Reliability-Based Load and Resistance Factor Design (LRFD) Guidelines for Hull Girder Bending

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ABSTRACT

Future guidelines for ship hull girders design will be developed using reliability methods, and can be expressed in a special format such as the Load and Resistance Factor Design (LRFD) format. The main objective of this paper is to summarize the development methodology and results of reliability-based guidelines (i.e., LRFD guidelines) for ship structures that were performed for the U. S. Navy and other government agencies. The methodology for developing LRFD format for ship hull girder bending used in this paper consists of the following steps: (1) probabilistic characteristics of basic strength and load random variables that are used in structural design were analyzed. Values for these characteristics were recommended for reliability-based design purposes. They were determined based on the statistical analysis of data collected of these design parameters, on values recommended in other studies, or sometimes based on personal judgment. (2) Different load combinations were established and presented with combination and correlation factors, these combinations included the stillwater bending, wave-induced, and wave dynamic bending moments. The correlation between 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 structural modes of failures. (4) A

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comparison among different design practices were conducted based on the determination of the nominal values of strength and load values for ship structures to recommend the format required for each design variable. Methods for determining the design (nominal) values of both strength and load variables were presented as detailed calculation procedures. (5) Target reliability levels as used in other studies were summarized and ranges of target reliability levels were selected for the limit states. (6) Partial safety factors for the ranges of target reliability levels were calculated based on level 2 reliability methods.

The paper also includes a detailed description of the methodology and sample guidelines for ship hull girder design with demonstrative examples of their use.

1. INTRODUCTION

Hull girders are very important components in ship and offshore structures, and therefore they should be designed for a set of failure modes that govern their strength. They form the backbone of most ship's structure, and they are by far the most vital structural elements in commercial and naval ships. Failure of hull girders can lead to catastrophic collapse of the whole ship, resulting in gross human and monetary losses. Hull girders of Naval ships, in particular, need careful design procedures to provide the in-depth overall protection required by the navy or the military. These ships operate in both combat and peaceful environments, and therefore, are prone to enemy's missile attacks. A Peaceful environment does not necessarily preclude a naval ship from being attacked. Example of this situation is the USS Stark (Figure 1) incident of 1987. During the Iran-Iraq war, the Stark was on routine patrol mission in the Persian Gulf to protect neutral shipping when she was hit by an Exocet Iraqi missile. Although, this incident had been caused by complementary errors of interpretation, the missile killed 37 servicemen and caused severe hull structural damage, which led to a complete malfunctioning of the ship's defensive weapons systems. Another missile impacted the Stark shortly thereafter causing a large fire (Figure 2) in the aluminum superstructure that was not put out for some time.

Ship structural integrity is an essential element for survivability as was recently experienced with the USS Cole (Figure 3) in the Arabian Sea at the port of Aden, Yemen. Seventeen sailors aboard the USS Cole were killed as a result of an explosion on October 12, 2000, which left a 40-foot by 40-foot hole in the port side of the destroyer (U.S. Navy website, http://www.chinfo.navy.mil/navpalib/news/news_stories/cole-shippix.html). If the above two examples are indicative of anything, they highlights the importance of rigorous design of delicate and expensive key structural elements such as the hull. Reliability methods are very well suited for the design of these important structures.

Reliability of a structural system can be defined as its ability to fulfill its design functions for a specified time period. This ability is commonly measured using probabilities. Reliability is therefore, the occurrence probability of the complementary event to failure. Based on this definition, reliability is one of the components of risk. Safety can be defined as the judgment of risk acceptability for the system making it a component of risk management.

The performance of ship hull girder and its components is defined by a set of requirements stated in terms of tests and measurements of how well the system or element serves various or intended functions over its service life. Risk and reliability measures can be considered as performance measures that can be specified in the form of 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 and the risk associated with it.

Future design guidelines 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 guidelines for ship structures based on structural reliability theory can be built on previous and currently used specifications for ships, buildings, bridges, and offshore structures. In recent years, ship structural design has been moving toward the LRFD approach. This approach is more rational than the deterministic design methods. 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 reliability-based design guidelines 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. A more elaborate and detailed discussion of FORM methods and its uses in ship structural reliability can be found in Ayyub, et al. (2002).

2. HULL GIRDER STRUCTURAL COMPONENTS

One of the fundamental concepts of engineering is that of a system, which can be anything from a simple beam or detail to complicated multilevel subsystems. A ship obviously falls into the category of a relatively large and complex system. The ship consists of several subsystems, which are essential to the integrity of the whole system. Examples of these subsystems are the hull girders, unstiffened and stiffened panels, and structural details. Probably the most essential part of a ship design is the hull girder system or model. Environmental loads, either static or dynamic, that are due to sea environment and ship's motion are functions of the hull shape. However, much of these loads are relatively independent of the substructures (subsystems) such as unstiffened and stiffened plate elements, that is, they are not affected by the structural layout and shape or by scantlings. Therefore, the design of the hull girder is the first step toward designing the other substructures of a ship because much of the overall load effects on the hull girder can be used for designing these substructures or subsystems.

In a large structure, such as a hull girder, both the loading and the response are extremely complex, and therefore, the response analysis must be performed in two stages (Hughes 1988): (a) an analysis of the overall structure and (b) a separate and more detail analyses of different substructures. Many of the load effects from the overall analysis constitute the loads and boundary conditions at the substructure level. The overall structure of a ship is essentially a floating beam (box girder) that internally stiffened and subdivided, and in which the decks and bottom structure are flanges and the side shell and any longitudinal bulkheads are the web. External forces and moments on a hull girder are those forces or moments that are applied on a beam such as vertical shear force (f_y), longitudinal bending moment in the ship's vertical and horizontal planes (M_y and M_z), and longitudinal twisting moment M_x. The most significant of all these forces and moments is the vertical bending moment of the hull girder about the *z*-axis as shown in Figure 4. This load affect is due primarily to the unequal distribution of the weight (W) of the ship and buoyancy (B_F) along the length of the ship due to waves as shown in Figure 5. For many ships, the maximum value of the horizontal moment M_y is much smaller than the vertical moment M_z, typically 20% or less (Hughes 1988).

The vertical bending moment varies along the length of the ship. It can take values from zero at the ends to a maximum at or near the mid-length of the ship. This maximum value of the vertical moment for hull girder is the single most important load effect in the analysis and design of ship structures. Hull girder bending can be caused by either hogging or sagging depending on the curvature due to waves as shown in Figures 5a and b, respectively. The hull girder analysis and design assumes that the hull girder satisfies simple beam theory that implies the following assumptions (Hughes 1988):

1. Plane cross sections remain plane.
2. The beam is essentially prismatic
3. Other modes of response to the loads do not affect hull girder bending and may treated separately.
4. The material is homogeneous and elastic.

The structural components that make up the hull girder are the panels or plate elements. Ship panels, in general, are divided into three distinct categories: (1) unstiffened, (2) stiffened, and (3) grillages (see Figures 6 and 7). These panels (or called plate elements) are very important components in ship and offshore structures, and therefore they should be designed for a set of failure modes that govern their strength. They form the backbone of most ship's structure, and they are by far the most commonly used element in a ship. They can be found in bottom structures, decks, side shell, and superstructures. The modes of failure, which govern the strength of these panels, can be classified to produce two distinct strength and serviceability limit states. Strength limit states are based on safety consideration or ultimate load-carrying capacity of a panel and they include plastic strengths, buckling, and permanent deformation. Serviceability limit states on the other hand refer to the performance of a panel under normal service loads and are concerned with the uses of hull girder and its structural components such as the unstiffened and stiffened panels. They include such terms as excessive deflections and first yield. Also, strength limit states require the definition of the lifetime extreme loads and their combinations; whereas serviceability limit states require annual-extreme loads and their combinations.

