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Reliability-Based Load and Resistance Factor Design (LRFD) of Hull Girders for Surface Ships

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Abstract

The main objective of structural design is to insure safety, functional, and performance requirements of a structural system for target reliability levels, for specified period of time, and for a specified environment. As this must be accomplished under conditions of uncertainty, probabilistic analyses are necessary in the development of such probability-based design criteria of hull girders for surface ships. A methodology for developing load and resistance factor design (LRFD) rules for ship structures was developed in this paper, and demonstrated for surface ship hull girders.

The methodology used in this paper for developing LRFD rules for ship hull girders consists of several steps as described herein. The probabilistic characteristics of strength and load random variables that are used in hull-girder structural design were analyzed, and values for these characteristics were recommended for reliability-based design purposes. Different load

combinations for hull girders were established and presented with combinations and correlation factors that included the stillwater bending, wave-induced bending, and wave dynamic bending moments.

In this paper, the reliability methods for developing the partial safety factors (PSF's) for ship hull girder in bending are described. These factors were determined to account for the uncertainties in strength and load effects. The First-Order Reliability Method (FORM) was used to determine these factors based on prescribed probabilistic characteristic of strength and load effects. Also, strength factors were computed for a set of load factors to meet selected target reliability levels for demonstration purposes. The resulting LRFD rules are demonstrated in this paper using an example.

1. INTRODUCTION

In recent years, ship structural design has been moving toward a more rational and probability-based design procedure referred to as limit states design. Such a design procedure takes into account more information than deterministic methods in the design of structural components. This information includes uncertainties in the strength of various structural elements, in loads and load combinations, and modeling errors in analysis procedures. Probability-based design formats are more flexible and rational than working stress formats because they provide consistent levels of safety over various types of structures. In probability-based limit-state design, probabilistic methods are used to guide the selection of strength (resistance) factors and load factors, which account for the variability in the individual resistance and loads and give the desired overall level of reliability. The load and resistance factors (or called partial safety factors) are different for each type of load and resistance. Generally, the higher the uncertainty associated with a load, the higher the corresponding load factor; and the higher the uncertainty associated with strength, the lower the corresponding strength factor.

Ship designers can use the load and resistance factors in limit-state equations to account for uncertainties that might not be considered properly by deterministic methods without explicitly performing probabilistic analysis. For this reason, design criteria can be kept as simple as possible. Moreover, they should be developed in a form that is familiar to the users or designers, and should produce desired levels of uniformity in reliability among different types of structures, without departing drastically from an existing practice. There is no unique format for a design criterion. A criterion can be developed on probability bases in any format. In general, the basic approach to develop a reliability-based design rules is first to determine the relative reliability of designs based on current practice. This relative reliability can be expressed in terms of either a probability of failure or a reliability index. The reliability index for structural components normally varies between 2 and 6 (Mansour et al 1984). By performing such reliability analyses for many structures, representative values of target reliability (or safety) index can be selected reflecting the average reliability implicit in current designs. Based on these values and by using reliability analysis again, it is possible to select partial safety factors for the loads and the strength random variables that can be used as a basis for developing the design requirements.

For designing code provisions, the most common format is the use of load amplification factors and resistance reduction factors (partial safety factors), as represented by

$$\phi R \geq \sum_{i=1}^{n} \gamma_i L_i \tag{1}$$

where ϕ = the resistance R reduction factor; γ_i = the partial load amplification factor; and L_i = the load effect. In fact, the American Institute of Steel Construction (AISC) and other industries in this area have implemented this format. Also, a recommendation for the use of this format is given by the National Institute of Standards and Technology (Ellingwood et al 1980).

The First-Order Reliability Method (FORM) is commonly used to estimate the partial safety factors ϕ and γ_i for a specified target reliability index β_0. This method was used to determine the partial safety factors associated with the recommended strength models for ship hull girders as described in this paper.

2. RELIABILITY-BASED DESIGN METHODS

The reliability-based design of ship structures requires the consideration of the following three components: (1) loads, (2) structural strength, and (3) methods of reliability analysis. These three components are shown in Figure 1 in the form of several blocks for each. Also, the figure shows their logical sequence and interaction.

There are two primary approaches for reliability-based design: (1) direct reliability-based design and (2) load and resistance factor design (LRFD) as shown in Figure 1 (Ayyub et al 1998). The direct reliability-based design approach can include both Level 2 and/or Level 3 reliability methods. Level 2 reliability methods are based on the moments (mean and variance) of random variables and sometimes with a linear approximation of nonlinear limit states, whereas, Level 3 reliability methods use the complete probabilistic characteristics of the random variables. In some cases, Level 3 reliability analysis is not possible because of lack of complete information on the full probabilistic characteristics of the random variables. Also, computational difficulty in Level 3 methods sometimes discourages their uses. The LRFD approach is called a Level 1 reliability method. Level 1 reliability methods utilize partial safety factors (PSF) that are reliability based; but the methods do not require explicit use of the probabilistic description of the variables.

2.1. Reliability-based Design Philosophy

The design of any ship structural system or element must provide for adequate safety and proper functioning of that system or element regardless of what philosophy of design is used. The structural systems or elements must have adequate strength to permit proper functioning during their intended service life. The performance of a hull girder as presented in the paper is defined by a set of requirements stated in terms of tests and measurements of how well the hull girder serves various or intended functions over its service life. Reliability and risk measures can be considered as performance measures, specified as target reliability levels (or target reliability indices, β_0's). The selected reliability levels of a particular structural element reflect the probability of failure of that element. These levels can be set based on implied levels in the currently used design practice with some calibration, or based on cost benefit analysis.

The reliability-based design approaches for a system start with the definition of a mission and an environment for a ship. Then, the general dimensions and arrangements, structural member sizes, scantlings, and details need to be assumed. The weight of the structure can then be estimated to ensure its conformance to a specified limit. Using an assumed operational-sea profile, the analysis of the ship produces a stochastic stillwater and wave-induced responses. The resulting responses can be adjusted using modeling uncertainty estimates that are based on any available results of full-scale or large-scale testing.

The reliability-based design procedure also requires defining performance functions that correspond to limit states for significant failure modes. In general, the problem can be considered as one of supply and demand. Failure of a structural element occurs when the supply (i.e., strength of the element) is less than the demand (i.e., loading on the element). On the other hand, the reliability of this element is achieved when the supply is greater than the demand. A generalized form for the performance function for a structural component is given by

$$g = R - L \tag{2}$$

where g = performance function, R = strength (resistance), and L = loading on the structural element. The failure in this case is defined in the region where g is less than zero or R is less than L, that is

$$g < 0.0 \text{ or } R < L \tag{3}$$

whereas the reliability is defined in the region where g is greater than zero or R is greater than L, that is

$$g > 0.0 \text{ or } R > L \tag{4}$$

The reliability-based design approach as given assumes the strength R and the load L to be random variables. Typical frequency distributions of such random variables are shown in Figure 2. If R is greater than L, there will be a margin of safety. However, unless R is greater than L by a large amount, there is always a probability that L may exceed R. This is illustrated by the shaded area in Figure 2 where the two curves for R and L overlap. Due to the variability in both strength and loads, there is always a probability of failure that can be defined as

$$P_f = P(g < 0.0) = P(R < L) \tag{5}$$

The reliability of a system or a component can be defined as the probability that the system or the component meets some specified demands for a specified time frame. Mathematically, it is given by the following expression:

$$R_c = P(g > 0.0) = P(R > L) \tag{6}$$

where P_f = probability of the system or component and R_c = reliability of the system or component.

The many advantages and benefits of using reliability-based design methods include the followings:

1. They provide the means for the management of uncertainty in loading, strength, and degradation mechanisms.
2. They provide consistency in reliability.
3. They result in efficient and possibly economical use of materials.
4. They provide compatibility and reliability consistency across materials, such as, steel grades, aluminum and composites.
5. They allow for future changes as a result of gained information in prediction models, and material and load characterization.
6. They provide directional cosines and sensitivity factors that can be used for defining future research and development needs.
7. They allow for performing time-dependent reliability analysis that can form the bases for life expectancy assessment, life extension, and development of inspection and maintenance strategies.
8. They are consistent with other industries, AISC, ASHTO, ACI, API, ASME, …, etc.
9. They allow for performing system reliability analysis.

