Strength Models for Developing LRFD Rules for Hull Girders of Ship Structures

I.A. Assakkaf & B.M. Ayyub
Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742, USA

G.F.M. De Souza
Department of Mechanical Engineering, University of São Paulo, Brazil

Norma Jean Mattei
Department of Civil and Environmental Engineering, University of New Orleans, New Orleans, LA 70148

ABSTRACT: The objective of this paper is to summarize development in strength prediction models for hull girders of ship structures that are suitable for Load and Resistance Factor Design (LRFD) formats. Monte Carlo Simulation was utilized to assess the biases and uncertainties for the models. Recommendations for the use of the models and their biases in LRFD development are provided. The first-order reliability method (FORM) was used to demonstrate the development of partial safety factors for a selected limit state.

1 INTRODUCTION

Hull girders are very important components in ship structures, and therefore they should be designed for a set of failure modes that govern their strength. The modes of failures 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 the hull girders and they include plastic strengths, buckling, and permanent deformation. Serviceability limit states, on the other hand, refer to the performance of the hulls under normal service loads and are concerned with the uses of the hull girders and they include such terms as excessive deflections and first yield. To evaluate the 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 distortion; 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 paper, 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: (1) prediction models that can be used by the LRFD rules, (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 rules 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.

The objective of this paper is to summarize developments in strength prediction models for ship hull girders that are suitable for LRFD development for ship structures. Recommendations for the use of the models and their biases for the LRFD development are provided. The first-order reliability method (FORM) was used to demonstrate the development of partial safety factors for a selected limit state.

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 essential for the development of LRFD-based reliability design for ship hull girders.

There are two primary approaches for reliability-based design: (1) direct reliability-based design and (2) load and resistance factor design, LRFD (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 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 β''s. The relationship between the reliability index β and the probability of failure is given by

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

where $\Phi(.)$ = cumulative probability distribution function of the standard normal distribution, and β = reliability (safety) index. It is to be noted that Eq. 1 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. 1 can be used to evaluate P_f with sufficient accuracy (Ayyub and McCuen 1997).

2.2 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:

$$\phi R_n \geq \sum_{i=1}^{m} \gamma_i L_{ni} \tag{2}$$

where ϕ = strength factor, R_n = nominal (or design) strength, γ_i = load factor for the *i*th load component out of *n* components, and L_{ni} = nominal (or design) value for the *i*th 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:

$$\frac{R}{\text{FS}} \geq \sum_{i=1}^{m} L_i \tag{3}$$

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 that is used in this paper is given by Eq. 2.

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:

$$\phi R_n \geq \gamma_s L_s + k_{WD}\gamma_{WD}L_{WD} \tag{4}$$

$$\phi R_n \geq \gamma_s L_s + k_W\left(\gamma_W L_W + k_D\gamma_D L_D\right) \tag{5}$$

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.

2.3 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:

$$\beta \geq \beta_0 \tag{6}$$

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. 2. 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:

$$R_n \geq \frac{\gamma_s L_s + k_{WD}\gamma_{WD}L_{WD}}{\phi} \tag{7}$$

$$R_n \geq \frac{\gamma_s L_s + k_W\left(\gamma_W L_W + k_D\gamma_D L_D\right)}{\phi} \tag{8}$$

3 HULL GIRDER STRENGTH

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3.1 Moment Capacity of Hull Girder

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 shall be 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: (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, 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 1. 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. 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. The vertical bending moment varies along the length of the ship. It can

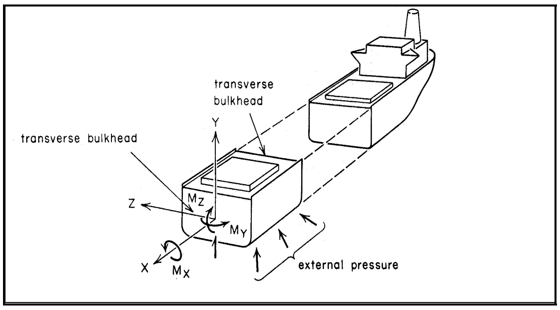

Figure 1. Hull Girder Model of a Ship (Hughes 1988)

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 waves. The hull girder analysis and design assume 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, and (4) the material is homogeneous and elastic.

4 HULL GIRDER STRENGTH MODELS

This section presents the development in strength predictions 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.

4.1 Vertical Hull Girder Bending Strength Capacity

4.1.1 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 midship section and the percentage of each type (Atua 1998). Detailed description of ULTSTR program can be found in Adamchak (1979), Assakkaf (1998), and Atua (1998).

4.1.2 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:

$$M_P = F_y SM_P \tag{7}$$

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

$$SM_P = A_d g + 2A_S\left(\frac{D}{2} - g + \frac{g^2}{D}\right) + A_B(D-g) \tag{8}$$

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:

$$g = \frac{D}{4A_s}(A_B + 2A_S - A_d) \tag{9}$$

4.1.3 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

$$M_u = F_y Z_p \tag{10}$$

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

$$Z_p = A_D Y_D + 2A_S\left(\frac{D}{2} - Y_D + \frac{Y_D^2}{D}\right) + A_B(D - Y_D) \tag{11}$$

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

$$Y_D = D\left(\frac{A_B + 2A_S - A_D}{4A_S}\right) \tag{12}$$

4.1.4 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 based on the geometry of the hull components. This methodology is also 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 moment 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 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.

