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Fatigue Life Evaluation of Butt-Welded Tubular Joints

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ABSTRACT: *Recent deepwater offshore structures in the Gulf of Mexico utilize butt welded tubular joints. Application of a welded tubular joint includes tendons, production risers, and steel catenary risers. Fatigue life assessment of these joints becomes more critical, as the structures to which they are attached are allowed to undergo cyclic and sometimes large displacements around an anchored position. Estimation of the fatigue behavior of these tubular members in the design stage is generally conducted by using S-N curves, as specified in the codes and standards. Applying the stress concentration factor of the welded structure to the S-N approach often results in a very conservative assessment, because the stress field acting on the tubular has a non-uniform distribution through the thickness. Fatigue life analysis using fracture mechanics has been applied in the design of the catenary risers. This technology enables the engineer to establish proper requirements on weld quality and inspection acceptance criteria to assure satisfactory structural integrity during its design life. It also provides guidance on proper design curves and a methodology for accounting for the effects of non-uniform stress distribution through the wall thickness. Still, there is inconsistency when designing tubular joints using a conventional S-N approach and when specifying weld flaw acceptance criteria using fracture mechanics approach. This study developed fatigue curves that are consistent with both the S-N approach and the fracture mechanics approach. Accounting for non-uniform stress distribution and threshold stress intensity factor were key parameters in relating both approaches. A series of S-N curves, generated from the fracture mechanics approach, were compared to the existing S-N curves. For flat plate butt joint, the S-N curve generated from fracture mechanics matches with the IIW class 100 curve when initial crack depth was 0.5 mm (0.02). The new curves for tubular joint agree very well with the experimental results. The comparison also indicated the degree of conservatism built into the API X design curve.*

1. Introduction

In the Gulf of Mexico, future trends will include oil and gas developments in water depth in the range of 900 ~ 1800m (3,000 to 6,000 feet). These developments require such deepwater structures as the tension leg platform (TLP), a moored floating production system and the compliant tower. There are several aspects that must be considered for deep water applications (Oil & Gas Journal, 1993; Kim and Smith, 1994), because shallow water applications generally do not require floating systems.

Many parts of the deepwater structures are allowed to undergo large displacements around an anchored position. The steel catenary riser (SCR) is a typical example of such a system. For many years, the steel catenary riser has been considered as an option for the transport of gas and crude oil from offshore platforms. A steel catenary riser is, in essence, an extension of the pipeline, suspended in a near catenary shape form a TLP or other floating production system to the sea floor.

One of the significant considerations during the initial design stage of SCR is the integrity of the welded pipeline under various loading conditions. Designing a riser system for deepwater requires consideration of fatigue life of the welded joints. To assure sufficient fatigue life throughout its designed life, establishing acceptable criteria for weld quality is an important task. Estimating the fatigue behavior of the material in the design stage is generally conducted by using S-N curves in the codes and standards, such as the American Welding Society (AWS) (1992), Department of Energy (DOE, 1984) of United Kingdom, or American Petroleum Institute (API) (1987). These curves are obtained from an empirical relationship, established from fatigue test data. Although the S-N curve approach is effective in predicting the total fatigue life, a fracture mechanics analysis

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is more appropriate to predict the tolerable fabrication flaw size. The fracture mechanics approach requires information on non-uniform stress distribution in the anticipated crack plane, a stress intensity factor, and a crack growth rate for the material in the environment of interest.

Recent development of offshore designs has provided the impetus for the introduction of fracture mechanics into offshore design. API recommends the use of fracture mechanics as a basis for reliability assessment in TLPs (DOE, 1984). The willingness of the industry to adapt to this new technology is motivated by a number of factors: 1) the use of higher strength materials, 2) acknowledging that weldment can have minor flaws, 3) better guidance on inspection and repair, and 4) capability of detailed case specific analysis. Fracture mechanics and fitness for service (FFS) technology have been applied in the design of the catenary risers for a TLP (Kim and Kopp, 1998). This technology enables us to establish proper requirements on weld quality and inspection acceptance criteria to assure satisfactory quality during its designed life. It also provides guidance on proper design curves to be used and a methodology for accounting for the effects of wet H_2S on fatigue. Fatigue cracks of SCRs are likely the result of the initiation and growth of small surface cracks at the root or toe of a weld. These cracks will continue to grow under the cyclic loading, excited by the relative movement of the floating system and the riser. The fracture mechanics approach utilizes the effects of non-uniform stress distribution through the wall thickness, initiated from the root of the weld.

