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Marine Structural Safety and Economy

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ABSTRACT

The various types, causes and modes of structure failure of marine structures are given. Particular emphasis is placed on the effects of inspection and maintenance on structural strength, probability of failure and the factor of safety. The main concepts of loading, strength and structural reliability are briefly stated. The main factors affecting the uncertainties of structural strength are clearly identified. A rational approach to structural safety of marine structures based on the minimisation of the total life cycle cost is presented. The variations of initial cost and cost of failure with the probability of failure is considered qualitatively. A simple example is presented to show the variation of the initial cost of a simply supported plate subjected to compressive stresses with the factor of safety against flexural bucking. It is shown that safety and economy of marine structures are greatly improved when effective inspection and maintenance schemes are incorporated in the design i.e. Design for Inspection and Maintenance (DIM). It is evident that much work is still needed to establish a rational design procedure incorporating safety, economy and maintainability of marine structures.

INTRODUCTION

Structural safety of marine structures depends on the variabilities and uncertainties of loading and strength, consequences of failure and the cost of failure. The variabilities of loading result basically from its random nature. The uncertainties of structural strength result from several causes among them are structural modelling, analysis procedure, fabrication defects, scantling tolerences, etc.

The life cycle cost of a marine structure is composed basically of the initial cost and the cost of failure. Both cost items depend, among other things, on structural reliability, probability of failure or factor of safety. The initial cost increases with increased structural reliability. The cost of failure, on the other hand, decreases with increased reliability. Therefore, there is an optimum value or range of values of structural reliability or the factor of safety which give a low value for the expected total cost in case of structural failure.

This paper presents a qualitative approach for the determination of the optimum structural reliability. The approach is supplemented by a simple example illustrating the effect of variation of the factor of safety on the initial cost of a simply supported rectangular plate subjected to compressive stresses. No attempt is made to consider the cost of failure because of the lack of data on the various failure cost elements.

It is shown that much work is still needed before this rational approach could be used in a practical way.

SAFETY ASSURANCE

A major requirement for any marine structure (a ship or an offshore structure) is to have low initial and operational cost, to be reasonably safe, not to have catastrophic failure, nor to cause much trouble in service due to frequent minor damages and failures.

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

The fundamental equation of safety assurance is given by [1]:

$$M = R - Q > 0 \qquad (1)$$

where:

M = margin of safety
R = strength
Q = load
The factor of safety "γ" is given by:

$$\gamma = R/Q \quad (2)$$

It should be realized that for a marine structure, or any part of it, the strength and load are time dependent. The strength normally deteriorates with time by a rate totally dependent on the effectiveness of the schemes of inspection, maintenance and repair adopted. The load normally increases with time.

The adverse effect of these variations on the margin of safety of a marine structure is illustrated by Figure (1). The effect of improper inspection and maintenance schemes on the variation of the factor of safety with time is illustrated by Figure (1).

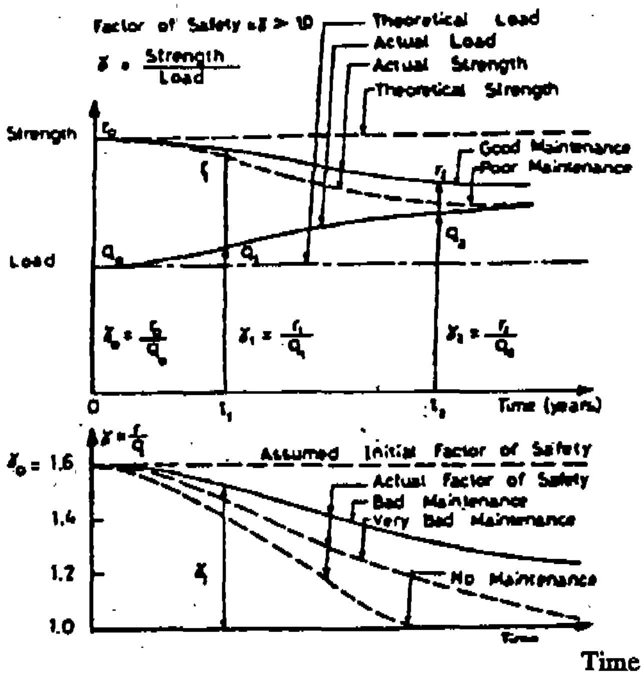

Figure 1. Variation of Q,R and γ with time.

