FATIGUE CRACK GROWTH IN TUBULAR WELDED T-JOINTS

W.D. Dover and G.K. Chaudhury

Department of Mechanical Engineering
University College London, U.K.

ABSTRACT

A static load test and a random load fatigue test have been conducted, under axial loading, on a tubular welded T-joint.

The static load test showed that the peak S.C.F. in the chord was 9.3. Finite element analysis showed the hot spot stress to consist of both tension and bending stresses.

The growth of fatigue cracks was monitored during the random load test and showed that the crack growth rate was different to that measured in earlier bend tests.

These results show that although the hot spot stress may be used to correlate crack growth data it is probably not suitable for 'stress-life' data.

KEYWORDS

Tubular welded T-joints, fatigue crack growth, hot spot stress.

INTRODUCTION

Concern over the structural integrity of offshore steel platforms has prompted a considerable amount of experimental and theoretical study on the various joint geometries. These studies have included the assessment of both static and alternating (including some random) loads and provided valuable data for the designer(1).

The initial intention was to provide 'stress-life' data but more recently the importance of crack growth has become more evident. This has produced a change in emphasis and redirected the studies towards a fatigue fracture mechanics approach.

A fatigue life calculation based on fracture mechanics requires more information than the 'stress-life' approach. In addition to the local stress value, data is required on the initial defect size, the critical defect size, the fatigue crack growth relationship, a suitable stress intensity factor expression and the mode of crack growth. Of these the provision of a suitable K vs crack length (a) expression has proved to be difficult and little progress has been made on understanding the mode of crack growth.

Previous work (2) has suggested that it should be possible to determine K vs a experimentally from the large scale model tests. In general the stress intensity factor, K, can be defined as follows:

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

where Y(S) is a factor dependent on crack shape and path, and Y(σ) is dependent on the applied forces, the joint geometry and the weld metal geometry. Y(S) and Y(σ) can vary throughout the fatigue life of a tubular joint but it is expected that these variations will only be important for Y(S) during the early life and important for Y(σ) during the later stages. As the only reliable crack growth data was for the later stages of the fatigue life it has only been possible to examine the nature of Y(σ). This has been done by assuming that Y(S) was constant during the later stages.

The procedure adopted was to determine the crack growth curve during the model test and interpret this in terms of da/dN vs a/t where t is the chord wall thickness. Given the crack growth relationship, obtained from simple precracked specimens, it is then possible to interpret each da/dN value in terms of a unique value of K. These values of K are denoted K_{exp}. If one assumes that:

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

then

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

Therefore the plot of $\dfrac{K_{exp}}{Y(S)\ \sigma\sqrt{\pi a}}$ vs $\dfrac{a}{t}$ can be interpreted as the plot of Y(σ) vs $\dfrac{a}{t}$.

The physical interpretation of Y(σ) is that the presence of fatigue cracks alters the local stiffness of the joint. This in turn means that the load path changes so that in effect the hot spot stress changes. This mechanism of local load transfer is one of the main problems met in attempts to resolve the problem analytically. This type of analysis for model test results has already been conducted for both in-plane and out-of-plane bend tests on T-joints (2). The present work reports the data recently obtained for the case of axial loading on joints of similar dimensions.

EXPERIMENTAL DETAILS

As part of materials research programme at the London Centre for Marine Technology a series of tests has been conducted on tubular welded T-joints using in-plane and out-of-plane bend, and axial loading. All the joints were of the same size and were made from BS4360 Grade 50C steel. The joints were fabricated using manual metal arc welding, stress relieved and inspected radiographically. Dimensions of the joints, composition and mechanical properties are given in Tables 1 and 2 respectively.

In all the cases, tests have been conducted in two stages. A static load test is performed to determine the stress distribution, and stress concentration factors, from strain gauge readings. This is followed by a random load fatigue test to determine the nature of the fatigue crack growth and provide information which can be used for the fracture mechanics approach to life estimation. This report covers the axial load tests; the bend tests have been reported earlier (2).

