FRACTURE MECHANICS BASED DESIGN OF TUBULAR JOINTS FOR OFFSHORE STRUCTURES

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ABSTRACT

The information available on crack growth in tubular joints has been reviewed and it has been found to be possible to provide several methods of crack growth prediction suitable for designers. These models are of varying complexity but in essence comprise three periods; crack initiation, early crack growth and large crack growth. The models can also be categorised as mainly theoretical or empirical. Predictions of fatigue, from these models, are shown for the particular case of a Y-joint and are compared to experimentally measured crack growth.

KEYWORDS

Tubular joints; Y-joints; fatigue; fracture mechanics; fatigue crack growth.

INTRODUCTION

Design of tubular welded connections for offshore platforms is based on the use of Stress/Life curves together with information on the tube dimensions, joint geometry, load history and mode of loading. However the nature of the failure process, for platforms located in the Northern North Sea is such that fatigue cracks are likely to occur after a short interval and to grow slowly for the remainder of the service life even for well defined joints. In these circumstances it is desirable that designers should be able to predict the crack growth curve for a particular joint or the crack growth rate for cracks found during routine inspection. To aid both conventional design and the fracture mechanics aspects research work has been conducted by the Department of Energy (DEn) through the United Kingdom Offshore Steels Research Project (UKOSRP) and the Science and Engineering Research Council (SERC) respectively. The former has resulted in the introduction of parametric equations, to aid stress analysis, and Stress/Life curves specifically for simple tubular joints of wall thickness 16-75mm. The latter work has concentrated on providing a theoretical analysis of crack shape evolution in T and Y joints and comparing these predictions with measured fatigue cracks in joints of 16mm wall thickness.

Sufficient information is now available from both these sources to give safe designs and to provide the fracture mechanics assessment of defects found during service life. The fracture mechanics assessment is not yet as soundly based as the Stress/Life procedure and this paper will assess the information available and the accuracy of the methods currently available.

EXPERIMENTAL RESULTS

Most of the fatigue crack growth measurements on tubular welded joints have been made at University College London (UCL) (Dover 1978, 1979, 1981) and more recently at Det Norske Veritas (Gibstein 1981). In both cases these measurements have been made with techniques based on a.c. field mesurement (Dover and others 1981) and it is now possible to automate such measurements using computer control (Dover 1983). At UCL these measurements are made using spot welded connections connected to a special purpose 64 way switch unit. This system is shown schematically in Fig. 1 and is currently in use for air tests on Y-joints and sea water tests on T-joints. A software package, FLAPS (Broome and others 1983), has been developed for measurements of crack shape evolution and includes also the capability for random load signal generation and graphics. The latter allows one to display the crack shape as it evolves or to display the crack depth versus N curve or the fracture mechanics equivalent da/dN vs Δ K. A typical crack growth curve, obtained in this way will be used in assessing the crack growth models to be presented but the main conclusions found were that crack propagation formed the major part of the total fatigue life and that for a given stress the crack growth rate was almost constant.

Some other data is also available from UKOSRP I work. Here a record was kept for the number of cycles to the first observable crack (N_1) and chord wall penetration (N_2). The stress/life curves used in DEn Guidance Notes are based on N_2. These fatigue tests cover a much wider range of geometries than the fatigue crack growth tests but only give these two points on the growth curve. The data has been reported in Issue M of the revised Guidance Notes (1981) but for the purpose of this analysis some of the results have been re-examined and are presented in Fig. 2, as a plot of N_1/N_2 vs chord wall thickness. This shows that the fraction of the fatigue life involved in initiation decreases as the wall thickness increases. It would appear that the in-plane bending (IPB) and axial tests follow a similar pattern of behaviour but that out-of-plane bending (OPB) tests are quite different and have a much smaller portion of the fatigue life devoted to crack initiation. The fatigue crack growth tests mentioned earlier also showed this feature and it can be attributed to the very poor load distribution found with this mode of loading. The results of Fig. 2 could also be explained on the basis of an initiation period independent of size and a constant crack growth rate (the dashed line which has been normalised to the 16mm data). However it must be remembered that N_2 for a given geometry and stress decreases with chord wall thickness which means that either the initiation period decreases (and the crack growth rate increases) with size or that the slight non-linearities seen in the crack growth period become important with the larger joints.

For the purpose of predicting crack growth in a tubular joint, however, this experimental data could prove to be adequate for the designer especially if the crack initiation life (N_1) could also be predicted. This has been attempted (Iida and others, 1981) using strain/life data for mild steel specimens with the full stress concentration (due to weld and geometry) and Stowell's equations interpreted using the true stress-strain behaviour.

Thus in principle it is possible to calculate the initiation period and with a few simple assumptions produce an elementary crack growth curve.

An example of this procedure will be given later but before doing this it is worth examining the fatigue crack growth experimental data in a little more detail. From the tests conducted at UCL it has become apparent that the failure process up to chord wall penetration can be considered as three distinct periods.