The primary purpose of a panel is to absorb out of plane (or lateral) loads and distribute those loads to the ship's primary structure. It also serves to carry part of the longitudinal bending stress because of the orientation of the stiffeners. The amount of in-plane compression or tension experienced depends primarily on the location of the panel within the ship. Deck panels tend to experience large in-plane compression and small lateral pressures, while bottom panels can be exposed to large in-plane tension and compression with a significant amount of lateral pressures.

The main type of framing system found in ships nowadays is a longitudinal one, which has stiffeners running in two orthogonal directions (Figure 6). Deck and bottom structures panels are reinforced mainly in the longitudinal direction with widely spaced heavier transverse stiffeners. The main purpose of the transverse stiffeners is to provide resistance to the loads induced on the bottom and side shell by water pressure (Soares and Soreide 1981). The types of stiffeners used in the longitudinal direction are the T-beams, angles, bulbs, and flat bars, while the transverse stiffeners are typically T-beam sections. This type of structural configuration is commonly called gross stiffened panel or grillage (Vroman 1995). Besides their use in ship structures, these gross stiffened panels are also widely used in land-based structures such as box and plate girders.

The overall collapse of a grillage involves global deflection of both longitudinal and transverse stiffeners. However, except for lightly stiffened panels found in superstructures, this type of failure rarely occurs because most ship structures are designed to prevent the overall mode of collapse (Soares and Soreide 1981). In most cases local plate buckling is the weakest failure mode. Global failure of a stiffened panel can be partially controlled by careful design of strength of the plate elements (unstiffened panels, Figure 7) between stiffeners. The most common mode of failure of the whole panel involves the collapse of the longitudinally stiffened sub-panel. Choosing the size of the transverse stiffeners so that they provide sufficient flexural rigidity to enforce nodes at the location of the transverse stiffeners can prevent the collapse of longitudinally stiffened sub-panel. If the transverse stiffeners act as nodes, then the collapse of the stiffened panel is controlled by the strength of the longitudinally stiffened sub-panel.

A typical longitudinal stiffened sub-panel, as shown in Figure 6, is bounded on each end by a transverse structure, which has significantly greater stiffness in the plane of the lateral load. The sides of the panel are defined by the presence of a large structural member that has greater stiffness in bending and much greater stiffness in axial loading. Structural members such as keels, bottom girders, longitudinal bulkheads, deck girders, etc., can act as the side boundaries of the panel. When the panel is located to be in a position to experience large in-plane compression, the boundary conditions for the ends are taken as simply supported. The boundary conditions along the sides can also be considered simply supported.

In ship structures, there are three primary types of load effects that can influence the strength of a plate-stiffener panel; negative bending moment, positive bending moment, and in-plane compression or tension. Negative bending loads are the lateral loads due to lateral pressure. They cause the plate to be in tension and the stiffener flange in compression. Positive bending loads are those loads that put the plating in compression and the stiffener flange in tension. The third type of loading is the uniform in-plane compression. This type of loading arises from the hull girder bending, and will be considered positive when the panel is in compression. The three types of loading can act individually or in combination with one another.

To evaluate the strength of a hull girder and its components it is necessary to review various strength prediction models and to study their applicability and limitations for different loading conditions acting on the element. Although hull girder strength has been studied for many years, several advanced strength models have been developed during the last few decades. These advanced models take into account the effects of initial distortion, weld induced residual stresses, and various parameters concerning strength prediction. Some of these models are empirical in nature but they are highly representative of real world scenario because they were developed on the bases of experimental data. An exact hull girder-strength prediction can only be achieved by a method of analysis, either numerical or experimental, in which all the characteristics of the panel and the loading variables are presented and are properly accounted for in the method.

3. DESIGN STRENGTH FOR HULL GIRDER

In this section, design (or called nominal) models for both the longitudinal strength of hull girders and bending are provided based on a literature review. The design values generated from these models can be viewed as the nominal values required by the LRFD guidelines for the preliminary design stages to satisfy the desired target reliability levels. 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.

In evaluating the design strength of ship hull girder it is necessary to review various strength predicting models and to study their applicability and limitations for different loading conditions. Although hull girders strength has been studied for many years, several advanced strength models have been developed during the last few decades. These advanced models take into account the effects of initial distortions; weld induced residual stresses, and various variables concerning strength prediction. Some of these models are empirical in nature but they are highly representative of real world scenario because they were developed on the bases of experimental data. An exact strength prediction can only be achieved by method of analysis, either numerical or experimental, in which all the characteristics of the hull girder and the loading variables are presented and are properly accounted for.

In this section, strength limit states for failure modes of ship hull girders are presented. For each limit state, commonly used strength models were collected from many sources to evaluate their limitations and applicability and to study their biases and uncertainties. Wherever possible, the different types of biases resulting from these models were computed. In doing so, these prediction models were classified as follows (Ayyub and Atua 1996): (1) prediction models that can be used by the LRFD guidelines, (2) advanced prediction models that can be used for various analytical purposes, (3) some experimental results from model testing, and (4) some real measurements based on field data during the service life of a ship. The bias and uncertainty analyses for these strength models are needed for the development of LRFD guidelines for hull girders of ship structures. The uncertainty and biases of these models were assessed and evaluated by comparing their predictions with more accurate ones or real values. In developing the bias factors, Monte Carlo simulation was used to assess the probabilistic characteristics of the strength models by generating basic random variables for a model and substituting the generated values in the model. Then, the results were statistically analyzed.

Two methods are provided for determining the design value of the hull: (a) elastic-based strength, and (b) 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 Hull Girder Design Strength Models

This section presents the development in strength design prediction models for ship hull girder bending. The strength models that are deemed suitable for LRFD development for ship hulls are collected from different sources and summarized. Recommendations for the use of the models and their biases in LRFD development are provided. The first-order reliability method (FORM) can be used to demonstrate the development of partial safety factors (PSF) for the limit states based on the recommended strength models given in this section. The strength capacity of hull girder is divided into three broad categories: vertical horizontal, and combined vertical and horizontal hull girder bending strength.

3.1.1 Vertical Hull Girder Bending Strength Capacity

3.1.1.1 *Adamchak (1979)*

The ultimate strength of a hull girder subjected to vertical bending can be computed using an incremental strain approach as suggested by Adamchak (1979) in his computer program on the ULTimate STRength (ULTSTR) of hull girders. The program calculates the moment-curvature relationship and the ultimate bending capacity of the ship's hull girder cross section using information about scantlings of all structural members contributing to the longitudinal strength of the hull girder, material properties, and an incremental strain with strain-compatibility constraints and statics. The ultimate bending strength value depends mainly on the section modulus and the yield strength of the different types of steel used in the mid-ship section and the percentage of each type (Atua 1998). Detailed description of ULTSTR program can be found in Adamchak (1979).

