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للأستاذ الدكتور محمد عبد الفتاح شامة

Published Papers (1981-2002)

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,

جمعية المهندسين البحريين ومهندسي بناء السفن
SOCIETY OF MARINE ENGINEERS & SHIPBUILDERS

On The Economics of Safety Assurance

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ON THE ECONOMICS OF SAFETY ASSURANCE

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S U M M A R Y

The probabilistic approach to safety assurance of offshore structures is examined. The emphasis is placed only on the failure resulting from the extreme values of load and strength.

The main factors affecting structural reliability are indicated. The effect of variability of structural strength and reliability with time is briefly considered.

The optimum structural reliability is examined. The optimality concept is based on the minimisation of the total cost of the structure. It is shown that offshore structural safety should be related to the economic and social consequences of failure.

1- Introduction :

For any project, or system, the benefits should exceed the penalties, or costs. Therefore, the selection of a design should be based on the achievement of maximum utility and minimum expected loss in case of failure. The optimality concept includes minimum weight, minimum cost, high utilisation, high reliability, long service life, etc. The achievement of all these desirable and perhaps conflicting features at the same time, is rather impossible. This could be practically realised by the minimisation of the expected loss associated with failure, while imposing certain limiting conditions on the utility, or benefits. It is not feasible to design an offshore structure which is absolutely free from any structural damage or failure.

Since initial and operational costs are both functions of structural reliability, the determination of the standard reliability (or safety level) is a techno-economic problem. As structural capability and demand are both stochastic phenomena, structural reliability is also a stochastic phenomenon. The determination of the standard reliability without taking into account the time factor does not give a rational solution. Structural reliability reduces with time by virtue of corrosion and damage accumulation (fatigue, cracks, bumps, etc.). These deteriorating effects can be catered for by considering structural capability as a random variable with a mean that is a decreasing function of time. The mean of the extreme loading is also a random variable that is an increasing function of time. Therefore, the standard reliability, or safety level, should be determined from economical considerations (minimisation of cost of failure) for the assumed service life.

2- Structural Failure :

Failure is the cessation of one function, or more, of a system. Structural failure is a random event and is defined in terms of a specified limit state, or mode of failure. The latter depends entirely on the types of loading, structural geometry, scantlings, configuration, etc. The modes of failure commonly encountered in offshore structures are [1]:

i- excessive yielding
ii- buckling
iii- brittle fracture
iv- excessive deformations
v- fatigue

Failture modes (i) to (iv) occur as soon as the applied load exceeds the critical strength, whereas mode (v) is time dependent.

It is not feasible to design an offshore structure which is absolutely free from any structural damage.

3- Structural Reliability

Reliability is defined as the probability that a system or member, does not fail during its projected service life; i.e. the probability of safe operation, or failureless operation of the system.

If the load on the system is Q and its capability for a particular mode of failure, is R, then structural reliability is given by:

$$P_S = \text{Probability } (R > Q)$$
$$= \int_{R>Q} P_{R,Q}(r,q)\, dr.dq$$

It is evident that the probability of failure is given by:

$$P_f = 1 - P_S$$

It should be noted that structural reliability is not an absolute measure of safety and should be related to the economic and social consequences of failure.

4- Loading (Demand)

The demand "Q" normally refers to the maximum value likely to occur over the expected service life of an offshore structure, and is normally based on a recurrence period of 50-100 years.

. Wind loads are evaluated by assuming sustained and gust wind speeds (2).

Wave loads are normally evaluated by means of one of the two following methods:

i- Design wave method (3).

ii- Spectral analysis method (4).

The latter method is based on either short or long term predictions, transfer functions, and the assumption that loads are linearly dependent on wave height.

The short term approach considers wave heights within a specified sea condition. It has been assumed that the peak values of any response of an offshore structure, as well as wave heights, follow the Rayleigh probability low (5).

$$f_X(x) = \frac{x}{m_o} \exp\{-x^2/2m_o\} \qquad x \geq 0$$

where: x = amplitude of response

m_o = area under spectrum.

The validity of this distribution function is based on the assumption that the random sea is a steady-state Gaussian process, the spectrum is narrow-banded and the responses are linear. In this case, the extreme value of responses in "n" encounters is given by:

$$\bar{y}_n = \sqrt{2m_o \ln(n)}$$

The expected maximum wave height is given by (4):

$$h_{max} = h_{1/3} \sqrt{0.5 \ln(n)}$$

where: $h_{1/3}$ = significant wave height.

The long term probability density function could be determined from the corresponding short term functions as follows:

Let $P_X(x)$ = p.d.f. of X over a short period corresponding to a particular sea state described by its root mean square value "E".

$g_E(e)$ = p.d.f. of "E" for a given Beaufort number "B".

$w_B(b)$ = p.d.f. of "B" over the lifetime of the structure.

Then, the long term p.d.f. of "X" is given by:

$$F_X(x) = \int_0^\infty\int_0^\infty p_X(x) \cdot g_E(e) \cdot w_B(b) \cdot de \cdot db$$

The distribution function commonly used to describe the long term variation is the Weibull distribution, given by:

$$F_X(x) = 1 - \exp\{-(\frac{x}{k})^l\}$$

where, k and l are the parameters of the distribution.

