FATIGUE DESIGN OF BUTT-WELDED TUBULAR JOINTS

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ABSTRACT

Recent deepwater offshore structures in Gulf of Mexico utilize butt welded tubular joints. Application of welded tubular joint includes tendons, production risers, and steel catenary risers. Fatigue life assessment of these joints becomes more critical because the structures to which they are attached are allowed to undergo cyclic and sometimes large displacements around an anchored position. Estimating the fatigue behavior of these tubular members in the design stage is generally conducted by using S-N curves specified in the codes and standards. Applying the stress concentration factor of the welded structure to S-N approach often results in very conservative assessment because the stress field acting on the tubular has a non-uniform distribution through the thickness.

Fracture mechanics and fitness for service (FFS) technology have 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 to be used and a methodology for accounting for the effects of non-uniform stress distribution through the wall thickness.

An attempt was made to develop set of S-N curves based on fracture mechanics approach by considering non-uniform stress distribution and a threshold stress intensity factor. Series of S-N curves generated from this 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"). Similar comparison with API X' was made for tubular joint.. These initial crack depths are larger than the limits of inspection by current Non-destructive examination (NDE) means, such as Automatic Ultrasonic Inspection (AUT). Thus a safe approach can be taken by specifying acceptance criteria that are close to limits of sizing capability of the selected NDE method.. The comparison illustrates conservatism built into the S-N design curve.

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 deepwater applications [1, 2], 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. A Steel catenary riser (SCR) is a typical example of the system. The steel catenary riser has been considered as an option for transport of gas and crude oil from offshore platforms for many years. A steel catenary riser in essence is an extension of the pipeline, suspended in a 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 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 American Welding Society (AWS) [3], Department of Energy of United Kingdom (DOE) [4], or American Petroleum Institute (API). 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 is more appropriate to predict the tolerable fabrication flaw size. In fact, without a fracture mechanics analysis, it is practically speaking only possible to establish allowable flaw sizes that are no larger than the worst flaw detected in a welded test specimen that was used to validate that the particular weld process meets the required design S-N curve. The fracture mechanics approach requires information on non-uniform stress distribution in the anticipated crack plane, a stress intensity factor and crack growth rate for the material in the environment of interest.

Recent development of offshore designs have provided the impetus for the introduction of fracture mechanics into offshore design. API recommends to use fracture mechanics as a basis for reliability assessment in TLP's [5]. The willingness of the industry to adapt 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 [6]. This technology enables us to establish proper requirements on weld quality and inspection acceptance criteria to assure satisfactory assurance 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 resulting from the initiation and growth of small surface cracks at root or toe of a weld. These cracks will continue to grow under the cyclic loading excited by the relative movement of floating system and the riser. The fracture mechanics approach utilizes the effects of non-uniform stress distribution through the wall thickness initiated from root of the weld.

In this study, an attempt was made to develop set of S-N curves based on fracture mechanics approach by considering non-uniform stress distribution and threshold stress intensity factor. Series of S-N curves generated from this approach were compared to the existing S-N curves. This approach reduces the effort of extensive fatigue life assessment using fracture mechanics. In fracture mechanics (da/dN) approach, the initial crack size is sensitive to the fatigue life. The study includes proper selection of initial crack size to match the S-N curve. The results were compared with the existing S-N curves such as published in International Institute of Welding (IIW) and American Petroleum Institute [7].

S-N CURVE AND FRACTURE MECHANICS APPROACH

Typically, S-N curve is expressed as follows:

$$N = A\,\Delta\sigma^{-m} \qquad (1)$$

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

$$da/dN = C\,(\Delta K)^n \qquad (2)$$

where ΔK is range of stress intensity factor, and da/dN is a crack growth rate per cycle.

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

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

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 [8].

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

Assuming the shape function f is insensitive to crack size, then the equation can be simplified

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

By 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.

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

There are many ways to determine the initial flaw size (a_i). In 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 factor of safety. Hence, the initial flaw size is used as 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 threshold stress intensity factor.

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

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

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'. Figure 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.

Fatigue design based on fracture mechanics was performed in order to define acceptable flaw size. Sensitivity analyses of fatigue life for various conditions were conducted. Parameters studied were initial crack size, stress distribution near toe of the root weld, threshold stress intensity factor (ΔK_{th}), and crack growth rate. The fatigue analysis was conducted using PREFIS a software program designed for API RP 579 "Fitness for Service" [8].