Historically, design of the welded tubular joint has been based on S-N curves, generated from smooth base metal specimens (Barsom and Vecchio, 1997). A factor of 20 was imposed to account for scatter of test data and a stress concentration factor of the welded joint by Maddox (1993). And many others (DNV, 2000; Canadian Standards Associations, 1999; API, 1999) have developed some forms of stress concentration factors or hot spot stress concepts in order to consider the local stress concentration effect. Connelly and Zettlemoyer (1993) proposed a stress concentration equation that does not utilize through-wall stress distribution. Most of the welded joints show high stress concentration at the surface, but the high stress concentration diminishes at a certain depth. Recently, Dong et al. (2002) proposed a master S-N curve that accounts for through-thickness stress distribution that is suitable for any type of welded joints. The master S-N curve is based on nodal equivalent stresses, which can be decomposed into membrane stress and bending stress.

When designing steel catenary risers, both S-N and fracture mechanics were applied. However, the technical basis for these two approaches is not the same. Therefore, there is inconsistency between the two methods. Prior to this study, many studies, such as the hot spot stress, stress concentration approach, and equivalent stress concepts were used for the better prediction of fatigue life. Prototype experimental test results indicated that a tubular welded with GTAW root showed better fatigue performance than with SMAW root. This data illustrates that a local stress distribution plays a role in fatigue life. This study developed fatigue curves that are consistent with both the S-N approach and the fracture mechanics approach. Non-uniform stress distribution and threshold stress intensity factors were key parameters to relate both approaches. A series of S-N curves, generated from a fracture mechanics approach, was compared to the existing S-N curves.

This approach reduces the effort of extensive fatigue life assessment using fracture mechanics. In the fracture mechanics (*da/dN*) approach, the initial crack size is sensitive to the fatigue life. The initial crack size is determined using a threshold stress intensity factor, which is a function of external loading. The results were compared with the existing S-N curves, as published in the International Institute of Welding (IIW) and the American Petroleum Institute (Hobbacher, 1997).

2. S-N Curve and Fracture Mechanics Approach

Typically, the S-N curve is expressed as follows:

$$N = A \Delta\sigma^{-m} \tag{1}$$

Fatigue life is evaluated based on linear elastic fracture mechanics and Paris Law. The Paris Law is written as:

$$da/dN = C(\Delta K)^n \tag{2}$$

where ΔK is the range of stress intensity factor, da/dN is a crack growth rate per cycle and C, n are material constants.

The range of stress intensity factor in a cylinder with an internal circumferential crack is expressed as:

$$\Delta K = \Delta\sigma\sqrt{\pi a}\, f(a/t,\, t/R_i,\, a/2c) \tag{3}$$

where c and, a are half crack length and depth, t, R_i are thickness and inner radius of tubular members.

Then, fatigue life is calculated by integrating the equation (2) from initial crack depth, to its critical crack depth which is calculated from the fitness for service method (API RP 579, 2001).

$$N = \int \frac{1}{C(\Delta K)^n} da = \frac{1}{C\pi^{n/2}} \int_{a_i}^{a_f} (\Delta\sigma \cdot f)^{-n} a^{-n/2} da \tag{4}$$

a_i and a_f are the initial and final crack depth respectively.

Assuming the shape function f is insensitive to crack size, the equation can be simplified as follows:.

$$N = \frac{-2}{C\pi^{n/2} f^n (n-2)} \Delta\sigma^{-n} (a_f^{-n/2+1} - a_i^{-n/2+1}), \quad n \neq 2 \tag{5}$$

Through examination, one sees that equation (5) is expressed in very similar terms as equation (1).

The final crack depth a_f is determined using fracture mechanics, depending on the toughness of the material:

$$a_f = \frac{K_c^2}{\pi f^2 (\sigma_m + \Delta\sigma)^2} \tag{6}$$

where σ_m is a mean stress.

There are many ways to determine the initial flaw size (a_i). In the tubular joint design approach, using fracture mechanics, the initial flaw size is determined by the total number of cycles experienced during the 30 years of its design life. The design life should consider a safety facto. Hence, the initial flaw size is used as an acceptable inspection criteria, allowing for inaccuracies in the particular inspection system. In this study, the initial crack size is also calculated as a function of a threshold stress intensity factor.

$$a_i = \frac{\Delta K_{th}^2}{\pi f^2 (\Delta\sigma)^2} \tag{7}$$

The stress range used in this calculation is the maximum stress during its life cycle.