The study of the extreme values can be considered as a special case of "order statistics" (Gumbel) (6), and could be determined from the original distributions, see fig. (1)

5- Strength (Capability):

The capability "R", for a particular mode of failure represents a limiting state beyond which the structure is expected to fail (damaged or collapse).

The variability of "R" results from the variabilities of the mechanical properties of the material, dimensional tolerances, fabrication defects, residual stresses, initial distortions, accuracy of stress analysis, errors in mathematical modelling, corrosion, wear and tear, etc.

Fatigue and buckling failures are recognized as the major hazards for offshore structures. Therefore, their corresponding strengths should receive the utmost attention with regard to the estimation of their mean values, their lower limits and their variabilities.

The prediction of fatigue life is subject to a number of systematic and random uncertainties, caused by model test results used as basis for S-N curves. The selected model test curve does not adequately represent the actual structure. The quality of the welds and the design of connections have a large influence on the fatigue life, see fig. (2).

The buckling strength of tubular columns is greatly influenced by several classes of perturbations, such as initial column deformations, local deformations, eccentricity of loading, presence of lateral loading, residual stresses, etc., see fig. (3) (7).

The benefitial effect of structural redundancy should be recognised as the failure of a single member does not necessarily lead to a catastrophic failure.

Practically, the capability should be represented by a truncated density function, whose lower and upper limits give the feasible range of variation. The lower limit represents the critical value and therefore should be controlled so as to give an acceptable safety margin. The upper limit represents the unnecessary extra strength, and hence extra steel weight, which may have adverse economical consequences (8). Therefore, adequate measures should be taken to ensure a narrow capability density function. This could be achieved by monitoring dynamic stresses.

The variability of the minimum capability could be represented by a p.d.f. using asymptotic relation, see fig. (4).

6- Safety Assurance :

A major requirement for any marine structure is to have low initial and operational costs, to be reasonably safe, not to have catastrophic failure, nor to cause much trouble in service due to frequent minor failures.

Safety is today concerned not only with the structure itself, but also with external damage that may result as a consequence of failure. The assurance of adequate safety for offshore structures is a complex problem, involving design, construction and operation. With increasing cost of offshore structures and the need to reduce risk, it is important to develop design criteria and procedures which optimise the overall cost of constructions and lifetime reliabiltiy.

The probabilistic approach to design provides an assurance of safety which is expressed in terms of probability of occurrence of possible structural failures. The fundamental equation to safety assurance is given by (9):

$$R > Q$$

i.e. strength > load

The margin of safety is given by:

$$M = R - Q > 0$$

The "safety factor" is given by:

$$\gamma = R/Q > 1.0$$

Classification societies remain the main authority responsible for the assurance of safety for ships and marine structures. For conventional ships, structural reliability is based on data collected from ships in service which are used for developing construction rules. Structures designed according to those rules are generally overdesigned.

For offshore structures, or novel ship types, the extrapolation from available data may be extremely difficult. Therefore, safety assurance should be based on the statistical parameters of loading and strength. It is evident that neither loading nor strength can be represented by a single value. Both are functions of several random variables and can be only treated statistically.

Assume that the random resistance "R" and the random load "Q" are known and that the uncertainties are strictlythose associated with the inherent randomness. The probability of failure in this case, is given by:

$$p_f = P(R \leq Q) = \int_0^{\infty} \left[\int_0^{q} f_R(r)\,dr \right] . f_Q(q)\,dq$$

$$= \int_0^{\infty} F_R(q) . f_Q(q) . dq$$

In the special cases when :

$Q = S$, then $p_f = F_R(S)$

$R = \bar{R}$, then $p_f = 1 - F_Q(\bar{R})$

The effect on the probability of failure of the selected distribution functions of "R" and "Q" is shown in fig. (5).

It is evident that it is technologically and economically unrealistic to totally eliminate the uncertainties associated with the parameters involved in the determination of both R and Q, nor to determine their reliable distribution functions. Consequently, some practical procedures have been developed for evaluating structural safety (10).

7- Standard Reliability :

The standard reliability, or the target total probability of failure, p_f , may be obtained from one of the following approaches (1):

i- Comparison with the annual probabilities of failure in related activities:

Based on the consequences of failure, the following target annual probabilities of failure are suggested:

- slight consequences : $p_f = 1x10^{-3} - 1x10^{-4}$
- normal consequences : $p_f = 1x10^{-4} - 1x10^{-5}$
- serious consequences : $p_f \geq 1x10^{-5}$

ii- Danger to human life:

Considering the chances of death, the target annual probability may be estimated as follows:

$$p_f = 10^{-4} \cdot k_s / n$$

where: n = number of persons involved in the accident

k_s = social criterion factor (K_s = 5 for marine structures)

Thus, for $n = 100$, $p_f = 5x10^{-6}$

iii- Economic consequences of failure:

This approach does not involve any loss of life and is based on the minimisation of the consequences of failure.

A marine structure of low reliability has a short service life, rapidly goes out of service and requires large expenditures for maintenance and repair. An increase in reliability implies a rise in the initial cost and possible reduction in operational costs.

