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On Ship Reliability and Safety

by

Prof. Dr. M. A. Shama

1- "Safety Assurance: Methods of Assessment for Ship Structures", IMAEM, September, (Italy-1981), Trieste, Second Conference, Shama, M. A.,

2- "ON the Economics of Safety Assurance", Soc. of Marine Engineers & Shipbuilders, Dec., (Egypt – 1984), 7th Symp. on Offshore Eng. and Technology, Shama, M. A.,

3- "Marine Structural Safety and Economy", SNAME, March, (USA-1991), Symposium, Marine Structural Inspection, Maintenance, and Monitoring, Shama, M. A.,

4- "Application of Reliability Assessment to Welded Tubular Joints", AEJ, Oct., (Egypt-1992), Shama, M. A., El- Gammal, M. Elsherbeini,

5- "Estimation of Fatigue life of Welded Tubular Connections Containing Defects", AEJ, No. 4, Oct., (Egypt-1992), Shama, M. A., El- Gammal, M. Elsherbeini,

6- "Impact on Ship Strength of Structural Degradation Due to Corrosion", AEJ, July., (Egypt-1995), Shama, M. A.,

7- "Shear Strength of Damaged Coastal Oil Tanker under Vertical Shear Loading", AEJ, April, (Egypt-1996), Shama, M. A., Leheta, H. W. and Mahfouz, A. B.

8- "Shear Strength of Damaged Seagoing Oil Tanker Under Vertical Shear Loading", Jan, (Egypt-1996), Shama, M. A., Leheta, H. W. and Mahfouz, A. B.

9- "Impact on Ship Strength of Structural Degradation Due to Corrosion", (Kuwait-1996), Second Arabian Corrosion Conference, Shama, M. A.

10- "Risk Management", AEJ, Vol. 37, No.2, March, (Egypt-1998), Shama, M. A.,

11- "Reliability of Double Hull Tanker Plates Subjected to Different Loads with Corrosion Effects", AEJ. Vol. 41, No. 4, (Egypt-2002), Shama, M. A., H. W. Leheta, Y. A. Abdel Nasser and A. S. Zayed,

12-, "Impact of Recoating and Renewal on the Reliability of Corroded Hull Plating of Double Hull Tankers", AEJ. Vol. 41, No. 4, (Egypt-2002), Shama, M. A., H. W. Leheta, Y. A. Abdel Nasser and A. S. Zayed,

ESTIMATION OF FATIGUE LIFE OF WELDED TUBULAR CONNECTIONS CONTAINING DEFECTS

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ABSTRACT

Fatigue failure of tubular weided connections, forming the primary framework of offshore platforms, is considered the major failure model. In this paper, four design concepts related to fatigue failure, have been summarized and discussed. The combination between the safe-life and fail-safe concepts is defined as the working life concept. A comparison between Miner's method and a proposed method as fatigue damage concepts have been made using the two design codes: API and DNV. The proposed method, is based on the working life concept includes the effect of environment and structural uncertainties. The application of the working life concept on tubular welded connections shows the different factors that may impair the connection life, and the significance of each factor.

INTRODUCTION

Marine structures, including offshore platforms are subjected to wind-driven waves, water current, tied, wind, etc. Such loads are stochastic random cyclic loads. Therefore, fatigue mode of failure become the most significant mode for the assessment of structural safety. Due to the favorable drag behaviour of circular tubes, in comparison, with other sections, they are specially used in offshore structures. Design concept of tubular connections, under cyclic loading, depend on the time at which complete failure occurs.

The loads applied on the tubular connections and their response are a matter of statistics and probability. Also uncertainties due to environmental and fabrication conditions, and their variations are affecting the loads and strength estimations. Then the expected fatigue life will be liable to probabilities.

2. FATIGUE DESIGN CONCEPTS

Fatigue design approach may follow one of the following four concepts:

2.1 *Initial fatigue life concept* [1]

It is the traditional design criterion applied to structures subjected to cyclic loads. Definition of failure is based on the maximum applied cyclic stresses. The fatigue life is the lime till the applied cyclic stresses are equal to or over the endurance limit.

This concept have been developed to introduce the concept of fracture mechanics and actual operation time.