LOADING (DEMAND)

The demand "Q" normally refers to the maximum value of loading (shear force, bending moment, etc.) likely to occur over the expected service life of a Marine Structure.

For an offshore structure, the demand is normally based on a recurrence period of 50-100 years. Wind loads are evaluated using assumed values of sustained and gust wind speeds [2]. Wave loads on Marine structures 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 the assumption that load are linearly dependent on wave heights. Either short or long term prediction of structural responses (stresses, strains, ect.) are normally considered. Efforts have been made to include nonlinear effects in the estimation of sagging moments and shear forces in fine ships [5].

The long term probability density function could be determined from the corresponding short term functions. However, the distribution function commonly used to described the long term variation is the Weibull distribution [6].

The distribution function of the extreme load could be determined from the density function of the load using asymptotic relations [7].

STRENGTH (CAPABILITY)

The strength "R" of a marine structure or any part of it, represents for any particular mode of failure, a limiting state beyond which the structure, or element, is expected to fail (damage or collapse).

The variability of "R" results from the variabilities of the mechanical properties of the material, dimensional tolerances [8,9], fabrication defects [10], residual stresses [11], initial distortions [9], accuracy of stress analysis [1 errors in mathematical modelling, corrosion [13], wear and tear, lack of proper maintenance, etc. Figure (2), illustrates the variation of mechanical properties of shipbuilding steel (the range of variation could reach 25% of the lower limit). The relative frequency of corrosion rates for the deck, side and bottom plating of large oil tankers are given in reference [14].

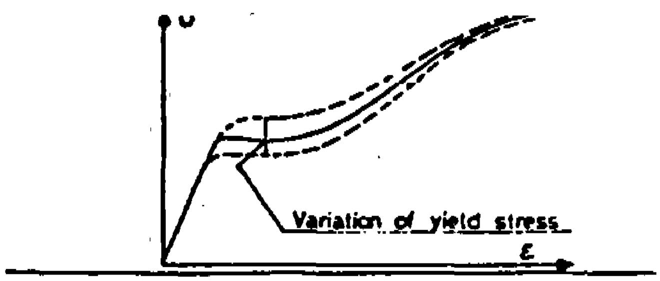

Figure 2. Stress-strain iagram.

The variation of structural strength with time, due to the effect of corrosion, among other things, could be obtained from the variation of material thicknesses with time. For a simply supported panel of plating subjected to compressive stresses, the variation of strength with time, i.e. R (t), relative to the original strength "R_o", could be obtained as illustrated by Figure (3). This Figure is based on the assumption that the variation of plate thickness with time may follow one of the following expressions:

i. $w(t) = w_o (1 - at^2)$

ii. $w(t) = w_o \exp(-bt)$

where:

$w_o, w(t)$ = original thickness and thickness at time "t"

a & b = constants representing the rate of decay of plate thickness.

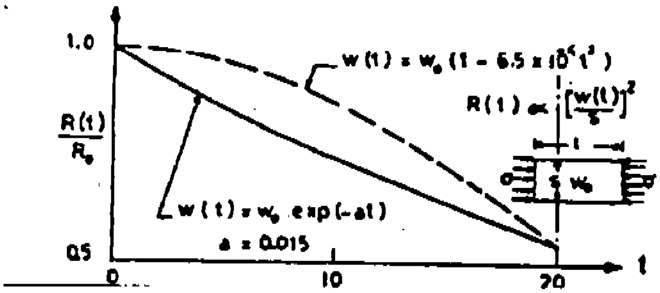

Figure 3. Variation of $R(t)/R_o$ with time.

The rate of decay of strength, therefore, should be controlled so as to ensure an acceptable limiting value over the expected life span of the marine structure.

