Reliability-Based Load and Resistance Factor Design (LRFD) Guidelines for Unstiffened Panels of Ship Structures

Ibrahim A. Assakkaf, Bilal M. Ayub, Paul E. Hess, III, and David E. Knight

ABSTRACT
The main objective of ship structural design is to ensure safety, functional, and performance requirements of the structural element for target reliability levels and for a specified time period. As this must be accomplished under conditions of uncertainty, probabilistic analyses are necessary in the development of such reliability-based designs of unstiffened panels for ship structures. The load and resistance factor design (LRFD) format is developed in this paper for unstiffened panels. Partial safety factors are determined to account for the uncertainties in strength and load effects. In developing these factors, Monte Carlo simulation is used to assess the probabilistic characteristics of strength models by generating basic random variables that define the strength and substituting them in these models. The First-Order Reliability Method (FORM) is used to determine the partial safety factors based on prescribed probabilistic characteristics of load effects. Also, strength factors are computed for a set of load factors to meet a target reliability level.

Introduction
Ship panels or plates are important components in ship structures, and therefore they should be designed for a set of failure modes that govern their strength. Plate elements, in general, are parts of stiffened panels whose strengths must be predicted. However, a global failure of a stiffened panel can be partially controlled by designing the strength of plate elements between stiffeners. To evaluate the strength of an unstiffened plate element it is necessary to review various strength predicting 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, which can be reduced by some procedures. On the other hand, the uncertainty associated with a strength design model is different and cannot be eliminated because it results from not accounting for some variables that influence 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. An advanced prediction model should account for more variables than the one that is being assessed for use in load and resistance factor design (LRFD) guidelines. Probably the most important parameter that affects plate strength is the slenderness ratio $B$ (Soares 1988). In ship plates, $B$, which is a non-dimensional parameter, can take a value between one and five. These values of $B$ correspond to a reduction of plate strength from yield strength $F_y$ to 0.4 $F_y$. The aspect ratio $a/b$ has less effect on plate strength than $B$. Most ship plates have $a/b > 1.0$. Typical plate strength changes by 5% as the aspect ratio varies from 0.6 to 1.0 (Frieze et al. 1977). Other parameters that can affect plate strength are its boundary conditions and material imperfections. A study conducted by Soares in 1988, which is based on experimental results of Moxham (1971), shows that in the range of slenderness ratios between 2.5 and 3.5, clamped (fixed) plates are between 15% and 30% stronger than simply-supported plates. Wherever possible, the different types of biases resulting from these models were computed. In doing so, these prediction models were classi-
fied as follows (Atua and Ayyub 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. Furthermore, the relationships and uncertainty analyses for these models are required. The relationships can be defined in terms of biases (bias factors). These bias factors can be expressed by the following expressions:

\[
B_{21} = \frac{\text{Advanced predicted value}}{\text{Rules value}} \\
B_{31} = \frac{\text{Experimental value}}{\text{Advanced predicted value}} \\
B_{41} = \frac{\text{Real value}}{\text{Experimental value}} \\
B_{43} = \frac{\text{Real value}}{\text{Rules value}} = B_{21}B_{32}B_{43}
\]

**Design Loads and Load Combinations**

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

Stillwater loads can be predicted and evaluated with a proper consideration of variability in weight distribution along the ship's 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 (wave 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 a 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), Sikora (1983) and, Ayyub et al. (2002b).

**DESIGN LOADS**

The design loads that are of concern in this study for developing reliability-based design for unstiffened panels of ship structures are those 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: (1) stillwater loads, (2) wave loads, and (3) dynamic loads. Each of these types of loads are presented subsequently under its own heading.

**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 plane. Then, the hull girder loads are developed based on the differences between the weights and the buoyancy distribution 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.

**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 (see Ayyub et al. 2002b) 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).

**Dynamic Bending Moment**

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). The average peak-to-peak whipping bending moments (ft-tons) for fine bow ships is described in Sikora (1983) as

\[
M_{wH} = 0.0022 LBP^2 B \quad \text{for} \quad LBP^2 B < 5 \times 10^6 \quad (5)
\]

and

\[
M_{wH} = 5.4 LBP \sqrt{B} \quad \text{for} \quad LBP^2 B < 5 \times 10^6 \quad (6)
\]

where \(M_{wH}\) = mean value of peak-to-peak whipping bending moment, \(LBP\) = length between perpendiculars of the ship (ft), and \(B\) = molded breadth of the ship (ft). For ships with bow flare or with flat bottom (such as auxiliaries and cargo ships), the whipping bending moments can be determined (ft-tons) using (Sikora 1989)

\[
M_{wH} = 0.0022 LBP^2 B
\]

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

\[
M_{wH} = 4.6M_{wH}
\]

where \(M_{wH}\) = extreme value of whipping bending moment in ft-tons.

**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).

**LOAD COMBINATIONS AND RATIOS**

Reliability-based structural design of unstiffened panels 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).

**Stillwater and Vertical Wave-induced Bending Moments**

The load effect (stress) on unstiffened panel element because of combinations of stillwater and vertical wave-induced bending moments is given by

\[
f_c = f_{sw} + k_w f_{wd}
\]

where \(f_{sw}\) = stress because of stillwater bending moment, \(f_{wd}\) = stress because of wave-induced bending moment, \(f_c\) = un-factored combined stress, \(k_w\) = correlation factor for wave-induced bending moment and can be set equal to one (Mansour et al. 1984).

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

The load effect on an unstiffened panel element because of combinations of stillwater, vertical wave-induced, and dynamic bending moments is given by

\[
f_c = f_{sw} + k_w (f_w + k_o f_o)
\]

where \(f_{sw}\) = stress because of stillwater bending moment, \(f_w\) = stress because of wave bending moment, \(f_o\) = stress because of dynamic bending moment, \(f_c\) = un-factored combined load, and \(k_o\) = correlation factor between wave-induced and dynamic bending moments. The correlation factor \(k_o\) is given by the following two cases of hogging and sagging conditions (Mansour et al. 1984):
FIGURE 1:
Correlation Coefficient of Whipping Bending Moment \( k_d \) for 300 < LBP < 1000 ft
(Mansour et al. 1984 and Ayyub et al. 1995)

![Graph showing correlation coefficient of whipping bending moment](image)

- **Hogging Condition:**
  \[
  k_d = \exp \left[ \frac{53080}{158LBP^{-0.2} + 14.2LBP^{0.3}} \right] LBP
  \]
  \( (11) \)

- **Sagging Condition:**
  \[
  k_d = \exp \left[ \frac{21200}{158LBP^{-0.2} + 14.2LBP^{0.3}} \right] LBP
  \]
  \( (12) \)

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 1.