2.2. Direct Reliability-Based Design

The direct reliability-based design method uses all available information about the basic variables (including correlation) and does not simplify the limit state in any manner. It requires performing spectral analysis and extreme analysis of the loads. In addition, linear or nonlinear structural analysis can be used to develop a stress frequency distribution. Then, stochastic load combinations can be performed. Linear or nonlinear structural analysis can then be used to obtain deformation and stress values. Serviceability and strength failure modes need to be considered at different levels of the ship, i.e., hull girder, grillage, panel, plate and detail. The appropriate loads, strength variables, and failure definitions need to be selected for each failure mode. Using reliability assessment methods such as FORM, reliability indices β's for all modes at all levels need to be computed and compared with target reliability indices $\beta_0^{'}$s. The relationship between the reliability index β and the probability of failure is given by

$$P_f = 1 - \Phi(\beta) \tag{7}$$

where $\Phi(.)$ = cumulative probability distribution function of the standard normal distribution, and β = reliability (safety) index. It is to be noted that Eq. 6 assumes all the random variables in the limit state equation to have normal probability distribution and the performance function is linear. However, in practice, it is common to deal with nonlinear performance functions with a relatively small level of linearity. If this is the case, then the error in estimating the probability of failure P_f is very small, and thus for all practical purposes, Eq. 6 can be used to evaluate P_f with sufficient accuracy (Ayyub and McCuen 1997).

2.3. Load and Resistance Factor Design

The second approach (LRFD) of reliability-based design consists of the requirement that a factored (reduced) strength of a structural component is larger than a linear combination of factored (magnified) load effects as given by the following general format:

$$\phi R_n \geq \sum_{i=1}^{m} \gamma_i L_{ni} \tag{8}$$

where ϕ = strength factor, R_n = nominal (or design) strength, γ_i = load factor for the ith load component out of n components, and L_{ni} = nominal (or design) value for the ith load component out of m components.

In this approach, load effects are increased, and strength is reduced, by multiplying the corresponding characteristic (nominal) values with factors, which are called strength (resistance) and load factors, respectively, or partial safety factors (PSF's). The characteristic value of some quantity is the value that is used in current design practice, and it is usually equal to a certain percentile of the probability distribution of that quantity. The load and strength factors are different for each type of load and strength. Generally, the higher the uncertainty associated with a load, the higher the corresponding load factor; and the higher the uncertainty associated with strength, the lower the corresponding strength factor. These factors are determined probabilistically so that they correspond to a prescribed level of reliability or safety. It is also common to consider two classes of performance function that correspond to strength and serviceability requirements.

The difference between the allowable stress design (ASD) and the LRFD format is that the latter use different safety factors for each type of load and strength. This allows for taking into consideration uncertainties in load and strength, and to scale their characteristic values accordingly in the design equation. ASD (or called working stress) formats cannot do that because they use only one safety factor as seen by the following general design format:

$$\frac{R}{\mathrm{FS}} \geq \sum_{i=1}^{m} L_i \tag{9}$$

where R = strength or resistance, L_i = load effect, and FS = factor of safety. In this design format, all loads are assumed to have average variability. The entire variability of the strength and the loads is placed on the strength side of the equation. The factor of safety FS accounts for this entire variability.

In the LRFD design format, ship designers can use the load and resistance factors in limit-state equations to account for uncertainties that might not be considered properly by deterministic methods (i,e., ADS) without explicitly performing probabilistic analysis. The LRFD format as described herein is concerned mainly with the structural design of ship hull girders under combinations of different load effects. The intention herein is to provide naval architects and ship designers with reliability-based methods for their use in both early and final design stages and for checking the adequacy of the scantlings of all structural members contributing to the longitudinal and transverse strength of ships. The general form of the LRFD format used in this paper is given by Eq. 8.

The probabilistic characteristics and nominal values for the strength and load components were determined based on statistical analysis, recommended values from other specifications, and by professional judgment. The LRFD general design formats for ship hull girders are given by one of the following two main cases, limit sate 1, and limit sate 2, respectively:

$$\phi R_n \geq \gamma_s L_s + k_{WD} \gamma_{WD} L_{WD} \tag{10}$$

$$\phi R_n \geq \gamma_s L_s + k_W\left(\gamma_W L_W + k_D \gamma_D L_D\right) \tag{11}$$

where ϕ = strength factor, R_n = nominal (or design) strength such as the ultimate stress, γ_s = load factor for stillwater load effect such as bending moment, L_s = nominal (or design) value for stillwater load effect such as bending moment, k_{WD} = combined wave-induced and dynamic bending moment factor, and γ_{WD} = load factor for combined wave-induced and dynamic bending moment, L_{WD} = nominal (or design) value for wave-induced and dynamic bending moments effect, k_W = load combination factor, γ_W = load factor for waves bending moment load effect, L_W = nominal (or design) value for waves bending moment load effect, k_D = load combination factor, γ_D = load factor for dynamic load effect such as bending moment, and L_D = nominal (or design) value for dynamic load effect such as bending moment.

The strength and load factors are called collectively partial safety factors (PSF's). These factors are determined using structural reliability methods based on the probabilistic characteristics of basic random variables for materials, geometry and loads including statistical and modeling (or prediction) uncertainties. The factors are determined to meet target reliability levels that were selected based on assessing previous designs. This process of developing LRFD rules to meet target reliability levels that are implicit in current practices is called code calibration.

2.4. Reliability Checking

The LRFD methods also provide formats for reliability (safety) checking for various types of hull structural elements. In order to perform a reliability checking on these elements, the computed reliability safety index β resulting from reliability assessment using for example FORM should not be less than the target safety index β_0 as given by the following expression:

$$\beta \geq \beta_0 \tag{12}$$

Reliability checking for different classes of ship structural elements can also be performed using the general form of the load and resistance factor design format of Eq. 8. Depending on the limit state, the nominal strength R_n of the structural component shall meet one of following two main requirements for limit states 1 and 2, respectively:

$$R_n \geq \frac{\gamma_s L_s + k_{WD} \gamma_{WD} L_{WD}}{\phi} \tag{13}$$

$$R_n \geq \frac{\gamma_s L_s + k_W \left(\gamma_W L_W + k_D \gamma_D L_D \right)}{\phi} \tag{14}$$

2.5. First-Order Reliability Method (FORM)

The First-Order Reliability Method (FORM) is a convenient tool to assess the reliability of a ship structural element. It also provides a means for calculating the partial safety factors ϕ and γ_i that appear in Eq. 8 for a specified target reliability level β_0. The simplicity of the first-order reliability method stems from the fact that this method, beside the requirement that the distribution types must be known, requires only the first and second moments; namely the mean values and the standard deviations of the respective random variables. Knowledge of the joint probability density function (PDF) of the design basic variables is not needed as in the case of the direct integration method for calculating the reliability index β. Even if the joint PDF of the basic random variables is known, the computation of β by the direct integration method can be a very difficult task.

In design practice, there are usually two types of limit states: the ultimate limit states and the serviceability limit states. Both types can be represented by the following performance function:

$$g(\boldsymbol{X}) = g(X_1, X_2, ..., X_n) \tag{15}$$

in which $\boldsymbol{X}$ is a vector of basic random variables (X_1, X_2, ..., X_n) for the strengths and the loads. The performance function $g(\boldsymbol{X})$ is sometimes called the limit state function. It relates the random variables for the limit-state of interest. The limit state is defined when $g(\boldsymbol{X}) = 0$, and therefore, failure occurs when $g(\boldsymbol{X}) < 0$ (see Figure 3). The reliability index β is defined as the shortest distance from the origin to the failure surface in the reduced coordinates at the most probable failure point (MPFP) as shown in Figure 3.

As indicated earlier, the basic approach for developing reliability-based design rules requires the determination of the relative reliability of designs based on current practices. Therefore, reliability assessment of existing structural components of ships such as the hull girder is needed to estimate a representative value of the reliability index β. The first-order-reliability method is very well suited to perform such a reliability assessment. The following are computational steps as described by Ayyub and McCuen (1997) for determining β using the FORM method:

1. Assume a design point x_i^* and obtain $x_i^{'*}$ in the reduced coordinate using the following equation:

$$x_i^{'*} = \frac{x_i^* - \mu_{X_i}}{\sigma_{X_i}} \tag{16}$$

where $x_i^{'*} = -\alpha_i^* \beta$, μ_{X_i} = mean value of the basic random variable, and σ_{X_i} = standard deviation of the basic random variable. The mean values of the basic random variables can be used as initial values for the design points. The notation x^* and $x^{'*}$ are used respectively for the design point in the regular coordinates and in the reduced coordinates.

2. Evaluate the equivalent normal distributions for the non-normal basic random variables at the design point using the following equations:

$$\mu_X^N = x^* - \Phi^{-1}\left(F_X(x^*)\right)\sigma_X^N \qquad (17)$$

and

$$\sigma_X^N = \frac{\left(\Phi^{-1}\left(F_X(x^*)\right)\right)}{f_X(x^*)} \qquad (18)$$

where μ_X^{N} = mean of the equivalent normal distribution, σ_X^N = standard deviation of the equivalent normal distribution, $F_X(x^*)$ = original (non-normal) cumulative distribution function (CDF) of X_i evaluated at the design point, $f_X(x^*)$ = original probability density function (PDF) of X_i evaluated at the design point, $\Phi(\cdot)$ = CDF of the standard normal distribution, and $\phi(\cdot)$ = PDF of the standard normal distribution.

