FATIGUE CRACK GROWTH IN THREADED 'TETHER' CONNECTIONS

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ABSTRACT

Large scale fatigue tests have been conducted on high strength taper connectors of the type used in the Offshore Industry. Periodic inspection of these threads has allowed the measurement of fatigue crack shape as a function of the number of cycles.

A finite element stress analysis of the thread has also been conducted and used to calculate the stress intensity factor. The results from both theory and experiment have been compared and are shown to give good agreement.

KEYWORDS

Fatigue; threaded connection; crack shape.

INTRODUCTION

Oil production platforms that are for use in the deeper waters of the Northern North Sea are likely to be floating platforms. Normally this type of platform is used for exploration rather than production because the motion of these platforms, under wave loading, makes them unsuitable for continuous use over long periods. However this problem can be overcome by tensioning the mooring lines, so that the platform displacement is greater than required for buoyancy and one such design is currently being constructed by Conoco for the Hutton Field.

The mooring lines for this type of platform, known as a Tension Leg Platform (TLP), are not a catenary but are direct links to the sea bed immediately below the platform. The tension leg elements, or tethers, are high strength light weight components, and so far both thick walled forgings and thin walled tubes have been considered for use (the former has been chosen for the Hutton Platform). A common feature of these tethers is that they are connected not by welding but by means of a thread. The design of these threaded connections has received considerable attention in order to provide light weight but good fatigue strength.

The nature of the environment, loading and the steels to be used, however, makes it necessary to conduct Non-Destructive Evaluation prior to service and to regularly inspect the components during service. One of the main requirements for such an N.D.E. is a fracture mechanics analysis based on fatigue crack shape evolution. In order to provide this sort of information for a range of competing designs the SERC funded a programme at UCL which commenced in 1981. This programme includes large scale fatigue tests on model tethers and finite element stress analysis to support the theoretical studies. Some of the preliminary findings from this work are reported here.

Most of the designs proposed so far have been based on tapered buttress threads and these are invariably to be used in service after torquing to produce a joint that will not open during service. This procedure reduces the effect of dynamic loading but only at the expense of introducing a high static preload. In a seawater environment this means that both corrosion fatigue and stress corrosion cracking must be considered as possible causes of failure. For the case of designing to resist fatigue, it is of primary importance in this case to ensure good resistance to crack initiation. However, it is also important that the design should take into account the need for inspection, both from the point of view of access for N.D.T. equipment and crack growth rates sufficiently slow so that failure will not occur between reasonable inspection intervals. A simple point here is that for the thin walled connection, a crack will penetrate the wall before final fracture, whereas for thick walled forging failure could well be from a surface crack. Inspection for the former case is much simpler.

The model tests completed so far have been mainly for the thick walled forging and this work will be presented here.

EXPERIMENTAL WORK

The fatigue tests conducted so far have been on model thick walled tethers, details of which are shown in Fig. 2, and also a proprietary casing type joint known as the VAM joint (licensed by British Steel). The tests have been conducted on a 1000 kN Instron Servohydraulic test machine shown in Fig. 1. The weight of the specimens used was such that crane loading was required and this was conveniently provided by attaching a purpose-built lifting system to the top cross head of the Instron machine. The two main experimental problems for these tests involved the specimen preload and inspection for crack size and shape during the test. The preload was applied for the thick walled tether using cam rings between the pin and box. For the VAM joint a torque rig was constructed of capacity 10 kNm. Both of these systems have proved to be successful.

The inspection technique used was a development from earlier work on threaded bolts (Michael, Collins and Dover, 1983). The system was based on a.c. field measurement using the Crack Microgauge (Dover and others, 1982) but it was quickly realised that two modifications were needed. Firstly, with the tapered threads, it was not possible to produce a uniform field using an impressed current. To overcome this an induced field probe was developed. In essence this type of probe is like a standard probe with an array of parallel field wires attached to it so that the field wires are close to the metal surface under inspection. The second modification concerned data collection. It was soon realised that to obtain detailed information on crack shape in a form suitable for analysis required the system to be automated so that crack shape data would be entered directly into the computer.