**Limit States and Design Strength**

An unstiffened panel of ship structure for all stations should meet one of the following conditions; the selection of the appropriate equation depends on the availability of information as required by these equations: For uniaxial compression,

**Limit State 1:**
\[
\phi_{u} f_{u} \geq \gamma_{sw} f_{sw} + \gamma_{wd} k_{wd} f_{w0}
\]
\( (13) \)

**Limit State 2:**
\[
\phi_{u} f_{u} \geq \gamma_{sw} f_{sw} + k_{w} \left( \gamma_{u} f_{u} + \gamma_{wd} k_{wd} f_{w0} \right)
\]
\( (14) \)

For biaxial compression,
\[
\left( \frac{f_{x1}}{\phi_{u} R_{u}} \right)^{2} + \left( \frac{f_{y1}}{\phi_{u} R_{y}} \right)^{2} - \eta \left( \frac{f_{x1}}{\phi_{u} R_{u}} \right) \left( \frac{f_{y1}}{\phi_{u} R_{y}} \right) \leq 1
\]
\( (15) \)

\[
\left( \frac{f_{x2}}{\phi_{u} R_{u}} \right)^{2} + \left( \frac{f_{y2}}{\phi_{u} R_{y}} \right)^{2} - \eta \left( \frac{f_{x2}}{\phi_{u} R_{u}} \right) \left( \frac{f_{y2}}{\phi_{u} R_{y}} \right) \leq 1
\]
\( (16) \)

For biaxial compression and edge shear,
\[
\left( \frac{f_{x1}}{\phi_{u} R_{u}} \right)^{2} + \left( \frac{f_{y1}}{\phi_{u} R_{y}} \right)^{2} + \left( \frac{f_{z}}{\phi_{u} R_{z}} \right)^{2} \leq 1
\]
\( (17) \)

Where
- \( f_u \) = ultimate strength (compressive stress) for a uniaxially stiffened panel,
- \( \phi_{u}, \phi_{x1}, \phi_{y} \) = strength reduction factors for ultimate strength capacity of a plate, the ultimate strength capacity \( R_u, R_{x1}, R_{y} \) depends on the loading conditions for the plate (i.e., uniaxial, edge shear, etc.),

**Table 1**

<table>
<thead>
<tr>
<th>LENGTH (FT)</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_{0226} )</td>
<td>0.5779</td>
<td>0.672</td>
<td>0.734</td>
<td>0.778</td>
<td>0.810</td>
<td>0.835</td>
<td>0.854</td>
<td>0.870</td>
</tr>
<tr>
<td>( k_{0226} )</td>
<td>0.2539</td>
<td>0.369</td>
<td>0.461</td>
<td>0.533</td>
<td>0.591</td>
<td>0.637</td>
<td>0.675</td>
<td>0.706</td>
</tr>
</tbody>
</table>
\( \phi_{R_u} \) = strength reduction factor for plates in shear,

\( R_u, R_w, R_w \) = ultimate strength capacity of a plate, the ultimate strength capacity \( R_u \), \( R_w \), and \( R_w \) depends on the loading conditions for the plate,

\( R_{ul} \) = ultimate load capacity of a plate in shear,

\( f_{sl} = \gamma_{SW} f_{SW} + k_{WD} \gamma_{WD} f_{WD} \), magnification of the applied stress in the \( x \)-direction for limit state 1,

\( f_{sl} = \gamma_{SW} f_{SW} + k_w (\gamma_{SW} f_{SW} + k_d \gamma_{OD} f_{OD}) \), magnification of the applied stress in the \( y \)-direction for limit state 2,

\( f_{sl} = \gamma_{SW} f_{SW} + k_{WD} \gamma_{WD} f_{WD} \), magnification of the applied stress in the \( y \)-direction for limit state 1,

\( f_{sl} = \gamma_{SW} f_{SW} + k_w (\gamma_{SW} f_{SW} + k_d \gamma_{OD} f_{OD}) \), magnification of the applied stress in the \( y \)-direction for limit state 2,

\( f_{sl} = \gamma_{SW} f_{SW} + k_{WD} \gamma_{WD} f_{WD} \), magnification of the applied stress in the \( y \)-direction for limit state 1,

\( f_{sl} = \gamma_{SW} f_{SW} + k_w (\gamma_{SW} f_{SW} + k_d \gamma_{OD} f_{OD}) \), magnification of the applied stress in the \( y \)-direction for limit state 2,

\( \gamma_{SW} \) = load factor for the stress because of stillwater bending moment,

\( f_{SW} \) = stress because of stillwater bending moment,

\( k_{WD} \) = combined wave-induced and dynamic bending moment factor,

\( \gamma_{WD} \) = load factor for the stress because of combined wave-induced and dynamic bending moment,

\( f_{WD} \) = stress because of combined wave-induced and dynamic bending moments,

\( k_w \) = load combination factor, which can be taken as 0.7,

\( \gamma_w \) = load factor for the stress because of wave bending moment,

\( f_w \) = stress because of wave bending moment,

\( k_d \) = load combination factor, which can be taken as 0.7,

\( \gamma_d \) = load factor for the stress because of dynamic bending moment,

\( f_D \) = stress because of dynamic bending moment,

\( n_B = \begin{cases} 0.25 & \text{if } a \geq 3.0 \\ 0.25 - \left( \frac{a - 3}{2} \right) & \text{if } 1.0 < a < 3.0 \\ 3.2e^{-2a} - 2.25 & \text{if } a = 1.0 \end{cases} \)

where \( a \) = aspect ratio of the plate \((a/b)\) and \( B = \text{plate slenderness ratio} \).

The nominal (i.e., design) values of the strength and load components should satisfy these formats in order to achieve specified target reliability levels. The nominal strength for unstiffened panels (plates) can be determined as described in subsequent sections.

**DESIGN STRENGTH FOR UNSTIFFENED PANELS**

The design strength of unstiffened panels (plates) can be computed using formulas that correspond appropriately to their loading conditions. This section provides a summary of these formulas. They shall be used appropriately based on the loading conditions of the plate between stiffeners. Both serviceability and strength limit states are provided herein although only the strength limit states were considered in the paper for computing strength reduction factors.