TABLE 1 Joint Dimension

Chord Diameter	18 in (460mm)
Chord Thickness	0.625 in (16mm)
Brace Diameter	12.75 in (325mm)
Diameter ratio	β = 0.71
Thickness ratio	τ = 0.8
Chord thinness	γ = 14.5
Brace thickness	0.5 in (12.7mm)

TABLE 2 Material Properties

Composition

Element	C	Si	Mn	No	S	P
%	0.24	0.55	1.6	0.1	0.06(max)	0.06(max)

Properties

Tensile strength	Yield strength	Elongation	Charpy V notch
500 MN/m^2	350 MN/m^2	20%	20J @ -5°C 7J @ -15°C

STATIC LOAD TEST

Strain gauges, rosettes and linear stress concentration gauges, were attached to the T-joint at sites around the welded intersection. These showed that the saddle region was the hot spot stress site and this was confirmed by a Finite Element stress analysis (3). The strain gradient at the hot spot stress site was measured on the chord and the brace. Linear extrapolation of this data to the weld toe gave an SCF of 9.3 for the chord and 6.13 for the brace.

RANDOM LOAD FATIGUE TEST

The fatigue test was conducted on a 700 KN Keelavite servohydraulic test rig as shown in Fig 1. The pseudo-random load sequence used had a broad band (double peak) frequency distribution and a clipping ratio of 3.9. The peaks were at 0.6 and 1.8 Hz which, on a range count basis, gives an average frequency of 1.69 Hz. The details of the loads used are given in Table 3. The nature of this signal is described in more detail in (4).

TABLE 3 Details of fatigue test loading

Mean load	355 KN
R.M.S. load	91 KN
Theoretical peak loads	0-700 KN

Crack growth monitoring during the tests was by means of the Crack Microgauge, an instrument developed at UCL which is now commercially available (5). This instrument uses an interpretation of a.c. field measurements to provide the crack size at any instant.

RESULTS

Under random loading the effective dynamic stress intensity at the crack tip can be quantified by using the weighted average range, K_h. This is defined as follows:

$$K_h = \sqrt[n]{\overline{h_k^n}} \qquad (2)$$

where h_k is an individual stress intensity factor range and n is the exponent in the fatigue crack growth relationship. For the loading used here, computer analysis showed that $K_h = 2.58\ K_{r.m.s}$ (Kr.m.s.; root mean square of the stress intensity factor. Under constant amplitude loading $K_h = \Delta K$. Thus the growth rate appropriate to a particular value of K_h can be obtained from constant amplitude fatigue data. For the material used in the tests reported here the fatigue crack growth relationship has been shown to be the following for both random load and constant amplitude specimen tests.

$$\frac{da}{dN} = 4.5 \times 10^{-12}\ (K_h)^{3.3} \qquad (3)$$

The fatigue damage was measured at intervals of 0.5 cm around the welded intersection at the weld toe using the Crack Microgauge. The first damage was detected at 9.1×10^4 cycles and appeared to be at more than one site. The crack sizes were monitored throughout the remainder of the test and some of this data is recorded in Fig 2. It can be seen that the cracks commenced in the chord at the saddle point, the region of highest local stress, and spread around the intersection. These cracks commenced in both hot spot regions. The initial cracks would seem to be small, semi-elliptical, cracks. These eventually joined up to form a larger crack of high aspect ratio. Penetration of the chord wall occurred at about 5.5×10^5 cycles. The through crack spread around the intersection from both hot spots until the remaining uncracked section at both crown positions was about 200 mm. The cracks then branched off from the welded intersection and ran parallel to the chord axis in the chord wall. After growth of about 50 mm,in this mode, chord and brace separation occurred as a fast fracture. The total fatigue life for this specimen was 7.5×10^5 cycles.

During the complete fatigue life the crack depth was monitored using the Crack Microgauge. Prior to the chord wall penetration the readings from this instrument could be interpreted directly in terms of crack depth. After wall penetration the readings were interpreted as being an indication of the length of the crack on the inner wall. This interpretation is not strictly justifiable as after wall penetration the a.c. field becomes non-uniform. However the results showed that the crack growth rate increased slowly as the crack spread around the intersection.

One of the problems in determining a crack depth plot is that because the crack shape changes and the several, semi-elliptical, cracks link-up, the depth plot varies with the site chosen. To overcome this the crack depth data has been averaged over 40 mm of the intersection. This average crack depth plot is shown in Fig 3.

DISCUSSION

In order to determine the K history for the fatigue cracks in the hot spot region it is necessary to interpret the a vs N curves in terms of Y(σ) vs a/t. This has been done for the data shown in Fig 3, using Eq.3. The results are plotted in Fig 4. Also included is the trend line for data obtained from the out-of-plane bend tests and a theoretical line for constant displacement cycling of an edge cracked specimen. The value of Y(σ) is always greater for axial loading but it does vary in a similar way to OPB. This implies that considerable local load transfer occurs with both axial load and OPB but that with the former the growth rates are always faster for a given hot spot stress.