1 Crack initiation
2 Growth of small thumbnail cracks which eventually coalesce
3 Growth of one long crack through to chord wall penetration.

Some results illustrating this point are shown in Fig. 3. These results are from a Y joint tested in air under random loading. It can be seen that two adjacent semi-elliptical cracks formed, grew separately for some time and then joined up to form a single semi-elliptical crack. Subsequent crack growth retained an irregularity in the crack front corresponding to these initial separate semi-elliptical cracks. Measurements of these changes in the aspect ratio, from this stress amplitude are shown in Fig. 4. These indicate that early growth and subsequent large crack growth gave an aspect ratio of approximately 0.1. The coalescence stage is characterised by an aspect ratio of much less than 0.1. For the models to be presented later it has been assumed that a constant aspect ratio of 0.1 can be used.

Following this observation, earlier models, based on a single crack growth rate (Dover and Dharmavasan, 1982, 1983) were modified to form a bi-linear model (Dharmavasan, 1983). These two periods can now be calculated theoretically given the crack size at which they commence. For the model these sizes have been set at 0.25mm and 1.3mm. Period 1 corresponds to the earlier definition of crack initiation (i.e., production of a 10mm surface crack length) proposed by Iida and others and can be calculated by their method. Period 2 is the region for which only a little detailed information is available. The crack growth in this region is currently assumed to be governed by the following assumptions:

$$K = \frac{1.1\sigma\sqrt{\pi a}}{\Phi} \quad \mathrm{MPam}^{\frac{1}{2}}$$

$$a/c = 0.1 \text{ and is constant}$$

$$a_i = 0.25 \text{ mm}$$

$$a_f = 1.3 \text{ mm}$$

$$\frac{da}{dN} = 4.5 \times 10^{-12} (\Delta K)^{3.3} \text{ m/cycle}$$

For period 3 an approximate analysis, based on a proposal by Albrecht and Yamada (1977), has been developed. This method defines a geometric correction F_G, which incorporates the non-uniformity of the stress field in a structural detail. This procedure requires information on the stress distribution in the uncracked body along the line of crack propagation. In the case of tubular, welded joints this would be along the welded intersection and it would be necessary to subdivide these hot spot stresses into bending and membrane components. The function F_G is defined as follows:

$$F_G = \frac{2}{\pi} \sum_{i=1}^{n} \frac{\sigma_{x_i}}{\sigma} \left[\arcsin \frac{x_{i+1}}{c} - \arcsin \frac{x_i}{c}\right]$$

where σ_{x_i} is the stress between x_i and x_{i+1} as defined in Fig. 5. This calculation has been incorporated into a fracture mechanics analysis software package for tubular joints and takes about 30 minutes on a Prime 550 computer, to produce a crack growth prediction.

DISCUSSION

Based on this information it is possible to propose several crack growth models. The assumptions and requirements for these models are listed below.

Model 1 Two Stage Empirical

1 N_1/N_2 as defined by UKOSRP 1 results
2 Constant crack growth rate after initiation
3 Tubular joint stress/life curve gives N_2
4 Hot spot stress

Model 2 Two Stage Part Theoretical

1 Strain/life data
2 Constant growth rate after initiation
3 Life to chord wall penetration given by

$$N = \frac{(t-a)}{(1.39 \times 10^{-13})(t-0.001)(t/0.016)^{0.75}(\Delta\sigma)^{3.0}}$$

4 Hot spot stress

Model 3 Bilinear Empirical

1 Strain/life data
2 Small crack growth 0.25 - 1.3 mm governed by a crack growth rate estimated from

$$K = 1.1\Delta\sigma\sqrt{\pi 0.00025} \quad \text{MPam}^{\frac{1}{2}}$$

and

$$\frac{da}{dN} = 4.5 \times 10^{-12}\,\Delta K^{3.3} \quad \text{m/cycle}$$

3 Large crack growth 1.3 - wall thickness governed by a crack growth rate estimated from

$$K = A(2)^{j}\Delta\sigma\ \sqrt{\pi t/2} \quad \text{MPam}^{\frac{1}{2}}$$

where A and j are constants dependent on geometry and mode of loading.
4 Hot spot stress

Model 4 Three Stage Part Theoretical

1 Strain/life data
2 Crack growth from a semi-elliptical defect of depth 0.25 mm and length 2.5 mm until reaching a depth of 1.3 mm.
3 Crack growth for a crack of constant aspect ratio (a/c=0.1) using the geometric correction factor F_G.
4 Finite element or acrylic model stress analysis of the joint.

The prediction from these four models are shown in Fig. 6 togeher with the experimental results for a tubular Y joint. Model 1 would seem to overestimate the depth throughout the life but would serve as a simple conservative estimate for many purposes. Model 2 underestimates the crack size initially but is quite good thereafter. The most serious drawback here is that there is little guidance on crack growth rates when the crack depth is less than say 4mm deep. Models 3 and 4 provide a better fit to the experimental data but require more effort either in experiment or theoretical calculation.