Figure (4). shows the effect of structural modelling on the calculated stresses in a side frame of a general cargo ship.

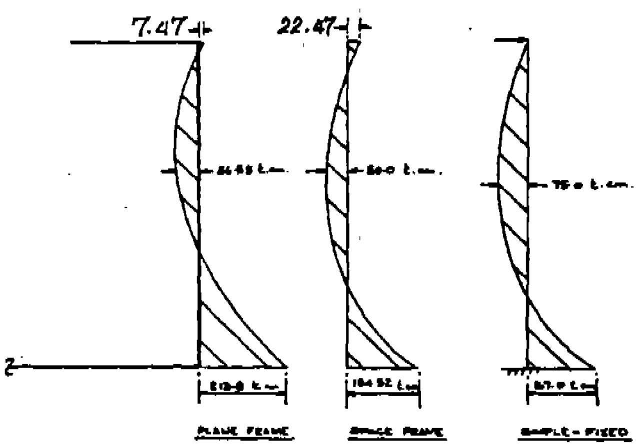

Figure 4. Effect of structural modelling.

Welding and forming residual stresses [11] are expected to have significant effects on the strength of cold formed and welded structural members (angle and T-sections).

The prediction of fatigue life is subject to a number of systematic and random uncertainties resulting from the quality of the welds and the design of connections. The selected model test curve does not adequately represent the actual structure, see Figure (5).

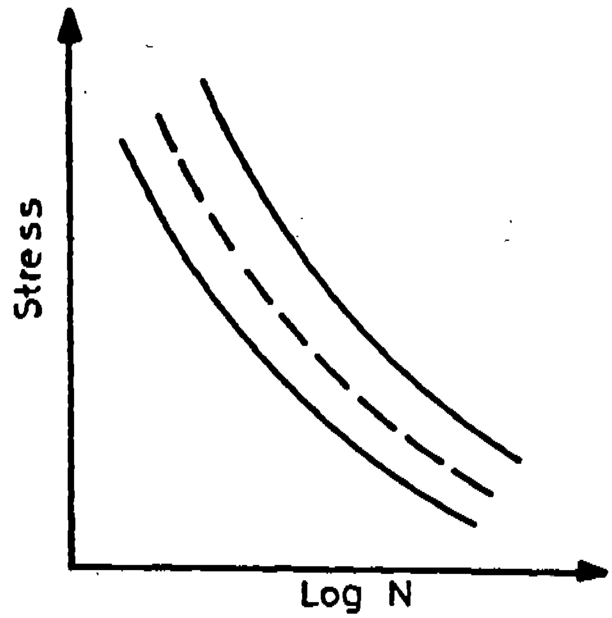

Figure 5. Fatigue model.

The buckling strength of tubular columns is greatly influenced by several classes of perturbations [15], such as initial column deformations, local deformations, eccentricity of loading presence of lateral loading, residual stresses, ect.

The beneficial effect of structural redundancy should be recognized and made use of 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 [16]. Therefore, adequate measures should be taken to ensure a narrow capability density function. This could be achieved by several ways, among them are: improving quality control during fabrication, monitoring dynamic stresses during operation, improving inspection and maintenance schemes, etc.