**UNIAXIAL COMPRESSION**

The ultimate strength \( f_u \) of plates under uniaxial compression stress are computed from one of the following two cases (Bleich 1952; Faulkner 1975):
1. for $a/b > 1.0$

$$f_v = \begin{cases} \sqrt{\frac{\pi^2}{3(1 - \nu^2)B^2}} & \text{if } B \geq 35 \\ \frac{2.25}{B} - \frac{125}{B^2} & \text{if } 1.0 \leq B < 35 \\ F_v & \text{if } B < 1.0 \end{cases}$$ (18)

2. for $a/b < 1.0$

$$f_v = F_v \left[ \alpha c + 0.08(1 - \alpha)(1 + \frac{1}{B^2}) \right] \leq F_v$$ (19)

where

- $F_v$ = yield strength (stress) of the plate,
- $\alpha = \frac{a}{b}$, aspect ratio of the plate,
- $a$ = length or span of the plate,
- $b$ = distance between longitudinal stiffeners
- $B = \frac{b}{t \sqrt{E}}$, plate slenderness ratio,
- $\nu$ = Poisson's ratio,
- $t$ = thickness of the plate,
- $E$ = the modulus of elasticity,
- $\alpha_c$ = aspect ratio of the plate,
- $c = \frac{a}{b}$, aspect ratio of the plate.

and

$$C_v = \begin{cases} \sqrt{\frac{\pi^2}{3(1 - \nu^2)B^2}} & \text{if } B \geq 35 \\ \frac{2.25}{B} - \frac{125}{B^2} & \text{if } 1.0 \leq B < 35 \\ 10 & \text{if } B < 1.0 \end{cases}$$ (20)

**EDGE SHEAR**

According to Basler (1963), the ultimate strength $f_{urt}$ of plates under pure edge shear stress can be computed as

$$f_{urt} = F_{ert} + F_{prt}$$ (21)

where $F_{ert}$ = critical or buckling stress and $F_{prt}$ = post-buckling strength using tension field action.

The buckling strength can be computed based on one of the following three conditions that correspond to shear yield, inelastic buckling, and elastic buckling:

$$F_{ert} = \begin{cases} F_y \sqrt{\frac{\pi^2 F_y^2}{12(1 - \nu^2)B^2}} & \text{if } B \leq \sqrt{\frac{k}{Q}} \frac{12(1 - \nu^2)B^2}{F_{y}} \\ \sqrt{\frac{k}{Q}} \frac{12(1 - \nu^2)B^2}{F_{y}} - F_y^2 & \text{if } \sqrt{\frac{k}{Q}} \frac{12(1 - \nu^2)B^2}{F_{y}} < B \leq \sqrt{\frac{k}{Q}} \frac{12(1 - \nu^2)B^2}{F_{y}} \\ \sqrt{\frac{k}{Q}} \frac{12(1 - \nu^2)B^2}{F_{y}} & \text{if } B > \sqrt{\frac{k}{Q}} \frac{12(1 - \nu^2)B^2}{F_{y}} \end{cases}$$ (22)
where $F_{cr} = \text{yield stress in shear}$ and $F_{p} = \text{proportional limit in shear}$ that can be taken as 0.8 $F_{cr}$. The buckling coefficient $k$, can be obtained from Figure 2 or from the following two expressions depending on whether the plate under pure shear is simply supported or clamped:

$$\frac{F_{cr}}{F_{p}} = k \frac{\pi^2}{12} \left( \frac{1}{\alpha} \right)^2$$

1. For $\alpha \geq 10$,

$$k = \begin{cases} 
5.35 + \frac{4.0}{\alpha^2} & \text{for simple supports} \\
8.98 + \frac{5.6}{\alpha^2} & \text{for clamped supports}
\end{cases}$$

(23)
2. for $\alpha \leq 10$, 

$$k = \begin{cases} 
4.0 + \frac{5.35}{\alpha^2} & \text{for simple supports} \\
5.6 + \frac{8.98}{\alpha^2} & \text{for clamped supports}
\end{cases}$$

(24)

The yield stress in shear $F_{y\tau}$ is given by

$$F_{y\tau} = \frac{F_y}{\sqrt{3}}$$

(25)

where $F_y =$ yield stress of the plate.

The post-buckling shear strength $F_{\tau}$ is given by

$$F_{\tau} = \frac{F_y - \sqrt{3}F_{y\tau}}{2\sqrt{1 + \alpha^2}}$$

(26)

where $\alpha$ is the aspect ratio of the plate ($a/b$). If the aspect ratio $\alpha$ exceeds 3.0, tension field action is not permitted. In this case, the ultimate shear stress of a plate shall be based on elastic and inelastic buckling theory such that

$$f_{\tau u} = F_{\tau}$$

(27)

where $F_{\tau}$ can be computed from Equation (22).

**LATERAL PRESSURE**

The ultimate strength $f_{u\sigma}$ of plates under lateral pressure is given as (Bruchman and Dinsenbacher 1991)

$$f_{u\sigma} = \frac{2.222F_y^2}{EB^2} \left[ \frac{w}{b} \right]^{\frac{1}{2}} \left[ \frac{1}{0.00356 + 0.01988\tanh\left( \frac{B}{60F_y} \right)} + 1 \right]$$

(28)

where $F_y =$ yield strength (stress) of the plate, $b =$ distance between longitudinal stiffeners or plate width, $B =$ slenderness ratio of the plate, $w =$ specified permanent set.

Values for the ratio of the permanent set to plate width ($w/b$) or the permanent set to plate thickness ($w_t/b$) vary with both the material type and the location of a plate within the ship. When using Equation (28), these values can be obtained from Tables 2 and 3, respectively.

**BIAXIAL COMPRESSION**

The ultimate strength $f_{u\sigma}$ and $f_{u\tau}$ of plates under biaxial compression stresses should meet the requirement of the following interaction equation (Valsgard 1980; Frieze et al. 1977):

$$\left( \frac{f_{xu}}{f_{xu}} \right)^2 + \left( \frac{f_{yu}}{f_{yu}} \right)^2 - \eta_b \left( \frac{f_{xu}}{f_{yu}} \right) \left( \frac{f_{yu}}{f_{yu}} \right) \leq 1$$

(29)

where

$$\eta_b = \begin{cases} 
0.25 & \text{if } \alpha \geq 3.0 \\
0.25 + \left( \frac{\alpha - 3}{2} \right) [32e^{-0.33\alpha} - 2.25] & \text{if } 1.0 < \alpha < 3.0 \\
32e^{-0.33\alpha} - 2 & \text{if } \alpha = 1.0
\end{cases}$$

(30)

and $\alpha = a/b$ the aspect ratio of the plate, $f_x =$ the applied stress in the $x$-direction, $f_y =$ the applied stress in the $y$-direction, $f_{\sigma} =$ the ultimate strength of the plate under compressive normal stress in the $x$-direction acting alone, and $f_{\tau} =$ the ultimate strength of the plate under compressive normal stress in the $y$-direction acting alone.

