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للأستاذ الدكتور محمد عبد الفتاح شامة

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On Ship Reliability and Safety

by

Prof. Dr. M. A. Shama

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APPLICATION OF RELIABILITY ASSESSMENT TO WELDED TUBULAR JOINTS

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ABSTRACT

Reliability concept, as a rational method for assessing marine structural safety is fined. The major elements of probability theory to calculate structural reliability, including the fully statistical and semi-statistical methods, are discussed. Safety index and safety margin parameters have been introduced to estimate the reliability of welded tubular connections against fatigue. An application showing the effect of load uncertainties, including slamming effect, and strength variation due to welding defects, residual stresses and corrosion, on the reliability of welded tubular connection against fatigue failure, have been discussed. It is concluded that the assessment of marine structural reliability should depend not only on statistical analysis of the applied loads and the structural capability, but also on the effect of environmental and structural imperfections.

INTRODUCTION

During the last five decades, better understanding of structural safety and economy of marine structures is realized. A new trend based on a more realistic relationship the demand and capability is recognized.

Naturally, neither the governing stresses due to the working loads (Demand) no the Strength (Structural Capability), has a certain specific value. Several factors may cause load variations, such as: [1]

1. Type of working loads, either static or dynamic, and their application methods to the structure.
2. Temperature distribution near the critical points.
3. Extreme values of wave heights and severe wind conditions.
4. Residual stresses due to different fabrication processes.

Strength uncertainty may result from:

1. Structural imperfections and defects, and their accumulation at different fabrications stages.
2. Corrosion effects, wear and tear, ... etc.
3. Degree of constraint
4. Eccentricity of loads
5. Lack of quality control during fabrication stages and improper maintenance programmes.

Therefore, the conventional methods of estimating the safety factor (Ω), as the ratio: Capability/Demand, is not a rational method. It does not take into account the variation o the load (S) and the capability (C). But, statistics as a tool and probability theory as a method are the must suitable approach used to avoid unrealistic results, to achieve a safe, reliable and economic structure [2].

STRUCTURAL SAFETY

The purpose of marine structural design is to ensure that non of the inadmissible limiting states will occur during the structure life time. Both the external loading and the structural capability are clearly random variables. To determine a suitable presentation of their distribution, a series of experiments at the same homogeneous conditions, should be carried out. The results be, accumulated and grouped. In the majority of cases, the upper and lower are not fully defined because of test device capability or the requirement of extreme long period survey. In order to ensure structural safety the estimated maximum loading (S) should not exceed the estimated minimum capability (C), i.e. max. S $\leq$ min. C/Ω, where (Ω) is the safety factor [3].

EMPIRICAL FORMULA OF SAFETY FACTOR

The general expression for safety factor may be as given by equation (1): [2]:

$$\Omega = \sum_{i=1}^{j} \Omega_i - \Omega_2\Omega_2\Omega_3 \ldots \Omega_j \qquad (1)$$

The partial safety factor ($\Omega_{i=1...j}$) should depend on the factor affecting the failures and the consequence of failures. For example:

Ω_1 is the safety factor for load calculations and stress analysis methods,
Ω_2 is the safety factor due to material imperfections,
Ω_3 is the safety factor for fabrication imperfections,
Ω_4 is the safety factor for economic reasons, ... etc.

These partial safety factors are estimated empirically, based on previous experiences.

RATIONAL APPROACH TO SAFETY

As the load (s) and capability (C) depend on a group of random intentioned parameters: Q ($q_1, q_2,.. q_j$): then their probability density may be assumed as shown in equation (2) [3].

$$P(Q) = P(q_1, q_2, q_3, q_4, ... q_j) \quad (2)$$

Therefore, the condition of inadmissibility of the limiting state is:

$$\Psi(q_1, q_2, ... q_j)=C(q_1,q_2,... q_j)-S(q_{i+1}, q_j)\geq 0 \quad (3)$$

Hence, the safety factor (Ω)

$$=\frac{C(q_1,q_2,...q_j)}{S(q_{i+1},q_{i+2},...q_j)}>1 \quad (4)$$

$$\text{let } P(\psi(Q)\geq 0) = \int_{\psi(Q)\geq 0} P(Q)\,dq_i \quad (5)$$

This value, in equation (5), should be close to unity and presents the safety range.

$$\text{let } P(\psi(Q)<0) = \int_{\psi(Q)<0} P(Q)\,dq_i \quad (6)$$

This value, in equation (6), should be very small, and presents the probability of reaching the limiting state; i.e, the probability of failure (P_f). Figure (1), shows the probability density function of the load ($f_s(s)$) and capability ($f_c(c)$), and the probability of failure (P_f).

