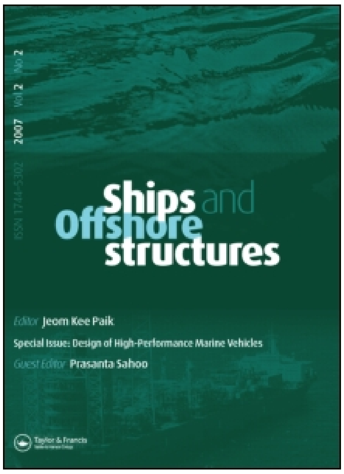

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M. A. Shama [a]
[a] Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, Egypt

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Basic concept of the factor of safety in marine structures

M.A. Shama*
Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, Egypt

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The basic elements involved in the determination of the factor of safety commonly used in preliminary design procedures of marine structures are outlined. The main factors affecting the magnitude of the factor of safety are highlighted. Probabilistic and semi-probabilistic approaches are briefly presented. The general equation and the main variables affecting the total safety factor are given. The different approaches used for the determination of the partial factors of safety are discussed and supported by numerical examples. Particular emphasis is placed on the characteristic and design value approaches. The variation of the factor of safety with time is illustrated. The effect of corrosion on the deterioration of the factor of safety is highlighted. The impact of the magnitude of the total factor of safety on the total life cost of the marine structure is clarified.

Keywords: factor of safety; characteristic values; marine structures

Introduction

A major requirement for any marine structure is to have low initial and operational costs, to be reasonably safe, not to have catastrophic failure and not 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. Therefore, safety is not an absolute measure and should be related to the economic and social consequences of failure. Structural safety could be ensured by introducing a set of safety factors controlling the expected variations in loading and strength. Structural failure occurs when the actual load Q exceeds the design strength R or when the actual strength is less than the design load. The load, Q, normally refers to the maximum value of loading likely to occur over the expected service life of a ship. The load generally varies over a wide spectrum, whose lower limit could be assumed as zero. The upper limit should be carefully estimated as it has a significant effect on structural safety and economy.

The strength, R, is the limiting state beyond which the structure is expected to fail, to be damaged, or to collapse. The variability of R results from the variability of the mechanical properties of the material, accuracy of stress analysis, errors in mathematical modelling, fabrication defects, dimensional tolerances, residual stresses, initial distortions, corrosion, wear and tear, etc. The strength should vary over a narrow spectrum. The lower limit represents the critical value regarding failure and the upper limit indicates some degree of over design, which has an impairing effect on economy.

Classification societies remain the main authority responsible for the assurance of safety for ships and marine structures. The methods commonly used are based on the control of design by specifying procedures and constraints, provision of corrosion margin to compensate for material deterioration, ensuring quality of materials, control of quality of construction, quality of maintenance and repair by providing regular and special surveys.

Basic concepts of structural safety

The fundamental equation of structural safety assurance is given by:

$$R > Q \tag{1}$$

where
R = Strength of structure
Q = Applied load on structure.
Equation (1) could be given in terms of the 'total factor of safety' γ, see Figure (1), as follows:

$$M = R - Q > 0 \tag{2}$$

$$\gamma = R/Q > 1.0 \tag{3}$$

*Email: mafshama@yahoo.com

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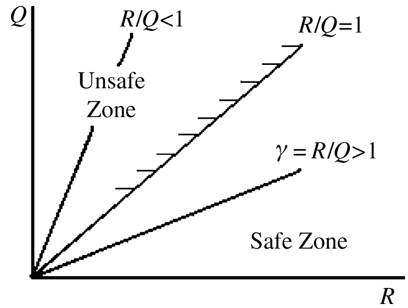

Figure 1. Safety concept.

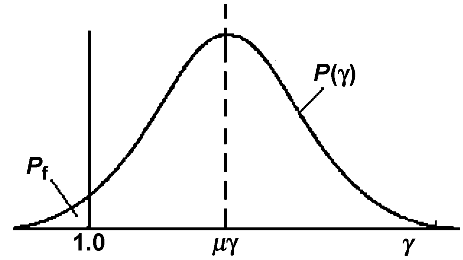

Figure 3. Probability of failure.

where
M = Safety margin
γ = factor of safety.
Structural safety assurance could be also expressed by probabilistic or semi-probabilistic methods as follows:

Probabilistically

Structural safety could be realised by ensuring that:

$P(R > Q) = P_S =$ an acceptable degree of safety where P_S = structural reliability = Probability of safety.