8- Determination of the Reliability Standard (optimum p_f)

The optimum p_f is determined from the minimisation of the total cost. The latter could be divided into:

i- Non-failure cost items

- initial cost
- scrap value
- depreciation
- insurance
- maintenance

ii- Failure cost items

- replacement cost
- cost of repair
- loss of DWT items
- salvage cost
- loss due to time out-of-service
- cost of pollution abatement, clean up, or other environmental effect
- loss of reputation, business and public confidence

Some of these cost items are independent of p_f while the others are totally dependent on p_f.

The generalised life cycle cost equation is given by:

$$C = C_I + \{C_{MR} + C_F \cdot p_f\} \cdot \eta$$

where: C_{MR} = inspection, maintenance and repair costs

C_F = expected cost of failure

η = a factor that transfers future cost items into their present worth values

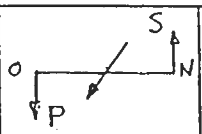
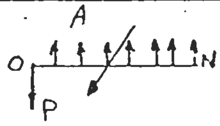
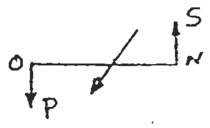
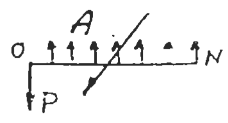
C_I = initial construction cost

In order to simplify the analysis, the generalised cost equation is given by (11):

$$C = C_I + \{C_F \cdot p_f\} \cdot \eta$$

The present worth of future cash flows are given in standard text books on Engineering Economy (12).

The following table gives η for different future payment conditions:

Rate of Interest	Annual (i%)		Continuous (r%)	
Present Worth Factor				
η	$(1+i)^{-N}$	$\frac{(1+i)^N - 1}{i(1+i)^N}$	e^{-rN}	$\frac{1-e^{-rN}}{r}$
			$r = \log(1+i)$	

Consider the particular case when the annual maintenance and repair costs are assumed constant.

Then : $PWV = P = C_I + A\ (PW - i\% - N)$

or $\delta P/A = \chi$

where: $\delta P = P - C_I$

The variation of χ with N is shown in fig. (6) for different values of the rate of interest i%.

It is shown that as N increases, the effect of the annual maintenance and repair costs becomes less significant with increased rate of interest.

9- Optimality Criterion

It is evident that C_I increases with increasing structural reliability, by virtue of using better material, better design, etc., whereas C_F increases with increasing p_f. It is necessary, therefore, to determine the optimum value of P_f, which minimises the expected total cost, see fig. (7).

Because of the scarcity of information regarding the economic consequences of failure, the criterion for selecting an optimal design is therefore treated only theoretically and is based on the determination of the optimum safety level, (probability of failure), which gives the minimum expected total cost C,

a) Optimum P_f (reliability standard)

1) When p_f is time dependent:

The actual reliability of a marine structure is some function of the time "t". Different longevity distributions may correspond to identical values of the initial and final reliabilities, $P_s(o)$ and $P_s(T)$ respectively (13), as shown in Fig. (8). Curve (1) represents good design, good material, good maintenance, etc., and therefore may require high initial cost. The selection of the function $P_s(t)$ is based on the minimisation of the expected total cost C, given by:

$$C = C_I + (C_F\ .\ p_f).\ \eta$$

Where C_I and C_F are both functions of the reliability $p_s(t)$. The form of these functions depends on:

i) the type of economic model used;

ii) type of marine structure, structural configuration, etc.;

iii) type of loading;

iv) properties of the material (resistance to corrosion, erosion, etc.);

v) mode of failure expected;

vi) expected service life.

It is evident that as the longevity increases, C_F diminishes because of the physical wear and tear as well as amortisation. Materials offering high potential for increased longevity, particularly for offshore structures, are rather expensive.

The mathematical expectation of the cost C is given by (13):

$$= C_I + \int_0^T \{ C_F \cdot \eta \cdot p_f(t) \} . dt$$

The calculation of the second term could be illustrated by the following example: Assume that:

i) $p_s(t) = e^{-p_0 t}$

ii) $C_F = g \cdot C_I.$

iii) $\eta = e^{-(r-s)t}$

where: p_o = annual failure probability

r = rate of interest

s = inflation rate

g = a factor relating cost of failure to initial cost

Hence: $$\bar{C} = C_I + \int_0^T C_F \cdot e^{-(r-s)t} \cdot p_0 \cdot e^{-p_0 t} . dt$$

$$= C_I \left[1 + g p_o \left\{ \frac{1 - e^{(-r+s-p_0)T}}{r - s + p_0} \right\} \right]$$

This equation could be represented by a diagram such as that shown in Fig. (9). The minimum value of C gives the optimum value of p_o.