3. Compute the directional cosines at the design point (α_i^*, i = 1,2, ..., n) using the following equations:

$$\alpha_i^* = \frac{\left(\dfrac{\partial g}{\partial x_i^{'}}\right)_*}{\sqrt{\sum_{i=1}^{n}\left(\dfrac{\partial g}{\partial x_i^{'}}\right)_*^2}} \qquad \text{for } i = 1, 2, ..., n \qquad (19)$$

where

$$\left(\frac{\partial g}{\partial x_i'}\right)_* = \left(\frac{\partial g}{\partial x_i}\right)_* \sigma_{X_i}^N \tag{20}$$

4. With α_i^*, $\mu_{X_i}^N$, and $\sigma_{X_i}^N$ are now known, the following equation can be solved for the root β:

$$g\left[(\mu_{X_1}^N - \alpha_{X_1}^* \sigma_{X_1}^N \beta), ..., (\mu_{X_n}^N - \alpha_{X_n}^* \sigma_{X_n}^N \beta)\right] = 0 \tag{21}$$

5. Using the β obtained from step 4, a new design point can be obtained from the following equation:

$$x_i^* = \mu_{X_i}^N - \alpha_i^* \sigma_{X_i}^N \beta \tag{22}$$

6. Repeat steps 1 to 5 until a convergence of β is achieved. The reliability index is the shortest distance to the failure surface from the origin in the reduced coordinates as shown in Figure 3.

The important relation between the probability of failure and the reliability (safety) index is given by Eq. 7.

2.5.1. Procedure for Calculating Partial Safety Factors (PSF) Using FORM

The first-order reliability method (FORM) can be used to estimate partial safety factors such those found in the design format of Eq. 8. At the failure point ($R^*, L_1^*, ..., L_n^*$), the limit state of Eq. 7 is given by

$$g = R^* - L_1^* - ... - L_n^* = 0 \tag{23}$$

or, in a general form

$$g(\boldsymbol{X}) = g(x_1^*, x_2^*, ..., x_n^*) = 0 \tag{24}$$

For given target reliability index β_0, probability distributions and statistics (means and standard deviations) of the load effects, and coefficient of variation of the strength, the mean value of the resistance and the partial safety factors can be determined by the iterative solution of Eqs. 16 through 22. The mean value of the resistance and the design point can be used to compute the required mean partial design safety factors as follows

$$\phi = \frac{R^*}{\mu_R} \tag{25}$$

$$\gamma_i = \frac{L_i^*}{\mu_{L_i}} \tag{26}$$

The strength factors are generally less than one, whereas the load factors are greater than one.

2.5.2. Determination of a Strength Factor for a Given Set of Load Factors

In developing design code provisions for ship hull girders, it is sometimes necessary to follow the current design practice to insure consistent levels of reliability over various types of ship structures. Calibrations of existing design codes is needed to make the new design formats as simple as possible and to put them in a form that is familiar to the users or designers. Moreover, the partial safety factors for the new codes should provide consistent levels of reliability. For a given reliability index β and probability characteristics for the resistance and the load effects, the partial safety factors determined by the FORM approach might be different for different failure modes for the same structural component. Therefore, the calculated partial safety factors (PSF's) need to be adjusted in order to maintain the same values for all loads at different failure modes by the strength factor ϕ for a given set of load factors. The following algorithm can be used to accomplish this objective:

1. For a given value of the reliability index β, probability distributions and statistics of the load variables, and the coefficient of variation for the strength, compute the mean strength needed to achieve the target reliability using the first-order reliability method as outlined in the previous sections.
2. With the mean value for R computed in step 1, the partial safety factor can be revised for a given set of load factors as follows:

$$\phi` = \frac{\sum_{i=1}^{n} \gamma`_i \mu_{L_i}}{\mu_R} \tag{27}$$

where $\phi`$ = revised strength factor, $\mu_{L_i}$ and $\mu_R$ are the mean values of the loads and strength variables, respectively; and $\gamma`_i$, i = 1, 2, ..., n, are the given set of load factors.

3. DESIGN STRENGTH AND LOADS FOR HULL GIRDERS

In this section, recommended design (or called nominal) models for both the longitudinal strength of hull girders and bending moments as loads are provided based on a literature review. These design values can be viewed as the nominal values required by the LRFD rules for the preliminary design stages to satisfy the desired target reliability levels. The LRFD formats take into considerations the variability associated with the design variables (for both strength and loads prediction). The focus in this section is on hull girder strength, stillwater bending, wave-induced bending, and dynamic bending moments. The hull girder strength can be determined using two approaches: elastic-based strength, and ultimate strength. The wave loads can be determined using extreme and spectral analysis.

3.1. Design Strength for Hull Girder

Two methods are provided for determining the design value of the hull: (1) elastic-based strength, and (2) ultimate strength. The ship's hull girder in both methods is treated as a beam subjected to combined bending moments, and has its own strength. The strength is a function of the section modulus of the hull girder at any section of interest based on mechanical and geometric properties of the hull materials.

3.1.1. Elastic-based Strength

The section modulus Z amidship is to be determined according to best engineering judgment and practices. The elastic-based bending strength of a hull girder shall be then computed as

$$M_u = cF_y Z \tag{28}$$

where c = buckling knock-down factor which was set to be a random variable with mean (or design) value of 0.36 in hogging and 0.74 in sagging (Atua 1998), F_y = yield strength of material, M_u = ultimate bending capacity of the hull girder, and Z = section modulus. The buckling knock-down factor is defined as

$$c = \frac{M_u}{F_y Z} \tag{29}$$

where M_u = ultimate bending capacity of the hull girder.

3.1.2. Ultimate Strength

The ultimate bending strength capacity for a section at any station can be estimated using the incremental strain approach by calculating the moment-curvature relationship and as the maximum resisting moment for the section. This approach calculates the moment-curvature relationship and the ultimate bending capacity of a ship's hull girder cross section using strength and geometry information about scantlings of all structural members contributing to the longitudinal strength. Computer programs are available and can be used for this purpose as described by Atua (1998).

3.2. Design Loads for Hull Girder

Primary structural loads on a ship are due to its own weight, cargo, buoyancy, and operation in a random environment, i.e., the sea. The loads acting on the ship's hull girder can be categorized into three main types: (1) stillwater loads, (2) wave loads, and (3) dynamic loads. The load effect of concern herein is bending moment exerted on the ship hull girder.

Stillwater loads can be predicted and evaluated with a proper consideration of variability in weight distribution along the ship length, variability in its cargo loading conditions, and buoyancy. Both wave loads and dynamic loads are related and affected by many factors such as ship characteristics, speed, heading of ship at sea, and sea state (waves heights). Waves height is a random variable that requires statistical and extreme analyses of ship response data collected over a period of time in order to estimate maximum wave-induced and dynamic bending moments that the ship might encounter during its life. The statistical representation of sea waves allows the use of statistical models to predict the maximum wave loads in ship's life.

Procedures for computing design wave loads for a ship's hull girder based on spectral analysis can be found in numerous references pertaining to ship structures such as Hughes (1988).

3.2.1. Hull Girder Loading

The loads that are of concern in this study for developing reliability-base design for panels and fatigue details of ship structures are the ones resulting from ship hull girder bending and their combinations. As indicated earlier, the loads acting on the ship's hull girder can be categorized into three main types: stillwater loads, wave loads, and dynamic loads. Each of these types of loads are presented subsequently under its own heading.

3.2.1.1. Stillwater Loads

The calm water or stillwater loading should be investigated in design processes although it rarely governs the design of a ship on its own. The ship is balanced on the draft load waterline with the longitudinal center of gravity aligned with the longitudinal center of buoyancy in the same vertical plan. Then, the hull girder loads are developed based on the differences between the weights and the buoyancy distributions along the ship's length. The net load generates shear and bending moments on the hull girders. The resulting values from this procedure are to be considered the design (nominal) values in the LRFD format for the stillwater shear forces and bending moments on the hull girder.

3.2.1.2. Wave-induced Bending Moment

Wave-induced bending moment is treated as a random variable dependent on ship's principal characteristics, environmental influences, and operational conditions. Spectral and extreme analyses can be used to determine the extreme values and the load spectra of this load type during the design life of the ship. The outcome of this analysis can be in the form of vertical or horizontal longitudinal bending moments or stresses on the hull girder. Computer programs have been developed and are available to perform these calculations for different ships based on their types, sizes, and operational conditions (Sikora et al 1983).