Structural reliability is given by:

$$P_{\mathbf{s}} = \int_{-\infty}^{\infty} f_{\mathbf{Q}}(q)\left[\int_{\mathbf{s}}^{\infty} f_{\mathbf{R}}(r)\, d\mathbf{r}\right] d\mathbf{q} \tag{4}$$

where
$f_X(\mathrm{x}) = (p.d.f.)$ of X, $X = R, Q$.

Probability of safety is also given by:
$P_S = 1.0 - P_F$.

The general equation of the probability of failure, Level 3 method, is given by:

$$P_F = \int_{-\infty}^{\infty} f_R(r)\left[\int_{-\infty}^{S} f_Q(q) d\mathrm{q}\right] \tag{5}$$

where P_F = probability of failure, see Figure (2).

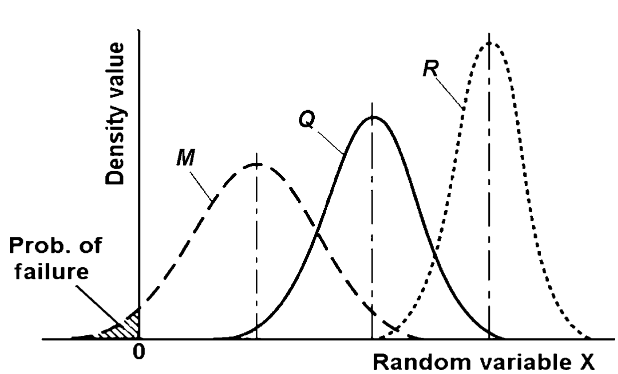

Figure 2. Concept of P_F.

The $p.d.f.$ of the factor of safety γ, could be obtained from the $p.d.f.$ of the load Q and strength R as follows see Figure (3):

$$f_\gamma(\gamma) = \int_{-\infty}^{\infty} f_R(\gamma_q).f_Q(q)dq \tag{6}$$

where $f_X(\mathrm{x}) = p.d.f.$ of X, $X = R, Q$.

Since $R < Q$ corresponds to $\gamma < 1.0$, then the probability of failure is given by:

$$P_F = P(\gamma \leq 1) = \int_{-\infty}^{1} f(\gamma)d\gamma.$$

Semi-probabilistic

Using the safety index concept, P_F is given by:

$$\text{Then } P_F = \int_{-\infty}^{0} f_{\mathbf{M}}(m)d\mathbf{m} \tag{7}$$

where $f_M(m) = p.d.f.$ of M, see Figure (2).

The safety index is given by:

$$\beta = u_M/\sigma_M$$

where
$u_M = u_R – u_Q$
σ_M = standard deviation of M
u_X = mean value of X, $X = R, Q, M$.

Basic concept of the factor of safety

See Figure (4). The general equation of structural safety is given by:

$$R_L \geq Q_H \tag{8}$$

where

R_L = expected lowest value of strength

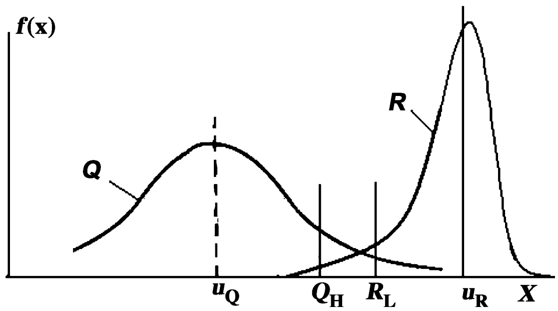

Figure 4. Lower and higher values.

Q_H = expected highest value of load.

Therefore, in order to ensure an acceptable degree of safety, the lower limit of strength and the upper limit of load should be carefully examined and controlled.