Alternatively, the generalised cost equation may be solved numerically using finite difference techniques (13):

b) When p_f is independent of time:

Because of the lack of data on the variability of structural reliability with time and the complexity of the calculations, it is sufficient at this stage, to treat structural reliability P_s as some number and ignoring the time factor and the longevity concept. In this case, the reliability standard (optimum p_f) could be determined from the minimisation of the generalised cost equation (14):

$$C = C_I + \{ C_F \cdot p_f \} \cdot \gamma$$

Assuming that: $C_I = A_o \, (1 - a \log_e p_f)$

$C_F = C_o + g \, C_I$

where:

A_o = cost of that part of the structure independent of p_f

a = a numerical factor

g = an inflation factor representing the increase in cost of structure

C_o = additional cost associated with failure

The optimum "p_f" is determined from the condition that:

$$\frac{\partial C}{\partial p_f} = 0$$

Substituting, we get the optimum "p_f" as follows:

$$p_{f_o} = 1 / \left\{ \frac{C_o + g A_o}{a \, A_o} \right\} \cdot \gamma$$

where: p_{f_o} = optimum value of p_f

Therefore, the expected minimum total cost, C_{min}, is given by:

$$C_{min} = C_I + \left\{ \frac{C_F \cdot a \cdot A_o}{C_o + g A_o} \right\}$$

If it is assumed that C_F is independent of p_f, the optimum p_f is given by:

$$p_{f_o} = A_o \cdot a / C_F \, \gamma$$

10- Concluding Remarks:

1- Structural reliability is not an absolute measure of safety, and should be related to the economic and social consequences of failure.

2- The optimum standards of safety assurance could be determined from the minimisation of the total life cycle cost, taking account of the probability of failure. However, because of the lack of adequate data on the economic consequences of failure, the methods presented should be used only qualitatively for comparing alternative designs.

3- The degree of sophistication and corresponding costs of inspection, maintenance and repair schemes of offshore structures should be determined in the light of the initial cost and probability of failure. The variation of the latter with time should be taken into account.

4- The available methods for determining extreme values of load and strength are adequate for estimating the probability of failure. The latter, however, should be considered as a relative measure of structural safety. Efforts should be directed to reduce the extreme values of both load and strength.

11- References:

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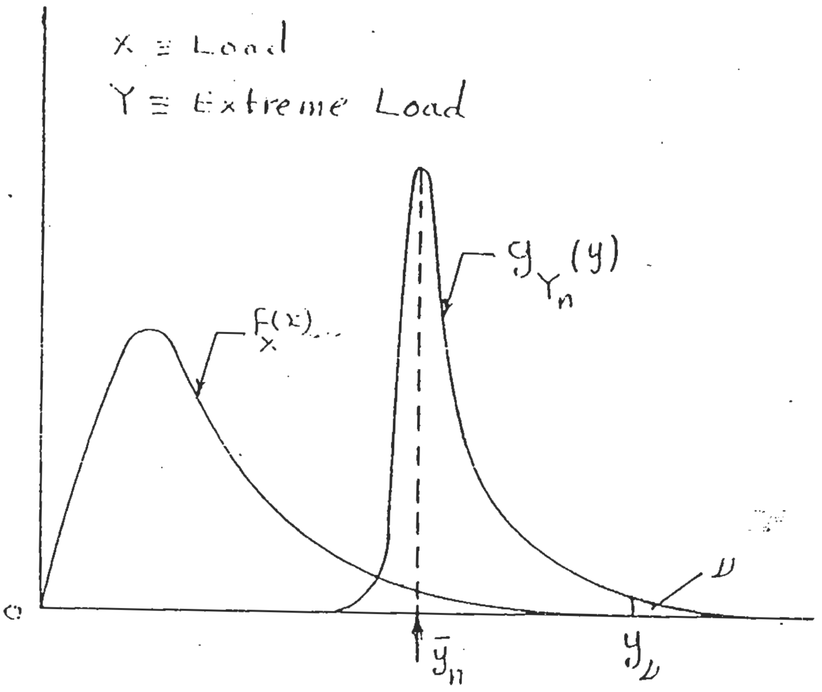


