STRENGTH MODELS FOR DEVELOPING LRFD RULES FOR STIFFENED AND GROSS PANELS OF SHIP STRUCTURES

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Abstract

The objective of this paper is to summarize strength prediction models of stiffened and gross panels that are suitable for LRFD development for ship structures. Monte Carlo simulation was used to assess the biases and uncertainties for these models. Recommendations for the use of the models and their biases in LRFD development are provided. The first-order reliability method (FORM) was utilized to develop the partial safety factors (PSF's) for selected limit states. The use of partial safety factors was demonstrated using an example.

Introduction

The main type of framing system found in ships nowadays is a longitudinal one, which has stiffeners running in two orthogonal directions (Figure 1). 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 bottom and side shell by water pressure. 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. A typical longitudinal stiffened sub-panel, as shown in Figure 1, 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.

In ship structures, there are three types of loading that can effect 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 to be positive when the panel is in compression. The three types of loading can act individually or in combination with one another.

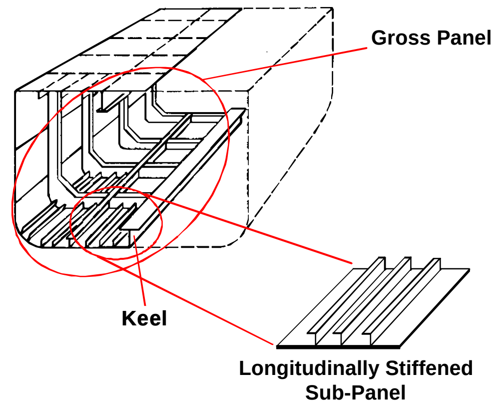

Figure 1. Portion of the Hull Girder Showing the Gross Panel and a Longitudinally Stiffened Sub-Panel (Hughes, 1988)

To evaluate the strength of a stiffened or gross panel element it is necessary to review various strength prediction models and to study their applicability and limitations for different loading conditions acting on the element. The uncertainties that are associated with a numerical analysis are generally a result of experimental approximation or numerical inaccuracies that can be reduced by some procedures. However, the uncertainties that are associated with a strength design model is different and cannot be eliminated because it results from not accounting for some variables which can have strong influence on the strength. For this reason, the uncertainty and the bias of a design equation should be assessed and evaluated by comparing its predictions with more accurate ones. Wherever possible, the different types of biases resulting from these models were computed. In doing so, these prediction models were classified as follows (Atua and Ayyub, 1996): (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. Furthermore, the relationships and uncertainty analyses for these models are required. The relationships can be defined in terms of biases (bias factors). In this paper, only selected strength models that are deemed suitable for LRFD design format are highlighted and presented.

Stiffeners

Stiffeners are very important structural components that are used to strengthen plates and to increase their load carrying capacity. In ship structures, most of gross stiffened panel failures are due to the collapse of one or more of the longitudinal and transverse stiffeners. Thus, the first and most basic principle with regard to stiffeners is that they should be designed at least as strong as the plating. Also, they should be sufficiently rigid and stable so that neither local stiffener buckling nor overall buckling occurs before local plate buckling. A plate stiffener can be subjected to a variety of primary and secondary loads and load combinations that cause the plate stiffener to fail in one of the following types of buckling: (1) column buckling, (2) beam-column buckling, and (3) flexural-torsional buckling. Numerous Strength models for stiffeners are available according to the type of stiffener buckling involved, and can be found in API (1993), Assakkaf (1998), Atua (1998), and others.

Longitudinally Stiffened Panels

In this section, a summary of selected strength models that are deemed suitable for LRFD design formats is presented. These strength models are for longitudinally stiffened panels subjected to various types of loading. They are presented herein in a concise manner, and they were evaluated in terms of their applicability, limitations, and biases with regard to ship structures. A complete review of the models used by different classification agencies such as the AISC (1994), ASSHTO (1994), and the API (1993) is provided in Atua (1998) and Assakkaf (1998).