The ultimate stresses $f_{\sigma}$ and $f_{\tau}$ can be computed from Equations (18) and (19), respectively. It should be noted that when using Equations (18) and (19) for calculating both $f_{\sigma}$ and $f_{\tau}$, the
Table 2

Ranges of the Ratio $w_c/b$

<table>
<thead>
<tr>
<th>ALUMINUM OR STEEL TYPE</th>
<th>YIELD STRENGTH $F_y$ (ksi)</th>
<th>TOP SIDE</th>
<th>LOWER SHELL/TANK</th>
<th>FLOODING/DAMAGE CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIN</td>
<td>REC</td>
<td>MAX</td>
<td>MIN</td>
</tr>
<tr>
<td>AL5086</td>
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<td>0.000</td>
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<td>0.000</td>
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<td>0.000</td>
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</tr>
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</table>

Table 3

Ranges of the Ratio $w_c/t$

<table>
<thead>
<tr>
<th>ALUMINUM OR STEEL TYPE</th>
<th>YIELD STRENGTH $F_y$ (ksi)</th>
<th>TOP SIDE</th>
<th>LOWER SHELL/TANK</th>
<th>FLOODING/DAMAGE CONTROL</th>
</tr>
</thead>
<tbody>
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</tr>
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</table>

Length of the plate $(a)$ is assumed to coincide with the $x$-direction and the aspect ratio $(l/a)$ is greater than unity. If, however, $(a/l)$ is less than unity, then $f_{uy}$ and $f_x$ should be interchanged in Equations (18) and (19).

BIAXIAL COMPRESSION AND EDGE SHEAR

The ultimate strength $f_{ux}, f_{vy},$ and $f_x$ of plates under biaxial compression and edge shear stresses should meet the requirement of following interaction equation as adopted by the API (1993) and the DnV (1977):

$$\left(\frac{f_x}{f_{ux}}\right)^2 + \left(\frac{f_y}{f_{vy}}\right)^2 + \left(\frac{f_{xy}}{f_{ux}}\right)^2 \leq 1$$  \hspace{1cm} (31)

where $f_x$ = the applied stress in the $x$-direction, $f_y$ = the applied stress in the $y$-direction, $f_{xy}$ = the applied shear stress, $f_{ux}$ = the ultimate strength of a plate under compressive normal stress in the $x$-direction acting alone, $f_{vy}$ = the ultimate strength of a plate under compressive normal stress in the $y$-direction acting alone, and $f_{xy}$ = the ultimate shear stress when the plate is subjected to pure edge shear. The ultimate stresses $f_{ux}, f_{vy}, f_x$ can be computed from Equations (18), (19), and (21), respectively.

OTHER LOAD COMBINATIONS WITH LATERAL PRESSURE

The loading conditions for unstiffened plates that are covered in this section are the combined in-plane and lateral pressure loads. Lateral pressure in combination with the other cases of loading presented in the previous sections can lead to a number of loading conditions that can have an effect on the overall strength of plates. The following cases can be identified:

1. Lateral pressure and uniaxial compression
2. Lateral pressure and biaxial compression
3. Lateral pressure, uniaxial compression, and edge shear
4. Lateral pressure, biaxial compression, and edge shear
5. Lateral pressure and edge shear

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LRFD Guidelines for Unstiffened Panels

**TARGET RELIABILITY LEVELS**

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

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

The recommended range of target reliability indices for unstiffened panel can be set to range from three to four (Mansour et al. 1996).

**STATISTICAL CHARACTERISTICS OF BASIC RANDOM VARIABLES**

The statistical characteristics of random variables of strength and load models are needed for reliability-based LRFD design and assessment of ship structures including unstiffened panels. The moment methods for calculating partial safety factors (Ang and Tang 1990; Ayyub and McCuen 1997; and Ayyub and White 1978) require full probabilistic characteristics of both strength and load variables in the limit state equation. For example, the relevant strength variables for an unstiffened panel element are the material’s yield strength (stress) $F_y$, length of a panel $a$, and thickness $t$ of a plate. While the relevant loads variables are the external pressures because of stillwater bending moment, wave bending moment, and dynamic loads.

The definition of these random variables requires the investigation of their uncertainties and variability. In a reliability assessment of any structural system, these uncertainties must be quantified. Furthermore, a partial safety factor (PSF) evaluation for both the
strength 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 $\beta$ or the PSFs. 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 $COVs$, 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 4, 5 and 6 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 (1998) and Assakkaf (1998).

Tables 7 through 10 provide all the recommended values of information required for establishing reliability-based LRFD guidelines for unstiffened panels of ship structures. This information includes limit state functions for different load combinations and 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 (biases) of these random variables, deterministic values of the probabilistic load-combination factors; mean ratios between different load components, the biases between different values of each of the random variables; and probabilistic characteristics of model and prediction uncertainty parameters. This information is needed to calculate partial safety factors (PSFs) for unstiffened panels using, for example, FORM as discussed in Ayyub et al. (2002a).

### CALCULATIONS OF PARTIAL SAFETY FACTORS

In this section, calculations of partial safety factors (PSFs) of both strength and load components in limit state functions for unstiffened ship plates are presented for demonstration purposes. The first-order

---

**Table 5a**


<table>
<thead>
<tr>
<th>RANDOM VARIABLE</th>
<th>BIASES INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of Plate $t$ (in)</td>
<td>Minimum $t$, Recommended $t$, Maximum $t$</td>
</tr>
<tr>
<td>Length of Plate $a$ (in)</td>
<td>Minimum $a$, Recommended $a$, Maximum $a$</td>
</tr>
<tr>
<td>Width of Plate $b$ (in)</td>
<td>Minimum $b$, Recommended $b$, Maximum $b$</td>
</tr>
</tbody>
</table>

$n/a = not available$

---

**Table 5b**


<table>
<thead>
<tr>
<th>RANDOM VARIABLE</th>
<th>STATISTICAL INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS $F_y$ (ksi)</td>
<td>Minimum 33.8, Recommended 37.3, Maximum 44.0</td>
</tr>
<tr>
<td>HS $F_y$ (ksi)</td>
<td>Minimum 39.6, Recommended 49.6, Maximum 66.0</td>
</tr>
<tr>
<td>$F_u$ (ksi)</td>
<td>Minimum 59.3, Recommended 61.6, Maximum 64.3</td>
</tr>
<tr>
<td>$E$ (ksi)</td>
<td>Minimum 28,980, Recommended 29,696, Maximum 30,200</td>
</tr>
</tbody>
</table>

