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Calibration of Technical Standards for Marine Structures

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ABSTRACT

A simple and efficient technique for calibration of reliability based technical standards for marine structures is presented. The design of structural elements is based on the definition of appropriate limit states. The reliability is quantified by the reliability index. Reliability based design formats are critically reviewed and reliability based design values are recommended for future code frameworks. Based on a code space metric derived from a utility analysis, the design values are calibrated for a specified reliability index. The proposed calibration procedure is demonstrated in design examples of marine structural components and is compared to current code requirements. The implementation of the obtained results in future technical standards is discussed and further research needs are identified.

INTRODUCTION

One problem of designing a marine structure is to find the least expensive design, which guarantees a specified safety level. In the past the requirement for sufficiently safe structures has been accomplished based on tradition and accumulated experience. Occasionally, this has led to a considerable non-uniformity of the safety level with varying economic implication of structural codes. Significant advances have recently been achieved in calculating reliabilities and in implementing these in code formats. The process of assigning values to the parameters in such a reliability based code format is called code calibration.

Code parameters are selected primarily with a view to achieve desired levels of reliability in different elements of a structure, which is assumed free of possible gross errors committed either during design, fabrication or operation. A code may be calibrated by judgement, fitting, optimization or by a combination of these approaches, [1]. In this paper a calibration technique based on cost optimization is presented. The implementation of reliability methods in structural design is critically reviewed and the application of reliability based design values is recommended for future code frameworks. A simple and efficient technique for the optimization of design values is developed and illustrated in examples.

IMPLEMENTATION OF RELIABILITY METHODS IN STRUCTURAL CODES

Reliability analysis

The design of structural elements is based on the definition of appropriate limit states. A limit state is a condition where a structure or component ceases to fulfill its intended function. Limit states are mathematically described in the form:

$$g(X_1, X_2, \ldots, X_n) = g(\mathrm{X}) \qquad (1)$$

where $\mathrm{X}=(X_1, X_2, \ldots, X_n)$ denotes the vector of the basic random parameters (loads, material strengths, geometry, etc.); failure occurs when $g<0$. In addition, the limit state function depends on deterministic design parameters.

The safety is assured by requiring a small probability p_F for the event that the limit state is reached:

$$p_F = \int \cdots \int f_X(x_1, x_2, \ldots, x_n) dx_1 dx_2, \ldots, dx_n \qquad (2)$$

in which f_{X} is the joint probability density function for $X_1, X_2, \ldots, X_n$ and the integration is performed over the region $g \leq 0$. The failure probability is thus the *quantitative measure* of the reliability of a structure or a structural element.

Direct n-fold integration of Eq.(2) is for most applications impractical. Therefore, numerical methods for reliability calculation have been developed during the past decade and the first-order reliability methods FORM (see [1] for a review) have been recognized as very accurate and efficient. The basic principles implied in FORM are the following:

- The variables $X_1, X_2, \ldots, X_n$ are transformed by a suitable transformation into a vector $\mathrm{U}=(U_1, U_2, \ldots, U_n)$ of standardized and independent normal variables.
- The limit state surface $g(\mathrm{u})=0$, formulated in this new space, is approximated by its tangent hyperplane at the point of smallest distance β to the origin as shown in Fig. 1 for the case of two random variables. The distance β is called the reliability or safety index and reflects the *quantitative measure* for the safety of a component with respect to the defined limit state.

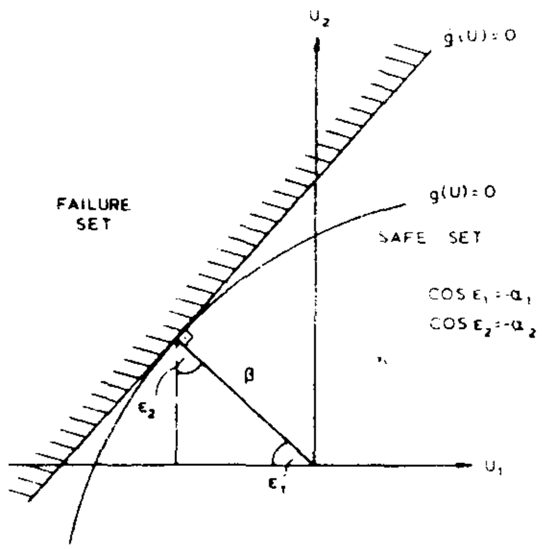

Fig. 1: Illustration of the reliability index β in the case of two random variables.