All of these models require further refinement and assessment but even so it would appear crack growth predictions are currently possible. Indeed current work is directed towards a model that predicts the full crack shape rather than the maximum depth. This has recently become possible because of the development of theoretical solutions for the estimation of stress intensity factors for irregular cracks subject to arbitrary normal stress fields (Albrecht and Yamada, 1977).

One of the features not previously mentioned is that these models can be easily adapted to suit specific environmental conditions known to exist at a crack site discovered during service. Thus a situation concerning cathodic overprotection, where the effects are dependent on crack depth, could easily be incorporated into Models 3 and 4. This phenomenon is described in a separate paper at this conference (Dover and Wilson) and the analysis described here as Model 4 will be applied to this data in the near future.

CONCLUSIONS

The sources of fatigue crack growth information for tubular joints and the stress intensity factor solutions have been briefly reviewed. Several models have been proposed for crack growth prediction, of varying complexity, and these have been assessed against experimental data. It would seem quite practical to use these procedures but a further necessary step would be to assess the confidence one could have in these estimates (by comparing with all available experimental fatigue crack growth data). The final step of developing procedures to predict crack shape has commenced and could be completed in the near future.

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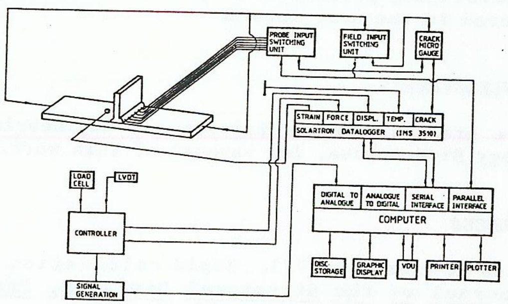

Fig. 1. Schematic diagram of automated fatigue test system for tubular welded joints.

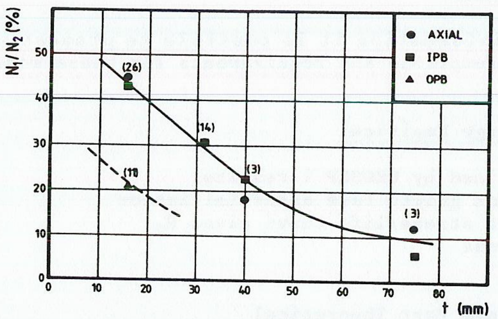

Fig. 2. Variation of the ratio of initiation life to total life with chord thickness for joints tested in UKOSRP I.

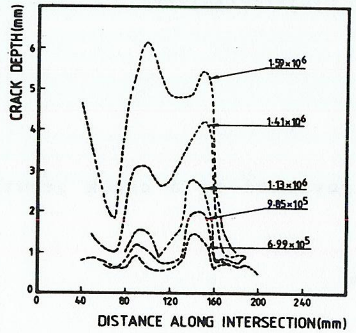

Fig. 3. Crack shape evolution for a Y joint subjected to in-plane bending.

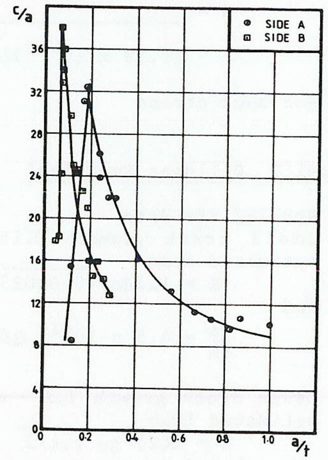

Fig. 4. Variation of aspect ratio with non-dimensionalised crack depth for the results shown in Fig. 3.

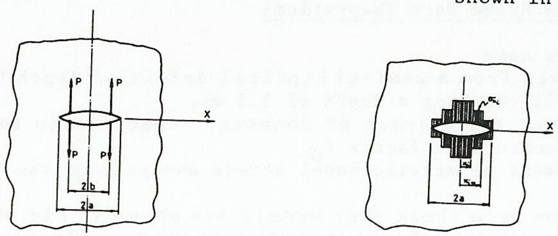

Fig. 5. Definition of parameters used in the derivation of the geometric correction factor F_G.

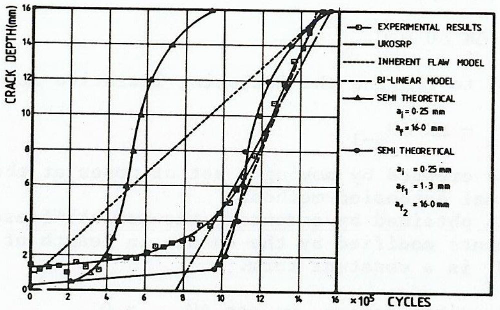

Fig. 6. Comparison of the crack growth curves predicted by the various models with experimental results obtained from a Y joint subjected to in-plane bending.