FATIGUE CRACK GROWTH IN UNSTRESS-RELIEVED WELDED JOINTS UNDER NON-STATIONARY NARROW-BAND RANDOM LOADING

L. P. Pook
National Engineering Laboratory, United Kingdom

INTRODUCTION

Some fatigue tests have recently been carried out(1) on unstress-relieved cruciform-welded joints made from a medium strength structural steel. Both constant amplitude and non-stationary narrow-band random (NBR) tests were carried out in room temperature air at zero mean stress, and non-stationary NBR tests at high mean stress. The NBR load history used consisted of four different levels of stationary NBR loading arranged in rising and falling sequence, with an overall block length of 100 000 cycles. The relationships of the NBR results to the constant amplitude results and to current design rules for offshore structures are discussed in Ref. 1. The fracture surfaces of the NBR loading specimens had programme markings correspoinding to the loading blocks. Various fracture mechanics calculations were carried out in an attempt to rationalize the observed crack-growth rates.

The original fatigue tests were carried out as part of the United Kingdom Offshore Steels Research Project, which was set up to obtain fatigue and fracture data relevant to tubular structures in the North Sea. The NBR load history used was intended to be representative of wave loading on North Sea structures. However, the fractographic observations and fracture mechanics analysis are felt to be of wider interest and significance.

FATIGUE TEST METHOD

Details of the specimens and test techniques used are given in Ref. 1 and outlined below. The specimens were cruciform-welded full penetration joints. All were manufactured from medium strength carbon-manganese structural steel plate to British Standard BS 4360-1979, Specification for Weldable Structural Steel, Grade 50D (modified) using manual metal arc welding, and were not stress-relieved after welding. Type A specimens were made from 25 mm plate, tensile strength 536 N/mm^2, 0.2 per cent proof stress 383 N/mm^2 and loaded axially. Type B specimens were made from 38 mm plate, tensile strength 538 N/mm^2, 0.2 per cent proof stress 370 N/mm^2 and tested in four-point bending. The non-stationary NBR loading load history used is shown in Fig. 1.

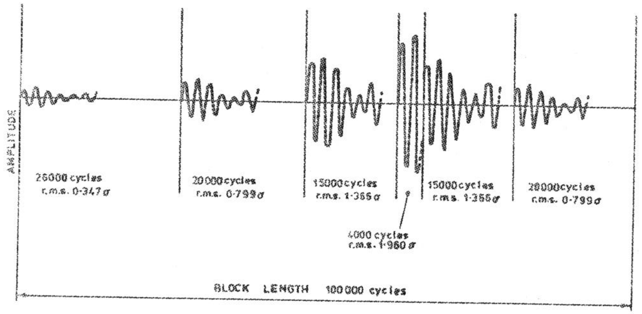

Fig. 1 Load History

The nominal clipping ratio which is the ratio of maximum load to the root mean square load was 7.7. All specimens failed by crack growth in the parent plate at the weld toe. Stresses referred to are nominal elastic direct or bending stresses at the failure site. References to 'yield stress' are to the measured 0.2 per cent proof stress in the parent plate.

The maximum nominal stress for all the tests at zero mean stress was below the yield stress. The mean stress for high mean stress tests was defined by the relationship

$$S_m + 3\sigma = S_y$$

where S_m is the mean stress, σ the r.m.s. stress and S_y the yield stress taken as the specification minimum 0.2 per cent proof stress (345 N/mm^2). To avoid premature failure of specimens by plastic collapse at the occasional high loads in the load history the nominal stress on the specimen was limited by clipping the load signal artificially. The limit used was the flow stress, taken as the mean of the specification minimum 0.2 per cent proof stress and tensile strength (530 N/mm^2). Results are given in detail in Refs 1-3.

FRACTOGRAPHY

A typical fracture surface is shown in Plate 1. Multinucleation was observed in all specimens so that the crack aspect ratio (ratio of surface length to depth) was always large.

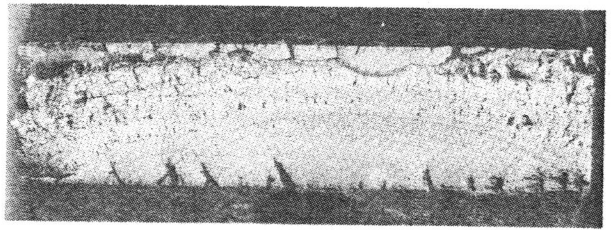

Plate 1. Typical Fracture Surface

Crack-growth data were obtained by measuring the programme marking spacing using a toolmaker's travelling microscope capable of being read to 0.01 mm. Measurements were made along a line passing through one of the multiple origins and at or near the greatest crack depth. Only limited data were obtained for some specimens, and none at all for others. Three factors limited the amount of data which was obtained. Firstly, programme markings below a certain size were not resolvable, even by the use of increased magnification. Secondly, few data were obtained for crack depths of less than 1 mm because of mechanical damage to the fracture surfaces which apparently occurred during the later stages of tests. Thirdly, some programme markings were obscured by corrosion which had occurred subsequent to the tests.