The point of smallest distance to the origin $\mathbf{u}^*$ is called the design point. The design point is determined by an appropriate algorithm. The probability of failure is estimated by:

$$p_F = P[g(\mathrm{U})\leqslant 0] \approx \Phi(-\beta) \qquad (3)$$

where $\Phi(.)$ is the standard normal distribution function. The relationship between failure probability and reliability index is illustrated in Fig. 2. The probability of failure decreases with increasing reliability index β.

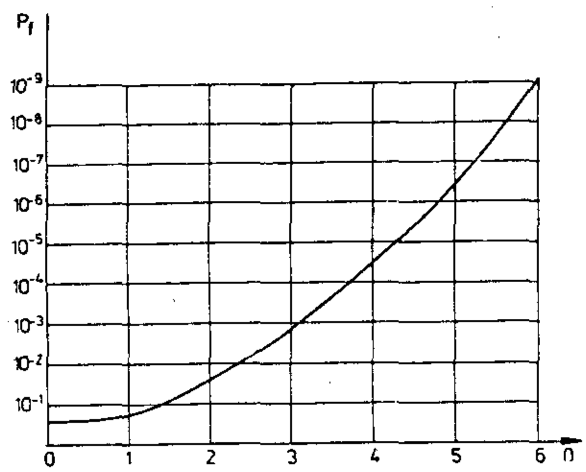

Fig. 2: Relation between reliability index and probability of failure.

The influence of each random variable on the failure probability is expressed through the so-called sensitivity or weighting factors α_i, which give the directional cosines of the design point (Fig. 1). For the α_i-values the following relationship is valid: $\sum_{i=1}^{n}\alpha_i^2=1.0$, where n is the total number of basic variables. α_i^2 can be interpreted as the fraction of the total uncertainty which is caused by uncertainty in the basic variable X_i. The effect of the uncertainty of one basic variable on the reliability index is expressed by the ratio:

$$\frac{\beta(X_i=m_i)}{\beta} \sim \frac{1}{\sqrt{1-\alpha_i^2}}, \quad \alpha_i \to 0 \qquad (4)$$

where the reliability index $\beta(X_i=m_i)$ in the numerator is obtained by replacing X_i by its median value m_i.

The design value x_i^* for each influencing random variable X_i with distribution function F_{X_i} is defined through its sensitivity factor α_i and the reliability index:

$$x_i^*=F_{X_i}^{-1}[\Phi(-\alpha_i\,\beta)] \qquad (5)$$

For load variables S, $\alpha_S \leqslant 0$, and for resistance variables R, $\alpha_R \geqslant 0$.

The general purpose reliability computation program, PROBAN [2], has been developed for the calculation of the failure probability of components and systems.

Reliability based design formats

Reliability based design formats can be ordered according to their consistence to an 'exact' reliability analysis procedure as follows:

a) allowable stress format
b) partial safety factor format
c) design value format
d) reliability index format

a) allowable stress or working stress format

Traditionally structural design has been based on code-specified or service loads and the desired safety has been assumed to exist if the elastically computed stresses did not exceed allowable working stresses which are a preset fraction of the yield strength, modulus of rupture, etc. The loads used in this design process have a high probability of occurrence during the life of the structure. The allowable stress format is simple to apply but has the following disadvantages:

i) A given set of allowable stresses will not guarantee a constant level of safety.
ii) The uncertainties of the different variables are not treated separately.
iii) The format may be unsafe when one load counteracts the effects of another.