Herzog's Model

Based on reevaluation of 215 tests by various researchers and on empirical formulation, Herzog (1987) developed a simple model (formula) for the ultimate strength of stiffened panels that are subjected to uniaxial compression without lateral loads. The ultimate strength F_u of a longitudinally stiffened plate is given by the following empirical formula (Herzog 1987):

$$F_u = \begin{cases} mF_y\left[0.5 + 0.5\left(1 - \dfrac{a}{rp}\sqrt{\dfrac{F_y}{E}}\right)\right] & \text{for } \dfrac{b}{t} \le 45 \\ mF_y\left[0.5 + 0.5\left(1 - \dfrac{a}{rp}\sqrt{\dfrac{F_y}{E}}\right)\right]\left[1 - 0.007\left(\dfrac{b}{t} - 45\right)\right] & \text{for } \dfrac{b}{t} > 45 \end{cases} \qquad (1)$$

where r = radius of gyration of one stiffener with fully effective plating, a = length (span) of stiffener, F_y = yield strength of material (steel), E = modulus of elasticity of the material, and m = 1.2, 1.0 , or 0.8, depending on weather the designer considers, respectively, (1) no or average imperfection and no residual stress, (2) average imperfection and average residual stress, and (3) average or large imperfection and high value for the residual stress.

The 215 tests evaluated by Herzog belong to three distinct groups. Group I (75 tests) consisted of small values for imperfection and residual stress, Group II (64 tests) had average values for imperfection and residual stress, while the third group (Group III, 76 tests) consisted of higher values for imperfection and residual stress. The statistical uncertainty (*COV*) associated with Herzog model of Eq. 1 is 0.218. The mean value m, standard deviation s, and *COV* of the measurement to prediction are given in Table 1.

Hughes's Model

According to Hughes (1988), there are three types of loading that must be considered for determining the ultimate strength of longitudinally stiffened panels. These types of loading are: (1) Lateral load causing negative bending moment of the plate-stiffener combination (the panel), (2) Lateral load causing positive bending moment of the panel, and (3) In-plane compression resulting from hull girder bending. The sign convention to be used throughout this section is that of Hughes (1988). Bending moment in the panel is considered positive when it causes compression in the plating and tension in the stiffener flange, and in-plane loads are positive when in compression (Figure 2). The deflection, w_0, due to the lateral load (i.e., lateral pressure) M_0 and initial eccentricity, d_0, are considered positive when they are toward the stiffener as shown in Figure 2. In beam-column theory, the expressions for the moment M_0 and the corresponding deflection w_0 are based upon an ideal column, which is assumed to be simply supported.

Disregarding plate failure in tension, there can be three distinct modes of collapse (see Figure 2) according to Hughes (1988): (1) Compression failure of the stiffener (Mode I Collapse), (2) Compression failure of the plating (Mode II Collapse), and (3) Combined failure of stiffener and plating (Mode III Collapse). The ultimate axial strength (stress) F_u for a longitudinally stiffened panel under a combination of in-plane compression and lateral loads (including initial eccentricities) can be, therefore, defined as the minimum of the collapse (ultimate) values of applied axial stress computed from the expressions for the three types (modes) of failure. Mathematically, it can be given as

$$F_u = \min(F_{a,u\mathrm{I}}, F_{a,u\mathrm{II}}, F_{a,u\mathrm{III}}) \tag{2}$$

where $F_{a,u\mathrm{I}}$, $F_{a,u\mathrm{II}}$, and $F_{a,u\mathrm{III}}$ correspond to the ultimate collapse value of the applied axial stress for Mode I, Mode II, and Mode III, respectively. The mathematical expressions for the collapse stress for each mode of failures are provided in Hughes (1988) and Assakkaf (1998).

Gross Stiffened Panels

The design criterion for the collapse of a gross stiffened panel can be prevented by choosing the size of the transverse stiffeners so that they provide sufficient flexural rigidity to enforce nodes at the location of the transverse stiffeners. The collapse of the stiffened panel then is controlled by the strength of the longitudinally stiffened sub-panel.

The design philosophy in this context is to design the gross panel so that its failure will be prevented and the problem to be reduced to the level of the failure of the longitudinally stiffened sub-panel. In the following section, one failure mode will be checked to fulfill the goal of this design approach.