3.2.1.3. Dynamic Bending Moment

Dynamic bending moments on the hull girder due to slamming or whipping can be determined using one of the following two methods:

1. Spectral and extreme analyses can be used to obtain the combined wave-induced and dynamic load effects on the hull girder. Computer programs can be used for this purpose as provided by Sikora (1983).
2. Equations 30 to 33, which are based on spectral analysis can be used for this purpose. The average peak-to-peak whipping bending moments (in ft-ton) for fine bow ships is described by Atua (1998) as

$$M_{WH} = 0.0022 LBP^2 B \qquad \text{for } LBP^2 B < 5\text{x}10^6 \text{ (ft}^3\text{)} \tag{30}$$

and

$$M_{WH} = 5.4 LBP\sqrt{B} \qquad \text{for } LBP^2 B \geq 5\text{x}10^6 \text{ (ft}^3\text{)} \tag{31}$$

where M_{WH} = mean value of peak-to-peak whipping bending moment, LBP = length between perpendiculars of the ship (in ft), and B = molded breadth of the ship (in ft). For ships with bow flare or with flat bottom (such as auxiliaries and cargo ships), the whipping bending moments can be determined (in ft-ton) using (Atua 1998)

$$M_{WH} = 0.0022 LBP^2 B \tag{32}$$

The lifetime extreme value of whipping bending moments for a ship was defined as the whipping bending moment value with a one percent chance of being exceeded in its lifetime and is given by (Atua 1998)

$$M_{WHe} = 4.6\ M_{WH} \tag{33}$$

where M_{WHe} = extreme value of whipping bending moment in ton-ft.

3.2.1.4. Combined Wave-induced and Dynamic Bending Moment

Spectral and extreme analyses can be used to determine the design value of the combined wave-induced and dynamic bending moments on a ship hull girder during its design life (Sikora et al 1983).

3.2.2. Load Combinations

The reliability-based structural design of ship hull girders for bending as presented in this paper is based on two load combinations that are associated with correlation factors as presented in the subsequent sections (Mansour 1994).

3.2.2.1. Stillwater and Vertical Wave-induced Bending Moments

The load combination for stillwater and vertical wave-induced bending moments is given by

$$M_u = M_{SW} + k_{WD} M_{WD} \quad (34)$$

where M_{SW} = stillwater bending moment, M_{WD} = wave-induced bending moment, M_u = ultimate capacity (moment) of hull girder, k_W = correlation factor for wave-induced bending moment and is set equal to one (Mansour 1994).

3.2.2.2. Stillwater, Vertical Wave-induced, and Dynamic Bending Moments

The load combination for stillwater, vertical wave-induced and dynamic bending moments is given by

$$M_u = M_{SW} + k_W (M_W + k_D M_D) \quad (35)$$

where M_{SW} = stillwater bending moment, M_W = waves bending moment, M_D = stress due to dynamic bending moment, M_u = ultimate capacity (moment) of hull girder, and k_D = correlation factor between wave-induced and dynamic bending moments. The correlation factor k_D is given by the following two cases of hogging and sagging conditions (Mansour 1994, and Atua 1998):

a. Hogging condition:

$$k_D = Exp\left[\frac{53080}{\left(158LBP^{-0.2} + 14.2LBP^{0.3}\right)LBP}\right] \quad \text{(in ft)} \tag{36}$$

b. Sagging condition:

$$k_D = Exp\left[\frac{21200}{\left(158LBP^{-0.2} + 14.2LBP^{0.3}\right)LBP}\right] \quad \text{(in ft)} \tag{37}$$

where LBP = length between perpendiculars for a ship in ft. Values of k_D for LBP ranging from 300 to 1000 ft can be obtained either from Table 1 or from the graphical chart provided in Figure 4.

4. EXAMPLE: LRFD RLES FOR HULL GIRDERS UNDER COMBINED LOADS

Hull girders are very important components in ship structures, and therefore they should be designed for a set of failure modes such as yielding, buckling, and fatigue of critical connecting components. In addition, they should be design for target reliability levels that reflect the levels in currently used design practices with some calibration, or based on cost benefit analysis. The performance of a hull girder is defined by a set of requirements stated in terms of tests and measurements of how well the hull girder serves various intended functions over its service life. Reliability and risk measures can be considered as performance measures, specified as target reliability levels (or target reliability indices, β_0). The selected reliability levels for a hull girder reflect its probability of failure.

Reliability-based load and resistance factor design (LRFD) for hull girder requires defining performance functions that correspond to limit states for its significant failure modes. It also requires the statistical characteristic of basic strength and load random variables. Quantification of these variables is needed for reliability analysis and design of the hull girder. For example, the first-order reliability method (FORM) requires the quantification of the mean values, coefficient of variation, and distribution types of all relevant random variables. They are needed to compute the safety (reliability) index β or the PSF's.

4.1. Target Reliability Levels

Selecting a target reliability level is required in order to establish reliability-based design rules for ship structures such as the hull girder. The selected reliability level determines the probability of failure of the structures. The following three methods can be used to select a target reliability value:

1. Agreeing upon a reasonable value in cases of novel structures without prior history.
2. Calibrating reliability levels implied in currently used design codes.
3. Choosing target reliability level that minimizes total expected costs over the service life of the structure for dealing with design for which failures result in only economic losses and consequences.

Since the development herein is limited to ship hull girders that are not novel structures, the first method is excluded. Ship hull girders modes of failure have serious consequences such as the entire loss of the ship, loss of lives, and environmental damages (water pollution in case of tankers or chemical carriers). Accordingly, the second method seems to be the proper one to be adopted for selecting target reliability levels since there are a lot of data available from currently used design codes that resulted in structures with adequate reliability.

4.2. Limit States for Hull Girder Bending

The hull girder of a ship for all stations should meet one of the following conditions, the selection of the appropriate equation depends on the availability of information as required by these equations:

$$\phi_M M_u \geq \gamma_{SW} M_{SW} + k_W \left(\gamma_W M_W + \gamma_D k_D M_D\right) \tag{38}$$

$$\phi_M c F_y Z \geq \gamma_{SW} M_{SW} + k_W \left(\gamma_W M_W + \gamma_D k_D M_D\right) \tag{39}$$

$$\phi_M M_u \geq \gamma_{SW} M_{SW} + \gamma_{WD} k_{WD} M_{WD} \tag{40}$$

$$\phi_M c F_y Z \geq \gamma_{SW} M_{SW} + \gamma_{WD} k_{WD} M_{WD} \tag{41}$$

where c = nominal buckling knock-down factor, ϕ_M = strength factor of ultimate bending capacity, F_y = nominal yield strength of steel, k_D = dynamic bending moment probabilistic combination load factor, k_W = wave-induced bending moment probabilistic combination load factor, k_{WD} = probabilistic combination load factor for combined wave-induced and whipping, γ_D = load factor for dynamic bending moment, γ_{SW} = stillwater bending moment partial safety factor, γ_W = load factor for environmental load, γ_{WD} = load factor for combined wave-induced and dynamic bending, M_D = nominal dynamic bending moment, M_{SW} = nominal value of stillwater bending moment, M_u = nominal ultimate bending capacity of ship hull girder, M_W = nominal value of wave-induced bending moment, M_{WD} = nominal combined wave-induced and whipping bending moment, and Z = section modulus of hull girder. The nominal (i.e., design) values of the strength and load components should satisfy these limit states in order to achieve specified target reliability levels.

4.3. Statistical Characteristics of Random Variables

The statistical characteristics of random variables of strength and load models are needed for reliability-based design and assessment of ship structures including hull girders. The moments methods for calculating partial safety factors (Ang and Tang 1990, Ayyub and McCuen 1997, and Ayyub and White 1987) require full probabilistic characteristics of both strength and load variables in the limit state equation. For example, the relevant strength variables for ship hull girders are the material's yield strength (stress) F_y, section modulus *Z*, and buckling knock-down factor *c*. While the relevant loads variables are the external pressures due to stillwater bending moment, wave bending moment, and dynamic loads.

The definition of these random variables requires the investigation of their uncertainties and variability. In reliability assessment of any structural system, these uncertainties must be quantified. Furthermore, partial safety factors (PSF's) evaluation for both the strengths and loads in any design equation also requires the characterization of these variables. For example, the first-order reliability method (FORM) as outlined earlier requires the quantification of mean values, standard deviations (or the coefficient of variation (*COV*)), and distribution types of all relevant random variables. They are needed to compute the safety index β or the PSF's. Therefore, complete information on the probability distributions of the basic random variables under consideration must be developed. Quantification of random variables of loads and strength in terms of their means, standard deviations or *COV*'s, and probability distributions can be achieved in two steps: (1) data collection and (2) data analysis. The first step is the task of collecting as many sets of data deemed to be appropriate for representing the random variables under study. The second is concerned with statistically analyzing the collected data to determine the probabilistic characteristics of these variables.

The objective herein is to compile statistical information and data based on literature review on both strength and loads random variables for quantifying the probabilistic characteristics of these variables. The quantification of the probabilistic characteristics of these variables is needed for reliability analysis and design of hull structural components. Tables 2, 3, and 4 provide summaries of the probabilistic characteristics of strength and loads random variables. The information given in these tables is tabulated based on data from a literature review performed by Atua et al (1996), and Assakkaf (1998).