$OS = Ordinary Steel, HS = Higher Strength Steel$
### Table 6

**Probabilistic Characteristics of Load Random Variables (Atua 1998)**

<table>
<thead>
<tr>
<th>RANDOM VARIABLE</th>
<th>DISTRIBUTION TYPE</th>
<th>MEAN TO NOMINAL RATIO</th>
<th>COEFFICIENT OF VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stillwater Bending Moment $M_{sw}$</td>
<td>Normal</td>
<td>0.4 to 0.6 for commercial ships, and 0.7 for naval vessels</td>
<td>0.3 to 0.9 for commercial ships, and 0.15 for naval vessels</td>
</tr>
<tr>
<td>Life-time Extreme Wave-induced Bending Moment $M_{w}$</td>
<td>Largest extreme value</td>
<td>1.0 (type I) Mean value can be determined using formulae based on spectral analysis</td>
<td>0.2 to 0.3</td>
</tr>
<tr>
<td>Whipping Bending Moment $M_{w}$</td>
<td>Extreme value (type I)</td>
<td>1.0</td>
<td>0.1 to 0.2</td>
</tr>
<tr>
<td>Springing Bending Moment $M_{sp}$</td>
<td>Extreme value (type I)</td>
<td>0.4 to 0.6 for commercial ships, and 0.7 for naval vessels</td>
<td>0.3</td>
</tr>
<tr>
<td>Hydrostatic Pressure because of Stillwater, $P_{sw}$</td>
<td>Normal</td>
<td>1.0</td>
<td>0.15</td>
</tr>
<tr>
<td>Hydrostatic Pressure because of Waves, $P_{w}$</td>
<td>Largest extreme value (type I)</td>
<td>1.0</td>
<td>0.15</td>
</tr>
<tr>
<td>Hydrostatic Pressure because of Dynamic Effects, $P_{d}$</td>
<td>Normal</td>
<td>1.0</td>
<td>0.15</td>
</tr>
<tr>
<td>Hydrostatic Pressure because of Combined Waves and Dynamic Loads, $P_{ax}$</td>
<td>Weibull</td>
<td>1.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### Table 7

**Recommended Total Bias and Coefficients of Variation (COV) for the Strength of Unstiffened Panel (Assakkaf 1998)**

<table>
<thead>
<tr>
<th>LOADING CASE</th>
<th>DISTRIBUTION TYPE</th>
<th>TOTAL BIAS $B_I$</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial Compression</td>
<td>Lognormal</td>
<td>1.16</td>
<td>18</td>
</tr>
<tr>
<td>Edge shear</td>
<td>Lognormal</td>
<td>1.13</td>
<td>20</td>
</tr>
<tr>
<td>Uniform Lateral Pressure</td>
<td>Lognormal</td>
<td>1.11</td>
<td>17</td>
</tr>
<tr>
<td>Biaxial Compression</td>
<td>Lognormal</td>
<td>1.10</td>
<td>20</td>
</tr>
<tr>
<td>Biaxial Compression and Edge Shear</td>
<td>Lognormal</td>
<td>1.06</td>
<td>11</td>
</tr>
</tbody>
</table>

### Table 8

**Recommended Total Bias and Coefficients of Variation (COV) for Basic Loads Acting on a Ship (Atua and Ayyub 1996)**

<table>
<thead>
<tr>
<th>TYPE OF LOAD</th>
<th>ABV. $M_{sw}$</th>
<th>DISTRIBUTION TYPE</th>
<th>TOTAL BIAS $B_I$</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stillwater Bending Moment</td>
<td>Normal</td>
<td>1.0</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Wave-induced and Dynamic Bending Moment</td>
<td>$M_{wd}$</td>
<td>Weibull</td>
<td>1.0</td>
<td>25</td>
</tr>
<tr>
<td>Waves Bending Moment</td>
<td>$M_{w}$</td>
<td>Type I Largest</td>
<td>1.0</td>
<td>15</td>
</tr>
<tr>
<td>Dynamic Bending Moment because of Whipping</td>
<td>$M_{d}$</td>
<td>Type I Largest</td>
<td>0.97</td>
<td>25</td>
</tr>
</tbody>
</table>

The reliability method (FORM) as outlined in Ayyub et al. (2002a) was used to develop the partial safety factors. The partial safety factors are defined as the ratio of the value of a variable in a limit state at its most probable failure point to the nominal value. The first section summarizes the methods for calculating partial safety factors. It also gives a brief review of recommended load and load combinations and their probabilistic characteristics used in computing the partial safety factors. The second section describes the development of a program for computing partial safety factors based on FORM as outlined in Ayyub et al. (2002a). The final section summarizes the results of partial safety factors calculations for an unstiffened panel under uniaxial compression.

**Performance Functions for Calculating Partial Safety Factors for Unstiffened Panels**

Reliability-based design LRFD format involves the ultimate strength capacity of an unstiffened plate element and the load random variable of stillwater, wave-induced, and dynamic...
bending moments. The partial safety factors format allows transforming the desired reliability index into separate safety factors for each of the design variables in the recommended format. Two recommended limit state formats for unstiffened panels are provided as follows:

### Table 9

<table>
<thead>
<tr>
<th>RATIO</th>
<th>RECOMMENDED VALUE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{M}_w / \overline{M}_w$</td>
<td>0.25 to 0.35</td>
<td>Mansour et al. (1996)</td>
</tr>
<tr>
<td>$\overline{M}_0 / \overline{M}_w$</td>
<td>0.25 to 0.35</td>
<td>Mansour et al. (1996)</td>
</tr>
<tr>
<td>$\overline{M}_{w0} / \overline{M}_w$</td>
<td>1.0 to 1.35</td>
<td>Assumed values</td>
</tr>
</tbody>
</table>

### Table 10

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>DETERMINISTIC VALUE</th>
<th>REFERENCES AND COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_w$</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>$k_0$</td>
<td>$\exp\left(\frac{53080}{\frac{581 LBP^{0.2}}{142 LBP^{0.3}} + \frac{142 LBP^{0.3}}{LBP}}\right)$ (Hogging)</td>
<td>Reference (Sikora et al. 1983) and Atua et al. (1996) - Ranging from 0.35 to 0.65 for LBP = (400 to 800) ft</td>
</tr>
<tr>
<td>$k_{w0}$</td>
<td>$\exp\left(\frac{21200}{\frac{581 LBP^{0.2}}{142 LBP^{0.3}} + \frac{142 LBP^{0.3}}{LBP}}\right)$ (Sagging)</td>
<td>- Ranging from 0.65 to 0.85 for LBP = (400 to 800) ft - Assumed value as defined in Sikora et al. (1983)</td>
</tr>
</tbody>
</table>

**Limit State I:**

$$g(R_u, f_{SW}, f_{WD}) = R_u - f_{SW} - k_{w0} f_{WD} \quad (32)$$

**Limit State II:**

$$g(R_u, f_{SW}, f_{SW}, f_{W}) = R_u - f_{SW} - k_0 (f_W + k_{w0} f_{W}) \quad (33)$$

where $g$ = the limit state or performance function, $f_{SW}$ = stress due to stillwater bending moment, $f_{w0}$ = stress due to combined wave-induced and dynamic bending moments, $f_w$ = stress due to waves bending moment, $k_{w0}$ = combined wave-induced and dynamic bending moments factor equals unity, $k_0$ = load combination factor equals unity, $k_w$ = load combination factor equals 0.7, and $R_u$ = ultimate strength capacity of an unstiffened plate. The ultimate strength capacity $R_u$ depends on the loading conditions for the plate (i.e., uniaxial, edge shear, etc.) and is given by the design strength models as previously described. The two limit states given by Equations (32) and (33) are referred to as limit state 1 and 2, respectively.