Hence, the probability of structural survival, i.e. structural reliability (R), can be given equation (7):

$$R = 1 - P_f \quad (7)$$

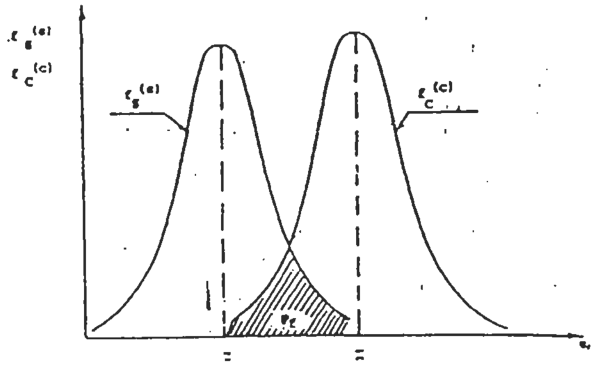


Figure 1. Probability of failure "P_f"

The safety assurance of a marine structures depends on one of the following criteria: [1]

a. Minimum carrying capacity, i.e. structural M = C - S
c. Total safety factor (Ω) > 1, where Ω = C/S

To satisfy any of these criteria, determination of both the load and the strength, and their variation, is necessary. Hence, calculation of safety margin, probability of failure, structural reliability and design safety factor is possible.

The External loads (S), applied on an offshore platform, is a function of wave height (q_q) wind speed (q_2), current velocity (q_3), tide range (q_4), sea-bed characteristics (q_5) ...etc.

$$\text{i.e. } S = Q(q_1, q_2, q_3, ... q_i)$$

Similarly, the strength (C) is a function of the expected life of the platform (q_{i+1}), properties of construction materials (q_{i+2}), method of fabrication (q_{i+3}), quality control level (q_{i+4}) ... etc.

$$\text{i.e. } S = Q(q_{i+1}, q_{i+2}, q_{i+3}, ... q_j)$$

Assuming normal probability distribution function for both C and S; hence: $S \equiv N(\bar{s},\sigma_s), C \equiv N(\bar{c},\sigma_c)$, where $\bar{s}$ and $\bar{c}$ are the mean of load and strength, σ_c are the load the load and standard deviation.

Assuming also that Q ($q_1, q_2, ... q_i$) are independent random variables, i.e. C and S are statistically independent hence:

$$\bar{m} = \bar{s} - \bar{c} \quad (8\text{-a})$$

$$\text{and } \sigma_M = \sqrt{\sigma_c^2 + \sigma_s^2} \quad (8\text{-b})$$

where $\overline{m}$ and σ_M are the mean and standard deviation of the safety margin (M).

i.e., $M = N(\overline{m}, \sigma_M)$.

In this case, the probability of failure (P_f) can be calculated as follows:

$$P_f = 0.5 - \int_0^{\omega} \frac{1}{2\pi} \exp\left(\frac{-t^2}{2}\right) dt \qquad (9)$$

where;

$$\omega = \frac{\overline{m}}{\sigma_M}, \text{ and } t = \frac{M - \overline{m}}{\sigma_M}$$

The probability of failure can be calculated, based on the semi-statistical approach. In this approach, the statistical parameters (mean and standard deviation) of the safety margin (M), are used to estimate the safety Index (I) as shown in equation (10) [2].

$$I = \frac{\overline{m}}{\sigma_M} = \frac{\overline{c} - \overline{s}}{\sqrt{\sigma_c^2 + \sigma_s^2}} \qquad (10)$$

Hence the probability of failure (P_f) is given as follows:

$$P_f = 1 - \phi\,(I) \qquad (11)$$

where ϕ is the standard normal function.

Figure (2) shows the probability of failure (P_f) estimated after the safety index (I) and safety Margin (M).