3. Results and Discussions

For preliminary design of the SCRs, several S-N curves from the existing codes and standards were examined. They are AWS C1, DOE E and API X and X'. Fig. 1 shows comparison of these curves on the same scale. As shown in the curve, the DOE E curve is more conservative than the corresponding AWS C1 and API X in the low stress amplitude region. Prototype test results of welded pipes, with manual gas tungsten arc welding (GTAW) root pass, revealed that the API X' curve for the butt-welded joint was appropriate.

A fatigue design, based on fracture mechanics, was performed in order to define an acceptable flaw size. Sensitivity analyses of fatigue life for various conditions were conducted. Parameters studied were initial crack size, stress distribution near the toe of the root weld, the threshold stress intensity factor (K_{th}), and the crack growth rate. The fatigue analysis was conducted using **PREFIS,** a software code designed for API RP 579 Fitness for Service.

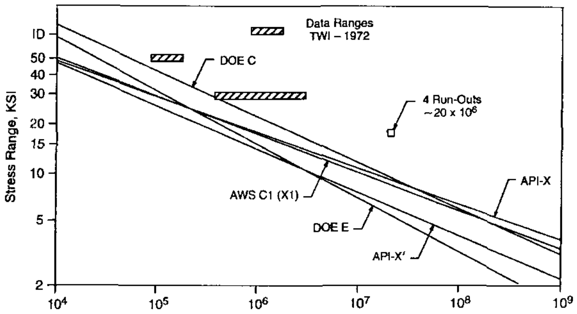

Fig. 1 Comparison of various fatigue curves

3.1 Butt welded flat plate

The fatigue life, as calculated from fracture mechanics, was compared with the IIW Class 100 curve for a welded flat plate. The data used for this assessment, shown in Table 1. Fig. 2, shows a comparison between IIW class 100 (butt welded joint) and the fracture mechanics approach. The comparison indicates that both curves match well with initial crack size with a depth of 0.5mm (0.02") and crack length 5mm (0.2"). The curve also shows the degree of conservatism built into the S-N curve. The fracture mechanics approach can reduce the degree of conservatism by introducing a reliable inspection system that can detect cracks smaller than 0.5mm deep.

3.2 Butt welded tubular joint

(a) Experimental fatigue testing

Several prototype fatigue tests were conducted to prove that the 305mm (12") welded pipe will have a sufficient fatigue life. The test configuration and dimension of the test specimen is shown in Fig. 3. Six welded tubes were tested, simultaneously. The diameter and thickness of the pipe is 305 mm and 16 mm, respectively. A special customized fatigue-testing machine was created to test this multiple welded joint. Total height of the specimen is 4.7m and the top and bottom of the test specimen was loaded into a tensile fatigue machine. Several strain gauges were attached for each weld. The specimen was designed to receive uniform stress at each weld, based on a finite element analysis. Various welding processes (SMAW root and GTAW root) were applied to check the effect of welding process on fatigue life. In some tests, if one weld fails, the weld is cut out and replaced with a new tube. The test continues until the next weld fails. A summary of the tests is plotted in Fig. 2, indicating that the test results are in good agreement with the S-N curves in the codes at high stress range. However, at stresses below 20 ksi, API X' predicts more conservatively than the test data. One of the reason for using an overly conservative estimation from the code S-N curve is that a conventional stress concentration factor did not consider through wall stress distributions..

Table 1 Input values used in flat plate fatigue life calculation (Kim and Kopp, 1998; Hobbacher, 1997)

S-N	A	2×10^{12}	1.1×10^{16}
	m	3	5
Da/dN	C	4.95×10^{-13}	
	n	3	
	K_{th}	$2.2MPa\cdot m^{0.5}$	

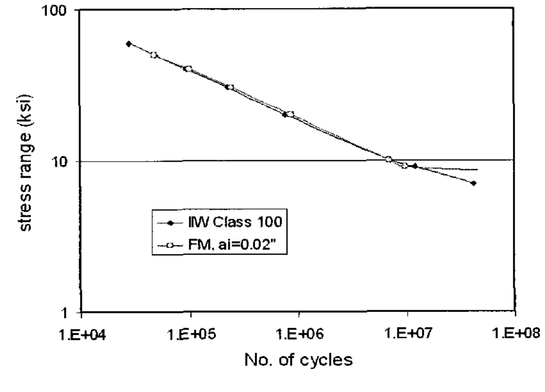

Fig. 2 Comparison of fatigue life between S-N and fracture mechanics of butt welded plate with surface crack (2c/a=10)