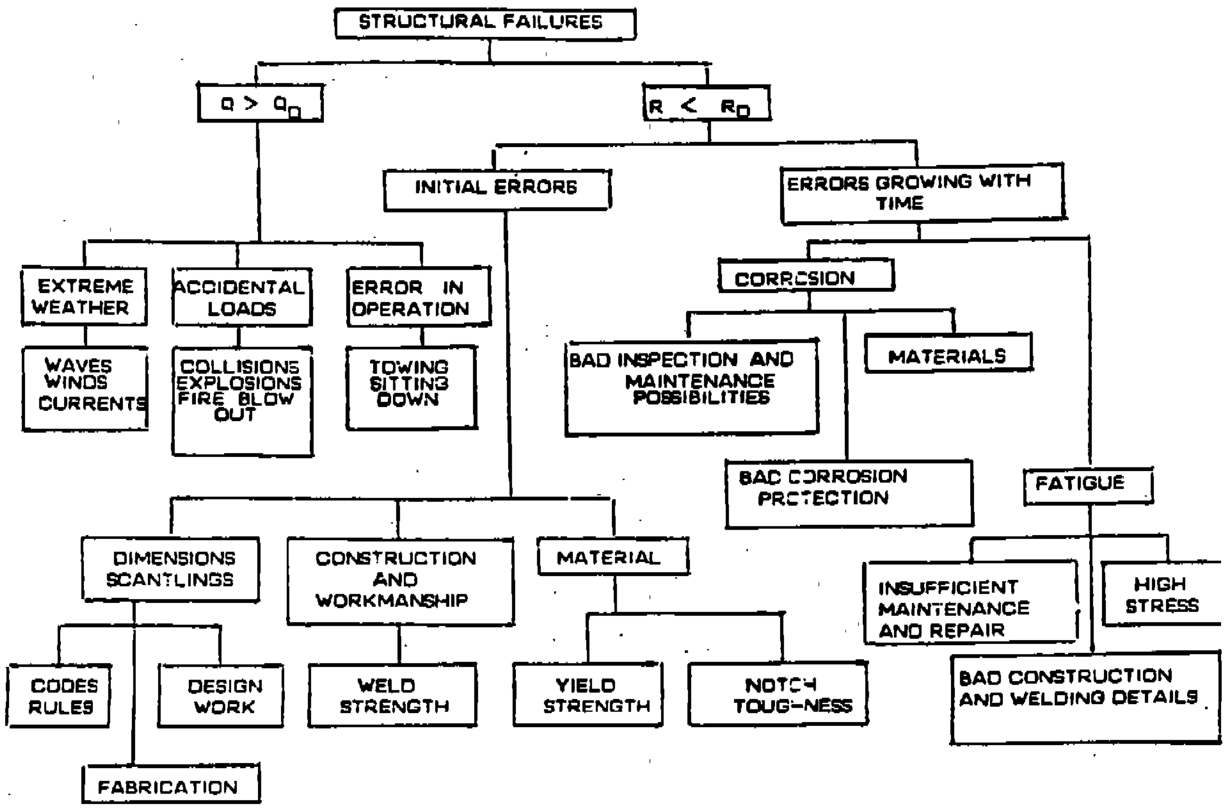

Figure 6. various causes of structural failure.

STRUCTURAL FAILURE

Structural failure is the inability of a structure to carry out its specified function. It is a random event and is defined in terms of a specified limit state, or mode of failure.

Failure may be divided into: Catastrophic or Damage. The former may involve complete loss of the Marine Structure. The latter may be divided into minor or major failure.

Structural failure results from several causes, among them are: heavy weather damages (due to pounding, slamming, panting, shipping green seas, dynamic forces due to rolling and pitching, vibration, etc.), overload, under-design, poor workmanship, wear and tear, corrosion, fatigue, etc. Wear and tear may result from general effects of corrosion or from local pitting [13]. Fatigue and brittle fracture may result from poor design and bad workmanship.

The modes of failure commonly encountered in ships and offshore structures are [7]:

i- Excessive yielding
ii- buckling
iii- Excessive deformations
iv- Brittle fracture
v- Fatigue fracture

Failure modes (i) and (iv) occur as soon as the load exceeds the critical strength whereas mode (v) is time dependent. Figure (6) shows the various causes of structural failure resulting from overloading ($Q > Q_D$) and / or underdesign ($R < R_D$)

where: Q, Q_D = load and design load
R, R_D = strength and design strength

Assuming that the uncertainties are strictly those associated with the inherent randomness of both strength (R) and load (Q) and that their distribution functions are known, or could be determined, the probability of failure is given by [1]:

$$P_f = R\,(R < Q) = \int_0^{\infty} F_r\,(r).\, f_Q\,(q).\, dq \qquad (3)$$

Figure (7) shows the variation of "P_f" with the c.o.v. of strength and load, when both are normally distributed.