These two changes have been made and the inspection system is shown in Fig.3 with the VAM joint being inspected. The joint is rotated using a stepping motor under computer control and the a.c. induced field voltage is measured by the probe seen on top surface of the thread. The probe is machined with a mating thread profile and is constructed so that the probe contacts are on adjacent thread crowns or adjacent thread crown and root. In this way rotation of the VAM joint causes the probe to traverse along the thread recording the variation in measured voltage. The reading of voltage and position is stored automatically on a PDP 11/02 computer which is part of the host-satellite network described elsewhere (Broome, 1983). This system is fitted with graphics so that the crack shape can be displayed or a hard copy produced.

A constant amplitude test has been conducted on a high strength steel specimen of the type shown in Fig. 2. The material composition is shown in Table 1; the loading details in Table 2. The test was interrupted periodically for the purpose of inspection and this meant releasing the cam joint and unscrewing the joint. Release of the cam rings requires the test specimen to be loaded to a value just greater than the preload and certainly higher than the dynamic load. Thus in reality the test consisted of constant amplitude loading with periodic overloads. During the latter stages of the test this produced crack markings and this facilitated optical measurements after completion of the tests. Unfortunately these crack marking sites caused an electrical short circuit across the crack faces so that the a.c. technique was not capable of predicting the full depth. Thus the crack shape curves are a mixture of a.c. and optical and for this test the two measurements could not be compared. However all our previous work suggests that the a.c. readings in the early part of the test are reliable and this can also be seen from the crack growth data to be presented here.

Figure 4 shows the set of crack shape curves produced using the two techniques. The irregularities visible along the crack front are consistent for the two methods and would seem to be genuine. It should be noted that the scales adopted present a magnified view of the crack depth and that in reality these are quite long shallow cracks, two of which eventually joined up to give the final fracture. The final unstable fracture occurred from a surface crack of about 10mm depth. The data has also been replotted to show the crack growth rate at the three deepest points as seen in Fig. 5. This shows that for this test the crack initiation period is very short and also that the crack accelerates only slowly as it extends.

The elastic analysis for the model tether was conducted using the Finite Element package PAFEC on a Prime computer. In order to obtain the correct load distribution through the coupling it was necessary to model the whole connection. This meant that 25 meshing teeth were modelled.

An axisymmetric analysis was carried out using eight-noded rectangular and six-noded triangular isoparametric elements with two degrees of freedom at each node. The interface between teeth was modelled such that only compressive forces could be transferred across the load face. If deflections of the teeth become such that the teeth separated, this was accommodated in the model. Loading was applied as a uniform pressure across the core of the pin, remote from the first tooth. This was reacted at the coupling remote from the last tooth.

The results from the finite element analysis gave principal stresses at each element and node, from which the elastic stress concentration factors were calculated. The analysis also gave the tooth load distribution which is shown in Fig. 6. The size of the job makes it extremely difficult to conduct a 3D analysis of meshing teeth and was beyond the scope of this work. It is considered that an axisymmetric model is adequate for preliminary investigation and comparisons of thread geometry.

In service this type of pin box coupling would be given a preload which has the desirous effect of reducing the dynamic load on the threads, but at the expense of higher mean load. In effect the compressive residual stresses acting across the adjoining faces of the pin and box allow the transmission of part of the external applied tensile forces through the connection in a region remote from the thread. This load sharing between thread and compression faces has to be calculated if one wishes to estimate the local or even nominal stresses in the pin. This nominal stress is required for one particular cross-section; the first loaded thread. A 'finite element' model has been developed specifically for this calculation for the case of tapered buttress threads (N.B. It is also capable of dealing with simple threads.) This model can predict the load distribution along the thread and also the magnitude of the force transmitted directly into the box. In the present case it was found that 41% of the force was transmitted through the pin so that for the fatigue test with a load range of 750 kN only 308 kN would be producing a dynamic stress in the pin. At the cross-section containing the first loaded thread this represents a nominal stress range of 52 MPa for the fatigue test.

DISCUSSION

The eventual aim of this study is to provide designers with the appropriate procedures to allow prediction of crack shape evolution in the threaded connection likely to be used on tethers. At present information on only one type is available but it is hoped that after completion of the programme a more general analysis will be available. In order to compare the predictions between theory and experiment for the model tether described here it is necessary to interpret the measurements made on crack shape evolution during the fatigue test into a more suitable form. In general a fracture mechanics analysis makes use of the stress intensity calibration for a particular geometry. Often this is of the form shown below.

$$K = Y(S)\,\sigma\sqrt{\pi a}$$

where Y(s) is a constant for a particular geometry and crack size. Y(s) can be determined from analysis or experiment and in the present case the estimation of the variation of Y(s) with a/t, where t is the wall thickness, from both theory and experiment is a convenient method of assessing the accuracy of the Fracture Mechanics model.