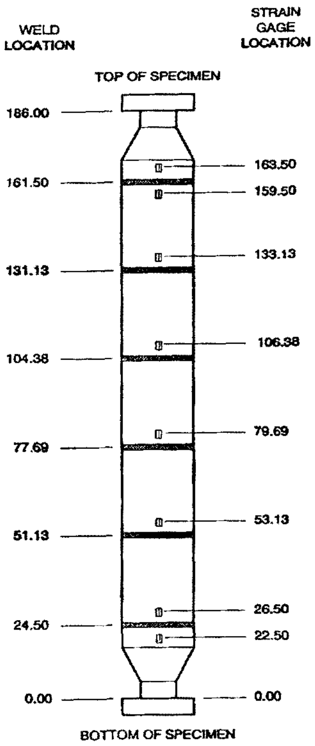

Fig. 3 Fatigue test of tubular welded joint

(b) Stress distribution

A single side-weld tubular joint contains weld root intrusions, as well as weld cap flaws. Geometrical discontinuity, such as root profile, creates a local stress concentration. misalignment, and eccentricity of the tube product also creates a non-uniform stress distribution through the wall thickness. Fig. 4 shows a typical cross-section of a welded tubular joint that failed during the fatigue test. Fig. 5 shows the through-thickness stress distribution of the joint. The stress distribution was obtained from a finite element analysis, by digitizing the weld profile for a root radius of 1.27mm (0.05"). The figure illustrates that highly localized stresses are concentrated near the weld root, with a stress concentration factor 1.6. Various finite element analyses indicated that the stress concentration factor strongly depends on the root radius at the root weld toe. For fatigue life analysis, however, the overall stress distribution is equally important to highly localized stress concentration factors. Fatigue lives were calculated for various stress distributions for various root radii of the weld profile digitized from the failed sample. Fig. 6 shows the comparison of fatigue lives of SCR with a crack for different through-thickness stress distributions for different root radii. The figure indicated that the local stress concentration factor at the root has little effect on the crack propagation life.

The result of the comparison also brings concerns about the definition of the stress concentration factor. The solid line in the figure represents a simplified stress field, which is the stress concentration factor 1.32 at the root of the weld accounting for bending stress due to misalignment, and decreases linearly up to 15% of the wall thickness. The stress concentration factor 1.32 was determined by multiplication of local bending due to mismatch 1.1 and local stress concentration 1.2. The linear distribution was established using the concept of local stress distribution at fillet-welded joint per BSI PD 6493 (1991). The simplified stress distribution provided comparable, yet conservative, fatigue lives. The stress concentration effect was further reduced, using the equation provided by Connelly et al (1993).

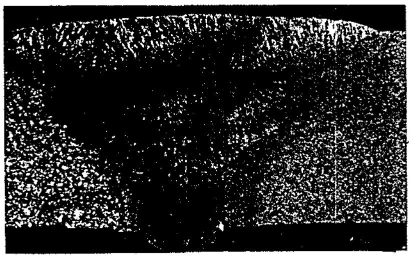

Fig. 4 Local welded profile

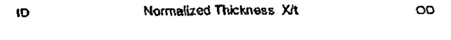

Fig. 5 Local stress distribution through thickness

(c) Effect of fatigue crack growth rate

A number of crack growth rates were obtained for various environments and stress ratios. A fatigue crack growth test program was initiated to (1) develop crack growth properties specific to the SCR environment, and (2) establish the existence of ΔK_{th} since this seems beneficial to the improvement of corrosion fatigue life. Proper crack growth rates and thresholds in various environments were determined from the test program (Hudak and Connolly, 1992).

Based on the test results, four test conditions were examined to cover various possible situations expected for risers. The fatigue crack growth is best represented by using a bi-linear curve with threshold (ΔK_{th}) as shown in Fig. 7. Two bi-linear crack growth curves used for this fatigue life assessment are given in Table 2.