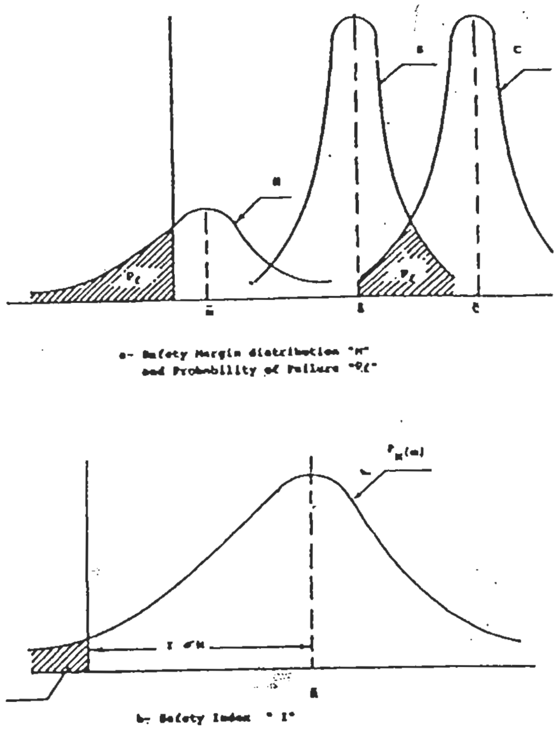


Figure 2. The probability of failure estimated after the safety index and safety margin; (after ref. 2).

ESTIMATION OF STRUCTURAL RELIABILITY AGAINST FATIGUE

The dynamic wave-induced stress spectrum, shown in Figure (3) may be represented by equation (12), [4].

$$n_i = \alpha E^{-\beta S_{ri}} \qquad (12)$$

while the response distribution, shown in Figure (4), may follow equation (13) [4];

$$N_i = \gamma (S_{ri})^{-m} \qquad (13)$$

where

S_{ri} = The applied stress range
n_i = number of applied cycles
N_i = endurance cycles
α, β, γ, and m are as shown in Figures (3) and (4)

Fatigue cumulative damage (D), after Miner's rule, is given in equation (14).

$$D = \sum_{i=1}^{j} \frac{n_i}{N_i} \qquad (14)$$

Substituting N_i in equation (14) by the value in equation (13), this results in equation (13).

$$D = \sum_{i=1}^{j} \frac{n_i (S_{ri})^m}{\gamma} \qquad (15)$$

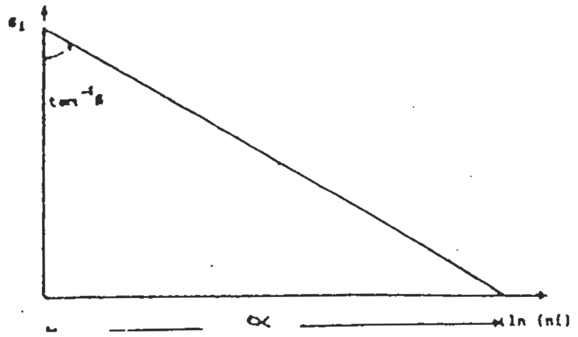


Figure 3. Wave-induced stress spectrum, (after ref. 4).

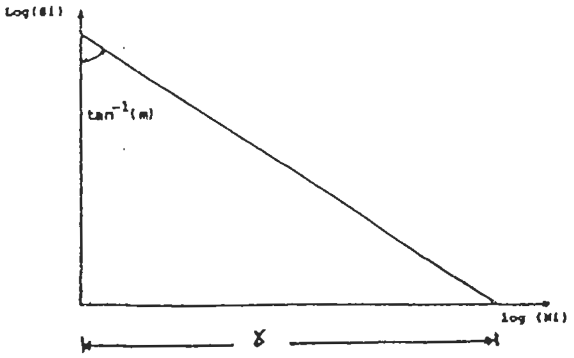


Figure 4. Structural response curve, (after ref. 4).

In all design codes, the cumulative damage (D) is assumed to be unity, i.e. ($D \geq 1$) [5].