2.2 *Safe-life concept* [1]

This concept is based on the relationship between the acting cyclic loads and the probability of failure under such loads i.e., failure under service fatigue stresses. The safe life may be estimated as follows:

1. Determine the load spectrum acting on the structure.
2. The expected life of the structure is to be determine analytically and experimentally.
3. Estimation of safe life as:

Safe life = Expected life/safety Margin

Crack initiation is considered to be the end of life, i.e, failure is the condition in which fatigue crack can be detected by ordinary means. This criterion may be used for water-tightness and oil-tightness.

2.3 *Fail-safe concept* [1,2]

This concept is based on the residual static strength of the structural joint, even if failure of the welded joint start take place. Expected fatigue life is based on the subcritical crack propagation rate (da/dN) of the cracked joint, allowing a certain crack size to be reached without complete failure, i.e., the critical crack size.

Failure is defined as reaching either the critical crack size or a value of static strength after which the marine structure may be considered in jeopardy.

This design concept is directly affected by the tube material, diameter, thickness and connection design.

2.4 *Working-life concept* [1,2]

The working life concept is a combination of safe-life and fail-safe concepts. The working-life can be estimated in two steps.

1. Good idea about wave spectrum and the corresponding response of the marine structural components i.e, damage at each stress level is to be calculated.
2. The expected life, using the modified safe-life concept according to a certain quality assurance, is to be estimated based on the following criteria, whichever is reached First: [2]

a. Total stress intensity factor :K_t" ≥ critical stress intensity factor "K_c" i.e., Brittle Fracture occurs.
b. Residual static strength of cracks (C_{res}) given in equation (1) [2] ≤ 0 i.e. fatigue failure or brittle failure.

$$C_{res} = \frac{S_u}{K_t(1-0.001\,a/t)}\;\frac{S_r(1-r)}{(1-a/t)} \qquad (1)$$

where

S_u Ultimate tensile strength N/mm^2
S_r Stress range N/mm^2
r Stress ration = S_{min}/S_{max}
k_t Total stress concentration factor
a/t Defect size/wall thickness ratio
c Total crack size "a_f" ≥ max. allowable size "a_m" after "n" years, i.e. fatigue failure.

Then either fatigue or brittle fracture depending on the applied criterion [1], will occur.

Hence, the working life "T_w" = crack initiation period "T_o" + Subcritical crack propagation period "T_{fs}".

To get a reasonable estimation of the working life, the effect of environmental and fabrication uncertainties, such as slamming, corrosion, residual stresses and welding defects, should be included.

3. FATIGUE DAMAGE CONCEPT

Linear concept of fatigue damage used by most design codes AWS [3], API [4] or DNY [5], is given by equation (5.1) i.e. "Palmagarin-Miner's rule".

$$D_f = \sum_{i=1}^{J} \frac{n_i}{N_i} \le 1 \qquad (2)$$

where

D_f cumulative damage ratio
n_i number of applied cycles, at a certain stress level "i".
N_i total number of cycle to failure as the same stress level "i".

This concept does not take into consideration the complete history of the wave-stresses applied to the structure. Therefore, total damage based on working life concept, may be as shown in equation (3) [2]:

$$D_T = -\int \frac{dn/dS_r}{N\,dS_r} \qquad (3)$$

where S_r: is the applied stress range (N/mm^2).

This concept takes into concept takes into consideration both the total stress spectrum and structural response distributions.

4. WAVE-STRESS SPECTRUM AND RESPONSE FUNCTION

The stress range (S_r), corresponding to each wave height (H_w) may be estimated empirically as follows, [6].

$$S_r = 1.5\, H_w^{1.25} \qquad (4)$$

The stress spectrum distribution, established from long-term wave measurement stochastic process, may be as shown in equation (5) [2].

$$n = \alpha e^{-\beta S_r} \tag{5}$$

where

S_r stress range (N/mm^2)
n number of applied cycles
α and β are constants depending on the statistical parameters of the stress spectrum shown in Figure (1), and can be estimated as given in references [2 and 7].

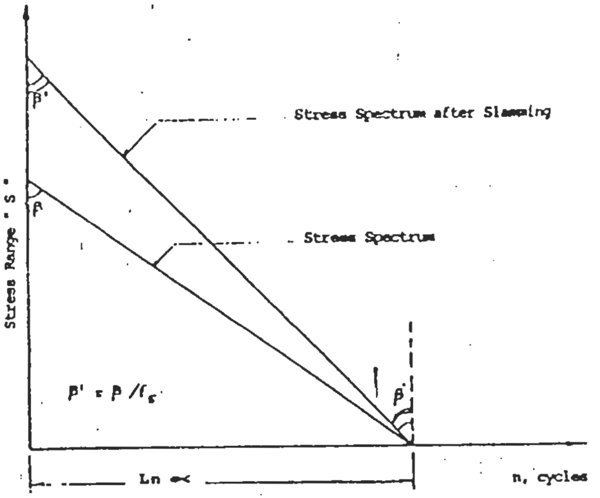


Figure 1. Stress spectrum (semi-log scale).

