Recent Development in the Reliability Fatigue Fracture Mechanics Analysis of Welded Structures

J C P KAM *

Welded structures in hostile environment such as the North Sea experience a large number of wave induced stress cycles in service. They are therefore susceptible to fatigue and cracking problems. In order to understand and assess the severity of the situation when such problems arise, fatigue and fracture mechanics analyses are usually employed. However, due to the many uncertainties in practical situations, the analyses need to be probabilistic in nature. This paper reports the development of the reliability based techniques for the fatigue and crack growth assessment of offshore structural components. When combined with non-destructive inspection, the techniques can be used to rationalise inspection, repair and maintenance practice for offshore structures. These will be discussed and illustrated with examples in this paper.

INTRODUCTION

Recent economic activities demand high performance structural components. One example is the large steel structures erected for the exploration and production of natural oil and gas in the North Sea. During the long operational life (up to 25 years), the structures could experience about 150 million wave induced stress cycles [1]. Consequently fatigue has been identified as one of the main causes for the long term degradation of structural integrity. Fatigue in offshore welded joints could occur in a relatively short period of initiation (turning "non-crack like" defects into cracks) and a long crack propagation life. The crack eventually penetrates the wall, resulting in leakage and loss of joint stiffness, and therefore a significant change in structural behaviour. Therefore, wall penetration has been defined by the UK Department of Energy as fatigue failure [2] due to the implications in structural behaviour.

In order to maintain the integrity of these structures, the Offshore Industry has adopted a practice of regular inspections. If defects are detected in-service, they are usually removed by grinding or in some cases by large scale repair. These types of underwater operations are very costly. The recent fatigue research in tubular structures, however, has shown that large fatigue cracks could develop in joints even well within the safe design life [3]. It may therefore be unnecessary to repair all the defects if the components in question can be shown to be "fit for purpose" with fatigue assessment and inspections. These findings have opened new possibilities in the approach of offshore structural maintenance.

* Dept. Mech. Eng., University College London, Torrington Pl., London WC1E

However, the fatigue and fracture mechanics assessment and underwater inspection are by no means completely reliable processes. In practical assessment situations, there are many uncertainties in the controlling parameters. In order to assess the combined effects of these uncertainties and possible "errors" in the modelling techniques, the reliability fatigue and fracture mechanics methodology (RFFM) has been developed. This development will be outlined in this paper and illustrated with examples.

FATIGUE AND FRACTURE MECHANICS ANALYSES

The complete fatigue behaviour of welded tubular joints can be modelled with combined initiation and crack growth analysis [such as 4]. A well established initiation analysis procedure [4] using Neuber rule and Manson Coffin strain-life curve (modified by Morrow mean stress correction) is used in this paper. Other local strain rules and mean stress correction can also be used without affecting the generality of the methodology presented here. The residual stress at the surface has been assumed to be at yield stress level and this assumption agrees reasonably well with experimental measurements [5]. The uncertainties in the materials "constants", (k' and n' in the stress strain curve, σ_f', ε_f', b and c in Manson Coffin's equation), the tolerable cumulative initiation damage (Δ) and the possible error in Neuber's rule (quantified by the variable M) are summarised in Table 1. More details of the equations used in the analysis can be found in [6].

There has been extensive research into the analyses of crack growth in welded tubular joints. The applicability of linear elastic fracture mechanics (LEFM) has also been confirmed [3]. The standard procedure involves the calculation of the stress intensity range (ΔK) and the instantaneous crack growth rate. ΔK is calculated using the effective stress range, taking into account the residual and crack opening stresses. The crack growth rate is calculated by using the weighted average growth rate method [7], which has found much success in the combination of random loading and the multiple segment format of corrosion crack growth data. The uncertainties in all the relevant parameters are summarised in Table 1. The initiation and crack growth are combined through an interface crack size (a_{int}). The uncertainties are given in Table 1.

RELIABILITY ANALYSIS

Having established a reasonably accurate procedure to calculate the mean case (where all parameters are constant and have the mean value in the distribution), structural reliability techniques can be used to assess the effect of uncertainties in the calculations. Given any structural assessment function g (x_1, x_2, ...) with random controlling parameters (x_1, x_2, ...), g can be formulated in such a way that ($g < 0$) represents failure.

The probability of failure (POF) can then be evaluated as,

$$POF = \int_{g(\underline{x}) \leq 0} f_{\underline{x}}(\underline{x})\, d(\underline{x}) \doteq 1 - \Phi(\beta) \tag{1}$$

where β is the reliability index, Φ is the standard Normal cummulative distribution and f_x is the joint probability density fuction of all x's.

