like that of the precracked specimen data and not the cruciform specimens. However rather than rely on this theoretical speculation it was decided that a series of corrosion fatigue tests on tubular welded T-joints should be conducted, with the aim of monitoring fatigue crack shape evolution, so that the effect of cathodic protection could be measured. Part of this work has already been completed and is reported here.

EXPERIMENTAL WORK

A series of fatigue tests, using random load North Sea spectra, has been conducted on both flat plate specimens and tubular welded joints made from BS 4360:50D. The details of the test rigs and random loading have been described elsewhere (Dover, 1979; Dover, 1982); a view of the tubular joint rig used for corrosion fatigue is shown in Figs. 1a and 1b. This rig is based on a 1000 kN Instron servohydraulic actuator and employs an a.c.crack measurement system (Dover, 1981a)developed for automatic computer controlled crack depth monitoring. The computer used is a PDP 11/10 acting as a satellite in a host-satellite network based on a PDP 11/23 as host and using Star-Eleven software (Broome, 1983).

Four T-joint tests have been conducted, using axial loading, two in air, one free corrosion and one with an impressed current cathodic protection of -1050mV. The seawater used was artificial seawater (based on ASTM D1141) and the temperature was maintained at 8-10°C (using a Conair chiller). The pH was kept at 7.8 - 8.2 during the two seawater tests.

For all four tests the crack depth was measured at various sites around the welded intersection so that the crack shape profile could be recorded. These measurements were originally made with a hand held probe but more recently spot welded permanent contacts have been used so that automatic monitoring of crack depth was possible. All crack depths were calculated from the voltages measured adjacent to, and just over, the crack. No calibration or correction has been used in these calculations mainly because it was found with the earlier surface cracked flat plate tests that a theoretical interpretation of the two measured voltages could predict the crack depth to within 5% (Collins, 1981).

RESULTS AND DISCUSSION

The four tests conducted were monitored to give details of the crack shape evolution but until all the tests are completed a full analysis will not be possible. A small fraction of the data already available is shown in Fig.2 and this data was obtained from air and free corrosion tests conducted at a hot spot r.m.s. stress of 112 MPa and 106 MP respectively. It can be seen that the crack front is irregular and this partly stems from the fact that the very early crack growth stage was from a series of semi-elliptical surface cracks. It would appear that the corrosion fatigue test produced an even more irregular crack front than the air test. For both tests the average crack growth rate varied along the length of the crack and for the air test it would seem that the crack shape was growing towards a stable shape governed by the tubular joint geometry and the mechanical stress distribution. For the corrosion fatigue test the preliminary conclusion was that a similar characteristic crack shape was also being produced but that local distortion occurred probably due to variations in the electrochemical conditions. This aspect of the study will be considered in more detail after completion of the fatigue test programme.

One of the problems encountered in this work has been the choice of the method for analysis of the data. For example from Fig. 2 it can be seen that the crack depth does not have a unique value and instead one has to choose from say

(a) A point by point analysis along the crack front.
(b) A best fit curve through the data.
(c) An average depth over the deepest portion.
(d) The deepest measured point along the complete crack front.

Option (a) and (b) are currently being studied; (c) has been used previously but (d) is the method chosen for this paper. A further problem relates to the fact that several different r.m.s. levels have been used and two slightly different tubular dimensions. Thus for the purposes of comparison a non-dimensional analysis is required.

In earlier work (Dover, 1982) it has been suggested that the stress intensity factor for cracks in tubular joints may be deduced from an expression of the form:-

$$K = Y(\sigma)\ \sigma\sqrt{\pi a} \tag{1}$$

where a is the crack depth and $Y(\sigma)$ is the calibration factor that takes into account the local stress redistribution that takes place during crack growth.

It was further suggested that if one used the Paris Law for this material:-

$$\frac{da}{dN} = 4.5 \times 10^{-12}\ (\Delta K)^{3.3} \tag{2}$$

then experimentally measured crack depth growth rates could be interpreted in terms of the effective stress intensity factor (K_{exp}).