Let: ΔR = expected maximum deviation of strength from its mean value.

ΔQ = expected maximum deviation of load from its mean value.

$$Hence: R_L = u_R - \Delta R,\ Q_H = u_Q + \Delta Q$$

Thus, the general equation of structural safety is given by:

$$u_R[1 - (\Delta R/u_R)] \geq u_Q[1 + (\Delta Q/u_Q)]$$

Let: $\gamma = u_R/u_Q$ = nominal factor of safety
And: $\Delta R/u_R = \varepsilon_R$, $\Delta Q/u_Q = \varepsilon_Q$
Then: $\gamma \geq (1 + \varepsilon_Q)/(1 - \varepsilon_R)$
Assuming: $\varepsilon_R = \varepsilon_Q = \varepsilon$,
Then: $\gamma = (1 + \varepsilon)/(1 - \varepsilon)$
where e = an acceptable percentage deviation from the mean values of Q and R.

The variation of γ with ε is given in Figure (5).

General equation of the safety factor

The degree of safety for any particular mode failure is generally given as the ratio of some particular values of Q and R, as given by Equation (3). Structural safety, in this case, is normally given by a number of partial safety factors, which take account of the variability and uncertainties of the load and strength.

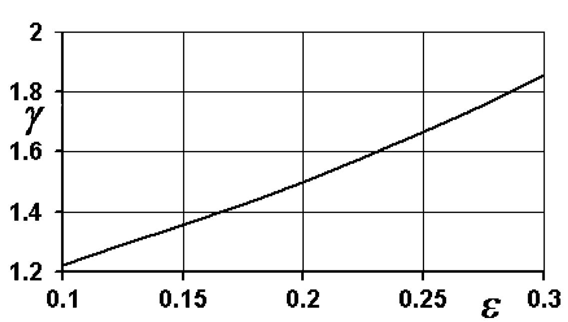

Figure 5. Variation of γ with ε.

The general equation of the total safety factor is given by:

$$\gamma = \prod_{j=1}^{n} \gamma_j = \gamma_1 \cdot \gamma_2 \cdot \gamma_3 \ldots \gamma_n \qquad (9)$$

where

γ_j = represent the factor of safety for the particular factor 'j' as follows:

γ_1 = *material factor*.
It takes accounts of the variability of the yield and ultimate stresses, difference between laboratory tests and service conditions and the ratio of yield/ultimate strength.

γ_2 = *design factor*:
It takes account of the presence of fatigue loading, stress concentration, etc.

γ_3 = *load factor*:
It takes account of the uncertainties of all parameters affecting the magnitude and distribution of load.

γ_4 = *stress analysis factor*:
It takes account of the degree of accuracy of the method of analysis.

γ_5 = *structure idealisation factor*:
It takes account of the uncertainties in the geometry, configuration, scantlings and geometrical characteristics of the idealised structure.

γ_6 = *mechanism of failure factor*:
It takes account of the uncertainties of the mechanism of failure such as type of failure (local or general, gradual or sudden, etc.) and mode of failure

γ_7 = *fabrication factor*:
It takes account of fabrication errors such as distortions, residual stresses, etc.

γ_8 = *time factor*:
It takes account of structural degradation due to wear and tare, corrosion, etc.

γ_9 = *maintenance and repair factor*:
It takes account of strength uncertainties due to improper maintenance and repair strategies and methods.

γ_{10} = *economic factor*:
It takes account of the economic consequences of failure.

γ_{11} = *loss of life factor*:
It takes account of the consequences of failure involving loss of human life.

It is evident that it is a formidable task to assign realistic values for all the above-mentioned safety factors. However, these factors could be grouped to form only two partial factors associated with load and strength uncertainties.

Thus, the general equation of the factor of safety is given by:

$$\gamma = \gamma_R \cdot \gamma_Q \quad (10)$$

where

γ_R = factor of safety that takes account of the uncertainties of strength.

γ_Q = factor of safety that takes account of all uncertainties of loading.