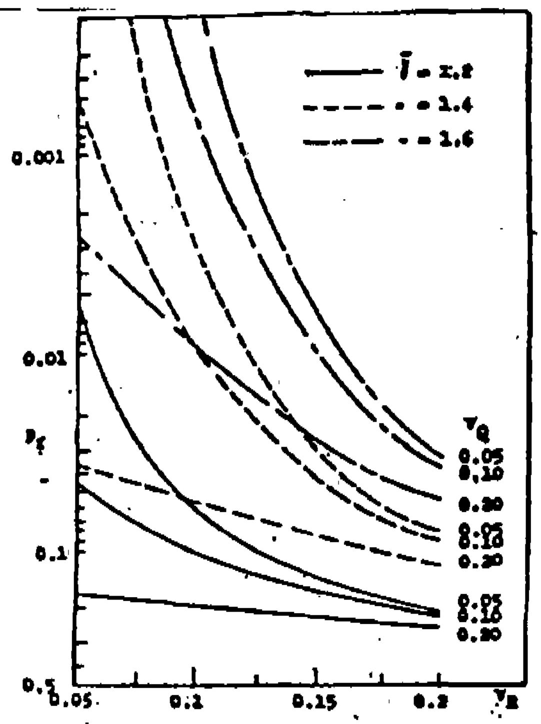

Figure 7. Probability of failure.

STRUCTURAL RELIABILITY

Structural reliability is defined in its simplest from, as the probability of failureless operation of the structure during its projected service life.

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

$$P_s = P\,(R > Q) = 1 - P_f$$

A marine structure of low structural reliability (for the various expected modes of failure) may require low initial cost but normally has a short service life, rapidly goes out of service and generally requires large expenditures for maintenance and repair. Increasing structural reliability may require high initial cost and an effective system of inspection and maintenance. This will increase the utilization of the marine structure and reduce damage and repair costs. Efforts should, therefore, be directed to determine, for any marine structure, the optimum structural reliability which gives the minimum life cycle cost. This may call for Design for Inspection and Maintenance (DIM).

The optimum structural reliability, or its complementary, the target total probability of failure, P_f may be obtained either by comparison with corresponding values in related activities [17] or by the minimisation of the life cycle cost of the marine structure [18].

DETERMINATION OF THE OPTIMUM PROBABILITY OF FAILURE P_f.

The optimum "P_f" is determined from the generalised life cycle cost equation which gives the total cost in terms of the initial cost and cost of failure.

The total cost, however, 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 effects
- 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". Including all these cost items into the life cycle cost equation as independent terms will make the problem rather difficult to solve. The simplification of the generalised cost equation could be achieved by separating the initial cost from all future cost items (cost of maintenance and repair, cost of failure) as follows:

$$C_t = C_I + \{ C_{MR} + C_F \cdot P_f\}\eta \qquad (4)$$

where: C_{MR} = Inspection, maintenance and repair costs
C_F = expected cost of failure
η = a factor that transfers future cash flow into present worth values
C_I = initial construction cost.

The present worth of future cash flow is given in standard text books on Engineering Economics [19].

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

$$C_{MR} = A$$

Then, $PWV = P = C_I + A\ (PW - i\% - N)$
$= C_I \{ 1 + \lambda\ (PW - i\% - N)$
$P = \psi . C_I \qquad (5)$
where: $\lambda = A/C_I$
$\psi = 1 + \lambda\ (PW - i\% - N)$

It is evident that increasing "C_{MR}" or "λ" increases the life span before failure and reduces the cost of failure C_F.

The present worth of "C_t" is given by:

$$C_t = \psi\, C_I + C_F . P_f . \eta \qquad (6)$$

The variation of "C_t" with "λ" could be illustrated by Figure (8). It is evident that there should be an optimum value of "λ" which minimizes the expected total cost "C_t".