b) Partial safety factor format

The partial safety factor format has been developed to treat uncertainties in different variables separately [3,4]. The typical inequality regarding safety by applying fixed partial safety factors is [5]:

$$R(f_{c_i}/\gamma_{m_i}) > S(s_{c_i}\gamma_{f_i}) \qquad (6)$$

in which:

γ_{m_i}: partial safety factor for material strength

f_{c_i}: characteristic value for material strength

γ_{f_i}: partial safety factor for load parameter

s_{c_i}: characteristic value for the load parameter

R: resistance function

S: load effect function

The characteristic values of load and resistance parameters are reference values to be used in the design process. The partial safety factors can be derived based on the first-order reliability method as:

$$\gamma_{m_i}=\frac{f_{c_i}}{f_i^*} \quad \text{and} \quad \gamma_{f_i}=\frac{s_i^*}{s_{c_i}} \qquad (7)$$

where f_i^* and s_i^* are the corresponding design values (see Eq.(5) and Table 1). A format similar to the partial safety factor format is the load and resistance factor design format (LRFD) [6], which is implemented in North American standards.

c) Design value format

The flexibility with respect to the safety level and to the optimal cost of the structure in applying fixed safety elements such as codified partial safety factors is only possible for specifical cases. The reason for this is that the partial safety factors *do not* represent a *quantitative measure* for the reliability in relation to a certain limit state. Also the influence of the random variables may differ significantly for different design cases. Therefore an improved reliability based design concept - the so-called design value format - has been developed [7,8] with the main goal to avoid the above mentioned shortcomings. The design value format is derived from first-order reliability methods and is sufficiently flexible to treat all important design aspects.

The design value for each influencing random variable is defined through Eq.(5). The design equation for each design case is then given by:

$$g(x_1^*, x_2^*, \ldots, x_n^*, \theta) \geq 0 \qquad (8)$$

where θ is the design parameter vector. The reliability is implied in the design values which depend on the safety level, the sensitivity factors and the distribution parameters.

The design values for common distributions are listed in Table 1. The design value can be written as:

$$x_i^* = \delta_i \mu_{X_i} \qquad (9)$$

where δ_i is a central design safety factor, depending on the distribution type, coefficient of variation (V_i), safety index and sensitivity factor. In view of a future probabilistic code, the central design safety factors δ_i can be specified for each random parameter at different safety levels. Before codes and standards in design value format can be introduced, simple rules must be formulated for selection of distribution types of random variables and for assessing values of sensitivity factors.

Table 1: Design values for commonly used distributions

Distribution	Design value
Normal	$\mu_{X_i}(1-\alpha_i\beta V_{X_i})$
Lognormal	$\mu_{X_i}\exp(-\alpha_i\beta V_{X_i}-0.5V_{X_i}^2)$
Gumbel	$\mu_{X_i}(1-0.78V_{X_i}(0.577+\ln(-\ln\Phi(-\alpha_i\beta))))$

Compared to the partial safety factor format the proposed design value format:

- accounts in a more consistent, direct and flexible way for the required safety level, the importance of variable uncertainty and the distribution parameters
- does not hide sources of uncertainty in partial safety factors
- allows dependence between loads to be included in a simple way
- results in a reliability level closer to the target

d) Reliability index format

The reliability index format is a full probabilistic format in which the design parameter is determined for each specific design case such that a specified reliability index is achieved. This can be done by a numerical iteration. For a starting value for the design parameter the reliability index is calculated and the computational procedure is repeated until the relative difference between the obtained reliability index and the target reliability index is within specified tolerance limits, [9]. The use of parametric sensitivity factors for the reliability index, [1], highly fascilitates this analysis.

