The Dual Crack Growth Modes in the Corrosion Fatigue of Welded Tubular Joints

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ABSTRACT

Following the completion of several major international research programmes on the fatigue of offshore structures, very useful data have been collected.

One major area of interest is the corrosion fatigue behaviour of welded tubular joints. Many cathodically protected (CP) large scale tubular joints were tested in corrosive (sea water) environment. The results showed that the fatigue life of the joints has been significantly reduced, despite the general belief that CP restores the corrosion fatigue life to that of air fatigue.

The stress life (SN) data showed an indication of a change in the fatigue accummulation behaviour when the equivalent fatigue stress range is reduced. These dual modes of behaviour became more obvious when the fatigue crack development history was studied.

This paper summarised the results obtained from a series of corrosion tests carried out under realistic in-service fatigue loading. The fracture mechanics analysis and modelling of the data has also been included.

KEYWORDS

Corrosion; fatigue; crack growth; tubular joints; realistic random loading; offshore structures.

INTRODUCTION

Fatigue has been identified for many years as one of the major causes for the degradation of offshore structural integrity in the North Sea (Marshall, 1976). The investigation of the fatigue behaviour of the main structural component, the welded tubular joints, has therefore attracted immense interests. Following the completion of the first phase of the United Kingdom Offshore Steel Research Programme (UKOSRP-I), the U.K. Department of Energy introduced a mean stress - life (SN) curve for tubular joint fatigue in air (D.En, 1984). A design curve was then derived from this mean curve as the mean minus two standard deviation (μ - 2σ) design "T" curve. Based on results obtained mainly from cruciform joints, it was further recommended that this air design curve can be used for assessing the corrosion fatigue of tubular joints under normal cathodic protection (at - 850mV).

New corrosion fatigue test results for tubular joints are now emerging from the UKOSRP - phase II (D.En, 1987), the European Coal and Steel Community Research Programme and the United Kingdom SERC/Department of Energy Cohesive Offshore Fatigue Research

Programme (Dover *et al.*, 1988). These new data suggested that the corrosion fatigue performance appeared to be significantly poorer than that of air fatigue. Fig. 1 and 2 summanrise the results published so far. All the results at higher stress ranges lie very near to the lower confidence bound of the air fatigue data. The fatigue lives at lower stress ranges, however, can be considered as comparable to the air fatigue lives.