Butt Welded Flat Plate

The fatigue life calculated from fracture mechanics was compared with the IIW Class 100 curve for a welded flat plate. The data used for this assessment is shown in Table 1. Figure 2 shows comparison between IIW class 100 (butt welded joint) and fracture mechanics approach. The comparison indicates that both curves matches well when initial crack size with depth of 0.5 mm (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 degree of conservatism by introducing reliable inspection system which can detect smaller than 0.5mm deep crack.

Butt Welded Tubular Joint

1. **Fatigue Testing**

Several proto-type 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 figure 3. Five welded tubes were tested at the same time. In some tests, if one weld fails, the weld is cut out and replaced with a new tube. For majority tests, if one weld failed, the other 5 were considered run outs. All welds were made using GTAW-manual or SMAW).

2. **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 tube product also create a non-uniform stress distribution through the wall thickness. Figure 4 shows a cross-section of a welded tubular joint that failed during the tubular joint fatigue test and the stress distribution near the weld. The stress distribution was obtained from finite element analysis by digitizing the weld profile. The figure illustrates that highly localized stresses are concentrated near the weld root.

Fatigue lives were calculated for various stress distributions near the weld root and figure 5 shows comparison of fatigue lives of SCR with a crack for various stress distributions and crack sizes. The figure indicated that the local stress concentration factor at the root has little effect to 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 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 simplified stress distribution provided comparable yet conservative fatigue lives. The stress concentration effect was further reduced using the equation provided by Connelly and Zettlemoyer [10].

3. Effect of Fatigue Crack Growth Rate

A number of crack growth rates were obtained for various environment 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 improve corrosion fatigue life. Proper crack growth rates and threshold at various environment were determined from the test program [9].

Based on the test results, four test conditions were examined to cover various possible situations expected for risers. Two bi-linear crack growth curves were obtained as shown in Table 2 (Figure 6).

Figures 7 shows comparison of the fatigue life between testing and result of fracture mechanics approach using the through-wall stress distribution. The curve obtained from fracture mechanics conservatively predicts the test results and they agree well. The figure illustrates that fatigue life can be predicted using fracture mechanics and the curves matches with existing codes and standards when initial crack is less than 0.5 mm (0.02”) deep.

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Table 1. Input values used in flat plate fatigue life calculation [6, 7]

S-N	A	$2X10^{12}$	$1.1X10^{16}$
	m	3	5
Da/dN	C	$4.95X10^{-13}$	
	n	3	
	ΔK_{th}	2.2 Mpa $m^{0.5}$	

Table 2. Crack Growth Rate Constants

	C*	n	C*’	n*’
Tested in Air	4.96E-14	8.3	1.4E-11	4.85
Tested in 40 ppm H2S	5.92E-19	15.3	9.32E-10	3.51

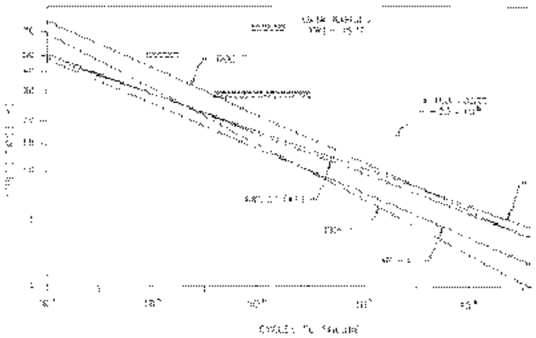

Figure 1. Comparison of various fatigue curves

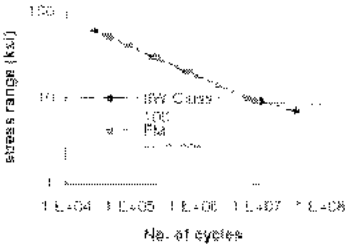

Figure 2. Comparison of fatigue life between S-N and fracture mechanics of butt welded plate with a surface crack (2c/a=10)