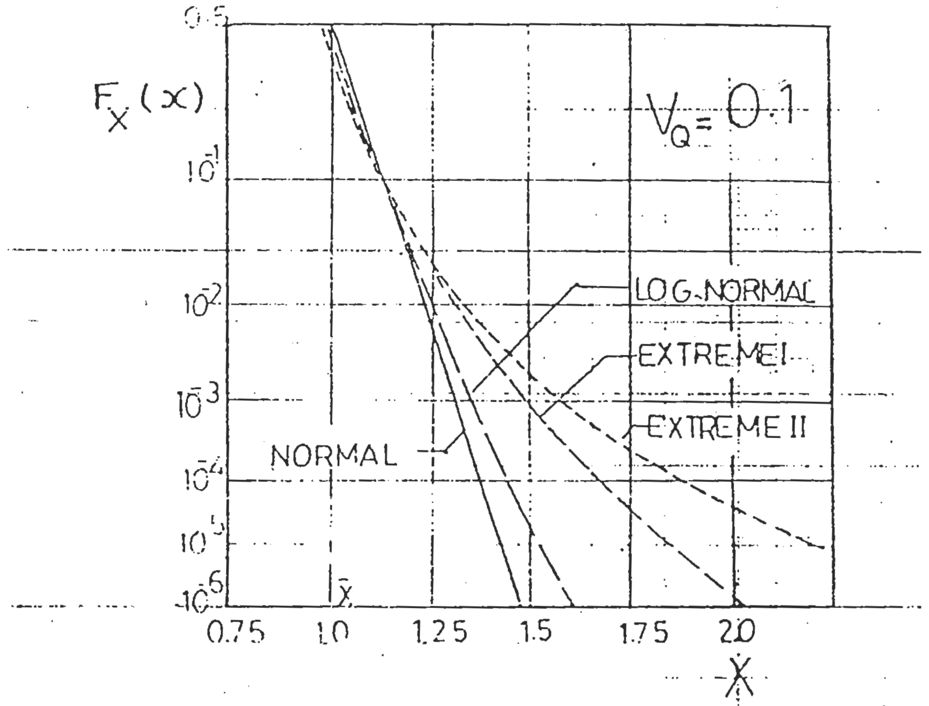


Fig.(1). Load and Extreme Loads

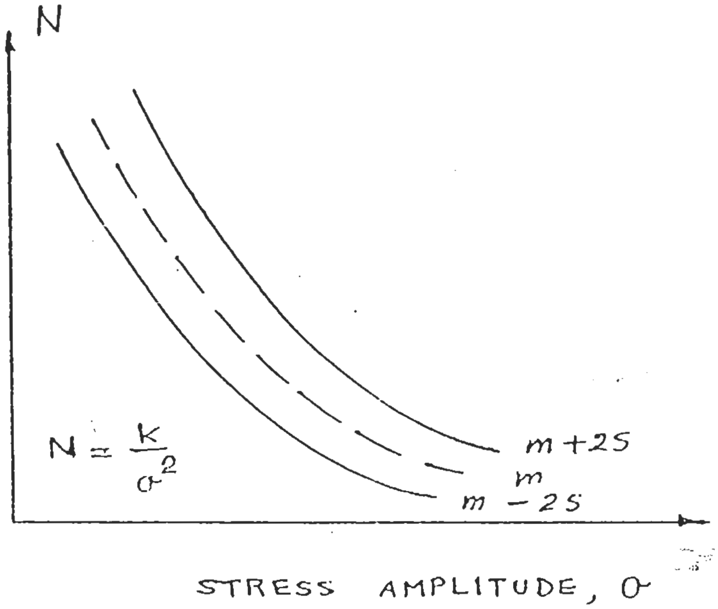


Fig.(2). Fatigue Model

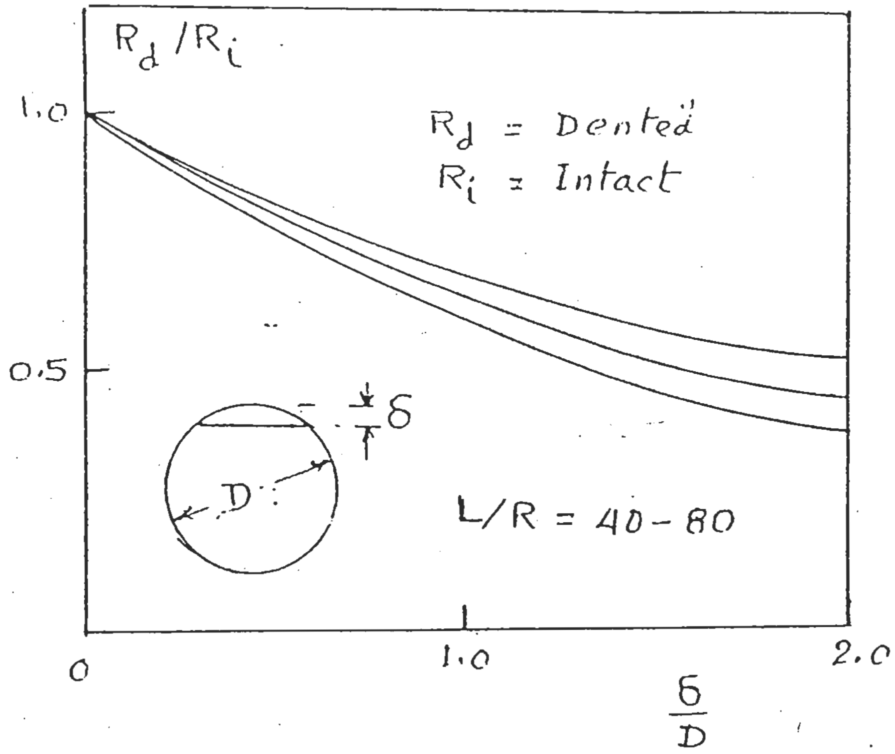


Fig.(3). Effect of Initial Deformations.