Tables 5 through 8 provide all the recommended values of information required for establishing a reliability-based design rules for ship structures. This information includes limit state functions for different load combinations; probabilistic characteristics (mean values, *COV*, and distribution type) of random variables involved in these limit state functions. The information also includes mean to nominal values of these random variables, deterministic values of the probabilistic load-combination factors; probabilistic characteristics of the buckling knock-down factor; mean ratios between different load components, ranges of target reliability index; the biases between different values of each of the random variables; and probabilistic characteristics of model and prediction uncertainty parameters.

The recommended range of target reliability indices for hull girder bending is set to be from 4.0 to 5.0 for a sagging condition and 5.0 to 6.0 for a hogging condition for naval ships (Mansour et al 1995).

4.4. Calculation of Partial Safety Factors for Hull Girders

Based on the ultimate capacity (ultimate moment), this example demonstrates the calculation of partial safety factors for the hull girders when they are under a combination of stillwater, wave-induced, and dynamic bending moments. The performance function of the limit state for this case is given by

$$g = \phi_M M_u - \gamma_{SW} M_{SW} - k_W \left(\gamma_W M_W + \gamma_D k_D M_D \right) \tag{42}$$

The partial safety factors for this limit state function were developed for demonstration purposes using a target reliability index β_0 of 4.0. This equation provides strength minus load effect expression of the limit state. The First-Order Reliability Method (FORM) as discussed in previous sections requires the probabilistic characteristics of M_u, M_{SW}, M_W and M_D. According to Table 5, the stillwater load effect M_{SW} is due to stillwater bending that can be assumed to follow a normal distribution with a coefficient of variation of 0.15. Both the wave-induced and dynamic load effects M_W and M_D can be assumed to follow an extreme value distribution (Type I largest) with a coefficient of variation of 0.15 and 0.25, respectively, as provided in Table 5. The mean values of stillwater, wave-induced, and dynamic bending moments that can be provided in the form of a ratio of stillwater/wave-induced and dynamic/wave-induced loads can range from 0.2 to 0.4 and from 0.25 to 0.35, respectively, as shown in Table 7. Table 9 summarizes the probabilistic characteristics of both the strength and the load effects.

The ratios of means for strength/wave-induced load and the partial safety factors for a target reliability of 4.0 are summarized as shown in Figure 5. Based on these results, the following preliminary values for partial safety factors are recommended for demonstration purposes:

Mean strength reduction factor (ϕ_M) = 0.44
Mean stillwater load factor (γ_{SW}) = 1.04
Mean wave-induced load factor (γ_W) = 1.22
Mean dynamic load factor (γ_D) = 1.05

The above partial safety factors for the strength and the loads can be converted to nominal values by multiplying them by the appropriate mean to nominal ratios. Based on the mean to nominal ratios of Table 5, the following preliminary nominal values for partial safety factors are recommended for demonstration purposes:

Nominal strength reduction factor (ϕ_M) = 0.48
Nominal stillwater load factor (γ_{SW}) = 1.04
Nominal wave-induced load factor (γ_W) = 1.22
Nominal dynamic load factor (γ_D) = 1.17

4.5. Calculation of Strength Factor For a Given Set of Load Factors

As indicated in earlier, for a given β and probabilistic characteristics for the strength and the load effects, the partial safety factors determined by the FORM approach might be different for different failure modes. For this reason, an adjustment is often needed on the strength factor ϕ_M to maintain the same values for all load factors γ's. The following numerical example illustrates the procedure for revising the strength factor for a given set of load factors. For instance, given $\gamma`_{SW} = 1.3$, $\gamma`_W = 1.8$, $\gamma`_D = 1.5$, $k_W = 1$, $k_D = 0.7$, and the mean values for M_{SW}, M_W, and M_D (ratios of 0.2, 1.0, and 0.25), the corresponding strength factor ϕ_M was calculated for a target reliability level $\beta = 4.0$. Using the first-order reliability method (FORM), the mean of M_u was found to be 4.1. With the mean value known, Eq. 27 gives

$$\phi`_M = \frac{\gamma`_{SW}\overline{M_{SW}} + k_W\left(\lambda`_W\overline{M_W} + k_D\gamma`_D\overline{M_D}\right)}{\overline{M_u}} = \frac{1.3(0.2) + (1)[1.8(1.0) + 0.7(1.5)(0.25)]}{4.1} = 0.57$$

5. SUMMARY AND CONCLUSIONS

Future design rules for ship hull girders will be developed using reliability methods and they will be expressed in a special format such as the Load and Resistance Factor Design (LRFD) format. The LRFD rules for ship structures based on structural reliability theory can be built on previous and currently used specifications for ships, buildings, bridges, and offshore structures. This paper provides methods for and demonstrates the development of LRFD rules for ship hull girders subjected to vertical bending due to combined loads.

The methodology provided in this paper for developing LRFD rules for ship hull girders consists of several steps as follows: (1) The probabilistic characteristics of strength and load random variables that are used in hull-girder structural design were analyzed, and values for these characteristics were recommended for reliability-based design purposes. These values were selected on the bases of statistical analyses performed on data collected for strength and load random variables, on values recommended in other studies, or sometimes on sound engineering judgment. (2) Different load combinations for hull girders were established and presented with combinations and correlation factors that included the stillwater bending, wave-induced bending, and wave dynamic bending moments. The correlation among these different load components was accounted for and expressed in the form of correlation factors. (3) Limit states for these load combinations were established based on critical modes of failures of hull girders and the identified load combinations. (4) Target reliability levels as suggested and used by other studies were summarized, and ranges of target reliability levels were selected for the hull girder limit states in bending. (5) The First-Order Reliability Method (FORM) can be used to assess the reliability of ships hull girder as well as to develop and establish the partial safety factors. In this paper, the FORM method was used to develop partial safety factors for demonstration purposes. These factors were developed for the ultimate design capacity (M_u) of hull girders under a combination of stillwater, wave-induced, and dynamic bending moments load effects. The prescribed probabilistic characteristics of hull strength and load effects were used to develop the partial safety factors based on a linear limit state. The partial safety factors were computed for a selected case. Based on these results and for a target reliability level β of 4.0, the following nominal values for partial safety factors were computed for demonstration purposes:

Strength reduction factor (ϕ_M)	= 0.48
Stillwater load factor (γ_{SW})	= 1.04
Wave-induced load factor (γ_W)	= 1.22
Dynamic load factor (γ_D)	= 1.17

The resulting partial safety factors can be used to design the ultimate capacity (ultimate moment) of a hull girder under a combination of stillwater, wave-induced, and dynamic bending moment by satisfying the following design criterion:

$$0.48M_u \geq 1.04M_{SW} - k_W\left(1.22M_W + 1.17k_D M_D\right) \qquad (43)$$

Therefore, reliability-based design rules can be expressed in a practical format that is suitable for the use of practicing engineers.

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7. REFERENCES

1. Ang , A. H-S., Tang, W. H., 1990. “Probability Concepts in Engineering Planning and Design,” Vol. II Decision, Risk, and Reliability, John Wiley & Sons, NY.
2. Assakkaf, I. A., 1998. "Reliability-based Design of Panels and Fatigue Details of Ship Structures," A dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
3. Atua, K. I., 1998. "Reliability-Based Structural Design of Ship Hull Girders and Stiffened Panels," A dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
4. Atua, K., Assakkaf, I. A., and Ayyub, B. M., 1996. "Statistical Characteristics of Strength and Load Random Variables of Ship Structures," Probabilistic Mechanics and Structural Reliability, Proceeding of the Seventh Specialty Conference, Worcester Polytechnic Institute, Worcester, Massachusetts.
5. Ayyub, B. M., and McCuen, R. H., 1997. “Probability, Statistics and Reliability for Engineers”, CRC Press LLC.
6. Ayyub, B. M., and White, A. M., 1987. “Reliability-Conditioned Partial Safety Factors”, Journal of Structural Engineering, Vol. 113, No. 2, February, ASCE, 280-283.

7. Ellingwood, B., Galambos, T. V., MacGregor, J. G., Cornell, C. A., 1980. “Development of a Probability Based Load Criterion for American National Standard A58,” National Bureau of Standards, Special Publication No. 577.
8. Hughes, O. F., 1988. “Ship Structural Design, A rationally-Based, Computer-Aided Optimization Approach,” The Society of Naval Architects and Marine Engineers, Jersey City, New Jersey.
9. Mansour, A. and Thayamball, 1994. “Probability-Based Ship Design: Loads and Load Combinations,” SSC-373, Ship Structures Committee, NTIS # PB94-188208, Springfield, Virginia.
10. Mansour, A. E., Jan, H. Y., Zigelman, C. I., Chen, Y. N., Harding, S. J., 1984. “Implementation of Reliability Methods to Marine Structures,” Trans. Society of Naval Architects and Marine Engineers, Vol. 92, 11-20.
11. Mansour, A.E., Wirsching, P.H., and White, G.J., and Ayyub, B. M., 1995. “Probability-Based Ship Design: Implementation of Design Guidelines,” SSC 392, NTIS, Washington, D.C., 200 pages.
12. Sikora, J. P., Dinsenbacher, A., and Beach, J. A., 1983. “A Method for Estimating Lifetime Loads and Fatigue Lives for Swath and Conventional Monohull Ships,” Naval Engineers Journal, ASNE, 63-85.