Different approaches of the determination of the partial factors of safety

Mean values approach

In this approach, the general equation of the limit state design is given in terms of the mean values of Q and R as follows:

$$\mu_R \geq \gamma \cdot \mu_Q \quad (11)$$

The total safety factor 'γ' is given in terms of two partial safety factors as follows:

$$\gamma = \gamma_r \cdot \gamma_q \quad (12)$$

Hence, the limit state design equation could be given in terms of the partial safety factors γ_r and γ_q as follows:

$$\mu_R/\gamma_r \geq \gamma_q \cdot \mu_Q \quad (13)$$

where

γ = Overall nominal factor of safety based on mean values of strength and load

μ_R, μ_Q = mean values of strength and load respectively.

γ_r = partial factor of safety that takes account of the uncertainties of R

γ_q = partial factor of safety that takes account of the uncertainties of Q.

Using the approximation given by:

$$\sqrt{\sigma_R^2 + \sigma_Q^2} \approx 0.75(\sigma_R + \sigma_Q)$$

the partial safety factors, γ_r and γ_q could be given in terms of the coefficients of variation of R and Q and a specified value of the safety indexas follows:

$$\gamma_r = 1/(1 - 0.75\beta_0 v_R) \quad (14)$$

$$\gamma_q = 1 + 0.75\beta_0 v_R \quad (15)$$

where

β_o = target safety index

v_X = coefficient of variation (cov) of X, $X = R, Q$

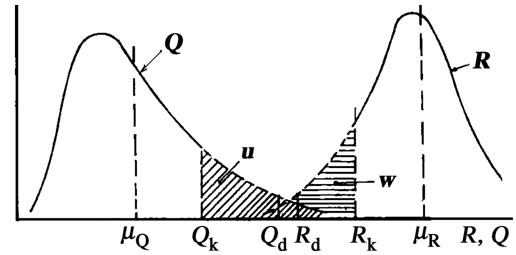

Figure 6. Characteristic values.

Characteristic values approach:

The factor of safety could be also given in terms of the characteristic values of R and Q, which represent the acceptable lowest extreme value of R and the acceptable highest extreme value of Q, as follows, see Figure (6):

$$R_K \geq \gamma_K \cdot Q_K \quad (16)$$

where

$$\gamma_K = \gamma_R \cdot \gamma_Q \quad (17)$$

Hence: the general equation of the limit state design is given by:

$$R_K/\gamma_R \geq \gamma_Q \cdot Q_K \quad (18)$$

where

γ_K = Overall factor of safety based on characteristic values of load and strength

γ_R = partial factor of safety that takes account of the uncertainties of R_K.

γ_Q = partial factor of safety that takes account of the uncertainties of Q_K.

R_K, Q_K = characteristic values of strength and load The characteristic values of R and Q are given by:

$$R_K = \mu_R - k_R \cdot \sigma_R$$

$$Q_K = \mu_Q + k_Q \cdot \sigma_Q.$$

R_K and $Q_K$are selected to satisfy the following conditions, see Figure (6)

$$P(R < R_k) = \int_{-\infty}^{R_K} f_R(r)d\mathbf{r} \leq w \quad (19)$$

$$\text{And } P\ (Q > Q_k) = \int_{Q_K}^{\infty} f_Q(q)d\mathbf{q} \leq u \quad (20)$$

Table 1. *Case 1*: $v_R = v_Q = 0.1,\ \gamma = 2.0$

$v_R = v_Q = 0.1,\ \gamma = 2.0$				
k_n	$1k_n.v_R$	$1+k_n.v_Q$	λ	γ_K
2.0	0.8	1.2	0.666	1.332
2.5	0.75	1.25	0.60	1.2
3.0	0.7	1.3	0.538	1.076

Table 2. *Case 2:* $v_R = v_Q = 0.05,\ \gamma = 2.0$

$v_R = v_Q = 0.05,\ \gamma = 2.0$				
k_n	$1-k_n.v_R$	$1+k_n.v_Q$	λ	γ_K
2.0	0.9	1.1	0.818	1.636
2.5	0.875	1.125	0.777	1.554
3.0	0.85	1.15	0.739	1.478

Where w and u are acceptable small quantities required to control the magnitudes of R_K and Q_K.