3.1.1.2 *Caldwell (1965)*

According to Krishnankutty (2000), the fully plastic collapse moment of hull girder strength was first proposed in 1965 by Caldwell. This approach assumes that the ultimate collapse condition is reached when the entire cross section of the hull including sides has reached the yield state, and the material is elastically-perfectly plastic and loads increase proportionally up to the collapse loads. Also, the possibility of bucking of compressive parts of the structure before the limit condition is reached in this particular case, and the effects of axial and shear forces are neglected. With the above simplifications, the fully plastic collapse moment, M_P, can be expressed as follows:

$$M_P = F_y SM_P \qquad (2)$$

where M_P = fully plastic moment, Fy = yield strength of the material, and

$$SM_P = A_d g + 2A_S\left(\frac{D}{2} - g + \frac{g^2}{D}\right) + A_B(D - g) \tag{3}$$

where A_d = cross section area of the deck including stiffeners, A_B = area of the bottom including stiffeners, As = area of one hull side including stiffeners, D = depth of the midship section, and g = distance from the center of the deck area to the plastic neutral axis. The distance g is given by the following equation:

$$g = \frac{D}{4A_s}\left(A_B + 2A_S - A_d\right) \tag{4}$$

3.1.1.3 *Kaplan et al. (1984)*

Kaplan et al. (1984) analyzed ship hull girder strength for two modes of failure: (1) failure resulting from yielding of hull girder (by entire deck or bottom-shell yield) due to bending, and (2) failure resulting from full plastic collapse of the entire hull cross section (including the sides). The ultimate bending capacity M_u according to Kaplan et al. (1984) is given by

$$M_u = F_y Z_p \tag{5}$$

where Z_p = plastic section modulus of hull girder and it is given as

$$Z_p = A_D Y_D + 2A_S\left(\frac{D}{2} - Y_D + \frac{Y_D^2}{D}\right) + A_B\left(D - Y_D\right) \tag{6}$$

and in which A_D = cross section area of the deck (including stiffeners), A_B = total effective area of the bottom (including stiffeners), A_S = effective area of one side (including stiffeners), D = depth of midship section (usually equals to ship's depth), and Y_D = distance from deck area to the plastic neutral axis, which is given by Kaplan et al. (1984) as

$$Y_D = D\left(\frac{A_B + 2A_S - A_D}{4A_S}\right) \tag{7}$$

3.1.1.4 *Paik et al. (1996)*

Paik et al. (1996) derived an analytical formula for predicting the ultimate vertical moment capacity of ships with multi-decks and multi-longitudinal bulkheads/side shell. This methodology is based on the assumption of a distribution of longitudinal stresses in the hull cross section. In the compressed parts of the section, the hull girder flange and a part of the side shell are at their ultimate strength compressive limit. In the flange parts of the section subjected to tension, full tensile yield develops, but the sides remain in the elastic state. The stress distribution in the vicinity of the neutral axis is linear.

The neutral axis of the hull section at the collapse is calculated based on two boundary conditions: (1) no net axial force acts on the hull girder, and (2) the stress distribution in the vicinity of the neutral axis is linear elastic. The ultimate moment capacity is then obtained by integrating the first moment of the longitudinal stresses with regard to the neutral axis. The expressions for this model for both sagging and hogging conditions can be found in Paik et al. (1996) and they are not reproduced in this paper due to space limitation. This model assumes longitudinal stress distribution over the hull cross section at the overall collapse state. This model assumes longitudinal stress distribution over the hull cross section at the overall collapse state as shown in Figure 8.

The hull cross section is divided in a series of horizontal and vertical members. The number of horizontal and vertical members is (m+1) and (n+1), respectively, as shown in Figure 8a. The coordinate y_i indicates the position of horizontal members (such as bottom and decks) above the base line, and z_j shows the position of vertical members (such as side shells and longitudinal bulkheads) from a reference (left/port) outer side shell. The sectional area of horizontal members at $y = y_I$ is denoted by A_{yi}, while the sectional area of vertical members at $z = z_j$ is denoted by A_{zj}. Again, detailed illustrations of these variables can be found in Paik et al. (1996).

3.1.1.5 *Mansour et al. (1995)*

The section modulus Z amid ship is to be determined according to best engineering judgment and practices. The elastic-based bending strength of a hull girder can be then computed as (Mansour et al. 1995)

$$M_u = c_b F_y Z \tag{8}$$

where c_b = 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, F_y = yield strength of materials, M_u =

ultimate bending capacity of the hull girder, and *Z* = section modulus. The buckling knockdown factor is defined as

$$c_b = \frac{M_u}{F_y Z} \tag{9}$$

The buckling knockdown factor is equal to the ultimate collapse bending moment of the hull, taking buckling into consideration, divided by the initial yield moment. The ultimate collapse moment can be calculated using nonlinear finite element program, or equivalently using computer software based on Idealized Structural Unit Method (ISUM). Approximate nonlinear strength analysis may also be used (Mansour et al. 1995). The initial yield moment is simply equal to the yield strength of the material multiplied by the section modulus of the hull at the compression flange (i.e., at deck in sagging condition, or at bottom in hogging condition). The default values for the buckling knockdown factor c_b may be taken as 0.80 for mild steel and 0.60 for high-strength steel (Manour et al. 1995).

3.1.1.6 *Mansour and Thayamballi (1993)*

Mansour and Thayamballi (1993) developed an expression for the ultimate bending moment of the hull girder similar to the expression given in Eq. 8. In this model, the authors included modeling uncertainty factor to account for variability and bias from assumptions and deficiencies in analytical and design procedures. The ultimate bending strength as described by Mansour and Thayamballi (1993) is given by

$$M_u = X_U Z F_{cr} \tag{10}$$

where *Z* = section modulus of hull girder amid ship, F_{cr} = critical strength (stress) in buckling, and X_U = a model uncertainty in strength with mean value of 1.0, *COV* of 0.15, and normal probability distribution.

3.1.1.7 *Paik and Thayamballi (1997)*

Based on previously collected and newly developed test data, Paik and Thayamballi (1997) developed an empirical expression for predicting the ultimate compressive strength of stiffened panels, expressed in terms of the plate slenderness ratio and the column (stiffener) slenderness ratio. The formula implicitly includes the influence of initial imperfections at moderately large level, and it is a revised version of Lin's (1985) formula.

Based on Paik and Thayamballi (1997) model for predicting the ultimate compressive strength of stiffened panels, the ultimate vertical moment capacity of the hull girder can be estimated from the following equation:

$$M_u = \frac{\overline{F_y} Z}{\sqrt{0.995 + 0.936\lambda^2 + 0.170\beta^2 + 0.188\lambda^2\beta^2 - 0.067\lambda^4}} \tag{11}$$

where Z is the hull section modulus to be determined according to best engineering judgment and practices, and $\overline{F_y}$ is the mean yield strength of stiffened panel, and

$$B = \frac{b}{t}\sqrt{\frac{\overline{F_y}}{E}} \tag{12}$$

$$\lambda = \frac{a}{\pi r}\sqrt{\frac{\overline{F_y}}{E}} \tag{13}$$

in which, a = length of longitudinal stiffener between transverse support frames, b = breadth between longitudinal stiffener (stiffener spacing), t = plate thickness, E = modulus of elasticity or Young's modulus of the material, and

$$r = \sqrt{\frac{I}{A}} \tag{14}$$

where I = moment of inertia of plating with full plating and A = area of stiffener with full plating. The area of stiffener with full plating is given by

$$A = bt + d_w t_w + f_w t_f \tag{15}$$

The moment of inertia (I) of one stiffener with fully effective plating is given by

$$I = \frac{bt^3}{12} + bt\left(z_0 - \frac{t}{2}\right)^2 + \frac{d_w^3 t_w}{12} + d_w t_w\left(z_0 - t - \frac{d_w}{2}\right)^2 + \frac{f_w t_f^3}{12} + f_w t_f\left(z_0 - t - d_w - \frac{t_f}{2}\right)^2 \tag{16}$$

where z_0 = distance of neutral axis from the base line of plate, t = thickness of plate, t_w = thickness of stiffener web, t_f = thickness of stiffener flange, d_w = stiffener web height, b = spacing between stiffener, and f_w = stiffener flange width. The distance of the neutral axis from the base line of plate can be computed using the following expression:

$$z_0 = \frac{\frac{bt^2}{2} + d_w t_w\left(t + \frac{d_w}{2}\right) + f_w t_f\left(t + d_w + \frac{t_f}{2}\right)}{A} \tag{17}$$