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. 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).

4.1.5 Manour et al. (1995)

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 can be then computed as (Mansour et al 1995):

$$M_u = c_b F_y Z \tag{13}$$

where c_b = buckling knock-down factor which is 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

$$c_b = \frac{M_u}{F_y Z} \qquad (14)$$

It 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 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, and Atua 1998).

4.1.6 Mansour and Thayamballi (1993)

Manosur and Thayamballi (1993) developed an expression for the ultimate bending moment of the hull girder similar to the expression given in Eq. 14. In this model, they 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

$$M_u = X_U Z F_{cr} \qquad (15)$$

where Z = section modulus of hull girder amidship, 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. The parameters Z and X_U are provided in Table 1 for different mode of failures for the hull.

Table 1. Critical Strength and Section Modulus of Ship Hull Girder for Different Failure Modes (Ayyub and Atua 1996)

Mode of Failure		F_{cr} / Fy
Buckling Instability	Plate between stiffeners	0.92
	Stiffeners and effective plating	0.96
	Cross stiffened panels	1.0
	Tripping of stiffeners	0.66
Hull Girder Instability Collapse		$-0.172 + 1.548\,\Phi_{cp} - 0.368\,\Phi^2_{cp}$
Serviceability Limit State		0.87

4.1.7 Paik and Thayamballi (1997)

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:

$$M_u = \frac{\overline{F_y} Z}{\sqrt{0.995 + 0.936\lambda^2 + 0.170B^2 + 0.188\lambda^2 B^2 - 0.067\lambda^4}} \qquad (16)$$

where Z is the hull section modulus to be determined according to best engineering judgment and practices, F_y is the mean yield strength of stiffened panel, and λ and B are the slenderness ratio of the panel.

4.2 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.

4.2.1 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.

4.3 Combined Vertical and Horizontal Bending Strength

4.3.1 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

$$\overline{M}_W = \sqrt{\overline{M}_v^2 + \left(\frac{Z_v}{Z_h}\right)^2 \overline{M}_h^2 + 2\rho_{vh}\left(\frac{Z_v}{Z_h}\right)\overline{M}_v \overline{M}_h} \qquad (17)$$

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.

4.3.2 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, the strength is given by

$$\left(\frac{M_V}{M_{Vu}}\right)^{\alpha_1} + \left(\frac{M_H}{M_{Hu}}\right)^{\alpha_2} = \delta \qquad (18)$$

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. The parameter δ on the right-hand side of the equation is assumed to be a random variable with mean value equals 1.

5 RECOMMENDED STRENGTH MODELS FOR LRFD RULES DEVELOPMENT

Development of reliability-based design rules for surface ships requires the definition of strength prediction models, their uncertainties, and biases from real (measured) values. For hull girder strength in LRFD format (or limit state), the following items are considered vital for selecting a strength model:

1. prediction models as used in LRFD rules
2. advanced prediction models that can be used for various analytical purposes
3. some experimental results from model testing, and
4. some real measurement from actual values that occurred during the surface life of the ship

Relationships and uncertainties analysis for these items are also needed. The relationships can be defined in terms of biases. The ultimate bias of interest herein is that between the LRFD rules values and real values. In formulating a strength design model for ship hull girders, a balance must be achieved between the model accuracy, applicability, and simplicity in the rules, all of which are desired features. The assessment of a model bias and uncertainty can be a difficult task. One way of assessing a model uncertainties and biases is by comparing its prediction with ones that are more accurate or real values from experimental test results. As was noticed in the previous sections, the level of complexity associated with hull girder strength models ranges from highly complex models to simple ones. The more complex theoretical models do not necessarily lead to less uncertainty. Although they can be accurate, they can be more uncertain because in most cases they involve a large number of variables, some of which may be very uncertain. On the other hand, simple empirical formulation such as that of Herzog (1987) or Paik and Thayamballi (1997) can lead to fairly good results. Although theoretically less rigorous, they can be of practical use because they represent real ship hulls. These models are limited to the slope of the underlying tests.

The objective of this section is to summarize hull girder strength models that are deemed suitable for LRFD design format. The selection of these models is based on the following three items: (1) the model accuracy, (2) applicability, and (3) simplicity in the rules. Tables 2 and 3 summarize these models for reliability-based LRFD rules of hull girder bending. Table 2 provides the models for vertical moment capacity, while Table 3 provides the models for combined vertical and horizontal bending moments of hull girder.

6 EXAMPLE: CALCULATION OF PARTIAL SAFETY FACTORS FOR HULL GIRDER

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

$$g = \phi_M M_u - \gamma_{SW} M_{SW} - k_W (\gamma_W M_W + \gamma_D k_D M_D) \qquad (19)$$

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.