In fact, the cumulative damage may have a critical value (Δ), which is less than unity [5]. The quantity of (Δ) may have a wide range, resulting from the uncertainties in the analysis of both the loads (S) and structural capability (C). Hence, failure can be defined as: ($D \geq \Delta$), and the probability of failure (P_f) can be given by equation (16).

$$P_f = P\,(D \geq \Delta) \tag{16}$$

Assuming the damage at failure (Δ) and endurance at unity stress level (γ) are random variables, and both may follow the log-normal distribution, [5], the actual root mean square of the stress range (S_{ri}), at the i-th sea state may be given by equation (17):

$$S_{ri} = Q\,S_{oi} \tag{17}$$

where

S_{oi}: The estimated root mean square of the stress range and

Q: A random variable quantifying the uncertainties in the stress analysis procedures. For tubular connections, uncertainties may refer to hot-spot stress analysis, [2] as shown in Figure (5).

Assuming that fatigue life = T, and the design life = T_o; hence the probability of failure is given by equation (18).

$$P_f = P\,(T \leq T_o) \tag{18}$$

Fatigue life (T), i.e. time to failure, can be written as a modification of narrow hand density function, as follows: [5].

$$T = \Psi\, \Delta\, \gamma \,/\, Q^m \tag{19}$$

where

γ : Correction for the narrow hand assumption.

As Δ, γ and Q follow the log-normal distribution hence the fatigue life (T) follows the log-normal function [5].

Let ln (T) is the mean of ln (T) and $\sigma^{(\ln T)}$ is th standard deviation of (ln T) where $\sigma^{(\ln T)} = \ln(1+V_\Delta^2)(1+V_\gamma^2)(1+V_Q^2)^m$ V_Δ, V_γ, V_Q: the coefficients of variation of (Δ),(γ) and (Q) respectively.

and

$$\overline{T} = \psi \frac{\overline{\Delta \gamma}}{\overline{Q}^m}$$

Hence, the probability of failure can be given by equation (20)

$$P_f = P\left(\frac{\ln T - \ln \overline{T}}{\sigma(\ln T)} \leq \frac{\ln \overline{T}_o - \ln \overline{T}}{\sigma(\ln T)}\right) \tag{20}$$

But, the standard normal distribution function (ϕ) is given by:

$$\phi = \frac{\ln T - \ln \overline{T}}{\sigma(\ln T)} \tag{21}$$

Hence,

$$P_f = \phi \frac{\ln(T_o/\overline{T})}{\sigma(\ln T)} \tag{22}$$

As the safety index (I) is expressed by equation (23)

$$I = \frac{\ln(t_o/\overline{T})}{\sigma(\ln T)} \qquad (23)$$

Hence $P_f = \phi(-I)$ (24)
and structural reliability against fatigue (R) is given by equation (25)

$$R = 1 - \phi(-I) \qquad (25)$$

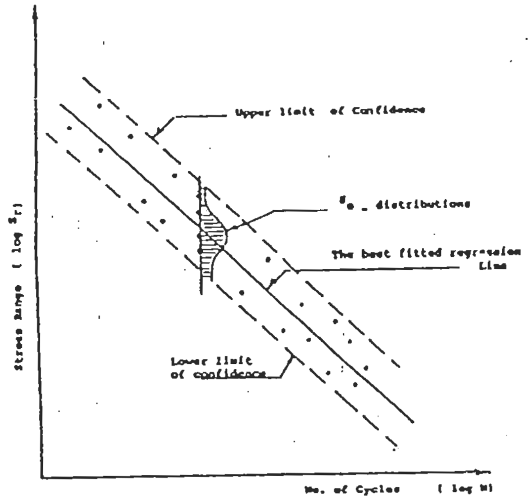


Figure 5. Fatigue strength curve, showing uncertainties in stress analysis procedures; (after ref. 2).

ASSESSMENT OF MARINE STRUCTURAL RELIABILITY AGAINST FATIGUE

Marine structure are subjected to two forms of fatigue stresses:

a. Low cycles, high amplitude stresses.
b. High cycles, low amplitude stresses.

Figure (6) shows the steps to assess marine structural reliability (R) against fatigue [2]. In the case of fatigue under low cycles loading, the probability of failure is defined as the probability the total number of applied cycles exceeds the endurance cycles, as shown in Figure (7-a). But, in case of fatigue under high stress cycles, the probability of failure is defined as the probability that the applied stress range exceeds the maximum stress range until failure (capability), as shown in Figure (7-b).

