ON THE LIFE ASSESSMENT OF A THROUGH-CRACKED WELDED TUBULAR T-NODE

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ABSTRACT

The tubular joints of offshore structures are subject to dynamic loading which causes initiation and propagation of fatigue cracks at the welded tubular intersections. When a through crack is detected, an assessment must be made on the remaining life and of the necessity to repair such a connection. From thin shell finite element analysis of a simple T-joint with different lengths of cracks, values of K_I are found in additional to the reduced stiffnesses. The imposition of peak static loads on a cracked node will increase the possibility of tearing and estimates of the loads to initiate tearing are made.

KEYWORDS

Tubular joint, through crack, fatigue, tearing.

INTRODUCTION

The design of large offshore structures has involved the use of large tubular sections, resulting in complex T, K, Y and X nodes. The requirement for data on stress elevation at such welded nodal joints led to a series of parametric equations (Kuang and others, 1977: Wordsworth and Smedley, 1978) relating stress concentration factors (SCF) at the intersection on both chord and brace to the geometric factors defining the joint. Jacket structures (Fig. 1 for example) are highly redundant optimised space frames.

The combination of incipient undetected flaws in areas of high stress concentration and the dynamic nature of the wind, wave and current loads on such structures gives rise to fatigue damage. The initial propagation of surface flaws around a damaged intersection is often difficult to detect by divers especially if the node is encrusted with marine growth. The through-thickness crack and the more significant loss of stiffness is more easily detected and it is this latter situation which is addressed in this paper.

Damage in a node initiates as flaws such as "thumbnail" surface cracks and spreads around the intersection at a significantly greater rate than into the thickness. The modelling of this situation requires 3-D finite element analysis or the use of a simpler shell analysis with "line springs" (Rice and Levy,1972). This latter approach is currently being pursued in order that estimates of initial crack propagation can be made. The later stage of crack propagation is related to the growth of through thickness cracks and this is analysed using a shell finite element approach by "unzipping" the intersection and monitoring the change of compliance and energy. This stage can occupy about 60% of the joint life.

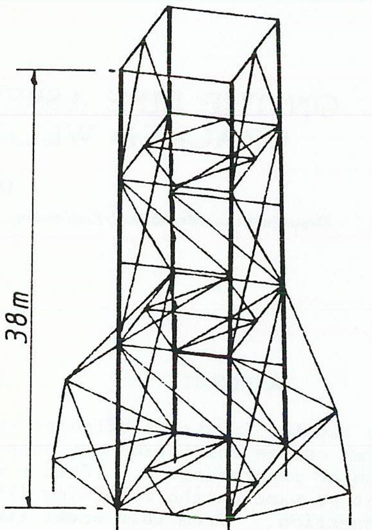

Fig. 1. Example of satellite platform

By calculating the compliance at different crack lengths, the stress intensity factor K_I can be found as a function of crack length 'a' (Brown, 1984). If the node is subject to an alternating load and thus ΔK_I, the crack propagation rate at any particular crack length can be found from the crack growth law for any particular material. As 'a' increases, ΔK_I increases for a similar loading sequence, producing finally accelerated crack growth. But, a damaged joint has a reduced stiffness and in a highly redundant structure alternative load paths will be found to transmit applied loads to the foundations. The net result is that load transmission through a damaged joint will reduce.

At long crack lengths the possibility of tearing will increase. By computing the work done by the applied loads at particular crack lengths values of $\mathcal{G}$ are found. Since any plasticity is very localised values of $\mathcal{G}$ and J are virtually identical. As any static load increases on the node with any particular crack length, the value of J increases until a value of J_C is reached, at which tearing will initiate. At small crack lengths this tearing load is well beyond any design loading and is liable to cause widespread yielding. However as the crack length increases, the critical load is less than the design load and is liable to cause only very localised plastic flow. The effect of reaching J_C at a node which is part of a structure which contains a lot of strain energy, could produce dramatic crack propagation - but this is not discussed further here (Paris and others, 1979).

In order to develope the technique, a relatively simple T joint was selected. The dimensions correspond to a nodal joint used in other experimental programmes (Irvine, 1981; Wylde and McDonald, 1981). The two in-plane loads, axial and bending (I.P.B.) were analysed, in addition to an out-of-plane bending solution which is not used here.