However, in order to simplify the procedure of determining the optimum value of "P_f" the C_{MR}" term is included in the "$C_F . P_f$ term as follows (20,21):

$$C_t = C_I + (C_f . P_f) . \eta \qquad (7)$$

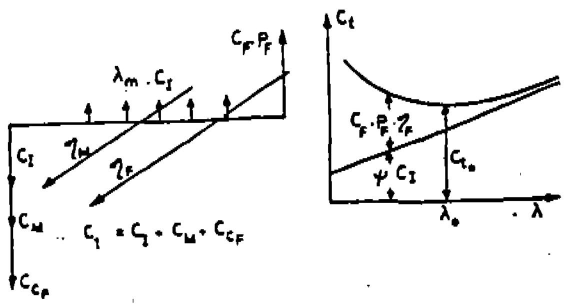

Figure 8. Variation of C_t with λ.

This simplification is logical and justifiable as the cost of maintenance and repair is dependent on "P_f" and its expected variation with time is also indirectly related the cost of failure "C_F". Figure (9) shows the effect of inspection, maintenance and repair on the variation of "P_f" with time

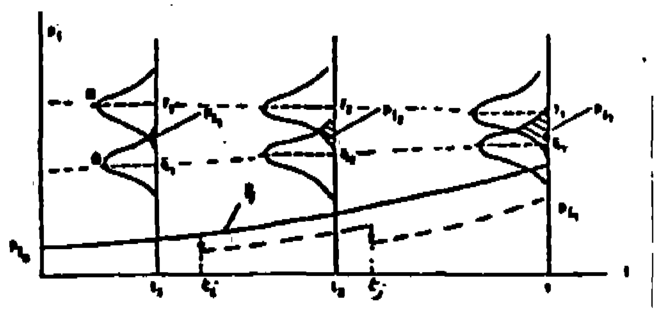

Figure 9. Variation of P_f with time.

It is evident that the variation of "C_I" and C_F" with structural reliability "P_s", the probability of failure "P_f" or with factor of safety "γ" depends on:

i- the type of economic model used: Price of material, fabrication cost, overhead cost, etc.
ii- type of marine structure: structure configuration, etc.
iii- type of loading: loading pattern, etc.
iv- Properties of the material used: strength, resista to corrosion, etc.
v- mode of failure: buckling, yielding, fatigue, etc.
vi- expected service life.

It is clear that the initial cost "C_I" increases with increasing "P_s" or "γ" by virtue of better material, better design, better workmanship, better inspection, maintenance and repair system etc. see Figure (10). On the other hand the cost of failure "C_F" decreases with increasing "P_s" or "γ" because of the physical wear an tear, among several other causes, see Figure (10). It is necessary, therefore, to determine the optimum value of "P_s", "P_f" or "γ" which minimises the expected total cost "C_t", see Figure (11).

It is evident that the calculation of the total cost "C_t" requires various data on all cost items, inflation rate, rate of interest, expected service life, annual failure probability, expected cost of failure, etc. Such data are not always available and in general is very difficult to estimate. It is therefore necessary to record all relevant cost data associated with Marine Structures that suffered minor or major failures.

Since structural reliability could be directly related to the factor of safety for any particular mode of failure [22,23], it should be possible to determine the optimum factor of safety for the mode of failure under consideration

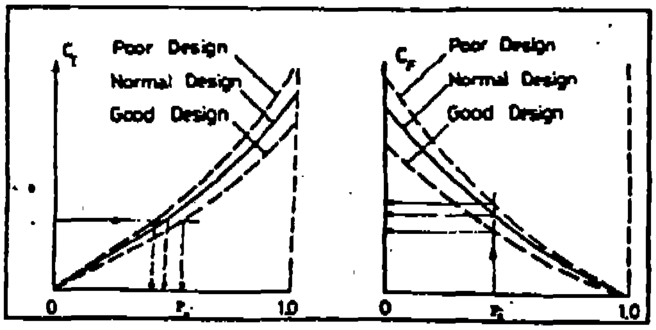

Figure 10. Variation of C_I & C_F with "P_s".