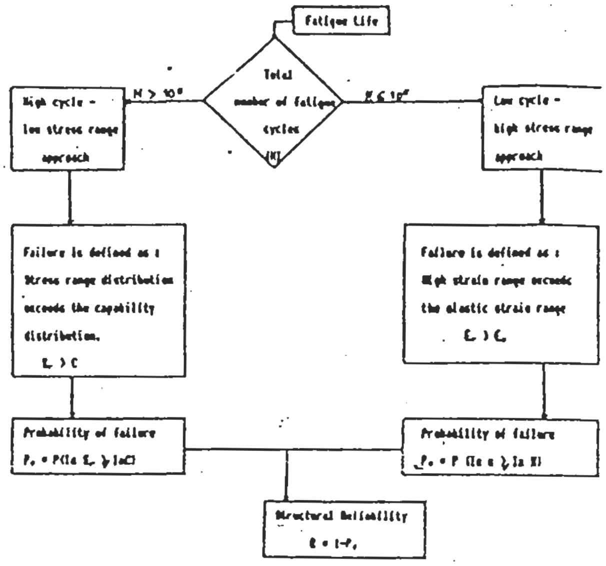
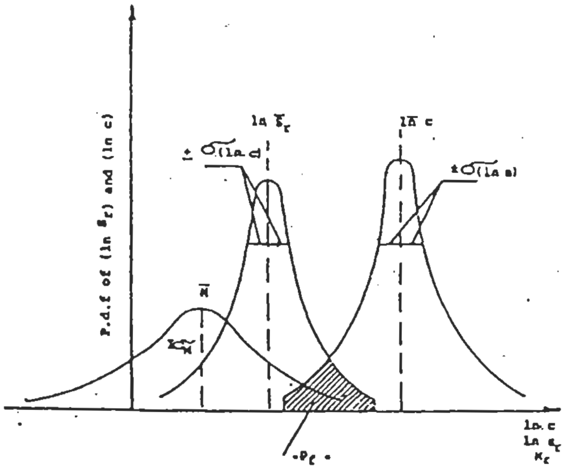


Figure 6. Assessment of marine structural reliability against fatigue.

Offshore platforms are subjected to fatigue under high cycles–low amplitude stress range. To assess the reliability of a tubular welded connection against fatigue, both the joint capability (C) and the applied stress (S) are assumed to be statistically intentioned and follow the log-normal distribution. Hence the safety index (I) can be given by equation (26):



a- High-Cycle Probability of fatigue failure

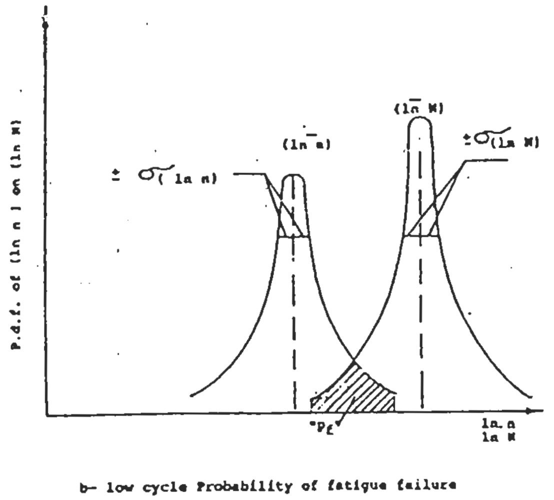


Figure 7. Probability fatigue failure and safety margin in low and high fatigue cycles.

$$I = \frac{(\overline{\ln C} - \overline{\ln Sr})}{\sqrt{\sigma^2_{(\ln c)} + \sigma_{(\ln s^2)}}} \qquad (26)$$

where: $\overline{\ln C}$ = mean of joint capability distribution

$$= \frac{\sum_{i=1}^{j} \ln C_i \ln N_i}{\sum_{i=1}^{j} \ln N_i}$$

$\sigma_{(\ln c)}$ = Standard deviation of (lNC)=

$$\left[\frac{\sum_{i=1}^{j} \ln C_i^2 N_i}{\sum_{i=1}^{j} \ln N_i} - (\ln \overline{C})^2\right]^{-1/2}$$

$\overline{\ln S_r}$ = mean of stress range spectrum

$$= \frac{\sum_{i=1}^{j} \ln Sr_i \ln n_i}{\sum_{i=1}^{j} \ln n_i}$$

$\sigma_{(\ln S)}$ = Standard deviation of (ln S)=

$$\left[\frac{\sum_{i=1}^{j} \ln S_{ri}^2 \ln n_i}{\sum_{i=1}^{j} \ln n_i} - (\ln \overline{S_{ri}})^2\right]^{-1/2}$$

Hence the probability of failure of the structural joint may be as given by equation (11) and the structural reliability (R) may be given in equation (7).