The load and load combinations probabilistic characteristics are shown in Table 8. The recommended mean and nominal load factors based on hull-girder bending are given in **Tables 11** and **12**, respectively. The recommended values for the load components in Table 8 were used to develop the partial safety factors for the loads and the strength models, while the recommended load factors of Tables 11 and 12 were used to calibrate the strength factors based on the recommended load factors.

**Development of FORM-based Partial Safety Factors**

The generalized FORM was selected to calculate the partial safety factors for the formats as given in Equations (32) and (33) because of the existence of non-normal basic random variables in the corresponding limit states for unstiffened panels. The generalized form of the limit state function can be set in any computational tool to the following form:

$$g(X) = C_1 X^{x_1} X_{y_1}^{x_{y_1}} + C_2 X^{x_2} X_{y_2}^{x_{y_2}} + C_3 X^{x_3} X_{y_3}^{x_{y_3}} X_{y_4}^{x_{y_4}}$$

$$X_{y_5}^{x_{y_5}} X_{y_6}^{x_{y_6}} \quad (34)$$
Table 11

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$\gamma_p$</th>
<th>$\gamma_{wd}$</th>
<th>$\gamma_{sw}$</th>
<th>$\gamma_{f_d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>1.05</td>
<td>1.30</td>
<td>1.20</td>
<td>1.05</td>
</tr>
<tr>
<td>3.5</td>
<td>1.05</td>
<td>1.35</td>
<td>1.25</td>
<td>1.05</td>
</tr>
<tr>
<td>4.0</td>
<td>1.05</td>
<td>1.40</td>
<td>1.30</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 12

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$\gamma_p$</th>
<th>$\gamma_{wd}$</th>
<th>$\gamma_{sw}$</th>
<th>$\gamma_{f_d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>1.05</td>
<td>1.30</td>
<td>1.20</td>
<td>1.05</td>
</tr>
<tr>
<td>3.5</td>
<td>1.05</td>
<td>1.35</td>
<td>1.25</td>
<td>1.05</td>
</tr>
<tr>
<td>4.0</td>
<td>1.05</td>
<td>1.40</td>
<td>1.30</td>
<td>1.05</td>
</tr>
</tbody>
</table>

\[ + C_s X_s^1 X_s^w + C_s X_s^w X_s^m X_s^{11} \]

where $g(X)$ = performance function, $C_s$ = deterministic coefficient, $X_i$ = probabilistic basic random variables, $n$ = real-valued power.

By equating the reliability index, $\beta$, with the target reliability index, $\beta_{0s}$, the partial safety factors are computed. The strength variables in the limit state at the design point are given by

\[ R_u^* = f_{sw}^* + k_{wd}f_{wd}^* \]  
\[ R_u^* = f_{sw}^* + k_w f_{w}^* + k_{wd} f_{wd}^* \]

(35)

(36)

Then the partial safety factors are computed as follows:

\[ \gamma_{f_u} = \frac{R_u^*}{R_u} \]

(37)

\[ \gamma_{f_{sw}} = \frac{f_{sw}^*}{f_{sw}} \]  
\[ \gamma_{f_{wd}} = \frac{f_{wd}^*}{f_{wd}} \]

(38)

(39)

\[ \gamma_{f_{sw}} = \frac{f_{sw}^*}{f_{sw}} \]  
\[ \gamma_{f_{wd}} = \frac{f_{wd}^*}{f_{wd}} \]

(40)

\[ \gamma_{f_{f_d}} = \frac{f_{f_d}^*}{f_{f_d}} \]

(41)

where the subscript $n$ means nominal value.

The partial safety factors calculations are iterative in nature to search for the PSFs that satisfy the target reliability level, $\beta_s$. In this iterative procedure, only one input variable is varied. In the limit states of Equations (32) and (33), this variable is the mean value of the ultimate capacity $R_u$ of a plate.

Results of the Partial Safety Factors Calculations

In this example, results of partial safety factors calculations for unstiffened panel under uniaxial compression are demonstrated. Similar results can be achieved for unstiffened panels under various type of loading (i.e., edge shear, lateral pressure, etc.). The two formats for limit states as given by Equations (32) and (33) were selected for the development of partial safety factors (PSFs). The ultimate strength $f_u$ of plates under uniaxial compression stress is given by Equations (18) and (19). The recommended range of target reliability index $\beta_0$ for unstiffened plates under uniaxial compression stress was set to be from three to four. These values are used in calculating the PSFs for both the strength and the loads.

Limit State 1:

The limit state function for plates under uniaxial compression is given by

\[ g = f_u - f_{sw} - k_{wd} f_{wd} \]

(42)

where $f_u$ is the ultimate strength for plates under uniaxial compression as defined by Equation (18) and (19), $f_{sw}$ = stress because of stillwater bending moment, $f_{wd}$ = stress because of combined wave-induced and dynamic bending moments, and $k_{wd}$ = combined wave-induced and dynamic bending moment factor set equal to unity (Mansour et al. 1996). The mean values of stillwater and combined wave-induced and dynamic stresses are given in the form of a ratio of $f_{sw}/f_{sw}$ as shown in Table 13. The table also shows the ranges of the target reliability index $\beta_s$ and the uncertainty (COV) in the strength $f_u$. The probabilistic characteristics for
Table 13
Ranges of Key Parameters for Limit State I

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_0$</td>
<td>3.0, 3.5, and 4.0</td>
</tr>
<tr>
<td>COV ($f_w$)</td>
<td>0.18</td>
</tr>
<tr>
<td>$f_{sw}/f_{wo}$</td>
<td>0.1, 0.2, and 0.3</td>
</tr>
</tbody>
</table>

both the strength and the loads are summarized in Table 14. The results of the partial safety factors using FORM (ASM) are provided in Table 15. Calibration (recalculation) of the strength factor for a recommended set of load factors is given in Tables 16 and 17.

Limit State II:
The limit state function for plates under uniaxial Compression is given by

$$g = f_u - f_{sw} - k_w (f_{sw} + k_0 f_w)$$  (43)

where $f_u$ is the ultimate strength for plates under uniaxial compression as defined by Equations (18) and (19), $f_{sw}$ = stress because of stillwater bending moment, $f_w$ = stress because of wave bending moment, $f_0$ = stress because of dynamic bending moment, $k_w$ = load combination factor equals 1.0 (Mansour et al. 1996), and $k_0$ = load combination factor equals 0.7 (Mansour et al. 1996). The mean values of stillwater, wave, and dynamic stresses are given in the form of a ratio of $f_{sw}/f_w$ as shown in Table 18. The table also shows the ranges of the target index $\beta$ and the uncertainty (COV) in the strength $f_u$. The probabilistic characteristics for both the strength and the loads are summarized in Table 19. The results of the partial safety factors using FORM (ASM) are provided in Table 20. Calibration (recalculation) of the strength factor for a recommended set of load factors is given in Tables 21 and 22.