CODE CALIBRATION

Basic aspects

The first step of this process is to decide upon a target reliability index β_t or target failure probability p_{F_t} for the structures or structural components to be designed using the code. This choice can be made by a process of probabilistic calibration to an existing code. A more direct approach to the choice of target failure probability has been recommended in modern codes, [10,11]. In these codes the target failure probability depends on the consequences of failure and on the nature of the failure mode or limit state. Three different safety classes are thereby introduced. Table 2 shows the target reliability levels proposed in [10] for three different safety classes according to the failure consequences. The target reliability indices are valid for normal buildings and correspond to a reference period of one year. In [11] fatigue limit states FLS and progressive collapse limit states PLS are treated separately from ultimate limit states.

Table 2: Annual target reliability indexes [10]			
Limit	failure consequences		
State	not serious	serious	very serious
ULS	4.2	4.7	5.2
SLS	2.7	3.3	3.7

The next step is to select weighting or usage factors h_j corresponding to the present and future frequency of usage of each design case j included in the calibration. This can be done based on engineering judgement and experience.

Distribution functions for the basic variables must be selected. Here a standardization must take place to avoid unfair competition between designers and producers using the most favourable distribution type which can not be rejected based on usual statistical tests of-goodness-of-fit. These statistical tests, however, use information from the central part of the distribution and not from the tails. Except in special cases, where a large number of data are available, the designer can therefore only be allowed to provide mean values, variances and covariances as input, while the distribution types are prescribed by the code.

Having chosen a target failure probability and specified distribution functions for the basic variables, the problem of selecting a set of design values may now be reduced to the problem of selecting a set of sensitivity factors. A simple and empirical set of α_i-values is generated by setting $\alpha_i = \pm 1$ for the most critical variable and then reducing as follows for the remaining variables, [4]:

$$\alpha_i = \sqrt{i} - \sqrt{i-1} \qquad (10)$$

where the variables are ordered according to their importance. If the variables are correlated, a slightly more complicated formula can be derived. Alternatives have been proposed. For example, [4,10] distinguishes between load S and resistance R variables and codifies $\alpha_S = -0.7$ and $\alpha_R = 0.8$ for the respective most important variables. For the remaining variables the procedure is as above, or $\alpha_i = \pm 0.4$ is set conservatively. This empirical rule is also suggested in recently developed code proposals.

In order to achieve optimal design values the following simple principle can be applied. Choose the set of sensitivity factors α', which minimizes the quantity

$$Z = \sum_{j=1}^{J} h_j M_j (p_{Fj}(\alpha'), p_{Ft}) \qquad (11)$$

where

$M_j(p_{Fj}(\alpha'), p_{Ft})$ is a specified penalty function

$p_{Fj}(\alpha')$ is the failure probability of the j th design case by applying α'

p_{Ft} is the target failure probability

h_j is the weighting factor indicating the relative importance of the j th design case

Instead of the failure probability the reliability index may also be used in Eq.(11).

Code space metric

A penalty function is used to penalize deviations (overdesign or underdesign) from a specified target reliability level. An appropriate loss or penalty function arises in a natural way from the utility concept. The expected total cost of a structure can be expressed as:

$$C_T = C_I + p_F C_F \qquad (12)$$

in which C_T, C_I and C_F are expected total cost, initial cost and failure cost, respectively. The initial cost can be assumed as a linear function of the reliability index, [12]:

$$C_I = a(1 + b\beta) \qquad (13)$$

where a and b are constants. The probability of failure p_F can be approximated by an exponential function of the reliability index:

$$p_F \approx c \exp(-\beta / d) \qquad (14)$$

where c and d are constants (usually $d \approx 0.2$, [12]; the value of d does not have a significant influence on the results). The total cost is from Eqs. (12), (13) and (14):

$$C_T = a(1 + b\beta) + C_F c \exp(-\beta / d) \qquad (15)$$

The condition for the minimum total cost at $\beta = \beta_t$ is:

$$\frac{dC_T}{d\beta} = ab - \frac{C_F c}{d} \exp(-\beta_t / d) = 0 \qquad (16)$$