The results of reduced stiffness were applied to a sample 2-D plane beam structure to illustrate load shedding from a damaged joint (Brown, 1984). Although the whole analysis is essentially two dimensional the technique could be generalised to three dimensions and the principles scaled up to a full size structure. The results produced are 'node specific' and, as in the case of the development of the parametric equations, a complete series of cracked node geometries will be required.

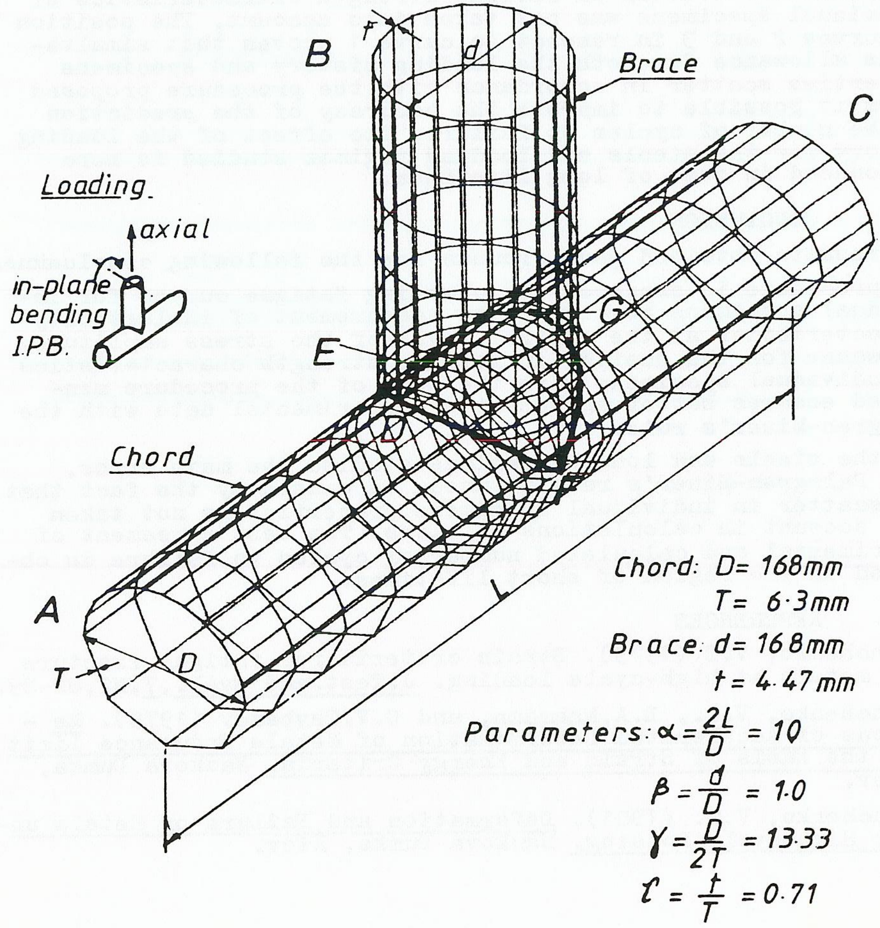

Fig. 2. Finite Element idealisation of T-node

FINITE ELEMENT ANALYSIS

The finite element idealisation of the T node is illustrated on Fig. 2 along with the dimensions. The loading was applied at brace end B with the boundary conditions at chord ends A and C being encastré. The sizes of the elements next to the point D were reduced to assess the accuracy of the effect of mesh size on stress concentration factors.

The 'unzipping' of the node was achieved merely by progressively separating nodes of the lower elements of the brace at the intersection from the corresponding nodes on the chord. This was done symmetrically about D and solutions for 5, 9. 11 (halfway E D F), 15 and 17 nodes separated were produced. No special crack-tip elements were used as they were deemed to little effect the response of the loading end B, at which stiffness and work values were computed.

The node mesh comprised thin shell elements and the solutions were run using FLASH2 (Walder and Green 1982) (Finite eLement Analysis of SHell, version 2) with an optimiser and run on an ICL2976 at the University of Glasgow. Each run took around 550 cpu secs., there being 528 elements, up to 537 nodes and three different loadings (Axial, IPB and OPB).