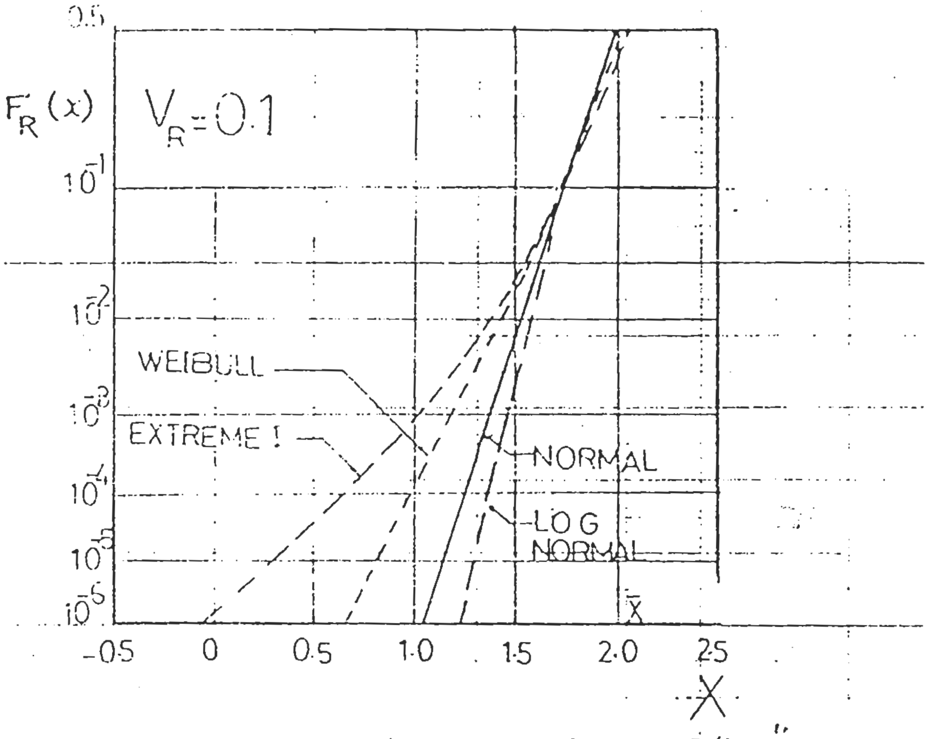


Fig.(4). Distribution Functions of "R"