Table 2. Recommended Strength Models of Hull Girder Vertical Moment Capacity for LRFD Rules Development

Model	Bias	*COV*	Reference	Type
ULTSTR	1.0	0.15	Adamchak (1979)	Advanced
$M_u = c_b F_y Z$ Sagging	1.21	0.34	Mansour (1995)	Simple
$M_u = c_b F_y Z$ Hogging	1.21	0.31	Mansour (1995)	Simple
Paik Model, Sagging	0.77	0.12	Paik et al. (1996)	Requires identification of hull cross section properties
Paik Model, Hogging	0.76	0.11	Paik et al. (1996)	Requires identification of hull cross section properties
Eq. 16	0.90	0.12	Paik and Thayamballi (1997)	Based on stiffened panel strength

Table 3. Recommended Strength Models of Hull Girder Combined Vertical and Horizontal Moments Capacity for LRFD Rules Development

Model	Bias (δ)	*COV* (δ)	Reference
$\left(\frac{M_V}{M_{Vu}}\right)^{\alpha} + \left(\frac{M_H}{M_{Hu}}\right)^{\alpha} = \delta$	0.93	0.11	Soares and Cordo (1997)
$\left(\frac{M_V}{M_{Vu}}\right)^{\alpha_1} + \left(\frac{M_H}{M_{Hu}}\right)^{\alpha_2} = \delta$	0.97	0.10	Paik et al (1996)

The First-Order Reliability Method (FORM) requires the probabilistic characteristics of M_u, M_{SW}, M_W and M_D. 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

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. The ratios of means for strength/wave-induced load and the partial safety factors for a target reliability of 4.0 were determined using FORM. Based on FORM, 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:

$$0.48M_u \geq 1.04M_{SW} - k_W\left(1.22M_W + 1.17k_D M_D\right) \tag{18}$$

7 CONCLUSIONS

Future design rules for ship hull girders will be developed using reliability methods and they will be expressed in a special and practical format such as the Load and Resistance Factor Design (LRFD). The recommended strength models for hull girder strength that deemed suitable for the development of LRFD rules are presented in this paper. Recommendations for the use of the models and their biases for the LRFD development are provided. The first-order reliability method (FORM) was used to demonstrate the development of partial safety factors for a selected limit state and for demonstration purposes.

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Appendix I. References

Adamchak, J. C., 1979. "Design Equations for Tripping of Stiffeners under Inplane and Lateral Loads," DTNSRDC Report 79/064, Carderock, Maryland.DC 20362.

Assakkaf, I.A. (1998) "Reliability-based Design of Panels and fatigue Details of Ship Structures." 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.

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.

Ayyub, B.M. and Atua, K., 1996. "Development of LRFD Rules for Naval Surface Ship Structures: Reliability-based Load and Resistance Factor Design Rules, Part I – Hull Girder Bending," Naval Surface Warfare Center, Carderock Division.

Ayyub, B.M., Assakkaf, I., Atua, K., Engle, A., Hess, P., Karaszewski, Z., Kihl, D., Melton, W., Sielski, R.A., Sieve, M., Waldman, J., and White, G. J. 1998. "Reliability-based Design of Ship Structures: Current Practice and Emerging Technologies," Research Report to the US Coast Guard, SNAME, T & R Report R-53.

Caldwell, 1965. "Ultimate Collapse Condition of the hull."

Herzog, A. M., 1987. "Simplified Design of Unstiffened and Stiffened Plates," Journal of Structural Engineering, 113 (10), 2111-2124.

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.

Kaplan, P., Benatar, M., Bentson, J., Achtarides, T. A., 1984. "Analysis and Assessment of Major Uncertainties Associated with Ship Hull Ultimate Failure," Ship Structure Committee, Report SSC-322, U.S. Coast Guard, Washington, DC.

Krishnankutty, A. (2000), A literature review of strength models for hull girder bending, specifically conducted for a project by UMCP, College Park, MD, and by UNO, New Orleans, LA.

Mansour, A. and Thayamball, 1994. "Probability-Based Ship Design: Loads and Load Combinations," SSC-373, Ship Structures Committee, NTIS # PB94-188208, Springfield, Virginia.

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.

Paik, J. K. and Lee, J. M., 1996. "An Empirical Formulation for Predicting the Ultimate Compression Strength of Plates and Stiffened Plates," Trans. Society of Naval Architectures of Korea, Vol. 33, No.3, pp. 8-21 (in Korean).

Paik, J. K. and Thayamballi, A.K, 1997. "A benchmark Study on the Ultimate Strength Formulations of Stiffened Panels," Joint PNU-ABS Research Project, Final Report to the American Bureau of Shipping, by Pusan National University, Department of Naval Architecture and Ocean Engineering, Pusan.

Paik, J.K., Thayamballi, A.K., che, J.S. (1996) "Ultimate strength of Ship Hulls Under Combined Vertical Bending, Horizontal Bending, and Shearing Forces." Transactions of the Society of Naval Architects and Marine Engineers, 104, 31-59.

Soares, C.G., and Gordo, J.M. (1997) "Interaction Equation for the Collapse of Tankers and Containerships Under Combined Bending Moments." Journal of Ship Research, SNAME 41(3), 230-240.