If it is assumed that for any crack depth the value of K_{exp} can be determined then

$$Y(\sigma) = \frac{K_{exp}}{\sigma\sqrt{\pi a}}$$

and a plot of Y(σ) vs a/t would give the variation of the calibration factor with crack depth.

This non-dimensional plot would only hold for a particular geometry, type of loading and environment but should be independent of stress level, wall thickness etc. In the present case only the environment has been varied which means that any differences in the Y(σ) plot reflect the use of the wrong constants in Eq.(2). The Y(σ) if used for both, the air and corrosion fatigue data should indicate the influence of environment on the growth rate. Figure 3 shows the crack growth curve for the free corrosion fatigue test using the maximum recorded crack depth at each interval. This was the first corrosion fatigue test on a tubular joint and consequently the test conditions were modified periodically in order to determine the effect of frequency. The test was a random load test and the two frequencies were 1.69Hz and 0.169Hz. These are average frequencies based on range counting. In terms of da/dt the crack growth slowed down each time the frequency was reduced. For da/dN however the growth rate was higher at the lower frequency.

Figure 4 shows the crack growth curve for the test with the cathodic protection, again using the maximum recorded crack depth at each interval. The test was conducted at an average frequency of 0.169Hz throughout but after 300000 cycles the r.m.s. stress was reduced from 120 to 90 MPa. From Figs. 3 and 4 it can be seen that for the major part of the crack growth period the growth rate is almost constant. This feature was first noted in air tests on T-joints subjected to out-of-plane bending but now appears to be a characteristic of all tubular joints and has led to the proposal of a bi-linear fracture mechanics model to describe fatigue crack growth in tubular joints (Dover,1983). The behaviour is quite different from cruciform specimens where it is found that the crack growth rate increases rapidly as the crack becomes deeper. The data from Figs. 3 and 4 and the air tests reported earlier (Dover, 1981b) have been analysed to produce the Y(σ) vs a/t plot shown in Fig. 5. It can be seen that the high frequency portion of the free corrosion test and the air data tend to fall on one curve and that the curve fitted to this data can be described by the following equation:-

$$Y(\sigma) = 0.5\ (a/t)^{-0.46} \tag{3}$$

The remainder of the data fall on curves above this air data indicating that the corrosion fatigue growth rate is higher than the equivalent air growth rate and that Eq.(2) is not applicable.

The free corrosion data can be fitted by the following expression.(Note that the data for the final portion of the free corrosion test at low frequency has been omitted from the analysis because it was felt that too few depths had been recorded.)

$$Y(\sigma) = 0.59\ (a/t)^{-0.51} \tag{4}$$

Finally the two portions of the data from the C.P. test have also been analysed. The test period at 120 MPa gave the expression shown below.

$$Y(\sigma) = 0.82\ (a/t)^{-0.50} \tag{5}$$

The period at 90 MPa gives almost a continuation of this curve but the data is not sufficient for a firm conclusion. Comparing expressions (3), (4) and (5) shows that for free corrosion the growth rate in a tubular joint is 2.1 x higher than for air whilst for CP at -1050mV the growth rate is approximately 6X x higher. These enhanced growth rates are similar to those predicted from precracked plate specimens (Thorpe, 1983) which means that the crack growth portion of the fatigue life of a tubular joint could probably be predicted from the data already available for a wide range of conditions. The results from UKOSRP I (Dept of Energy, 1983) showed that the crack initiation period could occupy between 10-40% of the life to chord wall penetration, depending on wall thickness and mode of loading. In general the percentage of life involved in crack initiation decreased as the chord wall thickness increased. Thus for a 75mm wall thickness T-joint, subjected to axial loading, the initiation period need only be 10%. For this worst case if one also used the most deleterious environmental condition, say CP at -1.05V, then the life to wall penetration would be reduced by a factor of 6X. Even with the correct CP or for free corrosion one would predict a reduction of about 2X.

These predictions, if confirmed, would seem to indicate that the Dept. of Energy Guidance Notes may need modification for use with tubular joints. The Notes are probably more relevant to Tee-butt welds or cruciform joints rather than Tubular joints. The behaviour of cracks in these two types of component is very different. These initial results show that one should be able to predict tubular joint behaviour from the results obtained on pre-cracked plate specimens. These preliminary findings can only be confirmed when the programme is completed. The remainder of the programme is to be funded by the Dept. of Energy.