Table 14
Probabilistic Characteristic of Strength and Loads for Limit State I

<table>
<thead>
<tr>
<th>RANDOM VARIABLE</th>
<th>COV (RECOMMENDED)</th>
<th>DISTRIBUTION TYPE</th>
<th>TOTAL BIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_u$</td>
<td>0.18 (0.18)</td>
<td>Lognormal</td>
<td>1.16</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>0.15 (0.15)</td>
<td>Normal</td>
<td>1.0</td>
</tr>
<tr>
<td>$f_w$</td>
<td>0.22 to 0.29 (0.25)</td>
<td>Weibull</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 15
Results of Partial Safety Factors Calculations using FORM (ASM) for Limit State I

<table>
<thead>
<tr>
<th>$f_d$</th>
<th>Mean of $F_s$</th>
<th>$\psi_s$</th>
<th>$\gamma_w$</th>
<th>$\gamma_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>2.56</td>
<td>0.64</td>
<td>1.04</td>
<td>1.43</td>
</tr>
<tr>
<td>3.5</td>
<td>2.85</td>
<td>0.59</td>
<td>1.04</td>
<td>1.47</td>
</tr>
<tr>
<td>4.0</td>
<td>2.17</td>
<td>0.54</td>
<td>1.05</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Table 16
Recommended Mean Strength and Load Factors for Limit State I

<table>
<thead>
<tr>
<th>$\beta_0$</th>
<th>$\psi$</th>
<th>$\gamma_w$</th>
<th>$\gamma_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.65</td>
<td>1.05</td>
<td>1.45</td>
</tr>
<tr>
<td>3.5</td>
<td>0.60</td>
<td>1.05</td>
<td>1.50</td>
</tr>
<tr>
<td>4.0</td>
<td>0.55</td>
<td>1.05</td>
<td>1.55</td>
</tr>
</tbody>
</table>

Table 17
Recommended Nominal Strength and Load Factors for Limit State I

<table>
<thead>
<tr>
<th>$\beta_0$</th>
<th>$\psi$</th>
<th>$\gamma_w$</th>
<th>$\gamma_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.75</td>
<td>1.05</td>
<td>1.45</td>
</tr>
<tr>
<td>3.5</td>
<td>0.70</td>
<td>1.05</td>
<td>1.50</td>
</tr>
<tr>
<td>4.0</td>
<td>0.64</td>
<td>1.05</td>
<td>1.55</td>
</tr>
</tbody>
</table>

Table 18
Ranges of Key Parameters for Limit State II

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_0$</td>
<td>3.0, 3.5, and 4.0</td>
</tr>
<tr>
<td>COV ($f_w$)</td>
<td>0.18</td>
</tr>
<tr>
<td>$f_{sw}/f_{wo}$</td>
<td>0.2, 0.3, and 0.4</td>
</tr>
<tr>
<td>$f_{sw}/f_w$</td>
<td>0.25, 0.30, and 0.35</td>
</tr>
</tbody>
</table>

Table 19
Probabilistic Characteristic of Strength and Loads for Limit State II

<table>
<thead>
<tr>
<th>RANDOM VARIABLE</th>
<th>COV (RECOMMENDED)</th>
<th>DISTRIBUTION TYPE</th>
<th>TOTAL BIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_u$</td>
<td>0.18 (0.18)</td>
<td>Lognormal</td>
<td>1.16</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>0.15 (0.15)</td>
<td>Normal</td>
<td>1.0</td>
</tr>
<tr>
<td>$f_w$</td>
<td>0.1 to 0.2 (0.15)</td>
<td>Type I Largest</td>
<td>1.0</td>
</tr>
<tr>
<td>$f_0$</td>
<td>0.2 to 0.3 (0.25)</td>
<td>Type I Largest</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Table 20

Results of Partial Safety Factors Calculations using FORM (ASM) for Limit State II

<table>
<thead>
<tr>
<th>$\beta_0$</th>
<th>Mean of $f_r$</th>
<th>$\phi_s$</th>
<th>$\gamma_{sw}$</th>
<th>$\gamma_w$</th>
<th>$\gamma_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>2.87</td>
<td>0.65</td>
<td>1.05</td>
<td>1.33</td>
<td>1.05</td>
</tr>
<tr>
<td>3.5</td>
<td>3.23</td>
<td>0.62</td>
<td>1.05</td>
<td>1.45</td>
<td>1.06</td>
</tr>
<tr>
<td>4.0</td>
<td>3.46</td>
<td>0.59</td>
<td>1.05</td>
<td>1.59</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Table 21

Recommended Mean Strength and Load Factors for Limit State II

<table>
<thead>
<tr>
<th>$\beta_0$</th>
<th>$\phi_s$</th>
<th>$\gamma_{sw}$</th>
<th>$\gamma_w$</th>
<th>$\gamma_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.71</td>
<td>1.05</td>
<td>1.40</td>
<td>1.10</td>
</tr>
<tr>
<td>3.5</td>
<td>0.88</td>
<td>1.05</td>
<td>1.55</td>
<td>1.10</td>
</tr>
<tr>
<td>4.0</td>
<td>0.88</td>
<td>1.05</td>
<td>1.70</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Table 22

Recommended Nominal Strength and Load Factors for Limit State II

<table>
<thead>
<tr>
<th>$\beta_0$</th>
<th>$\phi_s$</th>
<th>$\gamma_{sw}$</th>
<th>$\gamma_w$</th>
<th>$\gamma_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.83</td>
<td>1.05</td>
<td>1.40</td>
<td>1.10</td>
</tr>
<tr>
<td>3.5</td>
<td>0.79</td>
<td>1.05</td>
<td>1.55</td>
<td>1.10</td>
</tr>
<tr>
<td>4.0</td>
<td>0.79</td>
<td>1.05</td>
<td>1.70</td>
<td>1.10</td>
</tr>
</tbody>
</table>

and is given by the design strength models as previously described. The two limit states given by Equations (13) and (14) are referred to as limit state 1 and 2, respectively.

The nominal (i.e., design) values of the strength and load components shall satisfy these formats in order to achieve specified target reliability levels. The strength factors are provided in Table 23 in accordance with the following parameters: (1) target reliability level ranging from three to four, (2) the type of load combinations as shown in the table, and (3) ultimate strength prediction for unstiffened panel as previously provided. The target reliability should be selected based on the ship type and usage. Then, the corresponding factor can be looked up from Table 23 based on the strength model under consideration. The load factors that can be used in conjunction with strength factors are provided in Table 24.