From Eq. (16) follows:

$$C_F c = abd \exp(\beta_t / d) \qquad (17)$$

The increment in total cost from the cost at optimality is:

$$\Delta C_T = a(1 + b\beta) + C_F c \exp(-\beta / d) - a(1 + b\beta_t) - C_F c \exp(-\beta_t / d) \qquad (18)$$

from which follows:

$$\frac{\Delta C_T}{abd} = \left(\frac{\beta - \beta_t}{d}\right) - 1 + \exp\left(-\frac{\beta - \beta_t}{d}\right) \qquad (19)$$

The penalty function M_j is obtained based on Eq.(19) as:

$$M_j = \frac{(\beta_j(\alpha') - \beta_t)}{d} - 1 + \exp\left(-\frac{(\beta_j(\alpha') - \beta_t)}{d}\right) \qquad (20)$$

The penalty function of Eq.(20) is presented in Fig.3. The skewness indicates the different consequences of overdesign and underdesign.

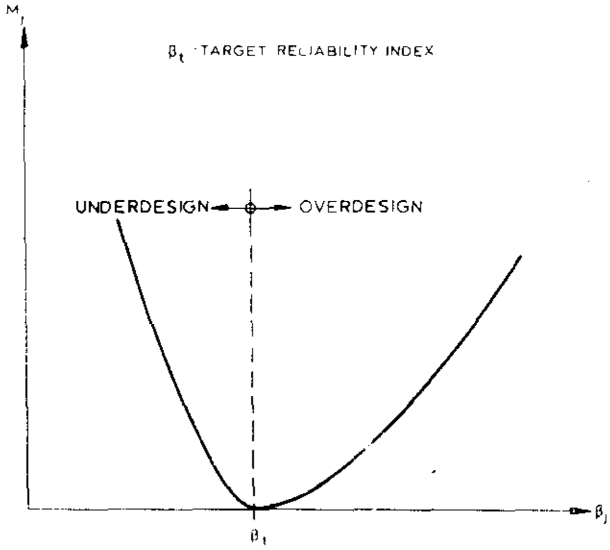

Fig. 3: Penalty function according to Eq.(20).

A simplified method for the computation of optimal sensitivity factors

Based on the first-order reliability methods a simple relationship can be derived between the reliability indices β_t and β_j. The optimal set of sensitivity factors α' defines a new design point $\mathbf{u}'^*$ which corresponds to the actual reliability index β_j as illustrated in Fig.4. If α_j is the original set of sensitivity factors leading to the target reliability index β_t in design case j, β_j is approximated by:

$$\beta_j(\alpha') \approx \beta_t \, \alpha_j \, \alpha' \qquad (21)$$

It should be noted that α' is not necessarily a unit vector. From Eqs. (11), (20) and (21) follows:

$$Z = \sum_{j=1}^{J} h_j \left[\frac{\beta_t(\alpha_j \alpha' - 1)}{d} - 1 + \exp\left(-\frac{\beta_t(\alpha_j \alpha' - 1)}{d}\right) \right] \qquad (22)$$

Obtaining the solution is a problem of unconstrained minimization for which a number of standard techniques are available. Additional constrains can be defined for the α' vector if some components are predefined or limited.

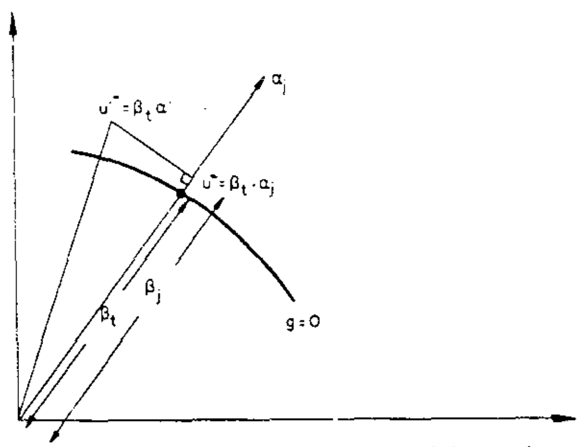

Fig. 4: Illustration of target reliability index β_t and actual reliability index β_j.