Reliability Checking for Gross Panels

To perform a reliability (safety) checking on the design of gross panel, the ratio of the stiffness of the transverse and longitudinal stiffeners shall not be less than the load effect given by the geometrical parameters shown in the second hand term of the following expression:

Group	Number of Tests	Mean Value (m)	Standard Deviation (s)	*COV*
I	75	1.033	0.134	0.130
II	64	0.999	0.100	0.100
III	76	0.981	0.162	0.169
All	215	1.004	0.136	0.135

Table 1. Statistics of 215 Tests Conducted on Longitudinally Stiffened Plates in Uniaxial Compression (Herzog 1987)

Target Reliability Index (b)	Gross Panel Strength Reduction Factor (f_g)
2.0	0.82
2.5	0.78
3.0	0.75

Table 2. Computed Partial Safety Factor for the Stiffness Ratio I_y/I_x

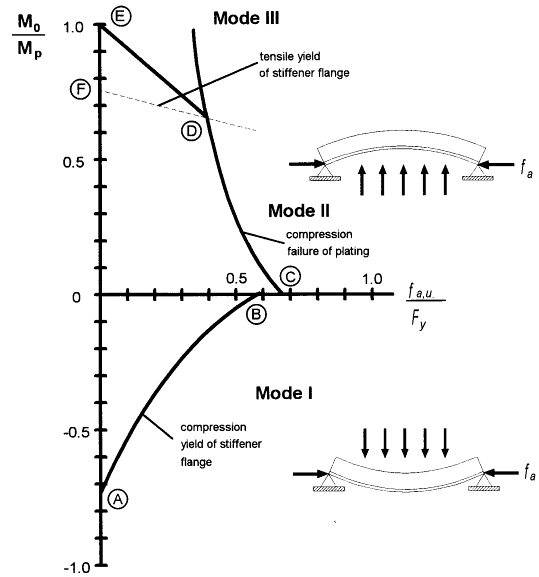

Figure 2. Interaction Diagram for Collapse Mechanism of a Stiffened Panel under Lateral and In-plane Loads (Hughes 1988)

$$f_g \frac{I_y}{I_x} \geq \frac{(n+1)^5}{np^2\left(0.25+\frac{2}{N^3}\right)}\left(\frac{b}{a}\right)^5 \qquad (3)$$

where I_x = moment of inertia of longitudinal plate-stiffener, I_y= moment of inertia of transverse plate-stiffener, a = length or span of the panel between transverse webs, b = distance between longitudinal stiffeners, n = number of longitudinal stiffeners, N = number of longitudinal sub-panels in overall (or gross) panel, and f_g = gross panel strength reduction factor. A target reliability level can be selected based on the ship type and usage. Then, the corresponding safety factor can be looked up from Table 2.

Example: LRFD-based Partial Safety Factors

The limit state for this case is given by

$$g = F_u - f_{SW} - k_W(f_W + k_D f_D) \qquad (4)$$

where F_u = ultimate uniaxial strength as defined by Eq. 1, f_{SW} = stress due to stillwater bending moment, f_W = stress due to waves bending moment, f_D = stress due to dynamic bending moment, k_W = load combination factor equals 1.0, and k_D = load combination factor equals 0.7. The partial safety factors for the above limit state equation (Eq. 4) were developed using a target reliability index b ranges from 3.5 to 4.5. The partial safety factors of both the strength and the load effects for this range of the target reliability are summarized in Tables 3. The resulting partial safety factors can be used, for example, to design the ultimate capacity (ultimate stress) of a stiffened panel under uniaxial compression (Herzog's Model) by satisfying the following design criterion:

$$\phi_u F_u \leq \gamma_{SW} f_{SW} + k_W (\gamma_W f_W + k_D \gamma_D f_D) \qquad (5)$$

A target reliability level can be selected based on the ship type and usage.

Target Reliability Index (β_0)	Strength Factor	Load Factors		
	ϕ_u	γ_{SW}	γ_W	γ_D
3.5	0.59	0.74	1.55	1.10
4.0	0.54	0.74	1.70	1.10
4.5	0.49	0.74	1.90	1.10

Table 3. Nominal Partial Safety Factors for Stiffened Panel under Uniaxial Compression

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