Assuming that:

$$v_R = \sigma_R/\mu_R \text{ and } v_Q = \sigma_Q/\mu_Q \qquad \text{Then, } \gamma_K = \gamma(1 - k_R \cdot v_R)/(1 + k_Q \cdot v_Q) \tag{21}$$

When both R and Q are normally distributed, γ_R and γ_Q, are given by:

$$\gamma_R \cong (1 - k_R v_R)/(1 - 0.75\beta_0 v_R) \tag{22}$$

$$\gamma_Q \cong (1 + 0.75\beta_0 v_Q)/(1 + k_Q v_Q) \tag{23}$$

Example: Assuming that both R and Q are statistically independent and have normal density functions and that: $w = u = 0.05$.

Then: $P\ (Q > Q_k) = P\ (R < R_k) = 0.05$

Hence: $k_R = k_Q = 1.645$

Thus: $R_{K.} = \mu_R(1 - 1.645\ v_R)$

And $Q_{K.} = \mu_Q\ (1 + 1.645\ v_Q)$

The overall factor of safety in this case is given by:

$$\begin{aligned}\gamma_k &= R_k/Q_k \\ &= (\mu_R/\mu_Q)[(1 - k_n \cdot v_R)/(1 + k_n \cdot v_Q)] \\ &= \gamma\ [(1 - k_n \cdot v_R)/(1 + k_n \cdot v_Q)]\end{aligned}$$

$$\text{i.e.} \gamma_k = \gamma \cdot \lambda$$

where $\lambda = (1 - k_n \cdot v_R)/(1 + k_n \cdot v_Q)$

Assuming that $k_Q = k_R = k_n$, the effect of variation of the magnitude of k is examined in the following Tables for the two cases.

Example: Assuming that: $k_R = 2, k_Q = 3$, calculate γ_Q and γ_R given that R and Q are statistically independent and normally distributed:

$$R = N\ (120, 10),\ Q = \mathrm{N}\ (75, 5)$$

Solution:

Mean value approach:

$$\gamma = \mu_R/\mu_Q = 120/75 = 1.6$$

Characteristic value approach:

$$R_K = \mu_R - k_R\sigma_R = 120 - 2 \times 10 = 100$$

$$Q_K = \mu_Q + k_Q \cdot \sigma_Q = 75 + 3 \times 5 = 90$$

Then, $\gamma_K = 100/90 = 1.11$

$$P(R < R_K) = P(Z \leq K_R) = P(Z \leq 2.0) = 0.0228$$

$$P(Q > Q_K) = P(Z \geq K_Q) = P(Z \geq 3.0) = 0.0013$$

Example: Consider the following case:

$$u_R = 185.7\ t \text{ and } u_Q = 100\ t,\ v_R = v_Q = 0.1,$$

$$k_R = k_Q = 2.5,\ \beta_o = 4.0$$

Mean value approach

Then:

$$\gamma_r = 1/(1 - 0.75\beta_0 v_R) = 1.43$$

$$\gamma_q = 1 + 0.75\beta_0 v_R = 1.3$$

$$\gamma = \gamma_r \cdot \gamma_q = 1.857$$

Characteristic value approach:

$$\gamma_R \cong (1 - k_R v_R)/(1 - 0.75\beta_0 v_R) = 1.072$$

$$\gamma_Q \cong (1 + 0.75\beta_0 v_Q)/(1 + k_Q v_Q) = 1.04$$

$$\gamma_K = 1.115$$

Design value approach:

In this approach, safety assurance is based on the design values for R, Q and the partial safety factors γ_X and γ_Y.

The general equation of limit state design is given by see Figure (6):

$$R_D \geq \gamma_D \cdot Q_D \tag{24}$$

$$R_D/\gamma_X \geq \gamma_Y \cdot Q_D \tag{25}$$

where $\gamma_D = \gamma_X \cdot \gamma_Y$

X_D = design value of X, $X = R, Q$

$$R_D < R_K$$

$$Q_D > Q_K$$

γ_D = overall factor of safety based on design values of strength and load

γ_X = factor of safety that takes account of all causes of failure.