EXAMPLES

Example 1: Platform design for a damaged state

Safety checking of a gravity based concrete platform for a damaged state where the utility shaft is flooded is a special design case. Due to the small probability of occurrence of this event a set of reduced partial safety factors was proposed with the characteristic value of the environmental loading reduced from the 100 year value to the 3 year value. The initially proposed safety factors for the ordinary ultimate limit state ULS_o (including ordinary environmental load) and the extraordinary ultimate limit state ULS_e (including extraordinary environmental load) were:

Table 3. Proposed load factors for normal and special design (2 load combinations in each case)

	Normal design load category				
ULS	R	P	L	D	E
ULS_o	1.25	1.3	1.3	1.0	0.7
ULS_e	1.25	1.0	1.0	1.0	1.3
	Special design load category				
ULS	R	P	L	D	E
ULS_o	1.1	1.1	1.1	1.0	0.7
ULS_e	1.1	1.0	1.0	1.0	1.1

with the notation: R: resistance (5% fractile as characteristic value), P: permanent load effect, L: live load effect, D: deformation load effect, and E: environmental load effect. The accidental flooding of the utility shaft and central tower is estimated to be a 2000 year event.

An analysis was performed to determine the reliability level implicit given by the two sets of partial safety factors and characteristic values. The fundamental requirement is that the annual failure probability due to flooding and subsequent failure must not exceed the annual failure probability in the normal ultimate limit state. In order to cover all possible failure cases due to flooding of the utility shaft a general limit state function was analyzed:

$$R - P - L - D - E < 0 \qquad (23)$$

The return period was computed for several ratios $r = \mu_E / \mu_P$, where μ denotes the mean value (expected value) of the basic variable indicated by the subscript. The failure probability in the normal condition is denoted p_{F_1} and the failure probability in the damaged state p_{F_2}. Results for p_{F_1} and p_{F_2} are shown in Table 4. The reliability level is not uniform and the proposed format is not well calibrated. The following calibrated safety factors were then derived by applying the proposed calibration technique (the design cases are equally weighted):

Table 4: Implied and calibrated failure probabilities						
	implied			calibrated		
r	p_{F_1}	p_{F_2}	$T=\frac{p_{F_2}}{p_{F_1}}$	$p_{F_{1,cal}}$	$p_{F_{2,cal}}$	$T=\frac{p_{F_{2,cal}}}{p_{F_{1,cal}}}$
0.01	$2.3\cdot10^{-6}$	$1.3\cdot10^{-3}$	560	$2.5\cdot10^{-6}$	$4.6\cdot10^{-3}$	1840
0.1	$2.3\cdot10^{-6}$	$1.7\cdot10^{-3}$	740	$2.2\cdot10^{-6}$	$4.4\cdot10^{-3}$	2000
0.2	$2.5\cdot10^{-6}$	$2.2\cdot10^{-3}$	880	$2.0\cdot10^{-6}$	$4.3\cdot10^{-3}$	2150
0.5	$3.9\cdot10^{-6}$	$3.3\cdot10^{-3}$	850	$2.6\cdot10^{-6}$	$4.5\cdot10^{-3}$	1730
1.0	$1.2\cdot10^{-6}$	$3.8\cdot10^{-3}$	3100	$2.5\cdot10^{-6}$	$4.2\cdot10^{-3}$	1700
2.0	$1.4\cdot10^{-6}$	$6.2\cdot10^{-3}$	4400	$1.9\cdot10^{-6}$	$3.7\cdot10^{-3}$	1950
5.0	$2.3\cdot10^{-6}$	$1.2\cdot10^{-2}$	5200	$2.3\cdot10^{-6}$	$4.3\cdot10^{-3}$	1870
10.0	$3.0\cdot10^{-6}$	$1.6\cdot10^{-2}$	5300	$2.6\cdot10^{-6}$	$4.7\cdot10^{-3}$	1810

Table 5. Calibrated load factors for normal and special design (2 load combinations in each case)					
	Normal design load category				
ULS	R	P	L	D	E
ULS_o	1.3	1.3	0.7	1.45	0.75
ULS_e	1.1	1.0	0.7	1.45	1.50
	Special design load category				
ULS	R	P	L	D	E
ULS_o	1.15	1.0	0.8	1.0	0.95
ULS_e	0.95	1.0	1.1	1.0	1.45

The results for the calibrated failure probabilities $p_{F_{1,cal}}$ and $p_{F_{2,cal}}$ are illustrated in the Table 4 and demonstrate the accuracy of the calibration method.