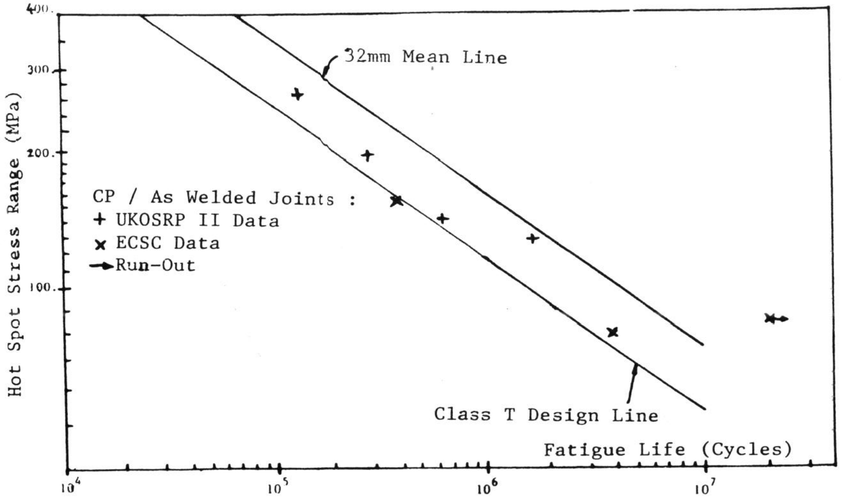

Fig. 1. CORROSION FATIGUE DATA ON TUBULAR T-JOINTS WITH 32mm THICK CHORD WALL

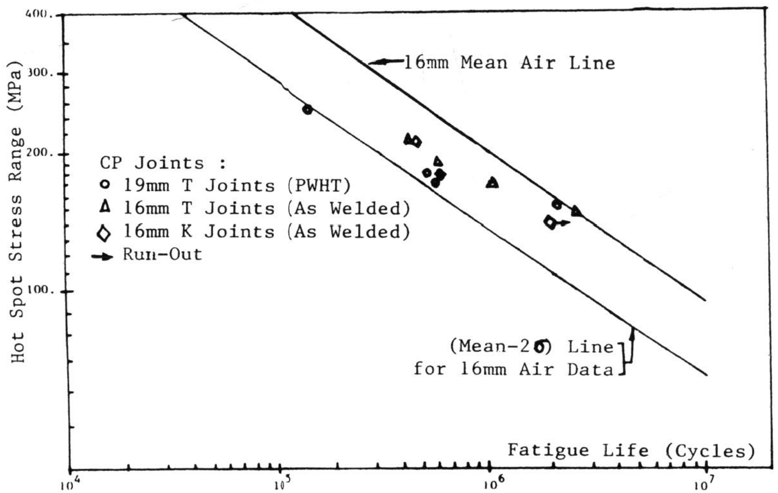

Fig. 2. CORROSION FATIGUE DATA ON TUBULAR T-JOINTS WITH 16mm & 19mm THICK CHORD WALL

Two explanations were possible for this difference in fatigue lives. Firstly, the behaviour may be simply due to the corrosion SN curve having a different slope for the curve. Secondly, the behaviour may have been caused by a change in the mode of fatigue crack growth. However, the SN data alone were not sufficient to distinguish one factor from the other. A useful extra piece of information, the fatigue crack development history in the tubular joints, will help in providing more insights into the true fatigue accumulation behaviour.

CONSTANT AMPLITUDE CORROSION CRACK GROWTH

A series of four large scale tests on T joints have been reported (Dover *et al*, 1986). The constant amplitude results provided the fundamental information concerning corrosion fatigue crack growth in tubular joints. The controlling crack dimension is the depth into the chord wall thickness. Fig. 3 contains all the leading crack depth development in the T joint series. There is an obvious prolonged initial crack development in the case of low stress range. The information is presented in a different format in the crack growth (da/dN vs ΔK) curves in Fig. 4. The stress intensity range (ΔK) was calculated in the following way;

$$\Delta K = Y \, \Delta S \sqrt{\pi a} \qquad (1)$$

where ΔS is the constant amplitude stress range,
a is the crack depth
Y is the stress intensity modification factor, calculated by the Two Phase Model (TPM), a well documented empirical model (such as Kam *et al*, 1987) developed for large scale tubular joints.

Two crack growth curves (each with 3 segments) could be plotted for the low ΔK region (Fig. 4). The curve with the higher growth rates is referred to as the "normal" corrosion crack growth. The curve with the lower growth rates is called "slow growth". With these