3.1.2 Horizontal Bending Strength

The same procedure as defined in the previous sections for vertical bending is to be followed in determining the horizontal bending strength capacity of the hull girder; however, it is to be noted that when using ULTSTR in this case, the incremental strain, buckling, curvature, and the bending moment are to be applied in the horizontal plan, i.e., about the ship's vertical center line.

3.1.2.1 Paik et al. (1996)

In the same manner as described for the pure vertical bending moment, Paik et al. (1996) defined a stress distribution over the hull cross section with horizontal bending moment to be assumed. Since the hull is symmetric with regard to the centerline, the magnitude of ultimate horizontal bending moment is the same in the positive and negative direction of the loading. Detailed mathematical expression for this model can be found in Paik et al. (1996).

3.1.3 Combined Vertical and Horizontal Bending Strength

3.1.3.1 Kaplan et al. (1984)

A formula for the mean value of combined lifetime extreme vertical and horizontal wave-induced bending moments was suggested by Kaplan et al. in 1984 and it is given by

$$\overline{M}_W = \sqrt{\overline{M}_v^2 + \left(\frac{Z_v}{Z_h}\right)^2 \overline{M}_h^2 + 2\rho_{vh}\left(\frac{Z_v}{Z_h}\right)\overline{M}_v \overline{M}_h} \tag{18}$$

where $\overline{M}_h$ = mean value of life-time extreme horizontal wave-induced bending moment, $\overline{M}_v$ = mean value of life-time extreme vertical wave-induced bending moment, ρ_{vh} = the correlation coefficient between vertical and horizontal wave-induced bending moments, Z_v = vertical section modulus of the hull girder, and Z_h = horizontal section modulus of hull girder.

3.1.3.2 Soares and Gordo (1997)

Soares and Gordo (1997) presented a methodology for the evaluation of the collapse of hull structures under combined bending moments. The method is based on the assessment of a moment-curvature relationship obtained by imposing a sequence of increasing curvatures to the hull girder, similarly to the ultimate vertical bending strength assessment executed with the program ULTSTR. The authors considered the most general case in which the ship is subject to curvature in the horizontal and vertical planes. The overall curvature is decomposed in curvatures in the vertical and horizontal planes. The strain in each area of the hull midship section is related to both curvatures and to the position of centroid of the area referred to the point of intersection of the neutral axis at each curvature and the centerline. Entering with these values in the load-strain curves defined for the elements, the load sustained by each element may be calculated. The bending moment sustained by the cross section, in vertical and horizontal direction, is obtained from the summation of the moments of the forces in the individual elements.

Soares and Gordo (1997) applied this methodology to evaluate the ultimate collapse of the midship section of tankers and container ship under combined vertical and horizontal bending moments. The results were used to define an interaction formula proposed to account for the combination of the load effects for design purpose. The general governing equation for the hull ultimate strength under bending is given by:

$$\left(\frac{M_V}{M_{Vu}}\right)^{\alpha} + \left(\frac{M_H}{M_{Hu}}\right)^{\alpha} = \delta \qquad (19)$$

where $\delta = 1$, M_V = the vertical bending moment due to combination of environmental loads effect, M_H = the horizontal bending moment due to combinations of environmental loads effect, M_{Vu} = the ultimate vertical bending moment, that can be taken as sagging or hogging depending upon which is the combination under analysis, M_{Hu} = the ultimate horizontal bending moment, and α = parameter of the equation.

According to those authors, the proposed interaction formula should have an exponent of 1.5 for tankers in both sagging and hogging. The exponent of the interaction formula for containerships is different for sagging and hogging. The authors proposed values of 1.2 and 1.5 for these two cases, respectively.

Theoretically, the parameter δ in the right-hand side of Eq. 19 is equal to unity. However, because of the various uncertainties with regard to modeling errors, its value will different than one. Therefore, this parameter should be treated as a random variable when performing reliability analysis using Eq. 19. DeSouza and Assakkaf (2000) conducted a statistical analyses based on Paik et al. (1996) data to quantify the modeling errors associated with the parameter δ. Based on their analyses, the uncertainty was found to have a mean of 0.925, standard deviation of 0.099, and *COV* of 0.11 for the modeling errors associated with the parameter δ.

3.1.3.3 Paik et al. (1996)

Paik et al. (1996) proposed a similar equation for the ultimate strength interaction relationship, but considering two different exponents for the vertical and horizontal bending moment. According to these authors, Eq. 19 is rewritten as

$$\left(\frac{M_V}{M_{Vu}}\right)^{\alpha_1} + \left(\frac{M_H}{M_{Hu}}\right)^{\alpha_2} = \delta \tag{20}$$

The authors established this relation based on nonlinear finite element calculations for eleven vessels: five tankers, two bulk carriers, two container vessels and two cruisers. The coefficients α_1 and α_2 were defined based on the analysis of these eleven ships, and not based on ship type as proposed by Soares and Gordo (1997). According to Paik et al. (1996) the coefficient α_1 is equal to 1.85 and the coefficient α_2 is equal to 1.0.

Theoretically, the parameter δ in the right-hand side of Eq. 20 is equal to unity. However, because of the various uncertainties with regard to modeling errors, its value will different than one. Therefore, this parameter should be treated as a random variable when performing reliability analysis using Eq. 20. Again, DeSouza and Assakkaf (2000) conducted a statistical analysis based on Paik et al. (1996) data to quantify the modeling errors associated with the parameter δ. Based on their analysis, the uncertainty was found to have a mean of 0.973, standard deviation of 0.097, and *COV* of 0.1 for the modeling errors associated with the parameter δ. The distribution type can be taken as normal.

4. 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). Wave 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) and Sikora (1989).

4.1 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.

4.1.1 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.

4.1.2 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).

4.1.3 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 in Sikora et al. (1983).
2. The average peak-to-peak whipping bending moments (in ft-ton) for fine bow ships is described by in Sikors (1989) as

$$M_{WH} = 0.0022\, LBP^2\, B \quad \text{for} \quad LBP^2\, B < 5\text{x}10^6 \tag{21}$$

and

$$M_{WH} = 5.4\, LBP\sqrt{B} \quad \text{for} \quad LBP^2\, B \geq 5\text{x}10^6 \tag{22}$$

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 (Sikora 1983)

$$M_{WH} = 0.0022\, LBP^2\, B \tag{23}$$

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

$$M_{WH_e} = 4.6M_{WH} \quad (24)$$

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

4.1.4 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).

4.2 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 et al. 1984).

4.2.1 Stillwater and Vertical Wave-induced Bending Moments

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

$$M_u = M_{SW} + k_{WD}M_{WD} \quad (25)$$

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 et al. 1984).