In general the function Y(s) will be dependent on the specimen geometry, crack aspect ratio and finite section size effects. In the present case it should be possible, for a preliminary analysis, to treat the thread as a circumferential groove in a cylinder for the long crack analysis, but to examine the local stress field at the root radius for small crack growth. One would not expect the crack aspect ratio to be of major importance for this case and this has been omitted from the analysis. Finite section size must be included, however, especially for the long crack analysis. For completeness the crack initiation life has also been calculated.

The analysis requires calculation of crack initiation cycles, small crack growth and long crack growth. Cycles to initiation were calculated using a notch strain analysis (Wetzel, 1977). This model uses the results from the elastic finite element analysis to describe the elastic/plastic stress strain conditions at the bottom of the tooth. The Manson-Coffin strain-life relationship is then used to calculate initiation life. Small crack growth was calculated using the local stress field shown in Fig. 8 together with an assumption of elastic behaviour. Long crack growth was calculated using an analysis by Harris (1967) based on Neuber's approximate stress concentration factors for notches. The results from the strain-life calculation predicted an initiation period of only 30,000 cycles but from Fig. 5 it can be seen that this is quite consistent with the experimental results. The results from the two crack growth analyses are shown in Fig. 7.

In order to assess the accuracy of the prediction in Fig. 7 it is necessary to provide the values of Y(s) from the experiment. This can be done from both fatigue crack growth and the fracture condition provided the basic material properties are known. The specimen tested was made from a low alloy steel of composition and properties shown in Tables 1 and 2. Fatigue crack growth resistance in a similar steel has been measured by Thielen and Fine (1975) and was found to be:

$$\frac{da}{dN} = 1.8 \times 10^{-11} \; (\Delta K)^{3.2}$$

Unfortunately the plane strain fracture toughness was not measured but from published data (Thielen and Fine, 1975) it is likely to be 40 $\mathrm{MPa.m}^{\frac{1}{2}}$ or greater.

Using this information with the preload model it is possible to reinterpret the fatigue crack growth of Fig. 5 into an experimental Y(s) vs a/t curve. The results are shown in Fig. 7. The agreement between theory and experiment shown in Fig. 7 is good and indicates that the approximate stress intensity factor solution is probably adequate for design purposes. It can also be seen from this test that quite a significant portion of the fatigue life, for this design, involves crack propagation. Modifying the thread root geometry, specifically the root radius will improve the crack initiation resistance but possibly at the expense of the crack propagation period as the larger root radius would reduce the S.C.F. but increase the size of the stress field. This aspect forms part of the remainder of the current programme where it is hoped that the rules for optimum thread design will be established.

CONCLUSIONS

1. It has been found to be possible to measure the crack shape evolution during a fatigue test on a large scale taper threaded tether model.

2. This data has been used to assess a fracture mechanics analysis of the thread. The analysis included crack initiation, small and long crack growth and was based on a F.E. stress analysis and a new 'Finite Element' Model for predicting load distribution. The correlation showed that the Fracture Mechanics analysis would be adequate for design purposes.

ACKNOWLEDGEMENT

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TABLE 1 Material Composition and Properties for 4145 Steel

Chemical Composition (%)

C	Si	Mn	S	P	Cr	Mo	Ni
0.45	0.25	0.96	0.033	0.017	1.10	0.25	0

Mechanical Properties

σ_y	σ_{ult}	% Elong.	Red.of Area	Brinell
870 MPa	1100 MPa	16	52%	302/318

TABLE 2 Loading Details

Cyclic Loading
P max = 800 kN
P min = 50 kN
F = 2 Hz

Joint Opening Load = 850 kN

Inspections 60 k, 110 k, 158 k, 207 k, 285 k, 336 k cycles

Failure 375 k cycles

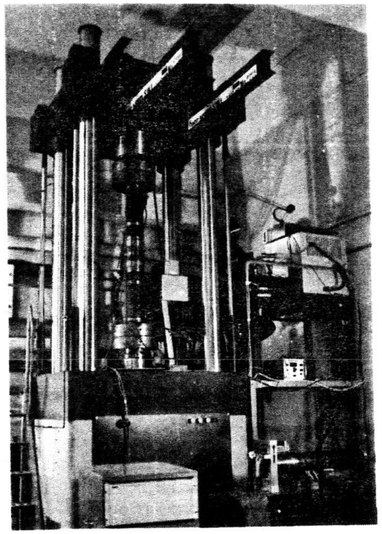

Fig. 1 Servohydraulic test rig.