Example 2: Shell buckling

The example deals with shell buckling in marine structures and its main objective is to demonstrate the applicability of the proposed calibration method. In particular the reliability index obtained by applying optimal sensitivity factors $\beta_{J_{opt}}$ is compared to the reliability index $\beta_{J_{emp}}$ obtained by applying the empirical sensitivity factors [4,10].

The critical stress σ_{cr} of a shell is defined by a single reference stress, [3]:

$$\sigma_{cr} = \frac{\sigma_k}{\sqrt{1+\lambda^4}} \tag{24}$$

where the reduced slenderness ratio λ is

$$\lambda = \left(\frac{\sigma_k}{\sigma_E}\right)^{0.5} \tag{25}$$

The characteristic material stress σ_k is

$$\sigma_k = \begin{cases} \sigma_F & \text{for normal stresses} \\ \frac{\sigma_F}{\sqrt{3}} & \text{for shear stresses} \end{cases} \tag{26}$$

where σ_F is the yield stress. The elastic buckling resistance σ_E of *unstiffened circular cylindrical shells* is given by, [3]:

$$\sigma_E = C\,\frac{\pi^2 E}{12\,(1-\nu^2)}\left(\frac{t}{l}\right)^2 \tag{27}$$

with E-Young's modulus, ν-Poisson's ratio, l-cylinder length, and t-shell thickness. The reduced buckling coefficient C varies with the loading type. If all edges are simply supported these relations are used

$$C^2 = \begin{cases} 1+0.36^2\dfrac{(1-\nu^2)l^4}{r^2t^2(1+\frac{r}{150\,t})} & \textit{compression} \\ 1+0.36^2\dfrac{(1-\nu^2)l^4}{r^2t^2(1+\frac{r}{300\,t})} & \textit{bending} \\ 28.5\,(1+0.009(\dfrac{\sqrt{1-\nu^2}l^2}{rt})^{3/2}) & \textit{shear or torsion} \\ 16\,(1+0.025\dfrac{\sqrt{1-\nu^2}l^2}{rt}) & \textit{lateral pressure} \end{cases} \tag{28}$$

where r is the shell radius. The general limit state is defined in the example as:

$$g = \sigma_{crit} - \sigma_P - \sigma_L - \sigma_{ENV} \tag{29}$$

where σ_P is the stress due to permanent load, σ_L the stress due to live load and σ_{ENV} the stress due to environmental load. Four different limit states are specified due to four different loading types: LS1 for axial load, LS2 for bending, LS3 for shear and torsion and LS4 for lateral pressure. The following classifications are introduced:

a) Type of limit state (4 types: LS1-LS4)

b) Geometric design group (5 groups: DG1-DG5)

c) Load ratio ($\sigma_P:\sigma_L:\sigma_{ENV}$; 3 ratios: LR1-LR3)

Due to the above classifications 4×5×3=60 cases are investigated. The values for the corresponding weighting factors have been estimated on the basis of engineering experience with offshore structures in the

North Sea and after discussion with experts. The input statistical parameters are given in Table 6. The values are based on statistical data concerning the load and material properties.