Introducing the slamming stress magnification factor (f_s), estimated from equation (6) [7], will yield the value of the stress range.

$$f_s = 1/\sqrt{[1-(\frac{W}{W_o})+[4(\frac{W}{W_o}d)^2]} \tag{6}$$

where

E_o The structural natural frequency
W The wave frequency = $2\pi/T_w$
T_w Wave period
d damping coefficient

Practically equation (6) is valid for ($w/w_o \leq 1$) and ($d \leq 50\%$).

Then, the stress distribution may be as given in equation (7).

$$n = \alpha e^{-(\beta/f_s) S_r} \tag{7}$$

Correlation tests show that the relation between stress range (S_r) and the corresponding number of cycles up to fatigue failure (N), may be as given in equation (8).

$$N = \gamma (S_r)^m \tag{8}$$

where γ and m are constants, depending on the statistical parameters of the response distribution, show in Figure (2). They can be estimated as given in references [2] and [7]. Concentration factors (K_t) should be included to estimate the hot spot stress range applied on the brace [7].

Therefore, the response curve, using the hot spot stress range, may be formulated as shown in equation (9).

$$N = \gamma (S_{rk})^{-m} \tag{9}$$

where

$$S_{rk} = S_r \times k_t$$

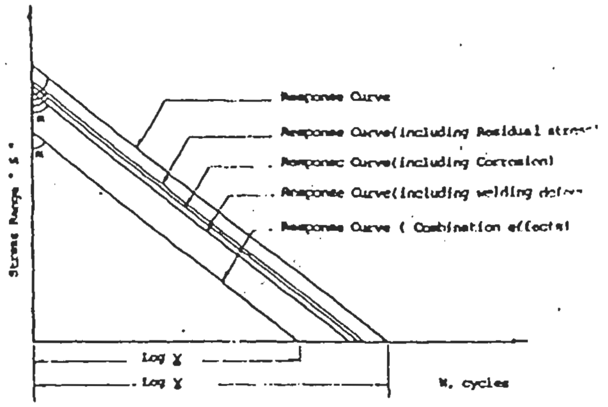


Figure 2. Response curve (log-log scale).

5. EFFECT OF ENVIRONMENTAL AND FABRICATION UNCERTAINTIES

Environmental and fabrication uncertainties, such as corrosion, welding defects and residual stress, may have direct effect on the total stress level applied on the welded connection. This may reduce the permissible endurance cycles significantly. Estimation of such uncertainties may be as follows:

5.1 *Effect of corrosion*

The effect of corrosion may be represented as the local reduction in material thickness. Therefore the corrosion factor (f_c) may be as shown by equation (10) [2].

$$f_c = (1 + C_c)^{\gamma} \qquad (10)$$

where

C_c corrosion coefficient = C_a/C_{ref}
C_a actual coefficient = $[(r_F\ t/T_D]$
R_F allowable reduction in thickness percen(10.1)
t tube wall thickness (mm)
T_D Design fatigue life (years)
C_{ref} The reference corrosion rate, given by the design code (0.25 mm/year) [3,8] can be estimated as shown in equation (10.2) [9].

$$C_{ref} = \frac{q \cdot W}{A_s \cdot \rho \cdot T} \qquad (10.2)$$

q A constant depend on the used unit
W The weight lost by the specimen during the lest
ρ Material density
A_s Surface area, subjected to the corrosive media
T Test duration
λ An exponential depending on the applied corrosion protective method if $\lambda = 1$, i.e. no protection
λ 0.25 – 0.5 for cathodic protection and good coating.

5.2 *Effect of Residual Stresses*

Although the effect of residual stresses may vanish with cycle-stresses, then may have an effect at very low cycles. Therefore, the effect of residual stress (f_R), in general, may be represented by equation (11)

$$f_R = 1 + R \exp\left[-\frac{(S_{rk})^2 . n}{E . S_y}\right] \qquad (11)$$

where

R residual stress ratio = S_R/S_y
S_R residual stress (mean tensile component)
S_y yield stress (N/mm^2)
n number of applied stresses (cycles)
E Modules of elasticity (N/mm^2)

For proper welding procedure, R may vary from 0.3 to 0.5.