γ_Y = factor of safety that takes account of the consequences of failure.

By introducing rating factors, it is possible to estimate the partial safety factors γ_X and γ_Y using the calculation procedure given in Table 1.

$$\gamma_x = 1.1 + 0.3\,(2A + 2B + C) + 0.45\,(AB + BC + CA)$$

$$\gamma_Y = 1.0 + 0.2\,(2D + E)$$

Example: Determine the factor of safety for a deck girder based on the following assumptions: (6, 7)

Construction:
Poor, Rating $A = 1.0$
Design:
Good, Rating $B = C = 1/3$
Danger to personnel:
Serious, Rating $D = 1/2$
Danger to economy:
Serious, Rating $E = 1/2$
Solution: $\gamma_X = 2.05$, $\gamma_Y = 1.3$,
Then: $\gamma = 2.665$.

Example: Determine the design factor of safety for the vertical stiffeners of transverse bulkheads in a cargo ship, for both cases:

a. Damage, i.e., occurrence of a permanent set.
b. Collapse, i.e., failure of the stiffener by forming a plastic hinge.

Assume the following data:

Design Load: Assume static pressure, neglect dynamic loading.

Construction: Assume fully controlled welding.

Analysis: Assume accurate methods of elastic and plastic analysis.

Consequences of Failure

- Damage:
  - Does not cause loss of human life.
  - Does not cause serious damage to ship structure.

- Collapse:
  - May cause risk to human life.
  - May lead to collapse of large area of ship structure.

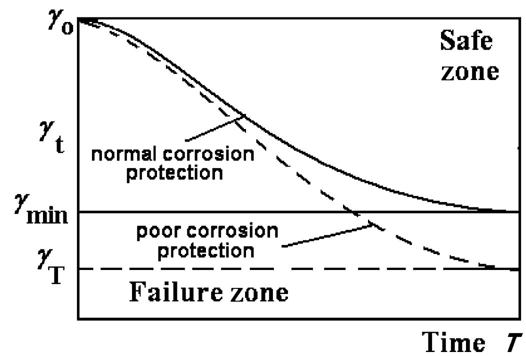

Figure 7. Deterioration of γ.

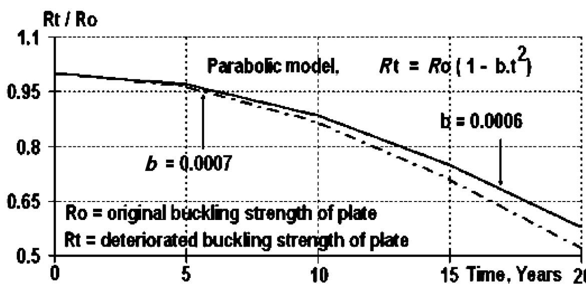

Figure 8. Deterioration of buckling strength.

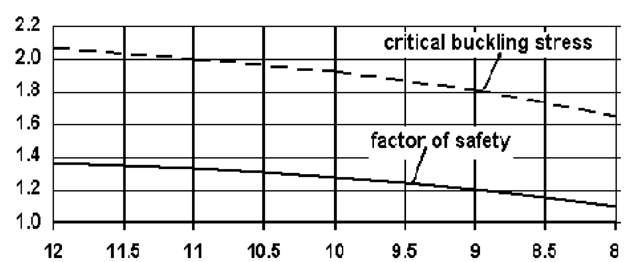

Figure 9. Deterioration of γ for plate buckling.

Case of damage

$\gamma_X = 1.3$, $\gamma_Y = 1.0$ and $\gamma_D = 1.3$.

Case of collapse

$\gamma_X = 1.5$, $\gamma_Y = 1.3$ and $\gamma_D = 1.95$.

Variation of the factor of safety with time

The factor of safety of any marine structure or any of its structural components deteriorates with time due to aging and corrosion, irrespective of the mode of failure. Proper structural maintenance, repair and upgrading improve the factor of safety by virtue of improving structural strength.

Figure (7) illustrates the accelerated deterioration of the safety factor γ with time due to poor maintenance and lack of adequate corrosion protection.