4.2.2 Stillwater, Vertical Wave-induced, and Dynamic Bending Moments

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

$$M_u = M_{SW} + k_W(M_W + k_D M_D) \quad (26)$$

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 et al. 1984):

a. Hogging condition:

$$k_D = Exp\left[\frac{53080}{\left(158LBP^{-0.2} + 14.2LBP^{0.3}\right)LBP}\right] \quad LBP \text{ in Feet} \qquad (27)$$

b. Sagging condition:

$$k_D = Exp\left[\frac{21200}{\left(158LBP^{-0.2} + 14.2LBP^{0.3}\right)LBP}\right] \quad LBP \text{ in Feet} \qquad (28)$$

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 9.

5. LRFD GUIDELINES FOR HULL GIRDER 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 designed 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.

5.1 Target Reliability Levels

Selecting a target reliability level is required in order to establish reliability-based design guidelines 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 a 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.

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).

5.2 Limit States for Hull Girder Bending

The hull girder of a ship for all stations should meet one of the following conditions of limit states, Limit State I and Limit State II; the selection of the appropriate equation depends on the availability of information as required by these equations:

<u>Limit State I:</u>

$$\phi_M c F_y Z \geq \gamma_{SW} M_{SW} + \gamma_{WD} k_{WD} M_{WD} \qquad (29)$$

$$\phi_M cF_y Z \geq \gamma_{SW} M_{SW} + k_W \left(\gamma_W M_W + \gamma_D k_D M_D \right) \tag{30}$$

Limit State II:

$$\phi_M M_u \geq \gamma_{SW} M_{SW} + \gamma_{WD} k_{WD} M_{WD} \tag{31}$$

$$\phi_M M_u \geq \gamma_{SW} M_{SW} + k_W (\gamma_W M_W + \gamma_D k_D M_D) \tag{32}$$

where c = nominal buckling knockdown 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.

5.3 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 knockdown 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 in Atua et al. (1996) and Assakkaf (1998).

Tables 5 through 8 provide all the recommended values of information required for establishing reliability-based design guidelines 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.

5.4 Sample LRFD Guidelines for Hull Girder

This section provides sample LRFD guidelines for demonstration purposes. Partial safety factors (PSF's) for both the strength and the loads are given for a range of target reliability levels. Ship designers and naval architects can use such as these in the limit states of interest without explicitly performing probabilistic analysis. These factors can be used for the design of hull girder of ships.

5.4.1 Partial Safety Factors

5.4.1.1 Strength Factors

This section gives strength (resistance) factors for ship hull girders for demonstration purposes. The hull girder of a ship for all stations should meet one of the limit states given in Section 5.2, namely Eqs 29 through 32. The first two equations (Limit State I) are based on the elastic properties of the hull, while the third and fourth equations (Limit State II) are based on the ultimate strength capacity of the hull (see Section 5.2).

The nominal (i.e., design) values of the strength and load components should satisfy these formats in order to achieve specified target reliability levels. Nominal strength factors for hull girders are provided in Tables 9 for both commercial and naval ships. The strength factors are provided in Tables 9 according to the following parameters:

1. target reliability level ranging from 4.0 to 5.5 for commercial ships,
2. target reliability level ranging from 4.5 to 6.0 for naval ships,
3. load combinations, and
4. elastic and ultimate bending strength prediction methods.

A target reliability level should be selected based on the ship type and usage. Then, the corresponding strength factor can be looked up from Table 9 based on strength model, and load combinations. The factors can be used for both sagging and hogging conditions.

5.4.1.2 Load Factors

This section provides load factors for hull girder design. The factors can be used in the limit state equations for the design of hull girders, and also for checking the adequacy of their strength capacity. The load factors are tabulated by load type and load combinations for selected target reliability levels β_0's as shown in Table 10. The ranges of target levels depend on the type of structural member under investigation. Recommended target reliability levels for various hull structural elements are provided in Table 11.

The factors are provided for the load effect of stillwater *SW*, wave-induced *W*, dynamic *D*, and combined wave-induced and dynamic *WD* bending moments for target reliability levels (β_0) ranging from 3.0 to 6.0. These load factors can be used in certain limit states and the load combinations presented in Section 4.2. A target reliability level, β_0, should be selected based on the ship type and usage. Then, the corresponding load factors can be looked up from Table 10 for the load combination of interest.

6. EXAMPLE: HULL GIRDER UNDER COMBINED LOADS

6.1 Calculation of Partial Safety Factors

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

$$g = \phi_M M_u - \gamma_{SW} M_{SW} - k_W \left(\gamma_W M_W + \gamma_D k_D M_D \right) \tag{33}$$

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 (Ayyub, et al. 2002) 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 12 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 10. 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 12, 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

6.2 Calculation of Strength Factor for a Given Set of Load Factors

As stated 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, the revised strength factor is calculated as follows:

$$\phi`_{M} = \frac{\gamma`_{SW}\,\overline{M_{SW}} + k_{W}\left(\lambda`_{W}\,\overline{M_{W}} + k_{D}\gamma`_{D}\,\overline{M_{D}}\right)}{\overline{M_{u}}}$$

$$= \frac{1.3(0.2) + (1)\left[1.8(1.0) + 0.7(1.5)(0.25)\right]}{4.1} = 0.57$$

7. SUMMARY AND CONCLUSIONS

Reliability of a system such as the hull girder can be defined as its ability to fulfill its design functions for a specified time period. This ability is commonly measured using probabilities. Reliability is therefore, the occurrence probability of the complementary event to failure. Based on this definition, reliability is one of the components of risk. Safety can be defined as the judgment of risk acceptability for the system making it a component of risk management.

The performance of ship hull girder and its components is defined by a set of requirements stated in terms of tests and measurements of how well the system or element serves various or intended functions over its service life. Risk and reliability measures can be considered as performance measures that can be specified in the form of 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 and the risk associated with it.

An important consideration in the choice of LRFD design criteria is the consequence of failure. Clearly the target reliability levels relative to the collapse of the hull girder should be larger than that of a non-critical welded detail relative to fatigue. The following three methods can be used to select a target reliability value: (1) agreeing upon a reasonable value in the case of novel structures without prior history using expert opinion elicitation, (2) calibrating reliability levels implied in currently and successfully used design codes, and (3) choosing target reliability level that minimizes the costs over the service life of the structure for dealing with design for which failure results in only economic losses an consequences.

Future design guidelines 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 guidelines 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 guidelines for ship hull girders subjected to vertical bending due to combined loads.