Table 6: Input parameters for application to shell buckling			
basic variable	mean value	C.O.V.	distribution type
σ_P	varies	0.08	normal
σ_L	"	0.10	lognormal
σ_{ENV}	"	0.20	extreme I
E_s	210000 MPa	0.06	normal
ν	0.3	0.06	normal
σ_F	determined	0.06	lognormal
t	varies	0.01	normal
l	"	0.005	normal
r	"	0.005	normal

The mean value for the yield stress has been chosen as the design parameter in this example. The first step is to calculate the actual sensitivity factors for the chosen target reliability index (in this example β_t=4.0). This was performed by using a computer program, [9], which calculates the design parameter (here mean value of yield strength) for a given target reliability index. The influence of the random parameters E_s, ν, r, l, t was found to be negligible and therefore only $\sigma_P, \sigma_L, \sigma_{ENV}, \sigma_F$ are taken into account in the optimization. Table 7 illustrates the computed optimal set of α-values together with the empirical values of [4,10]. Based on the optimal α values a more practical set has been proposed for the design. Table 8 illustrates the values $\beta_{j_{opt}}$ and $\beta_{j_{emp}}$ for the the design group DG2. The accuracy of the proposed method is obvious.

Table 7: Optimal and empirical set of α values			
variable	optimal	proposed	empirical
σ_P	-0.504	-0.50	-0.40
σ_L	-0.000	-0.00	-0.40
σ_{ENV}	-0.983	-1.00	-0.70
σ_F	0.056	0.00	0.80

AREAS OF PARTICULAR RELEVANCE FOR CALIBRATION

Deep water structures

In normal design practice of fixed offshore installations for moderate water depths, proportionality most frequently exists between a load and the

Table 8: Obtained β_j -values (β_t=4.0)		
design case	$\beta_{j_{opt}}$	$\beta_{j_{emp}}$
LS1-LR1	4.03	3.89
LS1-LR2	4.05	4.50
LS1-LR3	4.05	3.86
LS2-LR1	4.00	3.86
LS2-LR2	4.02	4.44
LS2-LR3	4.01	4.32
LS3-LR1	3.99	3.73
LS3-LR2	4.04	4.31
LS3-LR3	4.02	3.96
LS4-LR1	4.02	3.64
LS4-LR2	4.06	4.20
LS4-LR3	4.05	3.85

corresponding response in the structure. However, compliant structures and in particular in deep waters, may experience the extreme responses at load combinations not initially defined as the extreme load combinations according to present design. Thereby, load coefficients which are established for fixed platforms in moderate water depths, may not give the proper check for compliant deep water structures.

To satisfy the overall technical requirements in this context and to maintain the safety level, calibration of the deep water compliant structures may be required. Then, the most relevant load combinations and corresponding load coefficients may be derived to result in a reliability level equivalent to the experience from the present last generation of fixed platforms in North Sea.

Welded structures

Welded structures are analyzed by applying fracture mechanics theory. In the fracture mechanics analysis, the resistance is normally described by the fracture toughness properties derived from standard tests. Thus a very sensitive test for welded connections may reflect the real variation in fracture toughness between local areas of weldment. However, the integrated strength of the welded connection may not be far that sensitive to local brittle zones as shown in the scatter from standard component tests. The scatter obtained in standard fracture toughness tests may thus overexpose the risk of brittle fracture compared to what is experienced in larger component tests. These problem areas are of particular importance for welded structures, and proper calibration for a limit state format is highly requested.

CONCLUSIONS

The following conclusions can be stated:

- The implementation of reliability methods in technical standards for marine structures needs further improvement. The design value format can be developed as an alternative to the partial safety factor format.
- The proposed calibration method is very accurate and more efficient than the traditional calibration of partial safety factors, where the total amount of computational work is considerable because all reliability indices β_j must be re-evaluated for each adjustment of the safety factors. However, optimal partial safety factors can easily be derived from the calibrated design values.
- The empirical design rule proposed in [4,10] does not always lead to satisfactory results. The applicability range of the rule has to be checked.
- The developed method can be applied for any specific limit state or for a set of limit states. The optimal design values can be easily implemented in a reliability-based structural code.
- The proposed calibration method is especially recommended in the development of a reliability-based code for deep water structures and welded marine structures.

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