8. AUTHORS’ BIOGRAPHY

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Ibrahim A. Assakkaf is an instructor of Civil Engineering at the University of Maryland, College Park, MD. He is the director of reliability research at the Center for Technology and Systems Management (CTSM) at the University of Maryland. He completed both his B.S. degree (1990) and M.S. degree (1993) in civil engineering at the George Washington University in Washington DC., and his Ph.D. degree (1998) from the University of Maryland. Before 1890, Dr. Assakkaf was employed as a general manager for six years by Assakkaf Establishment, a major construction company in Saudi Arabia. This company was awarded a number of both public and private projects in Saudi Arabia. Some of these projects were part of the infrastructure construction projects awarded to the public by the government in the seventies and eighties, and hence costing the government millions of dollars. Because of his position as a vice president and general manager, Dr. Assakkaf gained a unique administrative experience in planning, design, and construction of buildings, waterways, and roads. Dr. Assakkaf's most recent experience was with the CTSM by working on projects funded by the U.S. Navy and other government organizations to develop Load and Resistance Factor Design (LRFD) for ship structures. His involvement in these projects provided him with unique academic and practical experience for reliability-based design of different steel components of ship structures. Dr. Assakkaf is the author and co-author of several papers and reports relating to reliability-based designs and analyses.

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9. Figures and Tables

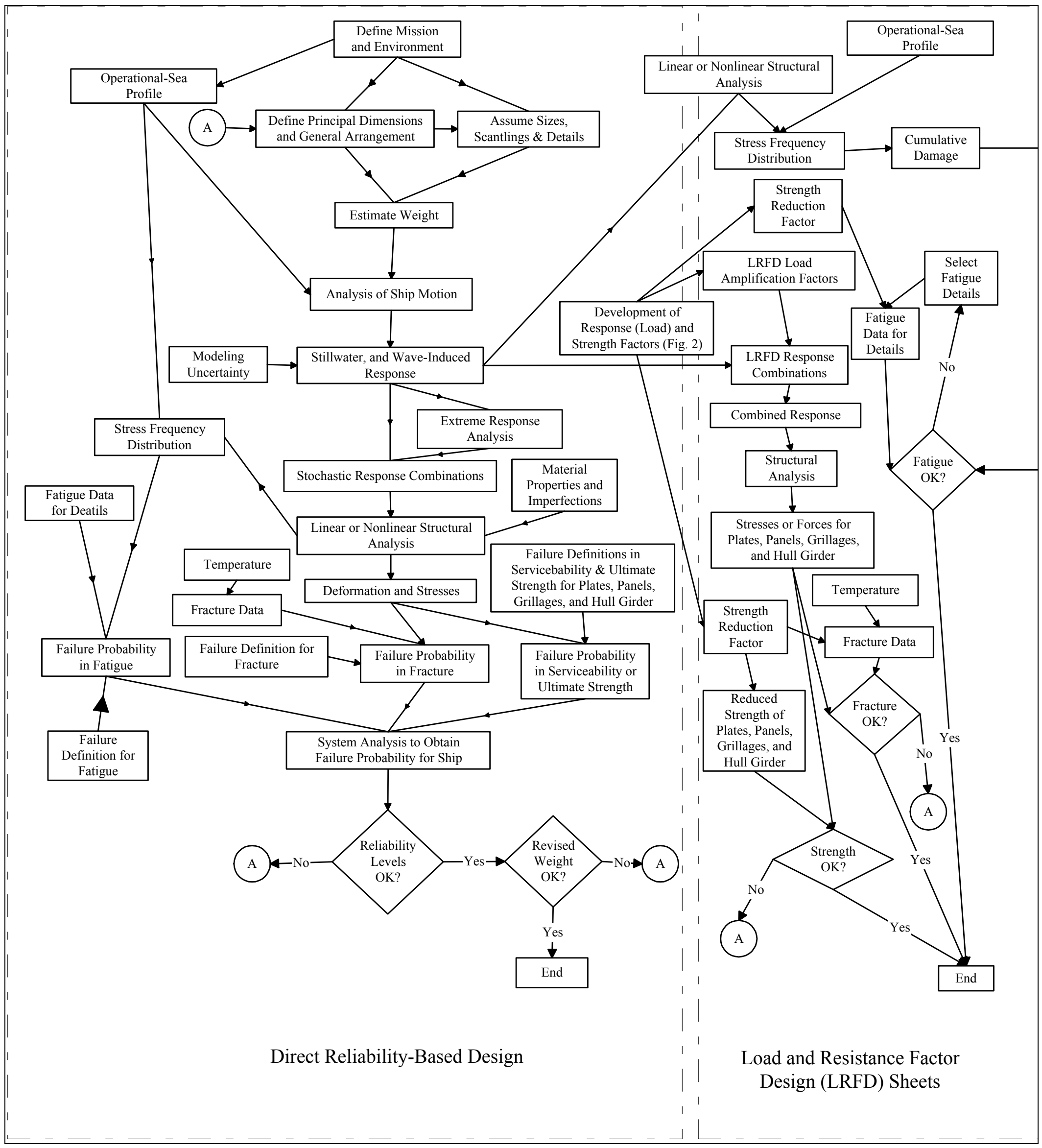


Figure 1. Reliability-based Design of Ship Structures (Ayyub et al 1998)