RESULTS

1. Stress Concentration Factors (SCF):

The SCF is calculated as the highest stress at the interface normalised against a nominal stress. The nominal stress is

$$\frac{\text{Applied Load}}{A_{\text{brace}}} \text{ for axial Loading} \quad \text{or} \quad \frac{\text{Applied Moment}}{Z_{\text{brace}}} \text{ for IPB}$$

where A = cross-section area, Z = section modulus

The highest stress exists at the point D (Fig. 2) on the chord at the brace/chord intersection for this node with axial and IPB loading. Extrapolation from element centroids to the intersection is required for stress values. The stress values used were the summation of membrane and bending stresses and expressed as an effective stress where (in principal stress).

$$\bar{\sigma} = \sqrt{\tfrac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]}$$

Comparison of the calculated SCF's with those from the parametric equations of Kuang (1977) and Smedley and Wordsworth (1978) is given in Table 1. Also given are experimental values as found by Irvine (1981).

TABLE 1 Comparison of S.C.F.

Loading \ Source	Kuang	Smedley & Wordsworth	Irvine (Experimental)	This Analysis
Axial	3.5	4.3	3.7	3.3
IPB	2.6	2.6	-	3.5

The variation in Table 1 illustrates very clearly the difficulty of calculating SCF's. The node geometry is at the validity limits of the parametric equations.

2. Compliance of Cracked Node

From each of the five cracked solutions the axial and IPB stiffness were calculated as:-

$$C_{ax} = \frac{\delta}{F} \quad \text{where} \quad F = \text{applied force on brace}, \quad \delta = \text{average axial displacement of brace end}$$

$$\text{and} \quad C_\theta = \frac{\theta}{M} \quad \text{where} \quad M = \text{Applied moment on brace}, \quad \theta = \text{average rotation of loading points.}$$

The flexibility of the chord was taken into account in each case.

Where U is the work done by the applied load, for a crack length 'a' $\mathcal{G}$ is defined as $\mathcal{G} = \frac{\partial U}{\partial a} = \frac{K_I^2}{E}.t$ in plane stress.

This results finally in

$$\frac{K_I}{P} \left(\text{or } \frac{K_I}{M}\right) = \sqrt{\frac{\partial}{\partial a}\left(\frac{EC}{2t}\right)} \quad \text{where compliance } C = C_{ax} \text{ or } C_\theta$$

The graphs of $\frac{EC}{2t}$ and $\frac{K_I}{P}$ against crack lengths are shown in Fig. 3.