At high mean stress the data extrapolate back to initial flaw depths of between 0.2 and 0.5 mm in accordance with the accepted view that the fatigue behaviour of welded joints is controlled by fatigue crack growth from crack-like flaws of around this depth. This is not the case at zero mean stress, where there is at times evidence of a substantial 'initiation' period. This can vary widely on the two sides of a specimen, although actual crack growth rates on each side of a specimen are generally similar. Comparison of data at high and zero mean stress for similar values of the r.m.s. stress amplitude shows that corresponding rates of crack growth are much the same.

The markings were also used to derive the fatigue crack growth rate data shown in Figs 2-5. To facilitate comparison the same prediction line is shown on all figures. The fatigue crack growth rate data da/dN was taken as the average between adjacent markings. The value of K_{rms} (root mean square value of the stress intensity factor) was calculated for the point midway between adjacent markings. Some points are omitted from crowded areas for clarity.

FRACTURE MECHANICS ANALYSIS

The analysis used, developed in Ref. 2, was based on expressions for stress intensity factors and fatigue crack growth data recommended by Det Norske Veritas. A typical fatigue crack growth threshold (ΔK_{th}) of 200 N/mm^2 was used.

For variable amplitude loading crack growth may be estimated by assuming that the amount of crack growth due to each load level is the same as if it were part of a constant amplitude loading; load levels below the fatigue crack growth threshold make no contribution to crack growth. This linear summation neglects 'interaction' effects which can occur when load levels are changing. The resulting prediction line is shown as a reference in Figs 2-5. However, for NBR loading, interaction effects may be modelled by using linear summation, but taking into accour elevation of the threshold due to the prior loading at the highest loads in the history.

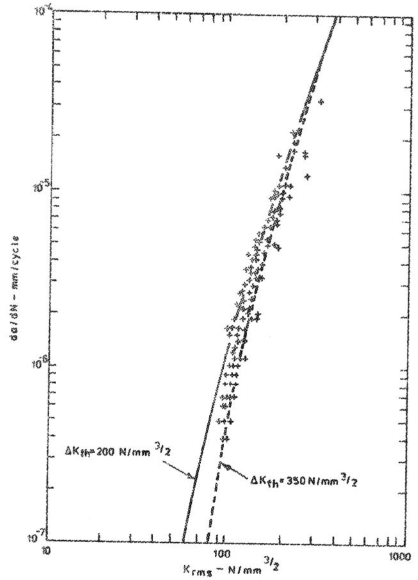

Fig. 2 Zero Mean Stress. Cracks 1½ mm Deep to General Yield.

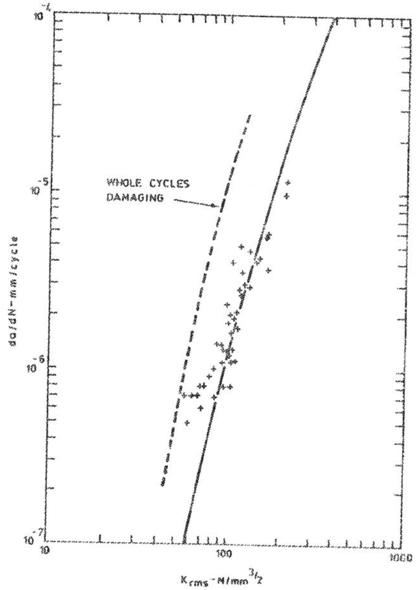

Fig. 3 Zero Mean Stress. Cracks <1½ mm Deep.

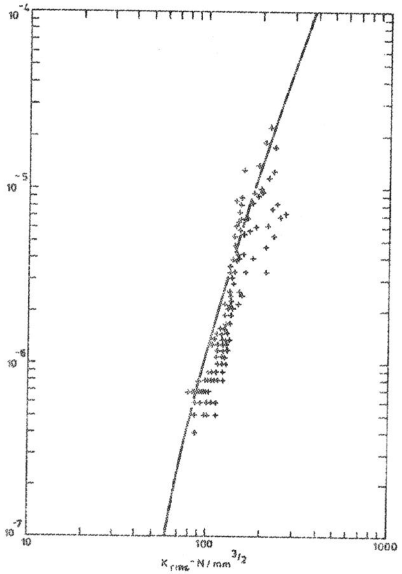

Fig. 4 High Mean Stress. Cracks >1½ mm Deep.