APPLICATION AND DISCUSSION

To study the effect of structural imperfections and their tolerances on the reliability of welded Tubular connections against fatigue, the tubular connection shown in Figure (8) have been chosen. Such tubular connection is located at the splash zone of an offshore platform installed in "Abu Qir bay-Egypt" [2]. The connection is subjected to the wind induced wave spectrum and the related stress spectrum, shown in Table (5), reference [2]. The stress spectrum is found to follow the formula given in equation (27).

$$n_i = 3.505 \times 10^7 \, e^{-0.451S} \qquad (27)$$

While the welded connection is designed according to API-Curve X [7]; and its response curve be as given in equation (28) [2].

$$N_i = 2.25 \times 10^{12} \, (S_i)^{-4.38} \qquad (28)$$

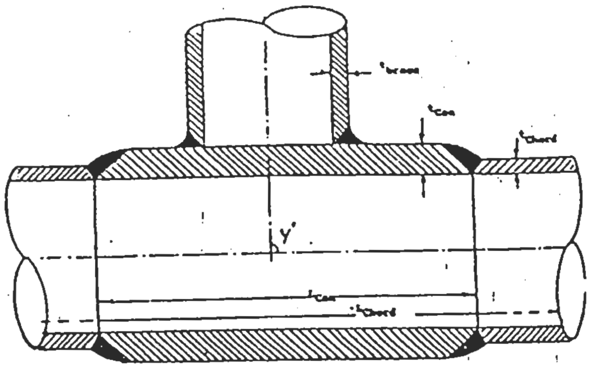


Figure 8. Tubular Connection with "Joint Can".

The flow chart of the computer program, given in appendix (VII) reference [2] is designed to estimate the reliability of the welded tubular connection, showing the effect of hotspot stress concentration, slamming effect, corrosion, residual stresses and welding discontinuities. Table (1), shows the summary of the output results.

Two categories of factors enlarging the distribution of the applied loads, such as slamming magnification factor. The second category is the factors reducing the joint capability, such as hot spot concentration factor, residual stresses, corrosion and welding defects. Figure (9), (10), and (11) show the probability density function (pdf) of both the load (S) and capability (C) of welded connection, showing the effect of uncertainties on the probability of failure (P_f).

Assuming an ideal case, where geometrical stress concentration factor (SCF) is unity and no effect of uncertainties, the connection reliability may be 99.6%. This value is reduce to 91.6% case of S.C.F. = 4.15; i.e. 8% increase in the probability of connection failure, as shown in Figure (8). From Figure (9) and Table (1), and additional 0.97% increase in the probability of failure may take place when including the effect of slamming. Corrosion allowance of 10% reduction in thickness with the proper protection methods, may reduce the connection reliability by additional 0.53%. Residual stresses may cause 0.043% increase in the probability of failure. This value may easily by neglected at high cycles stresses, beside residual stresses may show a narrow band distribution with limited deviation, as shown in Figure (10).

Surface undercut of 0.25 mm is accepted by A.P.I. [7] design code. The reliability of the connection when including such defect, and under the combination of all previously stated uncertainties, may have a value of 90.26%. Assuming the case of an embedded defect of the same size (0.25), the connection reliability may be improved to the value of 90.31 %, as shown in Figure (11).

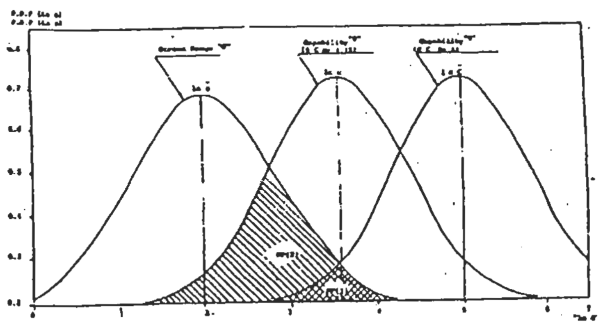


Figure 9. Effect of Geometric stress Concentration factor on joint capability and probability of failure.