CONCLUSIONS

1. It is now possible to monitor automatically fatigue crack shape evolution in both air and seawater tests on tubular welded T-joints.
2. Preliminary results from two corrosion fatigue tests on tubulars suggest that earlier precracked plate specimen test data could be used to predict the effect of environment on the fatigue crack growth behaviour in tubular joints.

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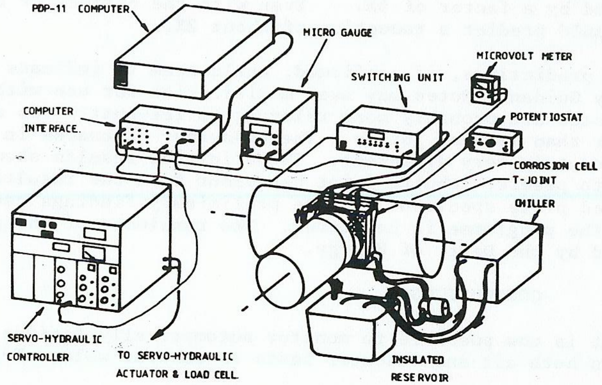
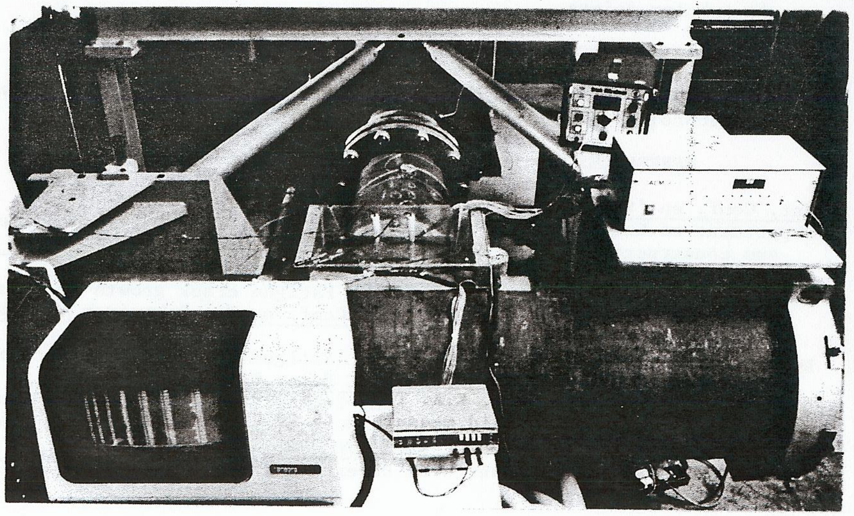


FIG. 1a & 1b.



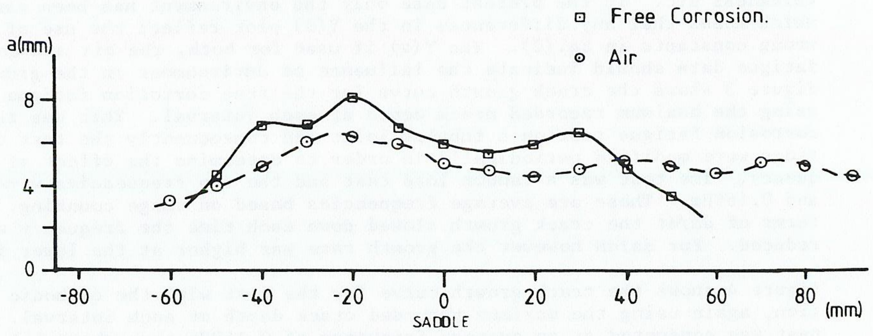


Fig 2. CRACK SHAPE COMPARISON.