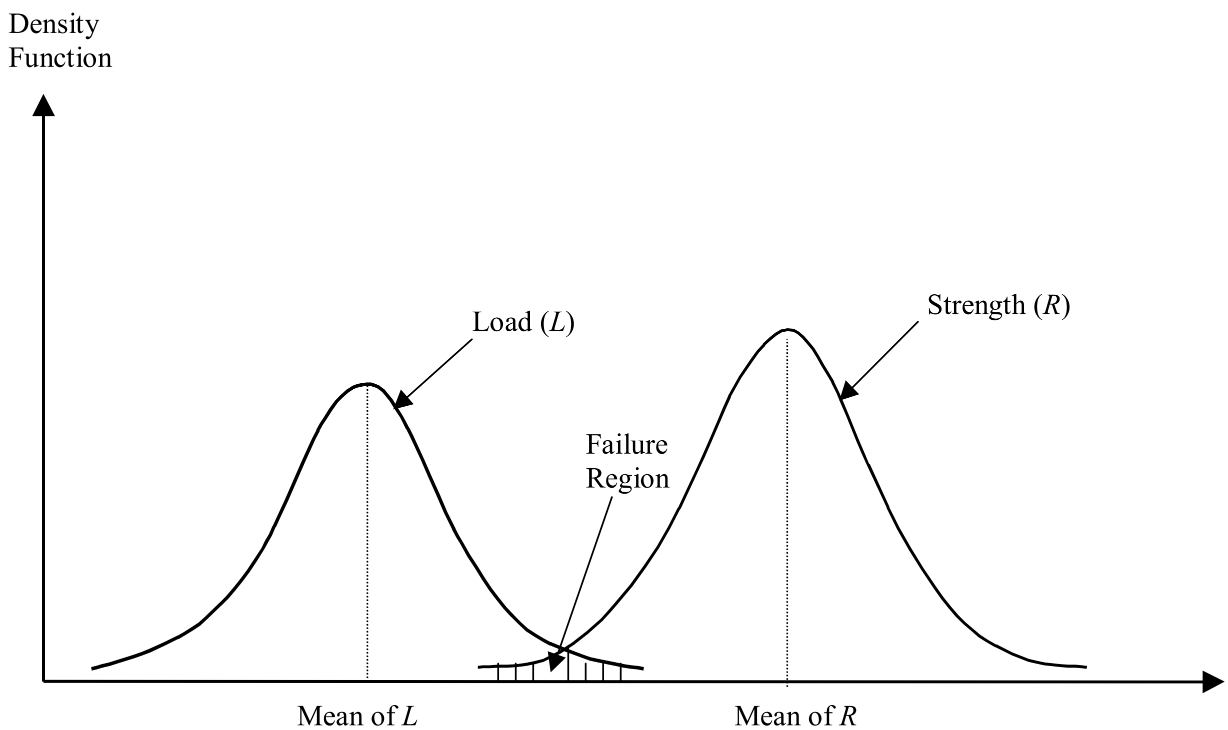


Figure 2. Frequency Distribution of Resistance R and Load L

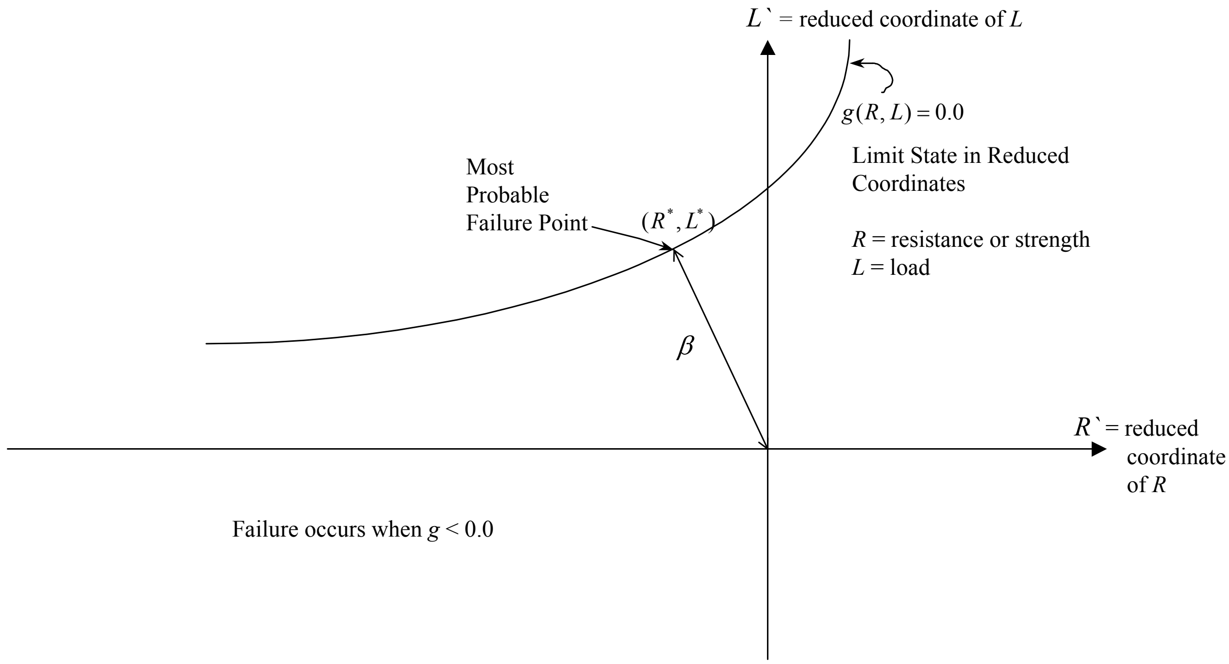


Figure 3. Space of Reduced Random Variables Showing the Reliability Index and the Most Probable Failure Point

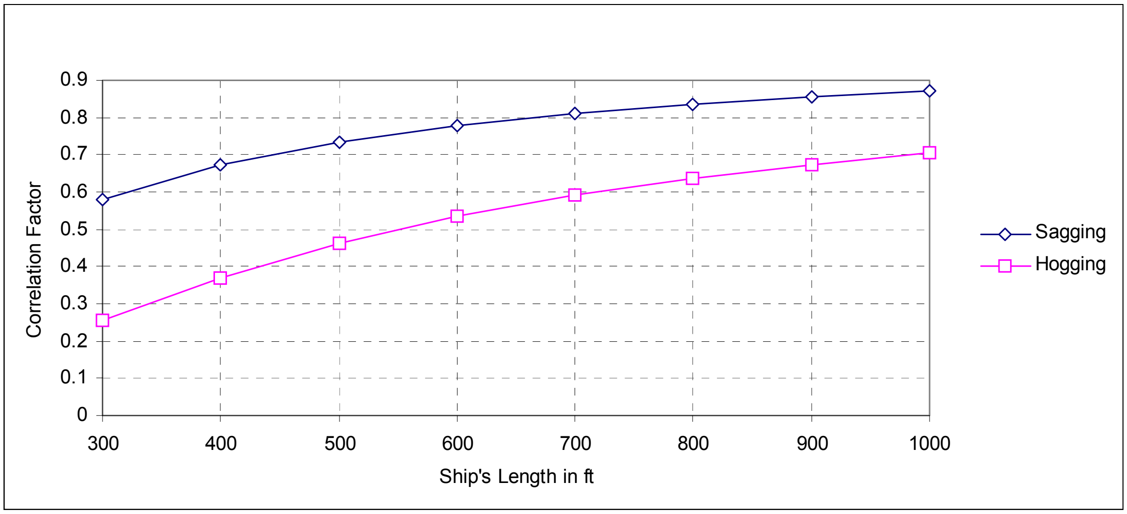
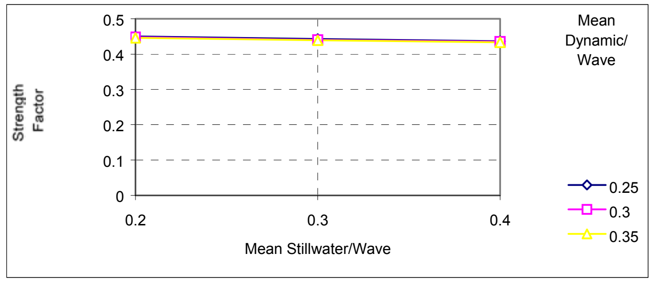


Figure 4. Correlation Coefficient of Whipping Bending Moment (kD) for 300 < LBP < 1000 ft (Mansour 1984, and Atua 1998)

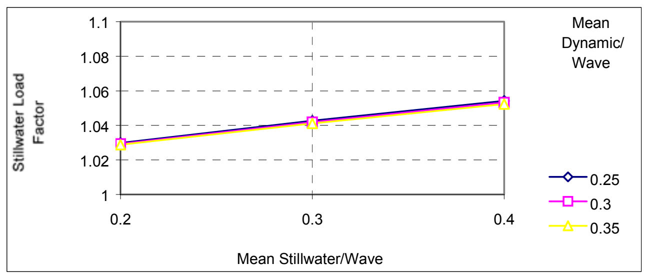
a. Strength Factor, ϕ_M

	M_{SW}/M_W		
M_D/M_W	0.2	0.3	0.4
0.25	0.449845	0.4427769	0.4365088
0.3	0.4479959	0.4403915	0.4353116
0.35	0.445773	0.4389671	0.4331058



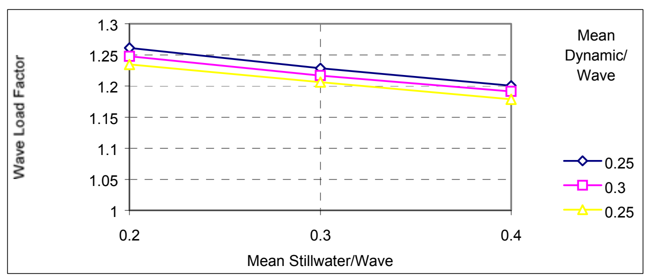
b. Stillwater Load Factor, γ_{SW}

λ_{Msw}	M_{SW}/M_W		
M_D/M_W	0.2	0.3	0.4
0.25	1.02981057	1.0426998	1.054247
0.3	1.029284	1.0419189	1.0532724
0.35	1.02873875	1.0411108	1.052369



c. Wave-induced Load Fcator, γ_W

	M_{SW}/M_W		
M_D/M_W	0.2	0.3	0.4
0.25	1.2612599	1.2282617	1.200301
0.3	1.247623	1.216849	1.1911799
0.35	1.23447644	1.2061922	1.1784201



d. Dynamic Load Factor, γ_D

	M_{SW}/M_W		
M_D/M_W	0.2	0.3	0.4
0.25	1.0328947	1.0289335	1.0250562
0.3	1.0492608	1.0441725	1.039316
0.35	1.0661246	1.0598484	1.054121

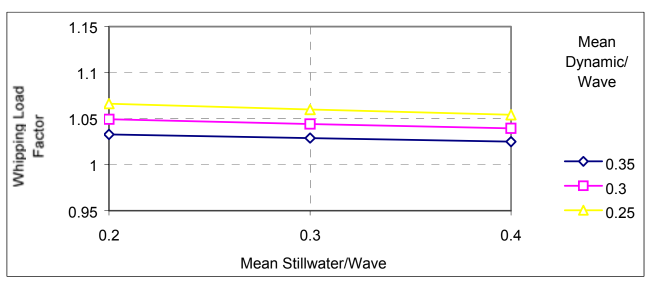


Figure 5. Variation of Strength and Load Partial Safety Factors versus Variation of the Ratios for the Mean Values of Load Components for the Example

Table 1. Correlation Coefficient of Whipping Bending Moment (k_D) for *LBP* between 300 and 1000 ft (Mansour 1994, and Atua 1998)