6.4.3 *Effect of welding defects*

Welding defects may cause very high stress concentration in tubular welded joint, specially those located along the weld toe of the hot-spot area [7]. The induced stress concentration factor (K_d), due to the presence of welding defects may be as given by equation (12) [7]

$$K_d = 1 - \left[g\left(\frac{a}{d}\right)^{0.5} \frac{1}{L} \sin\phi / \left(1 + \frac{0.85_y}{S_u}\right]\right. \qquad (12)$$

where

a defect size (mm)
l defect length (mm)
d_r defect tip radius = $2.5 \times 10^{-2} \left(\frac{2068}{S_u}\right)^{1.8}$ (mm)
S_u ultimate strength (N/mm^2)
S_y yield strength (N/mm^2)
ϕ angle between defect and nominal stress directions
L weld length
g a parameter depending on defect location and a/t ratio.

For surface defect: $g = 2\left[\frac{1-(a/t)}{1+(a/t)}\right]^{0.5} G_F$

For embedded defect: $g = 2\left[\frac{1-(a/t_f)}{1+(a/t_f)}\right]^{0.5} G_F$

t tube wall thickness
t_f Effective throat size, as percentage of wall thickness.
In general $t_f = 1.25\ t$ (mm) [5].
G_f The defect and loading geometrical factor. It is a function of defect size, wall thickness and tube diameter.. It may have the values and forms given in reference [7].

The combined defect of the three previously stated factors may be considered as given in equation (13)

$$F = f_c \, f_R \, K_d \tag{13}$$

Hence the connection response distribution may have the formula given by equation (14)

$$N = (S_{rk} \, F)^m \tag{14}$$

6. WORKING SAFE FATIGUE LIFE

As the cumulative damage (D), given by equation (3), is based on the working safe life concept, the fatigue life (T_c) may be estimated when the total damage is unity, as given n equation (15) [2].

$$T_o = \frac{1}{D_o} \tag{15}$$

From equation (5) and equation (9), substituting the values of (dn/dS_r) and (N) into equation (3), the total damage per time may be as given by equation (16).

$$D_o = \frac{\alpha \Gamma(m+1)}{\gamma(\beta / K)^m} \tag{16}$$

where Γ(.) is the Gamma function.
Therefore, the working-safe life (T_o) may be given as follows:

$$T_o = \frac{\gamma.(\frac{\beta}{k})}{\alpha \Gamma(m+1)} \tag{17}$$

The slamming effect (f_s) shown in Figure (1) and the combined effect of uncertainties on structural response distribution shown in Figure (2) may be included in the estimation of the working-safe life (T_f).

Substituting the value of (dn/dS_r) and (N), from equation (7) and (14), into equation (3) the total damage per unit time may be as given by equation (18).

$$D_f = \frac{\alpha \Gamma(m+1)}{\gamma(\frac{\beta}{K})^m}(f.f_s)^m \tag{18}$$

Substituting $f_T = f.f_s$ in equation (18), the correlated working-safe life (T_f) may be as given equation (19).

$$T_f = \frac{\gamma(\frac{\beta}{K})^m}{\alpha \Gamma(m+1)}(f_T)^m \tag{19}$$

Dividing equation (19) by equation (17), the reduction in working-safe life due to uncertainties may be as follows:

$$T_f/T_o = (f_T)^m \tag{20}$$

7. DISCUSSION AND APPLICATIONS

To estimate the fatigue strength of welded tubular connections, based on the working life concept, the following two methods of cumulative damage can be discussed:

a) Plamagren-Miner method
b) The proposed method, proposed in reference [2].

A comparison between the API-cure X [4] and DNV-curve DNV-curve [5], as design codes, have been included. The effect of environmental and fabrication uncertainties have been estimated based on the following concepts.

i Slamming effect; as a dynamic stress magnification factor.
ii Residual stresses; as a reduction in strength factor.
iii Welding discontinuities, as a stress concentration factor.
iv Corrosion effect as reduction in thickness factor.