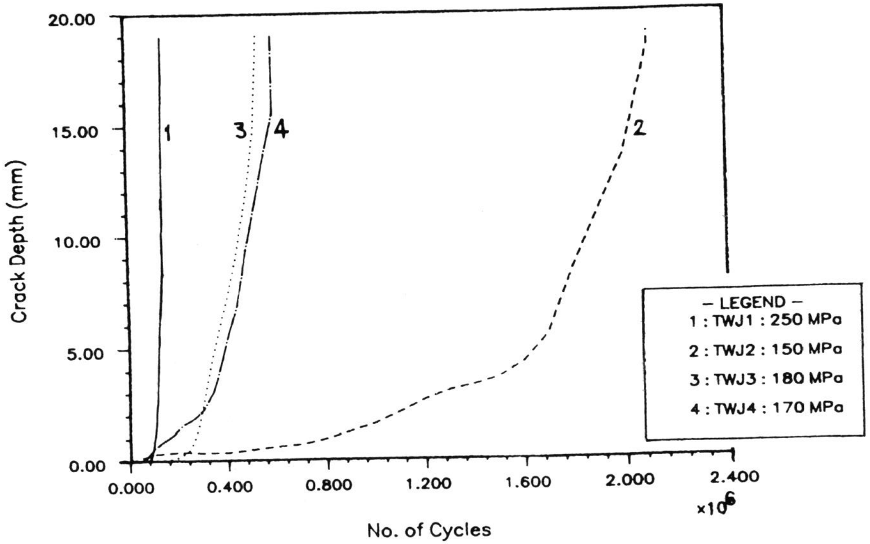

Fig. 3. EXPERIMENTAL CORROSION CRACK DEVELOPMENT IN TUBULAR T JOINTS

dual modes of crack growth, the experimental data could be modelled well. Fig. 5 and 6 show the two extreme cases where one crack development was "normal", the other was "slow". In fact there was not a gradual transition from one mode to another. The crack development in the joints appeared to have switched from one mode directly into the other when the fatigue stress range was reduced to 150MPa.

It remained to be verified whether these dual modes of crack growth were special features only in the constant amplitude tests or the same would occur in the fatigue under random load and realistic in-service load histories.

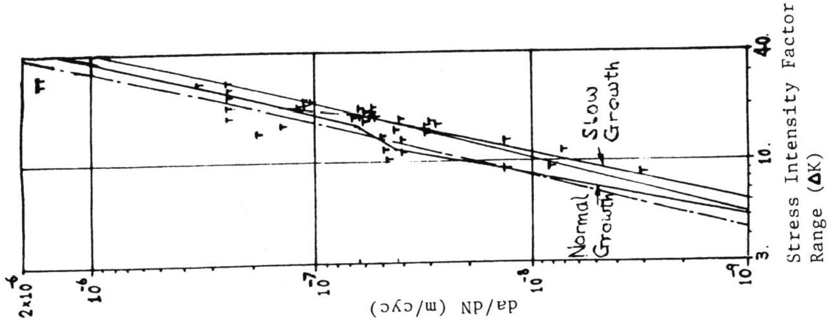

Fig. 4. EXPERIMENTAL da/dN vs PREDICTED ΔK (By TPM)

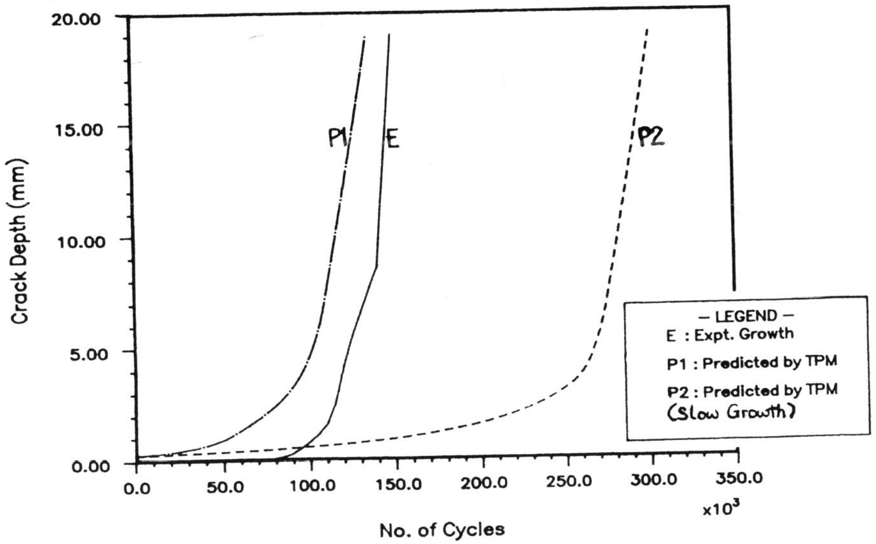

Fig. 5. COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED CORROSION CRACK GROWTH FOR TWJ1