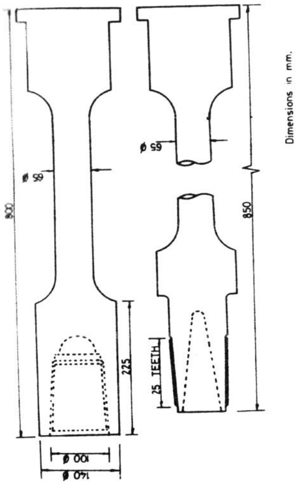

Fig. 2. Thick walled tether.

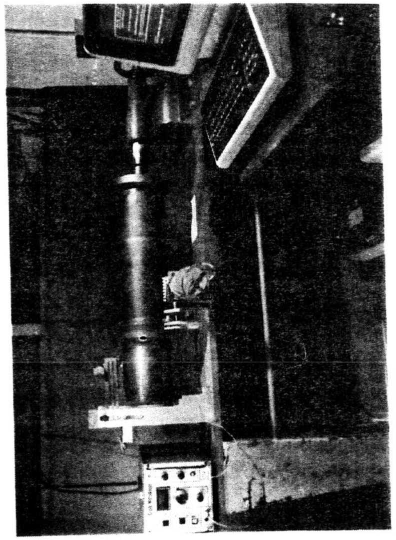

Fig. 3. Automated inspection rig.

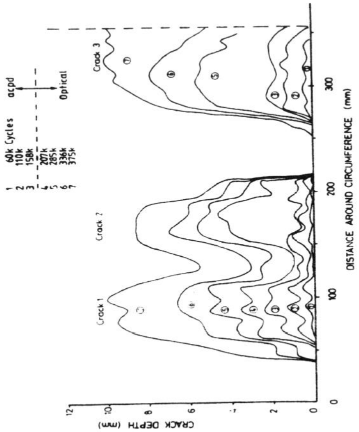

Fig. 4. Crack shape evolution.

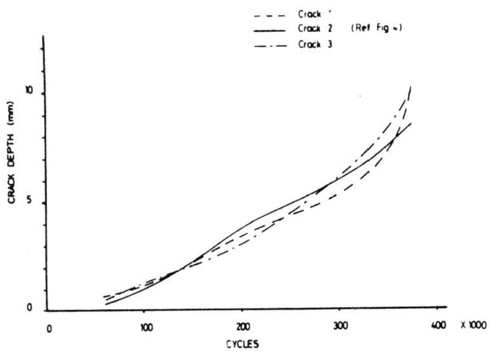

Fig. 5. Crack growth curves.

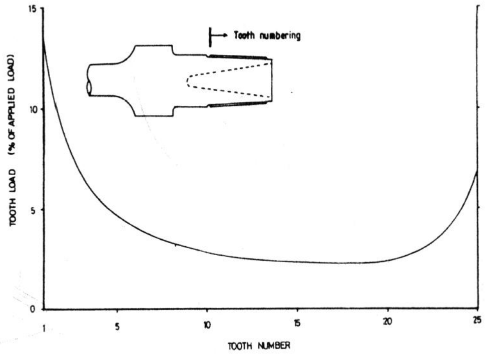

Fig. 6. Tooth load distribution.

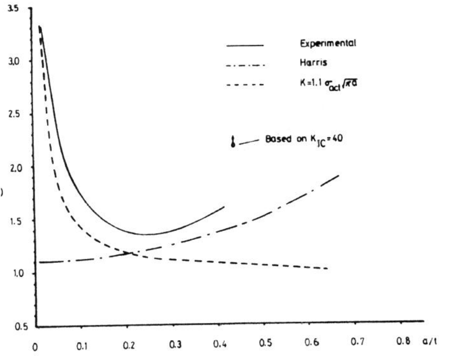

Fig. 7. Comparison of crack growth analyses.

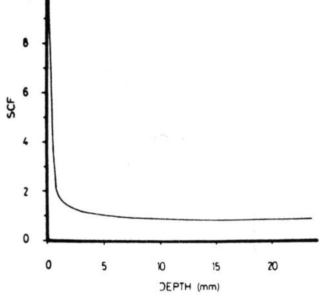

Fig. 8. Local stress field.