Figure (8) shows the deterioration of buckling strength of ship plating with time due to corrosion. Figure (9) shows

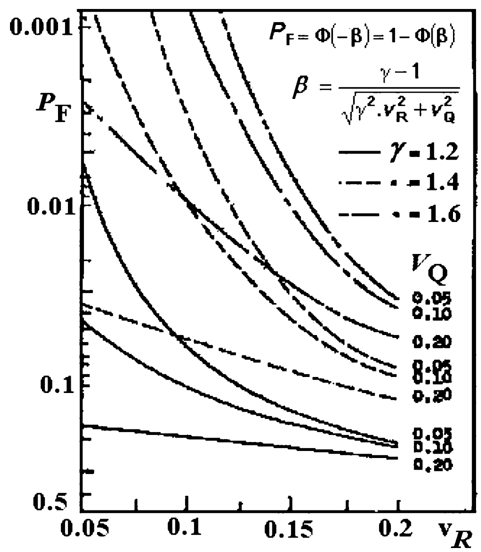

Figure 10. Variation of P_F with γ.

the deterioration of the factor of safety for plate buckling due to corrosion.

Variation of P_f with γ

The variation of the probability of failure P_f with the total factor of safety γ, for different values of the coefficient of variation (c.o.v.) of R and Q is illustrated in Figure (10).

Economics of structural safety of marine structures

Increasing ship structural safety requires the use of sophisticated methods of structural analysis, using steel with adequate yield and ultimate strength, increasing scantlings, improved quality control on fabrication and assembly work in shipyards and the use of more effective methods of ship structural maintenance and upgrading. Any increase in ship structural safety will require an increase of the initial cost of the ship and at the same time will reduce the probability and cost of failure.

The ideal objective is to establish a criterion for selecting a design that will maximise its utility for operation while minimising its expected loss in case of failure. In general, it is impossible to achieve both simultaneously. A reasonable approach is to minimise the expected loss associated with failure while imposing a certain limiting condition on the utility. The probability of failure must be considered in the context of minimising the costs associated with failure. The loss associated with failure includes not only the replacement cost but also the cost of compensation for possible damages caused by the failure of the structure.

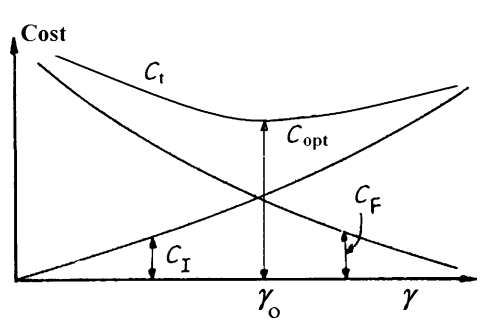

Figure 11. Optimum value of γ.

The optimum magnitude of the total factor of safety could be determined from the minimisation of the expected total cost, taking account of available data on the probability of failure. See Figure (11).

The optimum value of the factor of safety γ_{opt} could be determined from the minimisation of the total life cycle cost of the structure. The latter could be divided into:

- *Non-Failure cost items*: initial cost, scrap value, insurance, maintenance, depreciation
- *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, cleanup or other environmental effect, loss of reputation, business and public confidence

Some of these cost items are independent of the factor of safety γ while the others are totally dependent on it.

Since the magnitude of the probability of failure P_F is directly related to the factor of safety γ, a simplified generalised life cycle cost equation could be given by:

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

where

P_F = probability of failure
C_F = expected cost of failure
η = a factor that transfers future cost items into their present worth values
C_I = initial construction cost

Concluding remarks

- In the determination of the total safety factor, the lower limit of strength and the upper limit of load should be carefully selected so as to ensure the required degree of safety.
- The magnitude of the total factor of safety should be rationally selected so as not to have an impairing effect on both the cost of the marine structure and the environment.
- The characteristic value approach is more practical to be used in the preliminary design stages of marine structures.
- In the design of marine structures, the deterioration of the factor of safety with time should not be ignored when determining the magnitude of the total factor of safety.

- It is a formidable task and impractical to take all the factors affecting the magnitude of the safety factor into account.

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