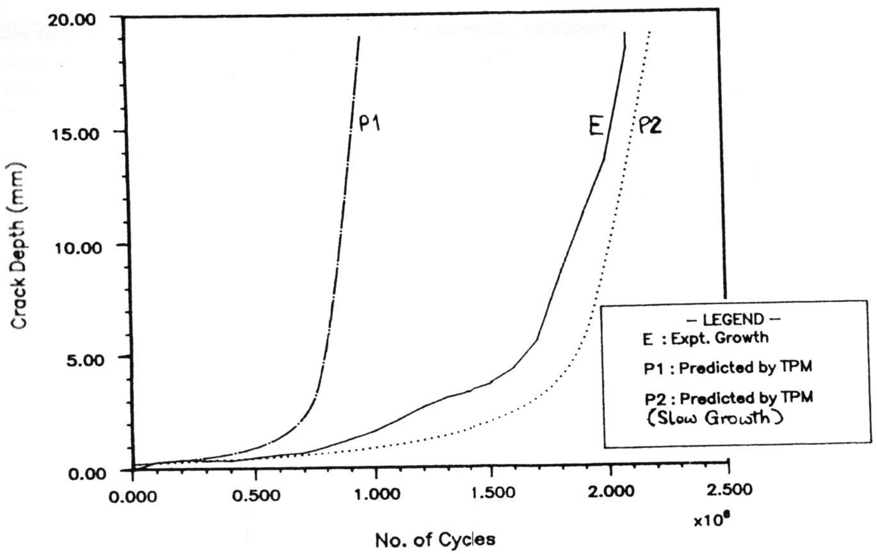

Fig. 6. COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED CORROSION CRACK GROWTH FOR TWJ2

FATIGUE UNDER RANDOM LOADING AND REALISTIC IN-SERVICE LOAD HISTORIES

Extensive offshore load monitoring has revealed that the in-service load histories are consisted of many randomly distributed sea states. Each sea state can be considered as a stationary broad brand random history. The stress power spectra of some typical sea states are shown in Fig. 7. The two peaks in the spectra correspond to the wave action - rigid body motion (first peak) and the structural resonance (second peak). Spectra of this type can be generated with the pseudo-random binary shift (PRBS) technique and the random sequence of sea states can be generated with the Markov chain technique. The detail of both of the techniques has been reported previously in (Dharmavasan *et al*, 1988).

Equivalent Stress For Random Load History

The equivalent stress concept was introduced to quantify a random load history using a single equivalent constant amplitude stress range S_h (such as Kam *et al*, 1987). S_h is calculated as,

$$S_h = \left[\int_0^{\infty} \Delta S^m \, p(\Delta S) \, d(\Delta S)\right]^{\frac{1}{m}}$$

$$= \left[\sum_i (\Delta S_i)^m P(\Delta S_i)\right]^{\frac{1}{m}} \qquad (2)$$

where $\Delta S, \Delta S_i$ is the individual stress range
$p(\Delta S)$ is the probability density of stress range ΔS
$P(\Delta S_i)$ is the probability of occurence for stress range ΔS_i

Equation (2) was shown to be equivalent for both Miner's sum (SN) calculation (with m being the slope of the SN curve) and fracture mechanics calculation (with m being the exponent of the Paris crack growth law), provided that there is no load interaction effect.

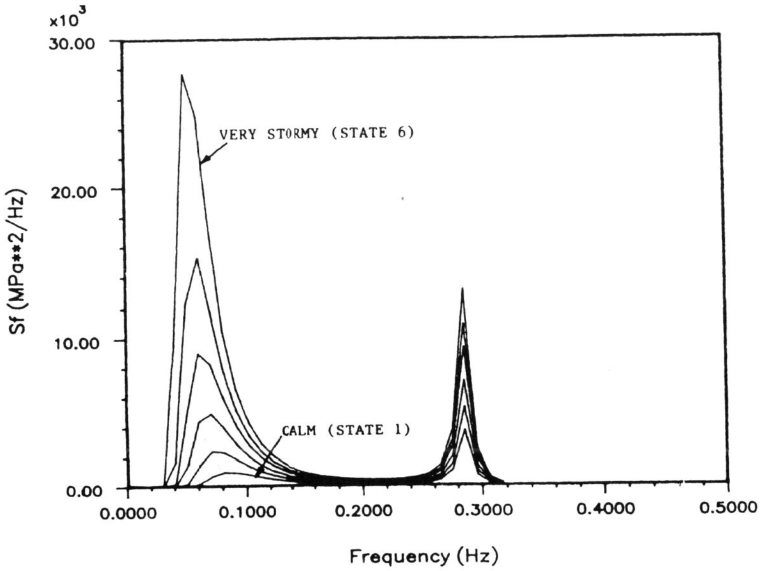

Fig. 7. TYPICAL SEA STATE STRESS POWER SPECTRA FOR TESTING

In the case of corrosion crack growth, there is no longer a single m value for the Paris crack growth curve (da/dN vs ΔK), therefore the equivalent stress can only be calculated for the SN curve.