For the OPB results it was noted that the value of K_h remained virtually constant for much of the fatigue life. This implies that Y(σ) must be a function of $a^{-1/2}$.

The data for OPB has been analysed to determine Y(σ) in terms of $a^{-\frac{1}{2}}$ and it was found that the following expression was a resonable fit to the data.

$$Y(\sigma)_{OPB} = 0.25\ \frac{t}{a} \qquad 0.16 < \frac{a}{t} < 0.72 \qquad (4)$$

If one performs the same analysis for axial loading the expression is similar and is shown below:

$$Y(\sigma)_{AX} = 0.25\ \frac{t}{a} + 0.28 \qquad 0.16 < \frac{a}{t} < 0.72 \qquad (5)$$

If one transforms these expressions into a stress intensity factor expression they become:

$$K_{OPB} = 0.25\ Y(S)\ \sigma\ \sqrt{\pi t}$$
$$K_{AX} = Y(S)\ \sigma\ (0.25\sqrt{\pi t} + 0.28\sqrt{\pi a} \qquad (6)$$

One possible physical interpretation of these expressions is that for bending one has a situation akin to constant displacement cycling and that for axial loading the same behaviour occurs plus a term which indicates that part of the hot spot stress is producing tensile stress cycling on the intersection. This latter part causes K to increase with crack length thus producing the faster growth rates under axial loading.

One important point to be noticed from this analysis is that for the crack growth stage the data can only be correlated if one assumes that the hot spot stress can be divided into bend and tensile components. As the intiation stage is very short this probably means that attempts to use hot spot stress to correlate the fatigue life for various geometries will not be successful, i.e. it will <u>not</u> be possible to produce one stress/life curve, for all joints, based on hot spot stress. Closer inspection of the fatigue life data (1) reveals that this is true even for the axial load and out-of-plane bend T-joint data.

In the past it has been assumed that if one uses a lower bound curve, fitted to all the fatigue life data, then the resulting designs would be adequate. However unless every conceivable type of tubular joint is tested, and the data included, this would not be true. Continued use of hot spot stress to correlate stress-life data could produce the situation that many joints were heavily overdesigned but that one or two were still underdesigned. Refining of the design approach, from punching shear to hot spot stress considerations, will not give the designer sufficient flexibility. A further step is needed to bring the analysis closer to the real physical model. This can only be achieved by abandoning the stress life approach in favour of the fatigue fracture mechanics approach or providing a series of S/N curves for different geometries.

CONCLUSIONS

1. Crack growth rates in tubular welded T-joints are higher for axial loading, as compared to out-of-plane bending, for a given hot spot stress.

2. Hot spot stress is not a suitable parameter for correlating fatigue life data for tubular joints irrespective of geometry.

3. Fatigue life for tubular joints should be assessed using fatigue fracture mechanics.

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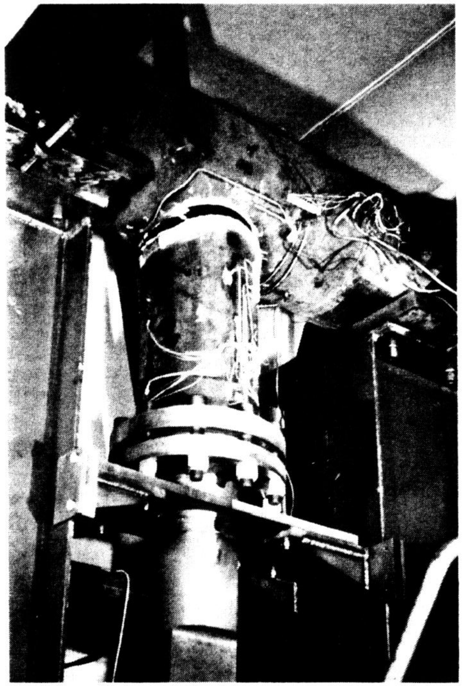

Fig 1. Axial load fatigue test rig for Tubular T-connections.