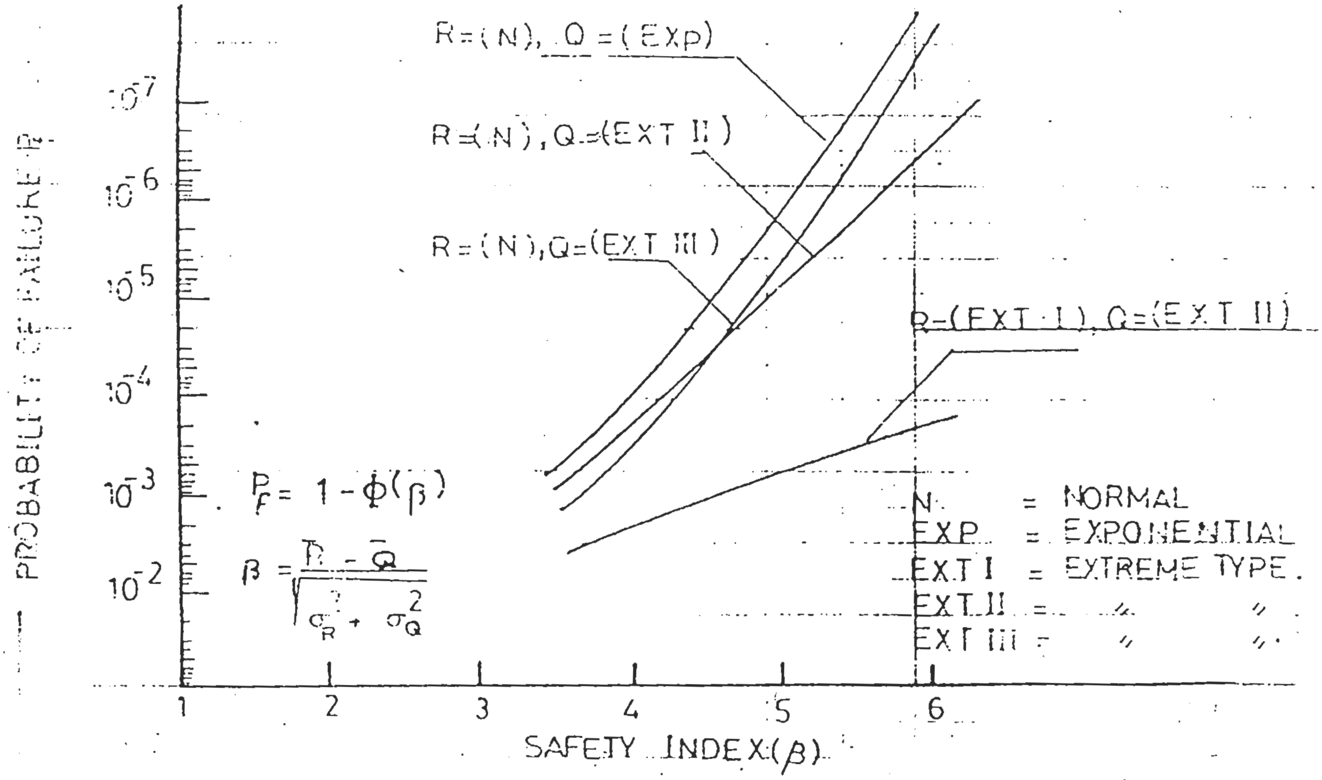


Fig.(5). PROBABILITY OF FAILURE (P_f) Vs THE SAFETY INDE

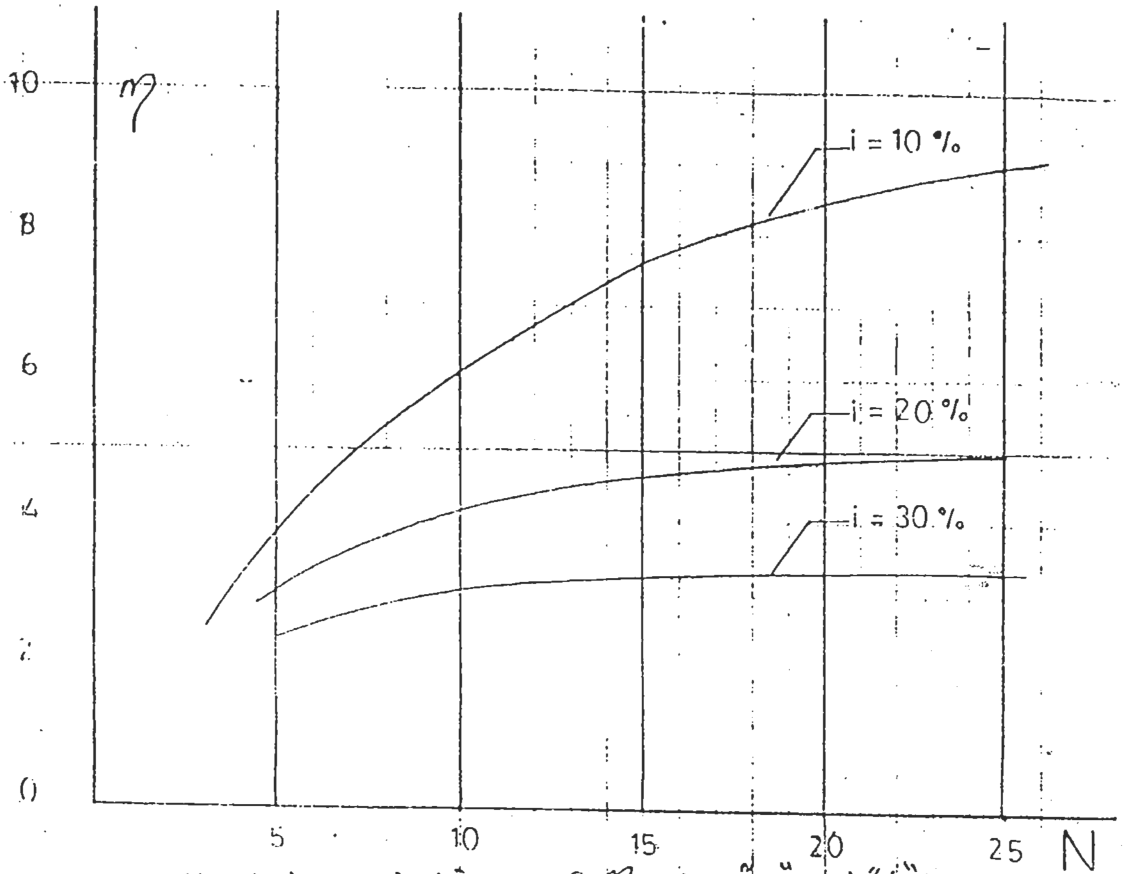


Fig. (6). Variation of η with "N" and "i"