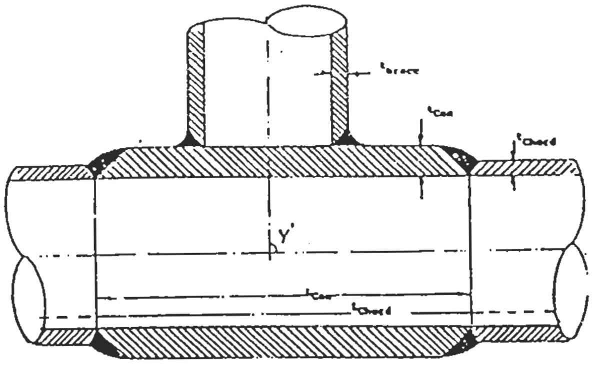
The data collected from an offshore platform, located in "Abu-Qir Bay-Egypt", have been feeded into the "BASIC" computer program, given in reference [7]. The welded tubular connection shown in Figure (3) located given by equation (21) [7].

$$n_i = 3.505 \text{ x } 10^7 \, e^{(0.451 s_i} \tag{21}$$

The connection stress concentration factor (S.C.F.) has been estimated using the connection properties shown in Figure (3).

Table 1. Response curve constants and fatigue life of welded tubular T-Connection, designed according to different strength curves.

	Strength curve	Distribution constants		Fatigue life using "Miner" rule		Fatigue life using the proposed method		T_P/T_M %
		GAMA	m	Damage (D_M)	Life (T_m) years	Damage (D_p)	Life (T_p) years	
1	API-RP2A Curve (X) (S.C.F. = 1)(1)	1.1506215 E+15	4.3799999	0.0004155	24061.597	0.00004288	23319.316	96.91
2	API-RP2A Curve (X) (S.C.F. = 4.15)	2.2589122 E+12	4.3799999	0.0211702	47.236	0.0218432	45.780	96.91
3	DNV-Curve (X) (S.C.F. = 4.15)	1.0862381 E+12	4.10000	0.0234343	42.672	0.02350	42.545	99.70



Chord Diameter	: 360	mm
Chord Thickness	: 25	mm
Chord Length	: 1500	mm
Brace Diameter	: 300	mm
Brace Thickness	: 20	mm
Material yield Strength	: 352	N/mm^2
Material Tensile Strength	: 610	N/mm^2
Modulus of Elasticity	: 210000	N/mm^2
Toughness parameter	: 3517	$N\ mm^{-3/2}$
Geometrical S.C.F.	: 4.15	

Figure 3. Tubular connection with "joint can".

Table (1), summarizes the results of response curve in case of API-curve X, with theoretical case SCF=1 and the actual case when SCF=4.14 and DNV curve X with (SCF=4.12). Although the applied stress spectrum is the same, introduced by the constants (α) and (β), the change in the response distribution, introduced by the constants (γ) (m), may have significant variation. A change in the stress concentration factor may change the γ-value only without any change in m-value. While changing the strength curve from API to DNV may cause variation in both (γ) and (m) values, i.e. total change in the response distribution.

The fatigue life estimation is significantly affected by the stress concentration factor. Increasing such factor from unity to 4.15 may cause an approximate reduction of 1/500 in the fatigue life. Therefore, the connection design should be optimized to keep the geometrical SCF as low as possible, as shown in Figure (4). Changing the strength curve from API-X to DNV-X may cause reduction of 9.6% in fatigue life. Comparing the proposed method to estimate fatigue life with Miner's method, only 0.3% reduction in life is yielded by DNV-curve X, while API-X yields 3% reduction in life. The proposed method is assumed to be more accurate, because it is using the whole stress spectrum and the response curve. Then The DNV-X gives an accurate estimation of fatigue life as both Miner's method and the proposed one gives nearly the same results.

The effect of environment and fabrication factors are shown in Figures (5) to (7). The slamming effect found to be significant when the wave period is as close as the structural natural period

Most of design API [4], DNV [5], GL [8] accept 10% reduction in thickness due to corrosion. Such reduction in thickness may cause 30% reduction in fatigue life, for tube wall thickness of 10 mm. While 50% reduction in fatigue life may take place for wall thickness of 20%, as shown in Figure (5-a). A better design parameter is reduction in thickness rate; e.g. mm/year. Corrosion protection parameter (γ) shown in Figure (5-b), may improve the fatigue life up to 37% based on better protective methods and quality.