Modelling Of Corrosion Crack Development Under Random Load History

There are many different stress ranges in a random load history. Normally the history is summarised as a stress range distribution (ΔS vs p(ΔS)). If load interaction can be ignored, each stress range corresponds to only one stress intensity range (ΔK) (according to equation (1)) and therefore only one crack growth rate at any instant. The mean corrosion crack growth rate for a random load history in a k segment crack growth (da/dN vs ΔK) curve can therefore be calculated as the summation of individual cycle ΔS_i,

$$\left(\frac{da}{dN}\right)_i = C_j \,(Y\, \Delta S_i \sqrt{\pi a})^{m_j} \tag{3a}$$

therefore for the whole history,

$$\left(\frac{da}{dN}\right)_{mean} = \sum_{j=1}^{i} C_j (Y\sqrt{\pi a})^{m_j} \int_{\Delta S_{j-1}}^{\Delta S_j} \Delta S^{m_j}\, p(\Delta S)\, d(\Delta S) \tag{3b}$$

where
- i is the i^{th} segment in the corrosion da/dN vs ΔK curve
- C_i, m_i are the Paris crack growth constants for the i^{th} segment
- ΔS_0 = 0
- ΔS_k = oo
- ΔS_i are also related to the current crack size through the Y factors and the transition ΔK_i.

Fatigue Tests

A series of tubular K joints were fatigue tested under out of plane bending (Fig. 8) using random loading. Two air tests, one with constant amplitude (Test-1A) another (Test-1B) with the top four (most stormy) sea states in Fig. 7, were carried out to confirm the Y predictions made by the TPM model. The details of the load histories, equivalent stress ranges and fatigue lives for all the tests have been summarised in table 1.

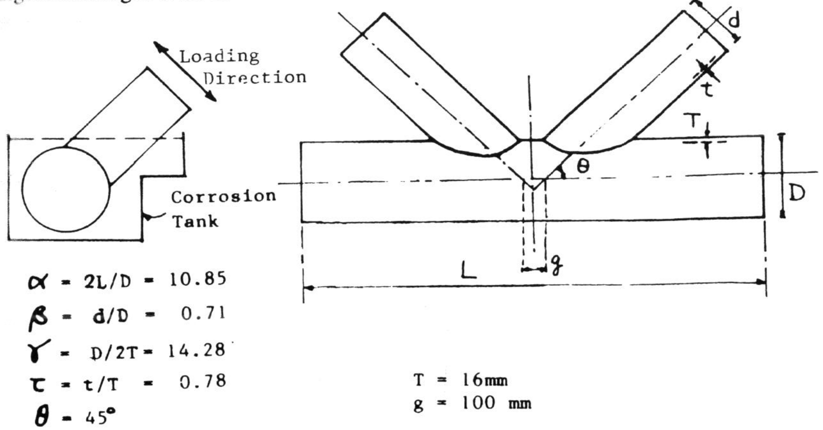

Fig. 8. SCHEMATIC DRAWINGS SHOWING THE GENERAL ARRANGEMENT AND DIMENSIONS OF K JOINTS TESTED IN CORROSIVE ENVIRONMENT UNDER OUT-OF-PLANE BENDING

The four sea state stress history used in Test-1B was also applied to the corrosion Test-2A. A serious retardation was observed in this test (Fig. 9). The crack depth was only around 1.5mm at the end of nearly two million cycles. The cause for this retardation is uncertain but crack closure due to calcareous deposits on crack surfaces was normally suspected for corrosion retardation. Crack closure is particularly effective when there is a high proportion of small cycles in the load history. Fig. 10 shows the exceedance curve for a total of 2 Million cycles in the four-state history. It is obvious that a large proportion of small cycles exists in the history. The test was stopped as a run-out.