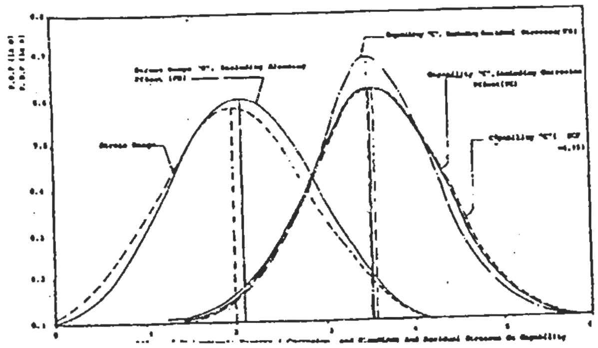


Figure 10. Effect of environmental factors (corrosion and slamming) and residual stresses on capability and failure probability.

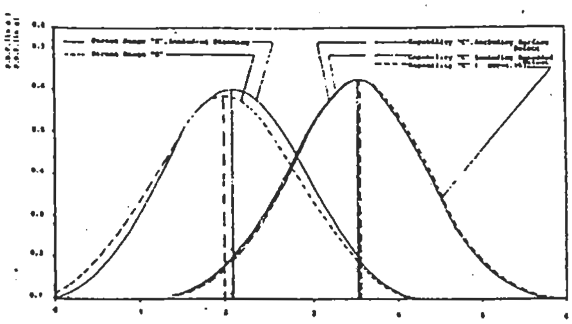


Figure 11. Effect of surface and embedded defects on capability and failure probability.

Table 1. Effect of structural imperfections on structural reliability.

Case description	Stress range (log S)			Capability (log C)			Safety margin			Safety index	Probability of failure (P_f)	Reliability (R)
	$\overline{LnS}$	$V_{(LnS)}$	$\sigma_{(LnS)}$	$\overline{LnC}$	$V_{(LnC)}$	$\sigma_{(LnC)}$	$\overline{M}$	$V_{(M)}$	$\sigma_{(M)}$	(β)		
1.Theoretical case: Geometrical S.C.F.=1	2.00497	0.685497	4.967577	0.584998:	0.5849981	0.76485	2.96260	1.27049	1.12716	2.646117	0.00405	0.99595
2. Effect of geometrical stress concentration factor	2.00497	0.685497	0.827947	3.564469	0.5849981	0.76485	1.55949	1.27049	1.12716	1.38355	0.0833	0.9167
3. Effect of slamming	2.00497	0.640815	0.800509	3.564469	0.5849981	0.76485	1.4647	1.22531	1.10716	1.3238	0.09292	0.90708
4. Effect of corrosion	2.00497	0.685497	0.827947	3.52534	0.5849981	0.74633	1.5203	1.27049	1.12716	1.34884	0.08852	0.91148
5. Effect of residual stresses	2.00497	0.685497	0.827947	3.513537	0.5570189	0.76484	1.50856	1.24251	1.11468	1.35335	0.837	0.9163
6. Effect of surface defect	2.00497	0.685497	0.827947	3.5461815	0.584962	0.76484	1.5432	1.27047	1.1271	1.369117	0.08535	0.91465
7. Effect of embedded defect	2.098727	0.640615	0.827947	3.550056	0.58498	0.676021	1.54506	1.27046	1.12715	1.37077	0.08525	0.91475
8. Combined effect, including surface defect	2.093727	0.640815	0.800509	3.4581261	0.4570048	0.676021	1.356398	1.09782	1.04776	1.29742	0.09731	0.90269
9. Combined effect including embedded defect	2.098727	0.640615	0.800509	3.46001	0.457006	0.67602	1.36127	1.097822	1.04777	1.29821	0.0969	0.9031

Therefore controlling uncertainties may significantly improve the connection reliability against fatigue failure.

CONCLUSIONS

(1) The rational approach to estimate structural reliability of welded tubular connections depends not only on statistical variations of the applied loads and structural capability, but also on the effects of environmental and structural imperfections.

(2) To improve the structural reliability of a welded tubular connection, it is necessary to control imperfections resulting during different fabrication stages.

(3) The safe and economic design of welded tubular connections should be based on an accepted probability of failure, and the corresponding optimum factor to safety value for the particular mode of failure nuder consideration.

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