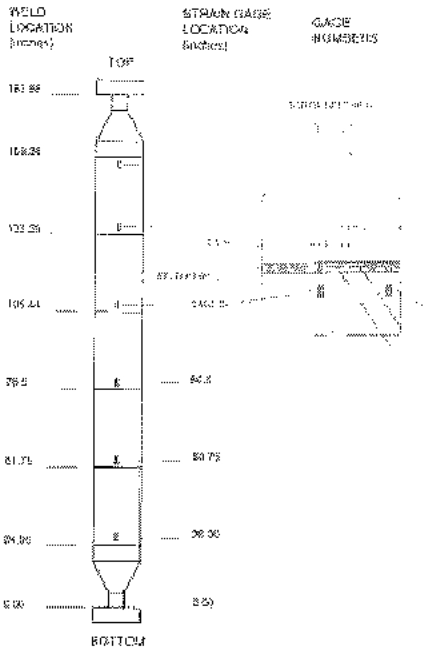

Figure 3. Fatigue test results of tubular welding joint

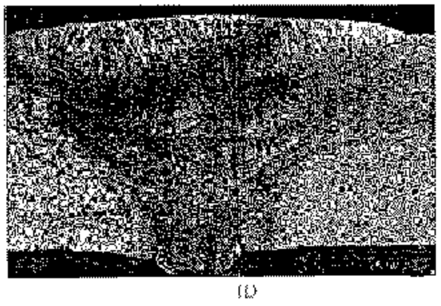

Figure 4 (a) Local weld profile

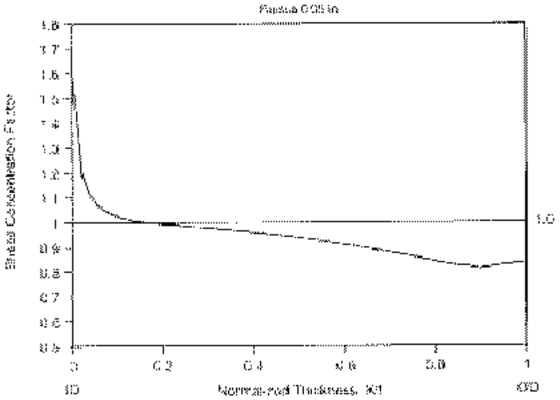

Figure 4 (b) Local stress distributions

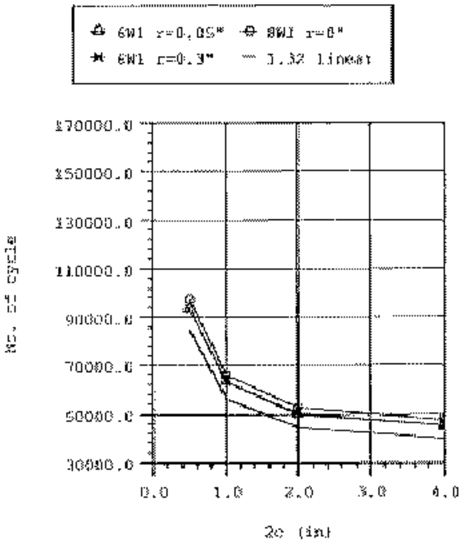

Figure 5. Comparison of fatigue life at various stress distributions

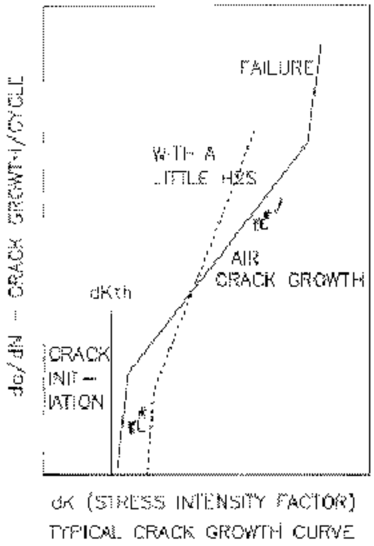

Figure 6. Bi-linear crack growth rate curve

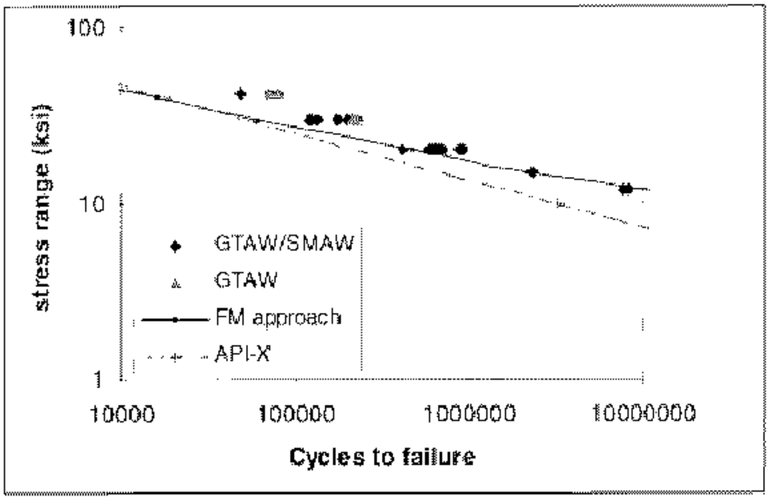

Figure 7. Comparison of fatigue life between S-N and fracture mechanics of a tubular joint with a surface crack (ai=0.02").