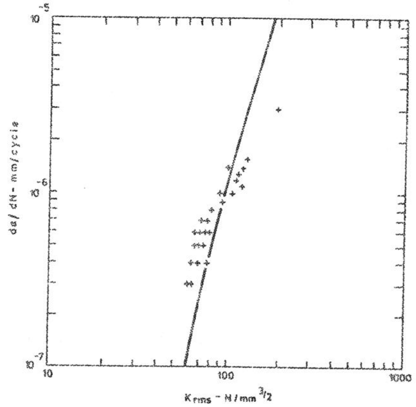

Fig. 5 High Mean Stress. Cracks <1½ mm Deep.

Predictions of crack length against number of cycles were carried out for all the zero mean stress tests for whcih fractographic data were obtained. Predicted crack growth curves compared with the fractographic data are shown in Refs 2 and 3. It was assumed that only the positive part of each load cycle contributed to crack growth.

The fatigue crack growth data derived from the zero mean stress tests are shown in Figs 2 and 3. Figure 2 shows results for medium depth cracks (1½ mm deep to the onset of general yield). The data are tightly grouped and are somewhat conservative compared with the prediction line. A revised prediction line with ΔK_{th} increased to 350 $N/mm^{3/2}$ provides a better fit especially at low crack growth rates. The shallow crack results (Fig. 3) are distinctly faster than those for medium cracks, especially at low crack growth rates. They approach a prediction based on whole load cycles with ΔK_{th} = 350 $N/mm^{3/2}$.

Fracture mechanics analysis of the High mean stress data is more difficult because the highest loads in the load history cause net section yielding. An elastic analysis based on stress intensity factors is not really appropriate although it can give some guidance. Attempts to predict crack growth curves were not very satisfactory(3), but the results imply that the crack is only open on part of the load cycle even at high mean stress. This is confirmed when data are plotted on a da/dN basis (Figs 4 and 5); not surprisingly scatter is greater than at zero mean stress. The increase of crack growth rates over the predicted rates at short crack lengths is much less marked than at zero mean stress.

DISCUSSION AND CONCLUSIONS

Any analysis of fatigue crack growth in residual stress fields is complicated by the difficulty of calculating accurate stress intensity factors, even when the residual stress distribution is known. For the unstress-relieved cruciform-welded joints tested at zero mean stress it can only be inferred through its effect on crack growth behaviour. For crack depths of over 1½ mm the effect of residual stress has died away, and fatigue crack growth rates can be predicted fairly accurately from constant amplitude data using linear summation, together with the assumption that the crack is only open on the positive half cycle. Detailed consideration of crack growth within 1½ mm of the surface is complicated both by the paucity of data and inevitable irregularity of the surface of a welded joint. Nevertheless it is clear that there must be high tensile residual stresses near the surface. There was some evidence of a significant 'initiation' period; the reason for this was not investigated.

Comparison(3) of the high mean stress raw crack growth data with the zero mean stress data shows detail differences in behaviour. At high mean stress there is no apparent 'initiation' period, and for cracks less than 1½ mm deep crack growth rates tend to be slower, but are significantly faster for deeper cracks. Overall the differences cancel out to give similar total lives. The implication is that at high mean stress cracks may only open in the positive half cycle was surprising, but an explanation must await an adequate elastic-plastic analysis.

The established view that for unstress-relieved welded joints fatigue life is controlled by stress range irrespective of mean stress is convenient for many purposes. However the present results show that even where the overall life is similar there may be significant differences in detail crack growth behaviour.

ACKNOWLEDGEMENTS

This paper is published by permission of the Director, National Engineering Laboratory, UK Department of Industry. It is British Crown copyright. The fatigue tests were carried out as part of the United Kingdom Offshore Steels Research Project. The remainder of the work was supported partly by UKOSRP and partly by the Engineering Materials Requirements Board of the UK Department of Industry.

REFERENCES

1 HOLMES, R. and KERR, J. The fatigue strength of welded connections subject to North Sea environmental and random loading conditions. Presented at the Conference on Behaviour of Offshore Structures, Boston, May 1982.

2 POOK, L. P. In ASTM STP 776 Residual stress effects in fatigue. American Society for Testing and Materials Philadelphia, PA (1982) pp 97-114.

3 POOK, L. P. The effect of mean stress on fatigue crack growth in cruciform-welded joints under non-stationary narrow-band random loading. NEL Report in preparation, National Engineering Laboratory, East Kilbride, Glasgow.