The most stormy (top) stress power spectrum (in Fig. 7) was then used for the two remaining tests in the series. Test-2B is a retest of Test-2A, but with a single spectrum. When the load was increased, the severe retardation seemed to have disappeared. However, when compared with the predictions made with the dual modes of crack growth rates (Fig. 11), the crack development in this test seemed to fall into the category of "slow growth".

According to the constant amplitude fatigue data, crack growth in Test-2B would have been in the "normal" category. The cause of this descrepancy was linked to Test-2A. The results seemed to indicate that the mechanisms behind the severe crack retardation and the "slow" corrosion crack growth were either related or effectively the same. The slow growth may therefore be considered as the average results of constant stopping and starting of crack growth.

Finally, Test-3A was carried out in two parts and the crack development was compared with the predictions. The first part of the test was carried out with an equivalent stress of 150MPa and slow growth was assumed in the modelling. The equivalent stress for the second part was 190MPa and "normal" corrosion growth was assumed for the modelling. It appeared that the prediction agreed well with the experimental data (Fig. 12).

Table 1. Detail of the fatigue tests reported

Test	Equivalent Fatigue Stress Range (m=3)	Stress History	R ratio or Clipping ratio	Environmental Condition	Life (Million cycles)
1A	180. MPa	Constant Amplitude	0.3 (R)	Air	1.55
1B	140. MPa	Realistic Service (4 states)	7.0 (CR)	Air	2.90
2A	140. MPa	Realistic Service (4 states)	7.0 (CR)		1.88*
2B	210. MPa	Single Spectrum	4.0 (CR)	Sea water with	0.46+
3A-1	150. MPa	Single Spectrum	4.0 (CR)	CP = -850 mV	-
3A-2	190. MPa	Single Spectrum	4.0 (CR)		-
3A-1+2	177. MPa	-	4.4 (CR)		0.60