Various methods have been developed to evaluate the above integral function, the most popular among the methods are the advanced level II techniques. The technique calculates the approximate POF through the use of β [8].

The fatigue initiation and crack growth analysis can be represented by a g function of the form,

$$g = \frac{N_I + N_{CG}}{N_Y.(time)} - 1 \tag{2}$$

where N_I, N_{CG} are the initiation and crack growth lives respectively. N_Y is the yearly cyclic rate (and time is in years). N_I and N_{CG} are functions encompassing the initiation and crack growth analyses outlined above.

EXAMPLES

The best way to illustrate the methodology is through the use of examples. A T joint is loaded axially under a random load history in sea water with Cathodic Protection. The steel is BS4360:50D. The exceedance curve describing the nominal loading is expressed through a two parameter (A,B) Weibull distribution [6,9]. The local weld defect could, for initiation purposes, induce another local stress concentration. A "defect stress concentration" (K_d) is therefore used in the example. The evaluation of the stress intensity factor is a complex subject as many papers have been published concerning the accuracy and applicability of different techniques. One of the models is used in this example to illustrate the applications. The model [10] uncertainties are quantified through two parameters F and p.

The variability in the yearly cyclic frequency of wave induced cycles (N_Y) is caused by the fluctuations for the occurrences of sea states and the uncertainties in estimating the dynamic response of the structure and members.

Results

The standard result in the RFFM analysis is the 'history' of the reliability index (β) as shown in Figure 1. This information is essential for reliability based maintenance decision making. Another useful set of data is the sensitivity of reliability to small changes in the statistics of the parameters. If the input information is well founded, these sensitivity results can pin-point the most efficient way of reducing uncertainties in the overall calculation by improving the values of individual uncertainty.

RATIONAL INSPECTION PLANNING

It is possible that during service life, the fatigue reliability decreases to an unacceptable level. Therefore, in-service inspections are carried out at regular intervals to "restore" or "update" the reliability to an acceptable level. The underwater non-destructive inspection, however, is not an entirely reliable process. The updating of structural reliability will therefore depend on the inspection reliability.

At the end of the 5th year, a crack is found. Having taken into account the NDI (un)reliability, the true size is deduced to be N (10.mm, 2.mm). The updated reliability history is shown in Figure 1 as the "U" curve. If inspection was carried out at 5 years interval before (5 yrs = a quarter of the operational life, and this is the usual practice in the Offshore Industry), the new inspection interval should be reduced in order to maintain the same reliability level. If repair is to be carried out for several joints, this reliability information could also provide guidance in setting priorities of works and in carrying out cost-benefit analysis. It has also been demonstrated [such as 11] that the methodology is useful for life-extension analysis and reliability re-assessment due to improved information on other input parameters.

CONCLUDING REMARKS

The foregoing has demonstrated that the effect of uncertainties in the fatigue analysis of offshore welded joints can be assessed with the RFFM methodology. The reliability technique used in RFFM, has an added advantage that the same reliability format is used in other more established failure mechanisms such as yielding, buckling and fracture. Therefore, the results in RFFM analysis can be easily incorporated into modern (limit state) design codes. This is an important argument supporting the use of the RFFM technique instead of other probabilistic fatigue models.

As a conclusion, although more refinements and data collection are still needed, major advances have been made in the reliability / integrity assessment of offshore structures subject to fatigue cracking. With the new data in NDI reliability, the Industry is being equipped with a set of tools to rationalise the costly but necessary effort in maintaining offshore structural integrity. Moreover, in-service testing of these techniques will create the scope for further refinements.

REFERENCES

1 Marshall, P.W. "Problems in long life fatigue assessment for fixed offshore structures". Proc. ASCE National Water Resources and Ocean Engineering Convention, San Diego, California, Apr., 1976.

2 Department of Energy. *Background Notes to the New Fatigue Design Guidance for Steel Welded Joints in Offshore Structures.* HMSO, London, 1983.

3 Dover W.D., Dharmavasan, S. ed. *Cohesive Programme of Research and Development into the Fatigue of Offshore Structures, July 1985 - June 1987, Final Report.* UCL, 1989.

4 Glinka, G., Dharmavasan, S., Dover, W.D., "An analysis of the effect of residual stress on the initiation and fatigue crack growth in tubular welded joints". Proc. Int. Conf. Steel in Marine Structures,

5 Porter Goff, R.F.D., Free, J.A., Tsiagbe, W.Y. "Residual stresses in welded tubular nodes". Proc. Int. Conf. Fatigue of Offshore Structures, ed. Dover, W.D., Glinka, G., London, Sept., 1988.

6 Kam, J.C.P., "The recent development and applications of reliability fatigue fracture mechanics analysis". Submitted to be published in Int. Jnl. Computation Mechanics Comm., 1990.