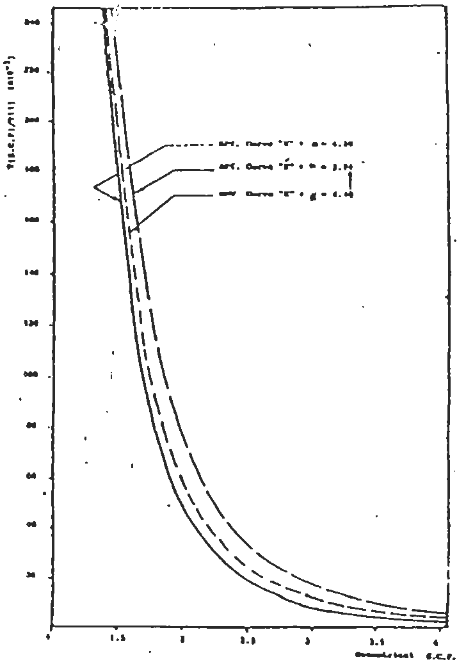
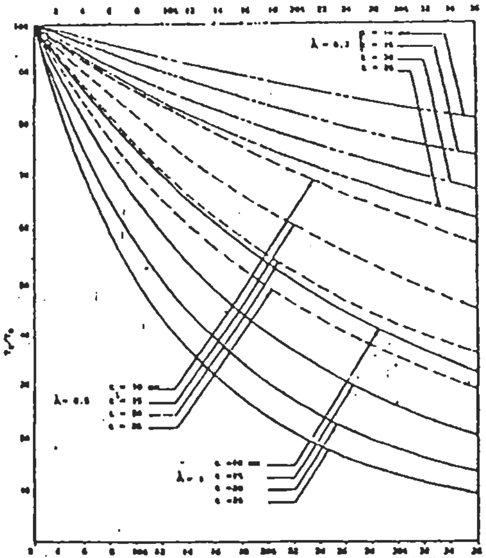
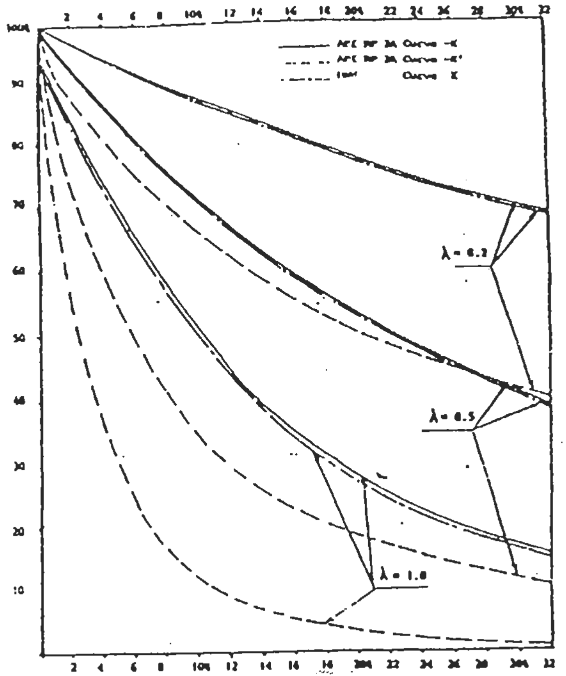


Figure 4. Effect of geometrical stress concentration factor on fatigue life of tubular welded connections.



percentage %

Figure 5-a. Effect of corrosion reduction in thickness factor on fatigue life for different protection parameters.



Factor

Figure 5-b. Effect of corrosion reduction in thickness factor on fatigue life for different protection parameters.

As different parameters are involved in estimating the effect of weld defects, Figures (6:a,b,c and d) shows the effect of each parameter separately. It is noted that 50% increase in defect length (l) may cause 20% reduction in fatigue life, while 12% reduction in life may result from 50% increase in defect size (a). For defects with 45° orientation 49% increase in defect size may be allowed. The allowable percent is reduced when increasing the defect orientation up to 90°. For T.K.Y. connections, defects in hot-spot areas are commonly 90° to the normal stress, therefore no defect allowance is recommended, specially surface defects. Surface defects may cause 28% reduction in life, compared with the embedded ones of the same size an length.

The primary structural elements of offshore platforms are made from high tensile steels, i.e. over 245 MN/m^2 Using steel with 352 MV/m^2 tensile strength ma reduce the fatigue life by 27%. In case of high stress cycles, the residual stress is neglected, as shown in Figure (7).