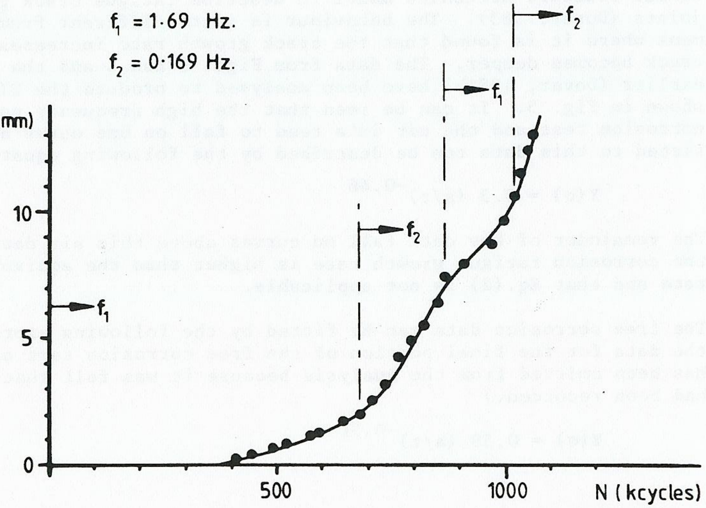


Fig 3 CRACK GROWTH – Free corrosion.

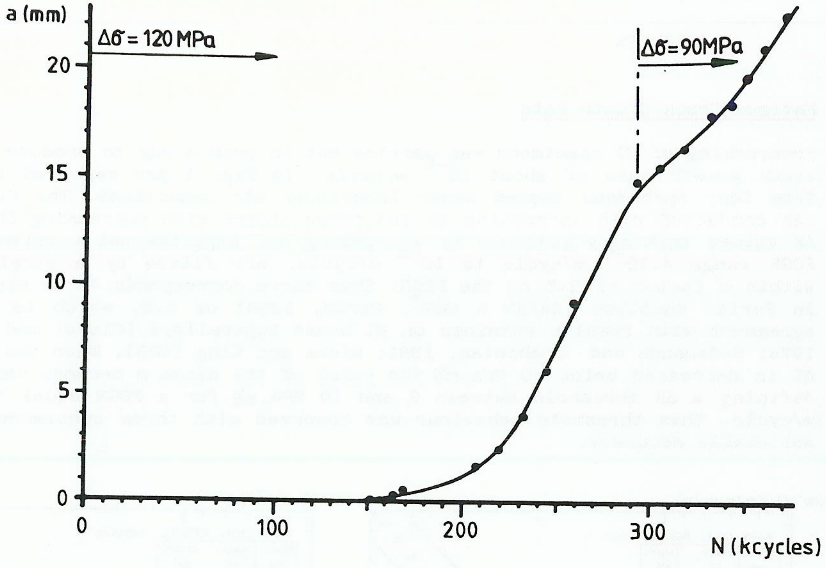


Fig 4. CRACK GROWTH -cathodic protection.

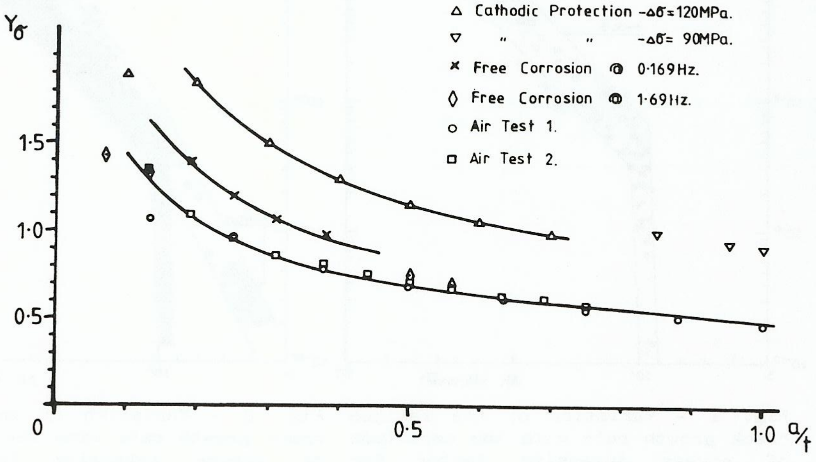


Fig 5 Y_σ v. a/t