Length (ft)	300	400	500	600	700	800	900	1000
$k_{D(sag)}$	0.57796	0.67163	0.7338	0.7777	0.8100	0.8348	0.8543	0.870
$k_{D(hog)}$	0.25396	0.36969	0.4613	0.5333	0.5906	0.6367	0.6746	0.706

Table 2a. Recommended Probabilistic Characteristic of Strength Basic Random Variables (Assakkaf 1998, and Atua 1998)

Variable	Nominal Value	Statistical Information		
		Mean	Standard Deviation	Distribution Type
t (in)	t	t	0.02	normal
a (in)	a	a	0.11	normal
b (in)	b	b	0.09	normal
d_w (in)	d_w	d_w	0.12	normal
f_w (in)	f_w	f_w	0.07	normal
t_w (in)	t_w	t_w	0.02	normal
t_f (in)	t_f	t_f	0.02	normal
L (ft)	L	L	0.08	normal
D (ft)	D	D	0.01	normal
B (ft)	B	B	0.01	normal

Table 2b. Recommended Probabilistic Characteristic of Strength Basic Random Variables (Assakkaf 1998, and Atua 1998)

Variable	Nominal Value	Statistical Information		
		Mean	Coefficient of Variation, *COV*	Distribution Type
Ordinary Strength (OS) F_y (ksi)	F_y	1.11 F_y	0.07	lognormal
High Strength (HS) F_y (ksi)	F_y	1.22 F_y	0.09	lognormal
F_u (ksi)	F_u	1.05 F_u	0.05	normal
E (ksi)	E	1.024 E	0.02	normal
ν	0.3	0.3	0	
Z	Z_r	1.04 Z_r	0.05	lognormal
M_y	$F_y Z$	$\overline{F}_y \overline{Z}$	0.15	lognormal
M_p	$F_y Z_p$	$\overline{F}_y \overline{Z}_p$ or $c\overline{F}_y \overline{Z}$	0.18	lognormal

OS = Ordinary Steel, HS = Higher Strength Steel, na = not available

Table 3a. Recommended Ranges for Statistics of Strength Basic Random Variables (Assakkaf 1998, and Atua 1998)

Random Variable		Bias Information: Mean	Bias Information: Standard Deviation
t (in)	Minimum	t	0.00520
	Recommended	t	0.01720
	Maximum	t	0.04170
a (in)	Minimum	a	na
	Recommended	a	0.10600
	Maximum	a	na
b (in)	Minimum	b	na
	Recommended	b	0.09300
	Maximum	b	na
d_w (in)	Minimum	d_w	na
	Recommended	d_w	0.1171
	Maximum	d_w	na
f_w (in)	Minimum	f_w	na
	Recommended	f_w	0.0649
	Maximum	f_w	na
t_w (in)	Minimum	t_w	na
	Recommended	t_w	0.0180
	Maximum	t_w	na

t_f (in)	Minimum	t_f	na
	Recommended	t_f	0.0212
	Maximum	t_f	na
L (ft)	Minimum	L	0.00000
	Recommended	L	0.08333
	Maximum	L	0.16777
D (ft)	Minimum	D	0.00694
	Recommended	D	0.01180
	Maximum	D	0.01390
B (ft)	Minimum	B	0.00200
	Recommended	B	0.01093
	Maximum	B	0.01390

Table 3b. Recommended Ranges for Statistics of Strength Basic Random Variables (Assakkaf 1998, and Atua 1998)

Random Variable		Statistical Information		
		Mean	*COV*	Bias
OS F_y (ksi)	Minimum	33.8	0.03	1.000
	Recommended	37.3	0.07	1.110
	Maximum	44.0	0.12	1.220
HS F_y (ksi)	Minimum	39.6	0.07	1.100
	Recommended	49.6	0.09	1.220
	Maximum	66.0	0.10	1.350
F_u (ksi)	Minimum	59.3	0.02	1.007
	Recommended	61.6	0.05	1.046
	Maximum	64.3	0.09	1.090
E (ksi)	Minimum	28,980	0.01	1.000
	Recommended	29,696	0.02	1.024
	Maximum	30,200	0.06	1.076
Z	Minimum	na	0.04	1.000
	Recommended	na	0.05	1.035
	Maximum	na	0.05	1.040
M_y	Minimum	na	0.10	1.0
	Recommended	$\overline{F}_y \overline{Z}$	0.15	1.0
	Maximum	na	0.15	1.0

M_p	Minimum	na	0.12	1.0
	Recommended	$\bar{F}_y \bar{Z}_p$	0.18	1.0
	Maximum	na	0.18	1.0
c	Recommended	0.6 for OS	na	na
		0.8 for HS	na	na

OS = Ordinary Steel, HS = Higher Strength Steel, na = not available

Table 4. Recommended Probabilistic Characteristics of Load Random Variables (Atua 1998)

Random Variable	Distribution Type	Mean to Nominal Ratio	Coefficient of Variation
Stillwater Bending Moment M_{SW}	Normal	0.4 to 0.6 for commercial ships, and 0.7 for naval vessels	0.3 to 0.9 for commercial ships, and 0.15 for naval vessels
Life-time Extreme Wave-induced Bending Moment M_W	Largest extreme value (type I)	1.0	0.1 to 0.2
Whipping Bending Moment M_D	Extreme value (type I) exponential	Mean value can be determined using formulae based on spectral analysis	0.2 to 0.3
Springing Bending Moment M_{SP}	Extreme value (type I)	1.0	0.3
Hydrostatic pressure due to stillwater, P_{SW}	Normal	0.4 to 0.6 for commercial ships, and 0.7 for naval vessels	0.15
Hydrostatic pressure due	Largest extreme	1.0	0.15

to waves, P_W	value (type I)		
Hydrostatic pressure due to dynamic effects, P_D	Largest extreme value (type I)	1.0	0.25
Hydrostatic pressure due to combined waves and dynamic loads, P_{WD}	Weibull	1.0	0.25

Table 5. Recommendations for Probabilistic Characteristics of Basic Random Variables (Atua 1998))

Random Variable	Mean/Nominal	Coefficient of Variation	Distribution Type	Biases or Error
c	Mean value = 0.74 (hog), 0.36 (sag)	0.22 (hog), 0.19 (sag)	Normal	na
F_y	1.11 (OS) 1.22 (HS)	0.07 (OS), 0.09 (HS)	Lognormal	1.11(OS) 1.22(HS)
Z	1.04	0.05	Lognormal	1.04
M_u	1.1	0.15	Normal	1.1
M_{SW}	0.7 to 1.0	0.15	Normal	0.7 to 1.0
M_W	1.0	0.1 to 0.2	Type I (EVD) - largest	1.0
M_D	1.11	0.2 to 0.3	Type I (EVD) - largest	1.0
M_{WD}	0.971	0.222 to 0.287	Weibull - smallest	0.971

na = not available, EVD = extreme value distribution

Table 6. Recommendations for Combination Factors for Load Components (Atua 1998)

Factor	Deterministic Value	References and Comments
k_W	1.0	Sikora (1983) and Mansour et al (1995)
k_D	$EXP\left[\dfrac{53080}{\left(158LBP^{-0.2}+14.2LBP^{0.3}\right)LBP}\right]$ (Hogging) $EXP\left[\dfrac{21200}{\left(158LBP^{-0.2}+14.2LBP^{0.3}\right)LBP}\right]$ (Sagging)	Sikora (1983) Ranging from 0.35 to 0.65 for *LBP* = (400 to 800) ft Ranging from 0.65 to 0.85 for *LBP* = (400 to 800) ft
k_{WD}	1.0	Assumed value as defined by Sikora (1983)

Table 7. Recommendations for Ratios of Different Load Components (Atua 1998)

Ratio	Recommended Value	Reference
$\overline{M}_{SW} / \overline{M}_{W}$	0.25 to 0.35	Mansour et al (1995)
$\overline{M}_{D} / \overline{M}_{W}$	0.25 to 0.35	Mansour et al (1995)
$\overline{M}_{WD} / \overline{M}_{W}$	1.0 to 1.35	Assumed values

Table 8. Recommendations for Ranges of Target Reliability Index (Atua 1998)

Range	Reference
4.0 to 6.0 (Sagging)	Mansour et al (1995)
5.0 to 6.0 (Hogging)	Mansour et al (1995)

Table 9. Probabilistic Characteristics of Strength and Load Variables for the Example (Atua 1998)

Random Variable	Mean/Nominal	Coefficient of Variation (recommended value)	Distribution Type	Biases
M_u	1.1	0.15 (0.15)	Normal	1.1
M_{SW}	1.0	0.15 (0.15)	Normal	1.0
M_W	1.0	0.1 to 0.2 (0.15)	Type I Largest	1.0
M_D	0.83 to 1.11	0.2 to 0.3 (0.25)	Type I Largest	1.0