7 Kam, J.C.P., Dover, W.D. "Corrosion fatigue of welded tubular joints : fracture mechanics modelling and data interpretation". Proc. 8th Int. Offshore Mechanics and Arctic Eng. Sym., ASME, The Hague, Apr, 1989.

8 Madsen, H.O., Krenk, S., Lind, N.C. *Methods of structural safety.* Published by Prentice - Hall Inc., 1986.

9 Pook, L.P. *Approximation of two parameter Weibull distribution by Raleigh distributions for fatigue tests.* National Engineering Laboratory Report, UK, 1983.

10 Kam, J.C.P., Topp, D.A., Dover, W.D. "Fatigue fracture mechanics modelling and structural integrity of offshore welded tubular joints". *ASME Trans. Jnl. Offshore Mechanics and Arctic Engineering,* Vol 111 Aug., 1989 pp 170 - 176.

11 Kam, J.C.P. "Fitness for purpose assessment of tubular welded joints in offshore structures". Proc. 7th Int. Offshore Mechanics and Arctic Eng. Sym., ASME, Houston, Feb., 1988.

Table 1 Input Parameters for the Example

Effective chord length = 4000. mm
Brace diameter = 767. mm
Chord diameter = 1080. mm

Brace wall thickness = 45 mm
Chord wall thickness = 45 mm = a_f

$RMS = 1.0\,MPa$ (see $\hat{B}$ for uncertainties)
Target life = 20 years
Hot spot SCF = 10. (see $\hat{K}_t$ for uncertainties)

Variable	Mean	Standard Deviation	Type of Distribution
A	1.53	0.322	Normal
$\hat{B}$	0.7	0.26	Log Normal
$\hat{K}_t$	0.85	0.20	Normal
K_n	1.75	0.586	Normal
K_d	3.23	2.643	Log Normal
M	0.8	0.1	Normal
n'	0.177	0.018	Normal
k'	1063. MPa	100. MPa	Normal
E	210. GPa	10. GPa	Normal
b	- 0.102	0.01	Normal
c	- 0.604	0.06	Normal
σ'_f	982. MPa	100. MPa	Normal
ε'_f	0.72	0.07	Normal
Δ	1.0	0.2	Log Normal
F^*	0.4696	0.014	Log Normal
p^*	0.0555	0.011	Log Normal
r	0.5	0.1	Normal
a_{int}	0.35 mm	0.309mm	Log Normal
$C_1{}^+$	3.6337E-12	3.1237E-12	Log Normal
$C_2{}^+$	1.3829E-11	1.0220E-11	Log Normal
N_Y	6. M cycles	1.25 M cycles	Normal

* = parameters used in the fracturemechanics model[10], + = for da/dN in (m/cycle), ΔK in (MPa $\sqrt{m}$), $m_1 = 3.77$, $m_2 = 2.99$

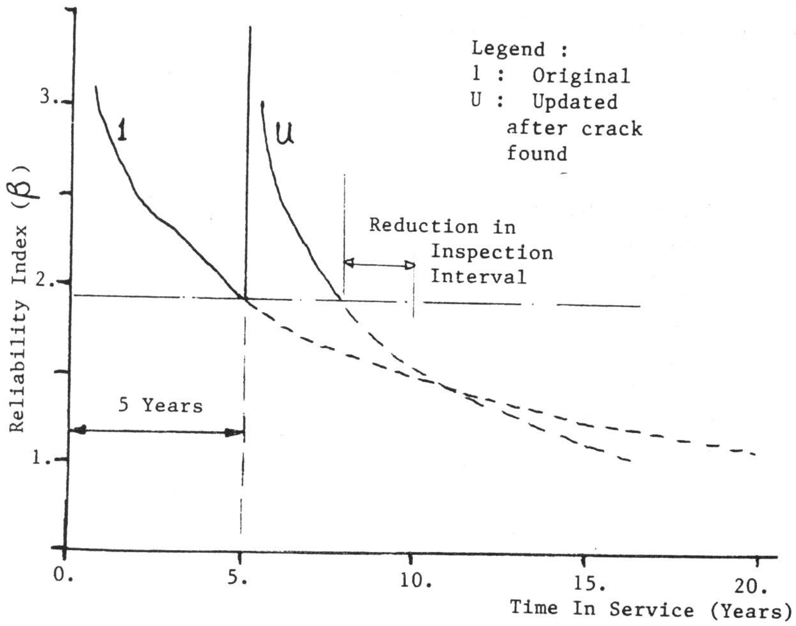

FIGURE 1 RELIABILITY HISTORY OF A WELDED TUBULAR JOINT