The methodology provided in this paper for developing LRFD guidelines 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 ship hull girders 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 design strength (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 the results of the example presented in this paper, 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 in the preliminary design of 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:

$$0.48M_u \geq 1.04M_{SW} - k_W\left(1.22M_W + 1.17k_D M_D\right) \tag{34}$$

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

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Figure 1. The USS Stark (US Navy)

Figure 2. The USS Stark, a U.S. frigate, was attacked in 1987 by an accidental Iraqi air-to-sea missile and severely damaged (US Navy)

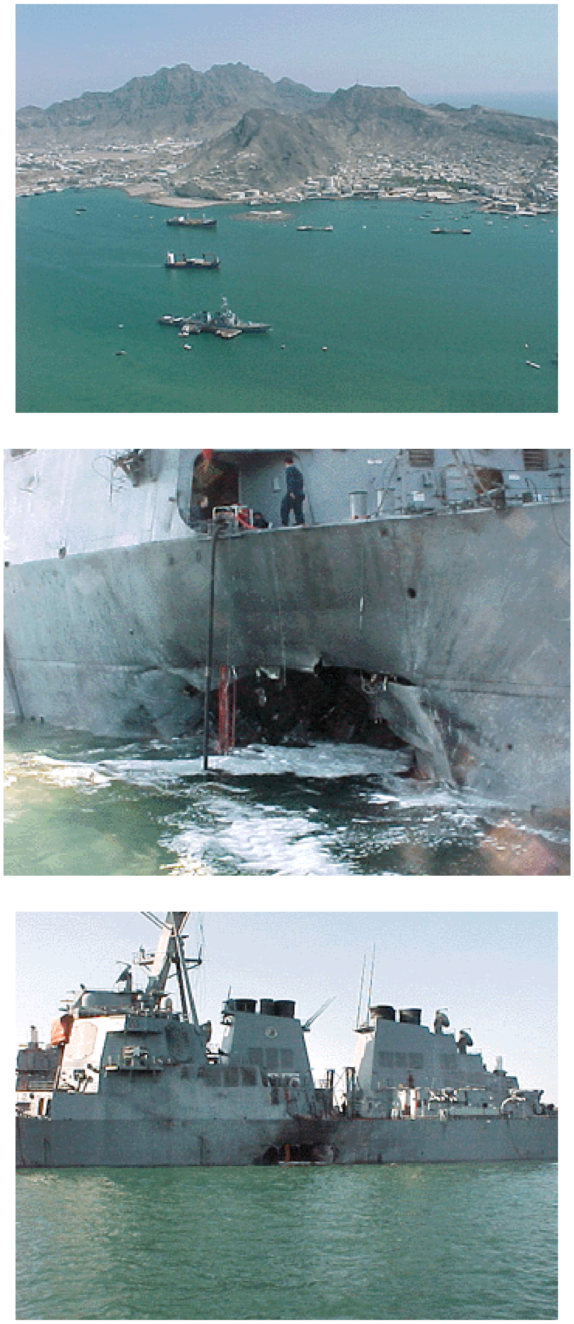


Figure 3. Port of Aden, Yemen, Oct. 13, 2000; USS Cole (DDG 67) After an Explosion on Oct. 12, 2000 which left a 40 foot by 40 foot Hole in the Port side of the Norfolk, VA-based Destroyer; Damaged Ship (U.S. Navy photos)

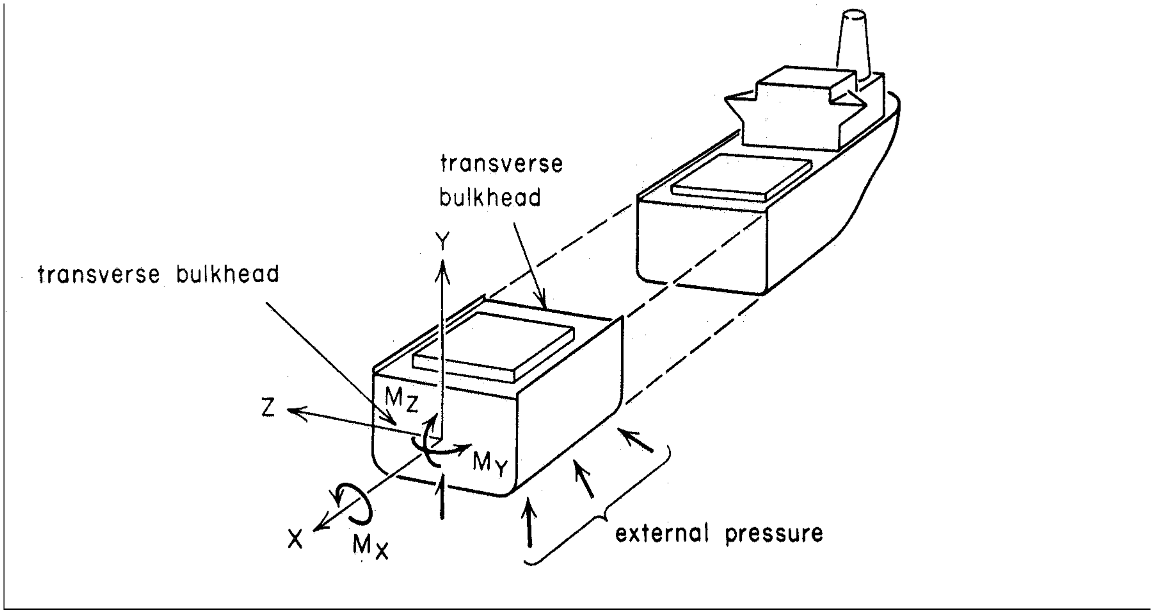


Figure 4. Hull Girder Model of a Ship (Hughes 1988)