Consider the case of a simply supported rectangular plate subjected to compressive stress "σ". The variation of the plate price, C_I, with the factor of safety γ for the buckling mode of failure could be easily established.

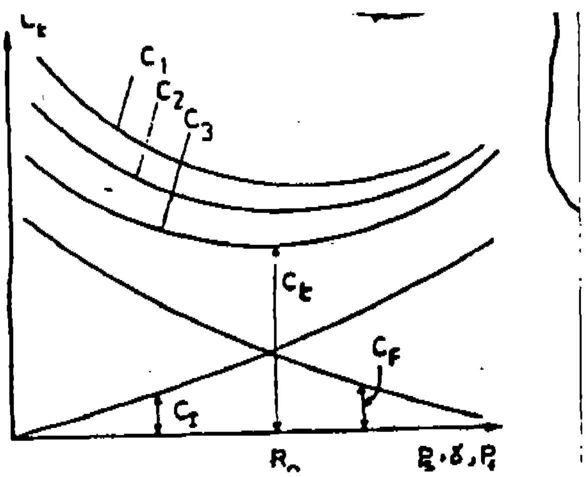

Figure 11. Variation of C_t with P_s, P_f or γ.

Figure (12). shows the variation of the relative price of the plate with factor of safety "γ".

$$\gamma = \sigma_{cr} / \sigma$$

$$\sigma_{cr} = \frac{\pi^2 . E}{3(1-\nu^2)} . (\frac{t}{s})^2$$

The pric of the plate is assumed, for simplicity, to vary linearly with the plate thickness.

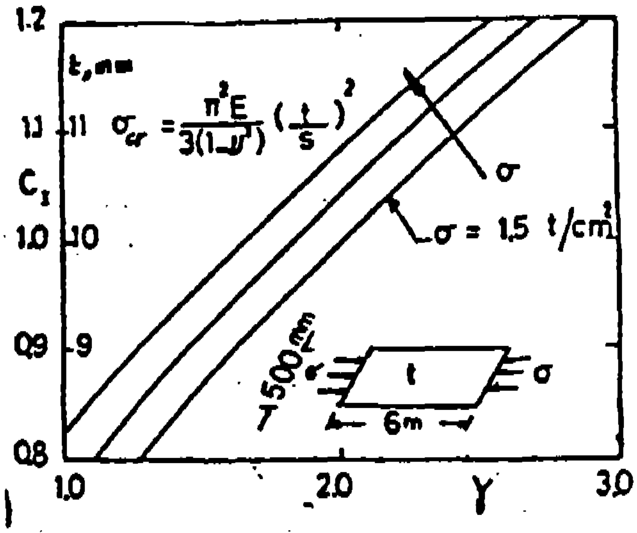

Figure 12. Variation of "C_I" with "γ".

CONCLUDING REMARKS

From the foregoing analysis, the following are the main conclusions:

a- It is technologically and economically unrealistic to totally eliminate the uncertainties associated with both load and strength nor to determine their reliable distribution functions.

b- Marine Structural Reliability should be related to the life cycle cost of the structure and the consequences of structural failure for the most probable modes of failure.

c- The optimum structural reliability could be determined from the minimisation of the total life cycle cost of the marine structure. Efforts should be made to take account of the effects of wear and tear, corrosion, inspection, maintenance and repair on the variation of structure reliability with time, for any particular mode of failure.

d- Improving quality control during fabrication, monitoring dynamic stresses during operation and improving inspection and maintenance schemes should improve significantly structural reliability and expected life span.

e- Maintainability of Marine Structures should be considered in addition to safety and economy, so as to ensure acceptable local and global structural reliabilities for the likely modes of failure.

f- The relatively high annual costs of inspection and maintenance of Marine Structures should not mask their beneficial effects on the minimisation of the total life cycle cost.

g- Much effort is needed to collect data on the various life cycle cost items of marine structures particularly from structures suffered moinor, major or catastrophic failures.

h- Efforts should be directed to study the variation of the initial cost and the expected cost of failure for certain modes of failure for typical structural configurations of marine structures.

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