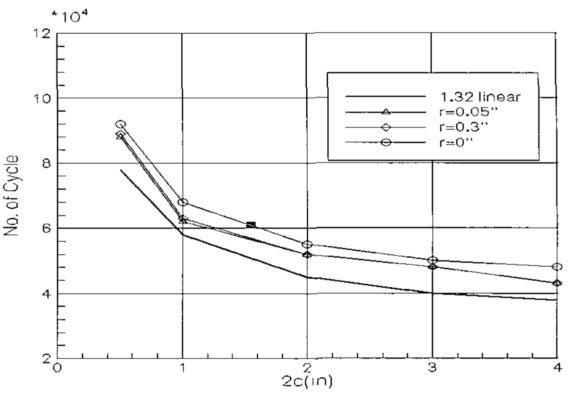

Fig. 6 Comparison of fatigue life at various stress distributions

Fig. 8 shows a comparison of fatigue life between testing and results of the fracture mechanics approach, using the through-wall stress distribution. The full-scale fatigue test results indicate that the API X curve provides conservative fatigue life for riser tubes. The curve obtained from fracture mechanics agrees well with the test results, and is still on the conservative side. The figure also shows that GTAW weld root shows slightly better fatigue life than SMAW root, which is generally understood, due to the smooth weld profile and a lack of weld discontinuities. The figure illustrates that fatigue life can be predicted using fracture mechanics, and the curves matche with existing codes and standards when the initial crack is less than 0.5 mm (0.02") deep.

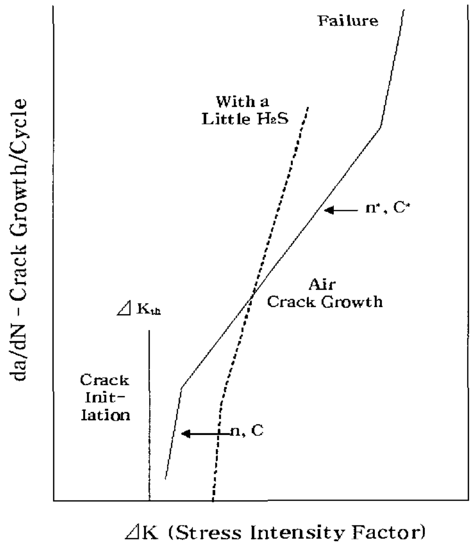

Fig. 7 Bi-linear crack growth rate curve

Table 2. Crack Growth Rate Constants

	C	n	C*	n*
Tested in Air	4.96×10^{-14}	8.3	1.4×10^{-11}	4.85
Tested in 40 ppm H_2S	5.92×10^{-19}	15.3	9.32×10^{-10}	3.51

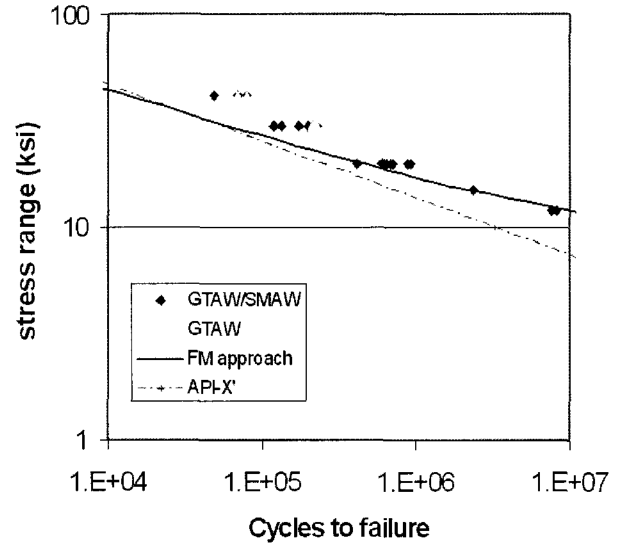

Fig. 8 Comparison of fatigue life between S-N and fracture mechanics of a tubular joint with a surface crack (a_i=0.5mm)

4. Conclusions

An attempt was made to correlate S-N fatigue test results with analytical fatigue life assessment, using through-thickness stress profile. The fracture mechanics approach not only provides reasonable fatigue life estimation, but also weld acceptance criteria. Based on the comparison, the following conclusions are obtained.

1. A reasonably good correlation between S-N and fatigue life assessment using fracture mechanics was developed. Through-thickness stress distribution, initial flaw size, and crack growth rate plays a major role for the comparison.
2. Bi-linear curve crack growth law is obtained. The bi-linear crack growth is a good representation to describe near threshold behavior and corrosion fatigue.
3. The fracture mechanics approach provides vital information to accept/reject the weld quality.

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