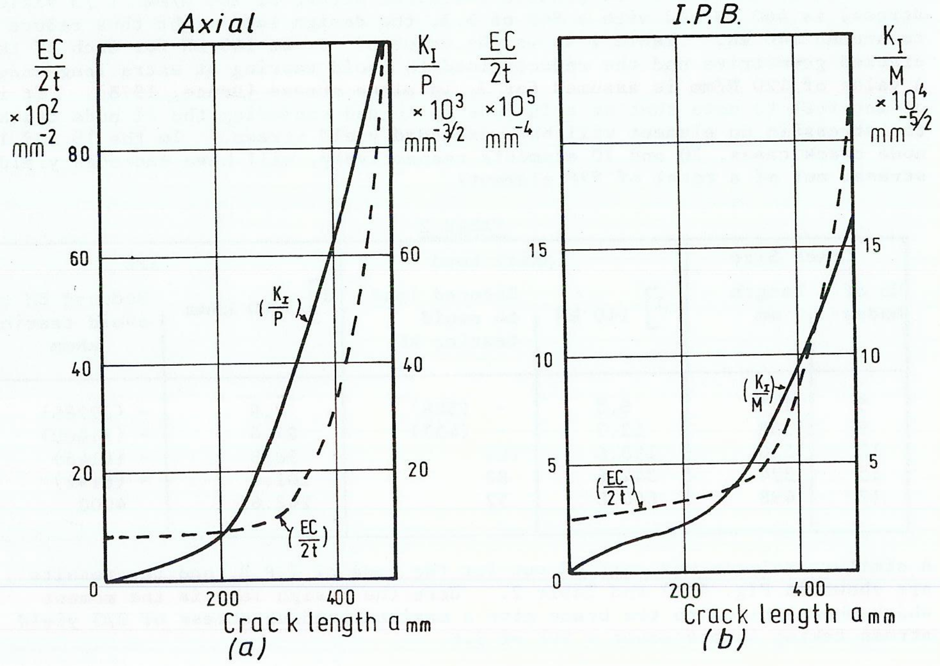

Fig. 3. Evaluation of stress intensity factor

From these graphs it can be seen that for a crack of length 100mm the value of $K_I/P = 3.35\times10^{-3}mm^{-3/2}$. For a tube of the given dimension, a load P of 230 kN will give a nominal axial stress of 98 N/mm^2 (about one third yield stress). Thus the value of K_I equals 24.38 $MNm^{-3/2}$. If the loading alternated 0 to 230 kN, the value of ΔK_I = 24$MNm^{-3/2}$ would be put into the crack propagation curve and produce a crack growth rate.

Similarly for the same crack 100mm in length $K_I/M = 1.91\times10^{-4}mm^{-5/2}$. A moment of 9000kNmm would give a nominal maximum bending stress of 93N/mm^2 and if this moment were applied to the cracked node a K_I value of 54 $MNm^{-3/2}$ would result.

3. Tearing

When the cracked node is progressively statically loaded, the pre-dominantly elastic structure will respond as in Fig. 4(a) under an axial load. At any particular load, say 1kN, the work done by the load $U = \frac{1}{2}P\delta$ increases with increasing crack length due to the greater compliance. If U is cross plotted onto Fig. 4(b) against crack length, the gradient of this graph gives a value of $t \times \mathcal{J} = \partial U/\partial a$ at any particular load. Assuming the structure to be elastic throughout $J = \mathcal{J} = \frac{1}{t}\ \partial U/\partial a$. The value of $\mathcal{J}$ or J at any load greater than 1kN is found by multiplying the gradient value by the square of the load. Thus at 1000N(1kN) $\partial U/\partial a$ = 0.00155 Nmm/mm for a crack length of 143mm. At 70kN, $\partial U/\partial a = 70^2\ 0.00155$ = 7.6 Nmm/mm leading to J = 1.7N/mm.

The value of axial load to produce a nominal stress of 200 N/mm^2 ($^2/_3$ yield stress) is 460 kN and with a SCF of 3.3, the design load might thus reduce to around 140 kN. Table 2 shows the value of J at 140 kN for each of the cracked geometries and the reduced load to avoid tearing at extra long cracks. A value of 120 N/mm is assumed for J_C in plane stress (Druce, 1978). It is of interest to note that on solutions up to and including the 11 node crack the stress in no element will have exceeded yield stress. In the 15 and 17 node crack cases, 30 and 70 elements respectively, will have exceeded yield stress, out of a total of 528 elements.

TABLE 2

Crack Size		Axial Load		IPB	
No of Nodes	Length mm	$J\rbrack$ 140 kN	Reduced load to avoid tearing kN	$J\rbrack$ 5700 kNmm	Reduced BM to avoid tearing kNmm
5	143	6.8	- (588)	7.9	- (22286)
9	258	12.3	- (437)	27.6	- (11800)
11	320	198.6	109	58.8	- (8143)
15	374	344.6	82	101.7	- (6192)
17	498	860.8	52	242.62	4000

A similar analysis was carried out for the case of I.P.B. and the results are shown in Fig. 4(c) and Table 2. Here the design load is the moment which when applied to the brace give a maximum bending stress of 2/3 yield stress taking into account a SCF of 3.4.