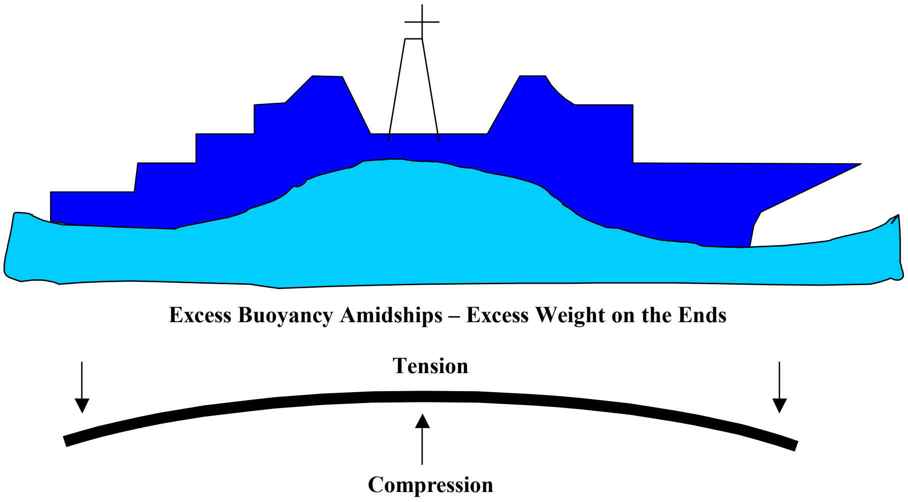


Figure 5a. Hogging Condition of a Ship due to Sea Waves

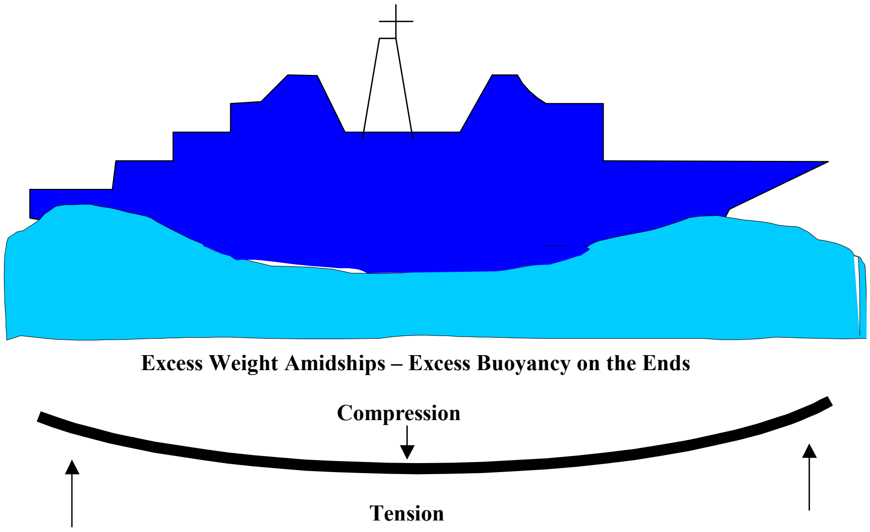


Figure 5b. Sagging Condition of a Ship due to Sea Waves

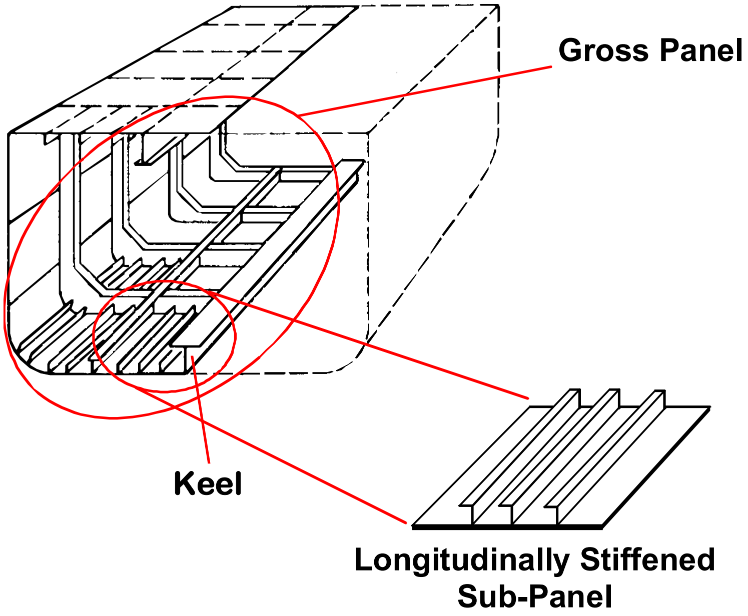


Figure 6. Portion of the Hull Girder Showing the Gross Panel (i.e., Grillage) and a Longitudinally Stiffened Sub-Panel (Hughes 1988)

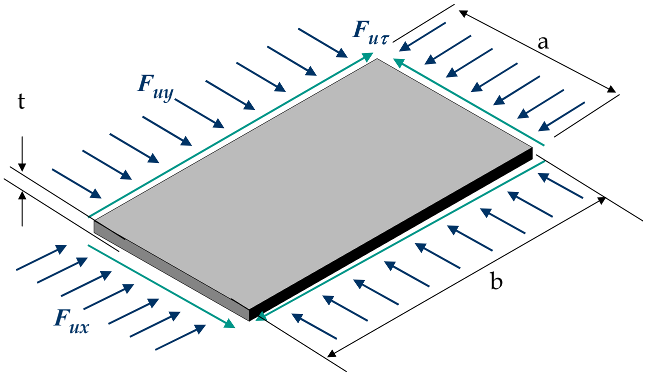
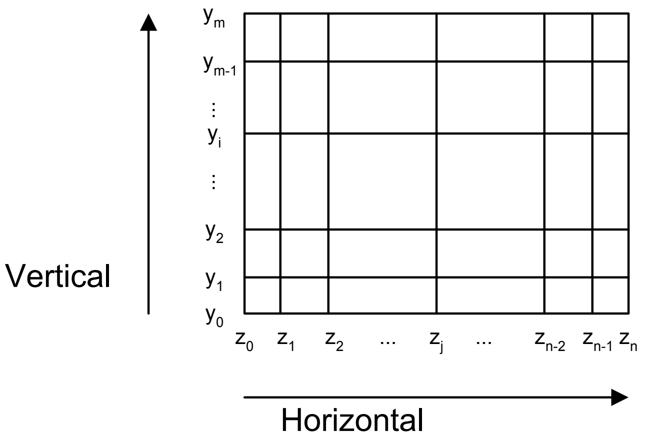
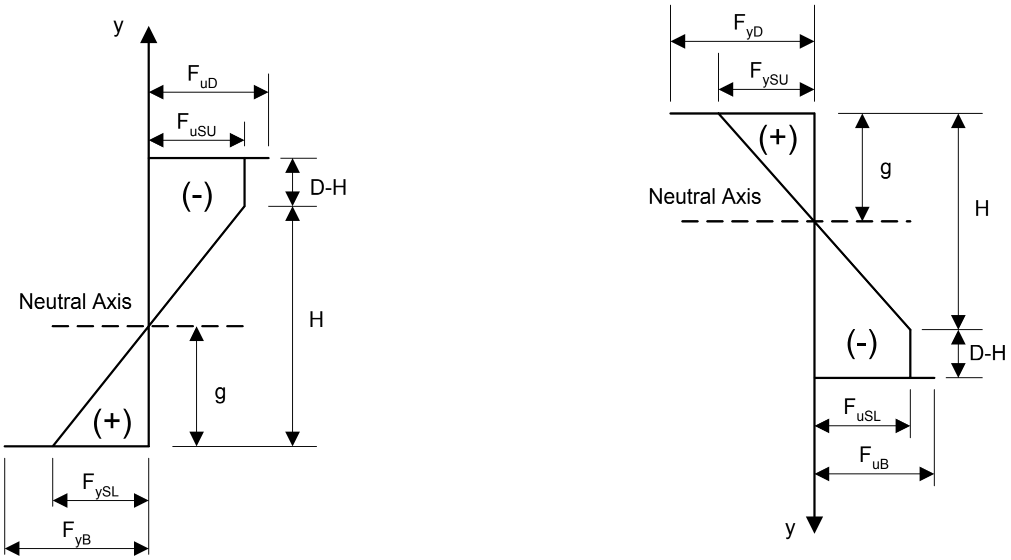


Figure 7. Unstiffened Panel Subjected to In-Plane Stresses



a. Midship Cross Section Representation



b. Stress Distribution
Sagging Condition

c. Stress Distribution
Hogging Condition

Figure 8. Vertical Bending Stress Distribution on Midship Cross Section (Paik et al 1996)

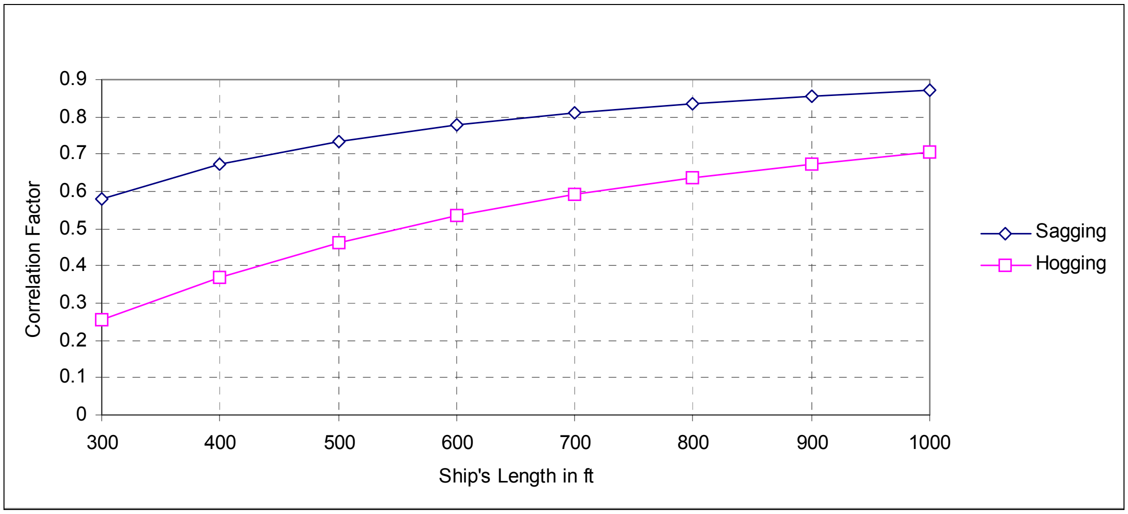
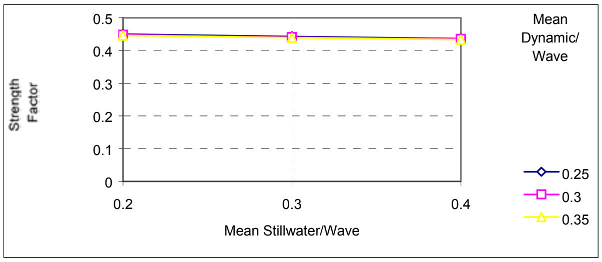