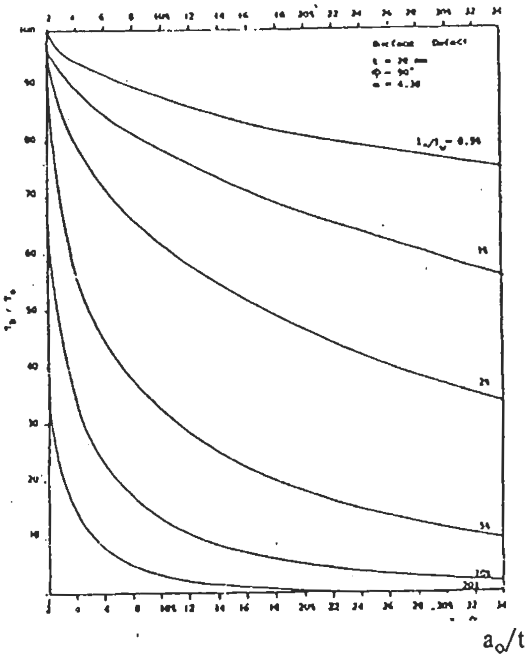


Figure 6-a. Effect of defect size and defect length on fatigue life.

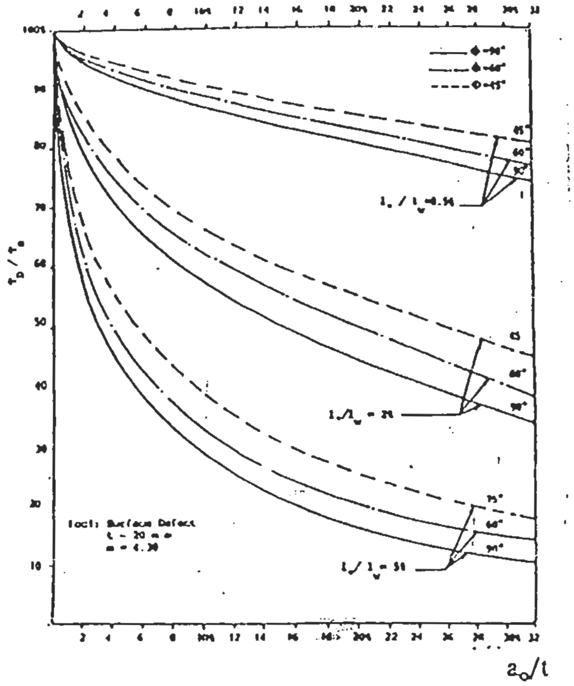


Figure 6-c. The effect of defect direction, with respect to nominal stresses on fatigue life.

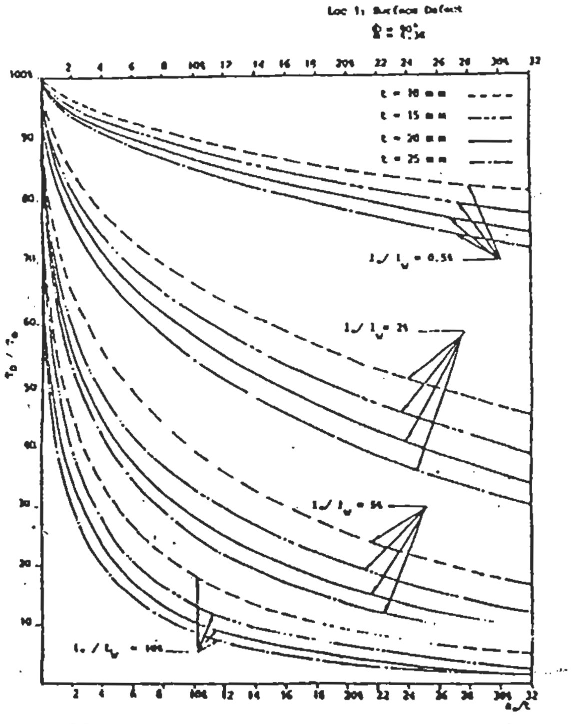


Figure 6-b. Effect of defect size and length for different tube wall thickness on fatigue life.