* A run-out test
\+ A re-test

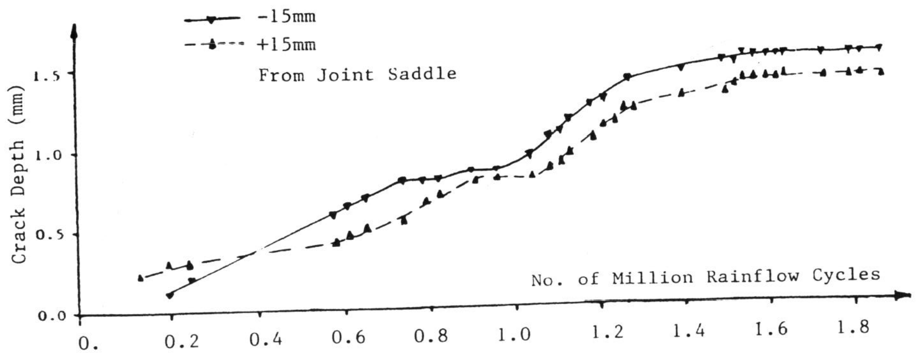

Fig. 9. LEADING CRACK GROWTH IN KOPB-2A

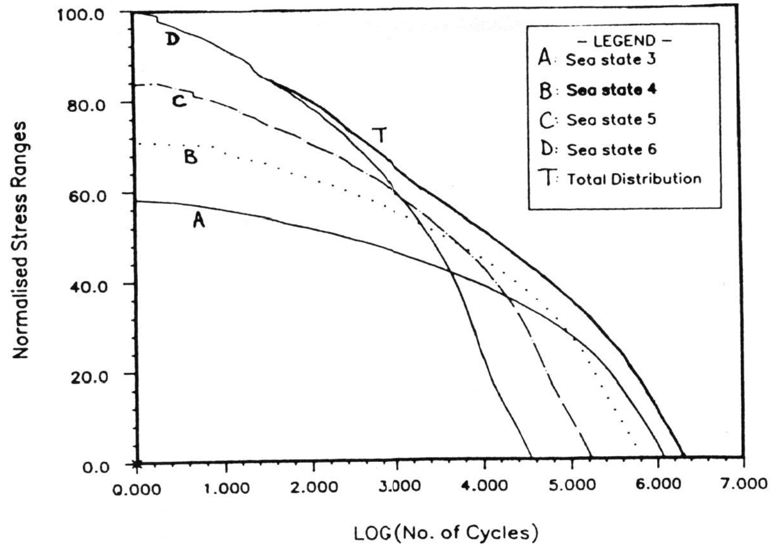

Fig. 10. CUMULATIVE DISTRIBUTION OF RAINFLOW CYCLES (TOP FOUR STATES IN Fig. 7)

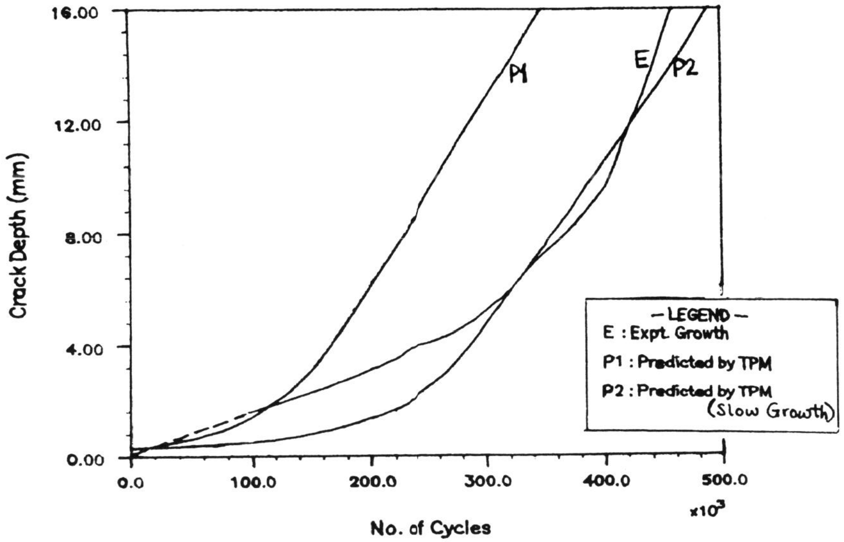

Fig. 11. COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED CORROSION CRACK GROWTH FOR KOPB-2B

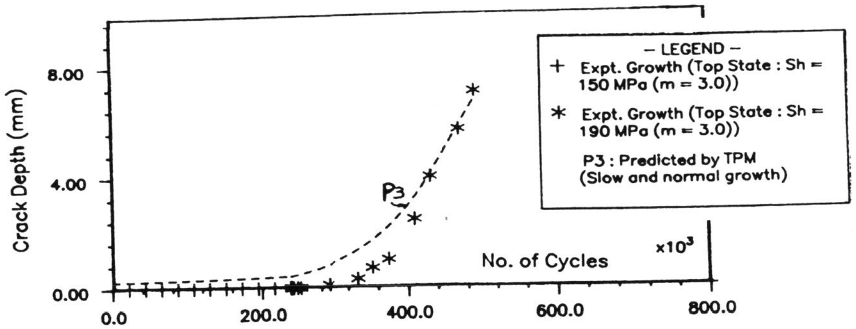

Fig. 12. COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED CORROSION CRACK GROWTH FOR KOPB-3A

CONCLUDING REMARKS

The corrosion fatigue crack growth of welded tubular joints can be described with the dual modes of crack growth. The "normal" mode can be used when the equivalent stress range is above approximately 150MPa. Below that level, the crack development can be reasonably modelled with the "slow" mode of growth.

Equation (3) is very useful in calculating the mean corrosion crack growth rates for a random load history. This modelling strategy gave very good predictions for all the experimental crack development data.

The severe retardation in Test-2A remains to be a major interest. Considering the potential benefits of prolonged fatigue life due to retardation, it will be useful if the cause, the mechanism and the conditions under which the retardation occurs, can be identified and reproduced in the operating condition. To achieve this goal, further studies on tubular joint corrosion fatigue are required.

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