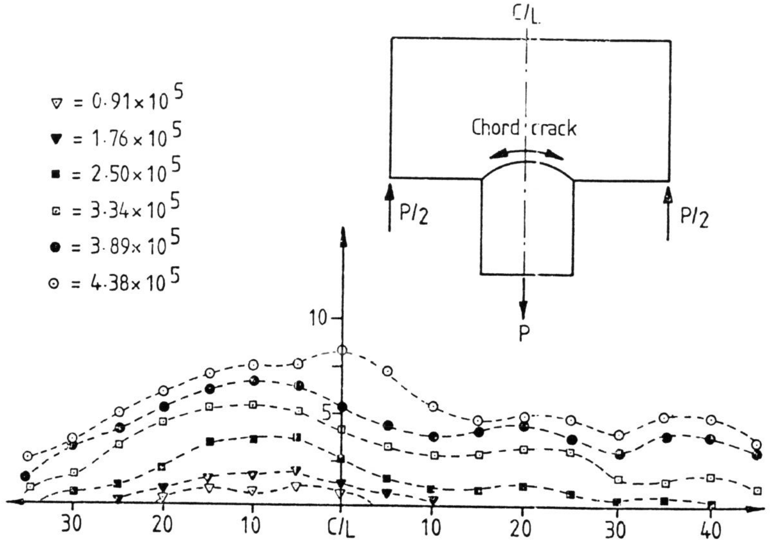

Fig 2. Variations of crack shape during a random load fatigue test on a T-joint subjected to axial loading.

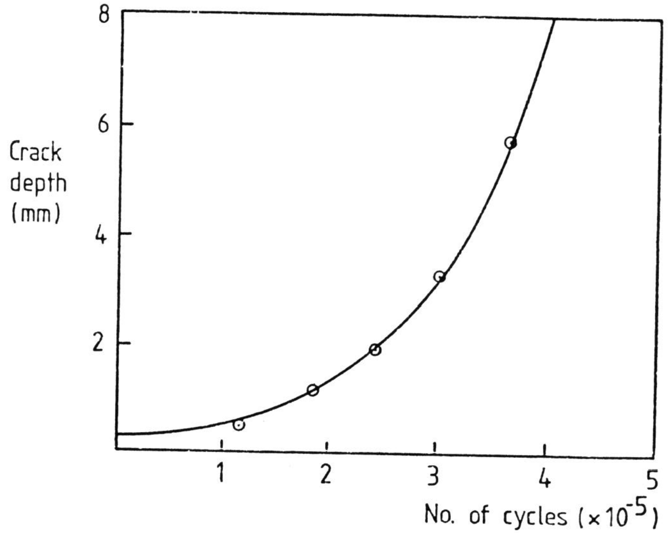

Fig 3. Average fatigue crack growth curve for axial load test on a T-joint.

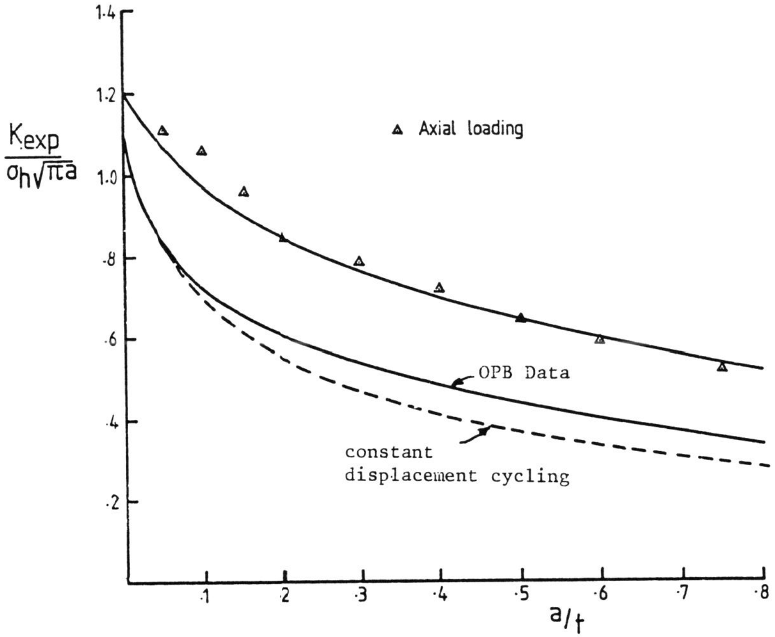

Fig 4. Variation of Y(σ) with crack length for the axial load test.