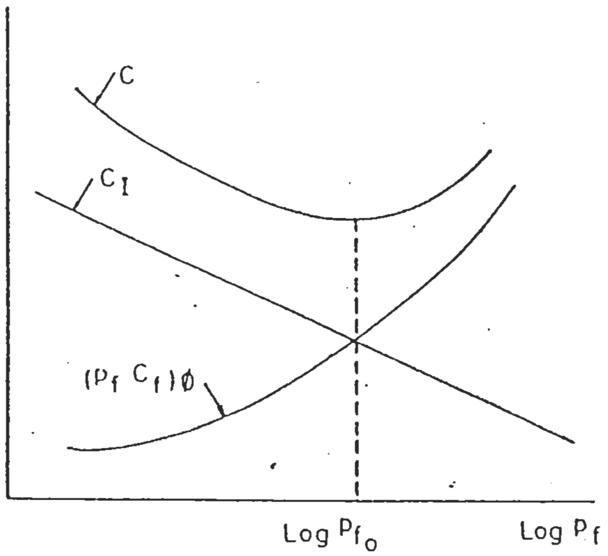
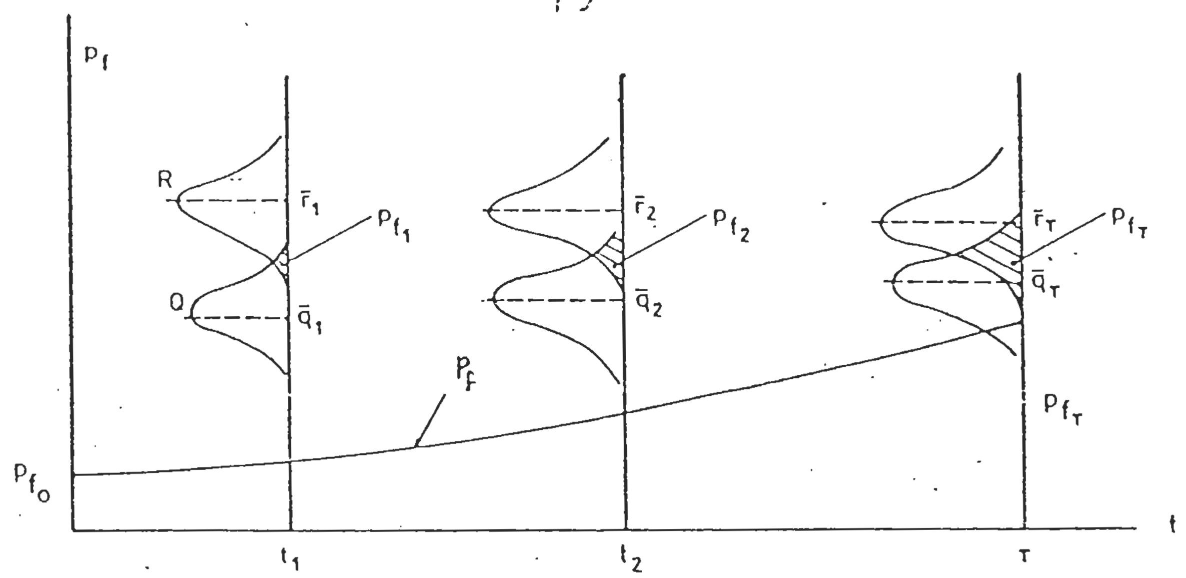


Fig.(7). OPTIMUM PROBABILITY OF FAILURE



VARIATION OF p_f WITH TIME

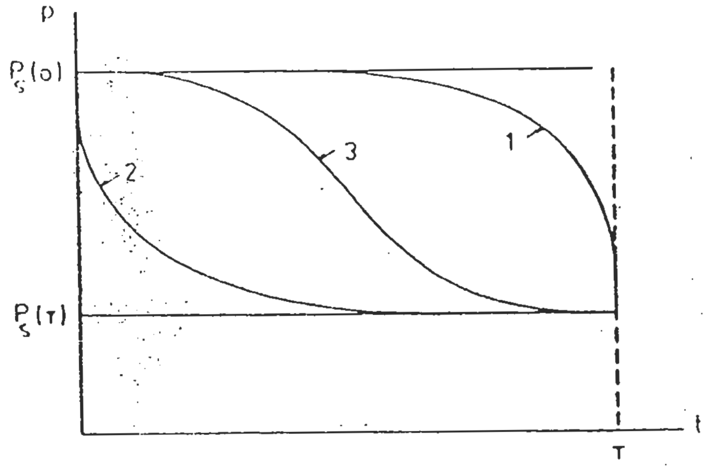


Fig.(8). VARIATION OF STRUCTURAL RELIABILITY WITH TIME.

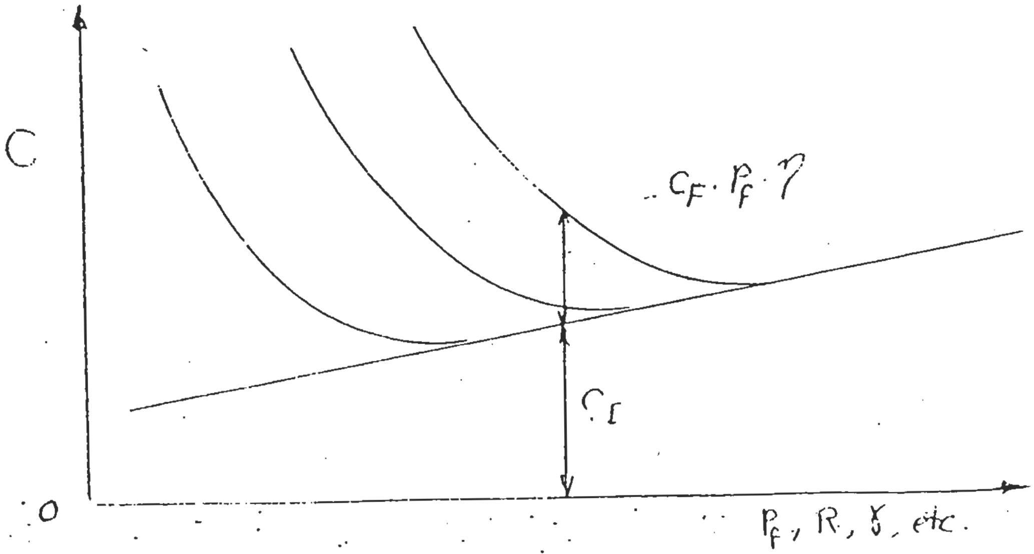


Fig. (9) Variation of Total Cost