Figure 9. Correlation Coefficient of Whipping Bending Moment (k_D) for 300 < LBP < 1000 ft (Mansour et al. 1984 and Ayyub et al. 1995)

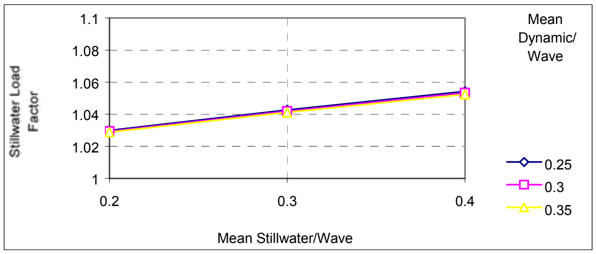
a. Strength Factor, ϕ_M

	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



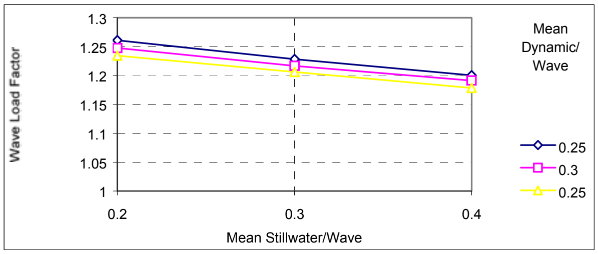
b. Stillwater Load Factor, γ_{SW}

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

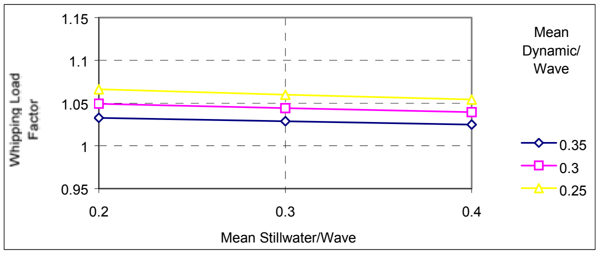


Figure 10. Variation of Strength and Load Partial Safety Factors versus Variation of the Ratios for the Mean Values of Load Components for the Example

Table 1. Correlation Coefficient of Whipping Bending Moment (k_D) for *LBP* between 300 and 1000 ft (Mansour et al. 1984 and Atua 1998)

Length (ft)	300	400	500	600	700	800	900	1000
$k_{D(sag)}$	0.5779	0.672	0.734	0.778	0.810	0.835	0.854	0.870
$k_{D(hog)}$	0.2539	0.369	0.461	0.533	0.591	0.637	0.675	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	*COV*	Distribution Type
Ordinary Strength F_y (ksi)	F_y	1.11 F_y	0.07	lognormal
High Strength 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	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	$F_y Z$	0.15	1.0
	Maximum	na	0.15	1.0
M_p	Minimum	na	0.12	1.0
	Recommended	$F_y Z_P$	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 to waves, P_W	Largest extreme value (type I)	1.0	0.15
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 et al. (1983) and Atua et al. (1996)
k_D	$EXP\left[\frac{53080}{\left(158LBP^{-0.2}+14.2LBP^{0.3}\right)LBP}\right]$ (Hogging) $EXP\left[\frac{21200}{\left(158LBP^{-0.2}+14.2LBP^{0.3}\right)LBP}\right]$ (Sagging)	Sikora et al. (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 in Sikora et al. (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. Nominal Strength Factors for Hull Girder Bending of Ships (Ayyub et al. 2000)

Load Combinations		Strength Factors (ϕ_M)				
		Target Reliability Index (β_0)				
		4.0	4.5	5.0	5.5	6.0
$\phi_M c_b F_y Z \geq \gamma_{SW} M_{SW} + k_{WD} \gamma_{WD} M_{WD}$		0.52	0.47	0.42	0.34	0.30
$\phi_M c_b F_y Z \geq \gamma_{SW} M_{SW} + k_W (\gamma_W M_W + k_D \gamma_D M_D)$		0.60	0.56	0.52	0.46	0.42
$\phi_M M_u \geq \gamma_{SW} M_{SW} + k_{WD} \gamma_{WD} M_{WD}$		0.66	0.61	0.56	0.40	0.37
$\phi_M M_u \geq \gamma_{SW} M_{SW} + k_W (\gamma_W M_W + k_D \gamma_D M_D)$		0.74	0.72	0.68	0.66	0.58
Based on the elastic capacity of the hull ($M_u = c_b F_y Z$)	$\left(\frac{M_{V1}}{M_{Vu}}\right)^{\alpha_1} + \left(\frac{M_{H1}}{M_{Hu}}\right)^{\alpha_2} \leq 1$	0.50	0.45	0.39	0.35	0.31
	$\left(\frac{M_{V2}}{M_{Vu}}\right)^{\alpha_1} + \left(\frac{M_{H2}}{M_{Hu}}\right)^{\alpha_2} \leq 1$	0.58	0.54	0.50	0.45	0.39
Based on the ultimate capacity of the hull	$\left(\frac{M_{V1}}{M_{Vu}}\right)^{\alpha_1} + \left(\frac{M_{H1}}{M_{Hu}}\right)^{\alpha_2} \leq 1$	0.63	0.59	0.53	0.38	0.36
	$\left(\frac{M_{V2}}{M_{Vu}}\right)^{\alpha_1} + \left(\frac{M_{H2}}{M_{Hu}}\right)^{\alpha_2} \leq 1$	0.72	0.69	0.66	0.63	0.56

Note: the subscript 1and 2 refer to limit state I and II, respectively, α_1 and α_2 can be taken as 1.9 and 1.0, respectively.

Table 10. Nominal Load Factors (Ayyub et al. 2000)

Target Reliability Index (β_o)	Load Factors			
	γ_{SW}	γ_W	γ_D	γ_{WD}
4.0	1.05	1.70	1.10	1.55
4.5	1.05	1.90	1.10	1.60
5.0	1.05	2.05	1.10	1.63
5.5	1.05	2.30	1.10	1.66
6.0	1.05	2.50	1.10	1.70

Table 11. Recommended Target Reliability Levels (β_0) for Hull Girders (Ayyub et al. 2000)

Ship Type	Ranges of β_0
Commercial	4.0 to 5.5
Naval	4.5 to 6.0

Table 12. 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

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