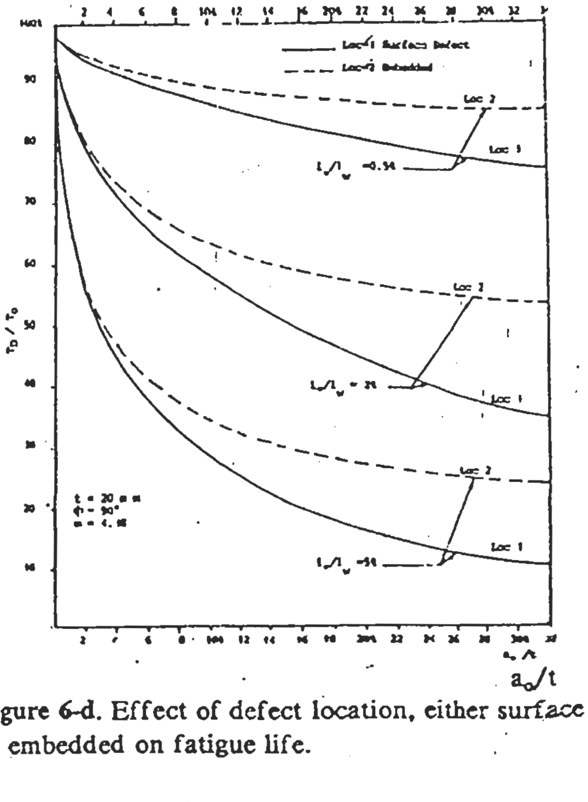


Figure 6-d. Effect of defect location, either surface or embedded on fatigue life.

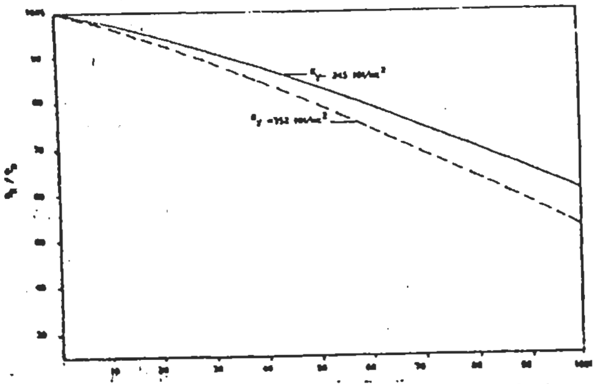


Figure 7. Effect of Residual stresses on fatigue strength.

CONCLUSIONS

From the work presented within the content of this paper, the following points may be concluded:

1. The working safe design concept is a rational method to estimate fatigue life of welded tubular connections.
2. The proposed cumulative damage method is more sensitive than Miner's method, as it is using the whole spectrum of both the stresses response curves. Also it facilitates studying the effect of uncertainties on fatigue life. As soon as enough information are available on both the stress spectrum and the response curve, the proposed method is recommended, although Miner's method may gives an easy quick results.
3. The strength curve designed by DNV-X found to be more accurate than the API-X, as both Miner's rule and the proposed method give the same fatigue life in DNV-X case.
4. Failure is concerned when reaching the critical value of one of the following 'criteria" Residual static strength of the connection, the crital stress intensity factor, or the maximum allowable crack length. These critical values are concerned at a specific probability of failure.
5. It is impossible to produce a welded joint free from stress raisers and defects. The interaction between surface defects, corrosive environment may impair the fatigue strength significantly.

REFERENCES

[1] El-Gammal, M.M., "Crack Failure in Ship Structures", *Department of Naval Architecture and Marine Engineering*, University of Alexandria, 1982.

[2] El-Gammal, M.M. "Design against fatigue in ship structures: A theoretical Study", *A thesis submitted in fulfillment of the requirements for the degree of Doctor of philosophy*, Department of Naval Architecture, University of New Castle on-Tyme, 1976.

[3] ANSI AWS-DI.I-85, "Structural Welding Code for Steel", *The American Welding Society*, 1985.

[4] API-RP 2A, "Recommended" Practice for Planning, Designing and Constructing Fixed offshore Platforms", *American Petroleum Institute*, 13 th. Edition, Jan. 1982.

[5] D.N.V., "Rules for the Design, Construction and Inspection of offshore Structure", Including Appendix A,B,C and G, Det Norske Veritas, 1982.

[6] Wirsching, P.M., "Fatigue Reliability In Welded Joints of Offshore Structures", *Proceeding of the 11th Annual Offshore Technology Conference (O.T.C)*, Houston, April & May 1979, pp. 197-206.

[7] El-Sherbiny, A.F., "Effect of Construction Defects and Tolerances on Structural Reliability", *M.Sc. Thesis*, Dept. of Naval Architecture and Marine Engineering, Univ. of Alex. 1989.

[8] G.L. Rules, "Rules for the construction and Inspection of Offshore Installation", *Germanischer Lloyd's Rules*, Vol. 1, 1976. (with supplements-1980).

[9] Fontana, M.G. and Green, N.D, *Corrosion Engineering*, Material Science and Engineering Series, Chapter 3, pp. 94-109 2nd Edition.