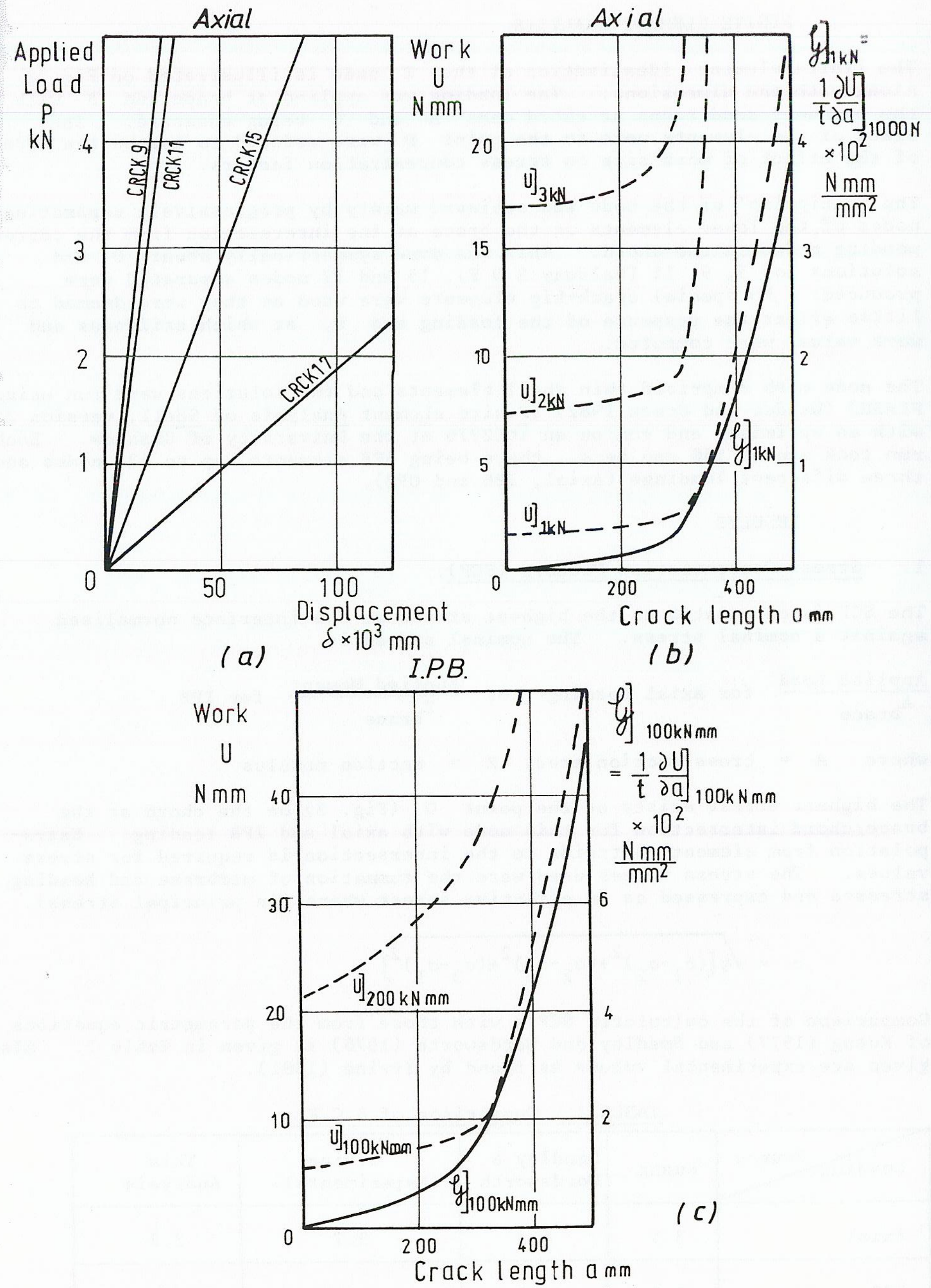

Fig. 4. Evaluation of $\mathcal{J}$

In Table 2, the likelihood of tearing is shown up to be significantly greater in axial loading than in I.P.B. It should of course be remembered that in any real situation a combination of loading would be present and the constituent values of $\mathcal{G}$ (or J) should be added, and the sum compared with J_C.

One of the more difficult parts of the above procedure is in the estimating of the gradient of the graph of U vs a. This is especially critical since this value at 1kN or 100 kNmm is multiplied by the square of the working or design load. Two curve fitting routines were tried - a polynominal fit and a fast Fourier transform (FFT) - but neither was completely satisfactory. It is thought that a truncated exponental series could produce a better function.

CONCLUSIONS

The procedure illustrated above refers specifically to a T-joint of particular dimensions and subject to in-plane loading. However the performance of any nodal joint under general loading could theoretically be treated in a similar fashion. The purpose of the analysis is to find a way to assess the remaining life potential of a significantly cracked joint. This significant proportion of the life is spent either in further fatigue growth or in tearing and an attempt has been made herein to quantify the likelihood of tearing.

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