**Design Examples**

The following two examples demonstrate the use of LRFD-based partial safety in the limit state equation for designing and checking the adequacy of unstiffened panels of ships:

**EXAMPLE 1: PLATE DESIGN**

Given: A 48"x 24"x $t$ unstiffened plate element is to be designed at the bottom deck of a ship to withstand a uniaxial compression stress because of environmental bending moment loads acting on the ship. The stresses because of the environmental loads are estimated to have the following values: 12 ksi because of stillwater bending, 4.8 ksi because of wave bending, and 1.8 ksi because of dynamic bending. If the yield strength of steel is 34 ksi, design the thickness $t$ of the plate assuming a target level of three.

Solution: For unstiffened panel under uniaxial compression, the strength is given by Equation (18) as

$$ f_n = \begin{cases} 
    F_s \sqrt{\frac{t^2}{3(1-\nu_b)B^2}} & \text{if } B \geq 3.5 \\
    F_s & \text{if } 1.0 \leq B < 3.5 \\
    F_y & \text{if } B < 1.0 
\end{cases} $$

Assume that $t = 0.25$ in., therefore
\[ B = \frac{b}{t} \sqrt{\frac{F_p}{E}} = \frac{24}{0.25} \sqrt{\frac{34}{29000}} = 3.29 \]

and

\[ f_s = f_y \left( \frac{2.25}{B} - \frac{1.25}{B^2} \right) = \frac{34}{(2.25 - 1.25)} = 19.33 \text{ ksi} \]

The design of the plate should meet the requirement of the LRFD guidelines as given in Tables 23 and 24 for the limit state under consideration and the appropriate partial safety factors for \( f_0 = 3.0 \), that is,

\[ \phi_{f_0} = \gamma_{sw} f_{sw} + k_w (\gamma_d f_d + \gamma_D k_D f_D) \]

\[ \phi_{f_u} = 0.83(19.33) = 16.04 \text{ ksi} \]

\[ \gamma_{sw} f_{sw} + k_w (\gamma_d f_d + \gamma_D k_D f_{sw}) = (1.05) (12) + (1) [1.4 (4.8) + (1.1) (0.7) (1.8)] = 20.7 \text{ ksi} \]

\[ \phi_{f_u} = 16.04 \text{ ksi } < 20.7 \text{ ksi } \]

Try a value of \( t = 0.350 \text{ in.} \), therefore unacceptable

\[ B = \frac{b}{t} \sqrt{\frac{F_p}{E}} = \frac{24}{0.35} \sqrt{\frac{34}{29000}} = 2.3 \]

and

\[ f_s = f_y \left( \frac{2.25}{B} - \frac{1.25}{B^2} \right) = \frac{34}{(2.25 - 1.25)} = 25.23 \text{ ksi} \]

\[ \phi_{f_u} = 20.94 \text{ ksi } > 20.7 \text{ ksi } \text{ acceptable} \]

Hence, select \( PL: 48 \times 24 \times 0.35 \)

**EXAMPLE 2: ADEQUACY CHECKING**

*Given:* Suppose that the plate of Example 1 is to be checked for the effect of lateral pressure. Would this plate be adequate to withstand the lateral pressure generated by the environmental loads?

*Solution:* For an unstiffened panel under pure lateral pressure, the strength is given by Equation (28) as
Reliability-Based Load and Resistance Factor Design (LRFD) Guidelines for Unstiffened Panels of Ship Structures

\[
f_{wp} = \frac{2222F_y^2}{EB^2} \left[ \frac{w_s}{b} \left( 0.00356 + 0.01988 \tanh \left( \frac{B}{60} \sqrt{\frac{E}{F_y}} \right) \right) \right]^{\frac{1}{3}} + 1
\]

For MS Steel, and Lower Shell/Tank, Table 3 gives

\[
\frac{w_s}{b} = 0.009
\]

With \( \beta = 3.0 \) as computed in Example 1, therefore,

\[
f_{wp} = \frac{2222(34)^2}{29000(3)^2} \left[ \frac{0.009}{0.00356 + 0.01988 \tanh \left( \frac{3}{60} \sqrt{\frac{29000}{34}} \right) } \right]^{\frac{1}{3}} + 1 = 17.21 \text{ ksi}
\]

The design of the plate should meet the requirement of the LRFD guidelines as given in Tables 23 and 24 for the limit state under consideration and the appropriate partial safety factors for \( \beta_0 = 3.0 \), that is,

\[
\phi f_{wp} \geq \gamma_{SW} f_{SW} + \gamma_w f_w + \gamma_D k_D f_D
\]

\[
\phi f_{wp} = 0.47(17.21) = 8.09 \text{ ksi}
\]

\[
\gamma_{SW} f_{SW} + \gamma_w f_w + \gamma_D k_D f_D = (1.05)(12) + (1) [1.4 \times (4.8) + (1.1) (0.7) (1.8)] = 20.7 \text{ ksi}
\]

\( \phi f_w = 8.09 \text{ ksi} \) < 20.7 ksi unacceptable

Hence, the plate will not be adequate for lateral pressure. A new plate should be designed.

Summary and Conclusions

Future design guidelines for unstiffened panels of ship structures 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 LRFD guidelines for unstiffened panels, which are based on structural reliability theory, can be built on previously 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 unstiffened plate elements subjected to various types of loading. These design methods were developed according to the following requirements: (1) spectral analysis of wave loads, (2) building on conventional codes, (3) nominal strength and load values, and (4) achieving target reliability levels.

The First-Order Reliability Method (FORM) was used to develop the LRFD-based partial safety factors (PSFs) for selected limit states and for various types of loading acting on unstiffened panel element. These factors were determined to account for the uncertainties in strength and load effects. FORM was used to
Table 23
Nominal Strength Factors for Unstiffened Panels

<table>
<thead>
<tr>
<th>LOADING CONDITION</th>
<th>LOAD COMBINATION</th>
<th>STRENGTH FACTORS, $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\phi_{SW}$, $\phi_{SW}$, $\phi_{WD}$, $\phi_{WD}$</td>
</tr>
<tr>
<td>Uniaxial Compression</td>
<td>$\phi_{SW} \geq \phi_{SW}$, $\phi_{SW}$, $\phi_{WD}$, $\phi_{WD}$</td>
<td>0.75, n/a, 0.70, n/a, 0.64, n/a</td>
</tr>
<tr>
<td>Edge Shear</td>
<td>$\phi_{SW} \geq \phi_{SW}$, $\phi_{SW}$, $\phi_{WD}$, $\phi_{WD}$</td>
<td>n/a, 0.70, n/a, 0.64, n/a, 0.59</td>
</tr>
<tr>
<td>Lateral Pressure</td>
<td>$\phi_{SW} \geq \phi_{SW}$, $\phi_{SW}$, $\phi_{WD}$, $\phi_{WD}$</td>
<td>n/a, 0.77, n/a, 0.73, n/a, 0.68</td>
</tr>
<tr>
<td></td>
<td>$\phi_{SW} \geq \phi_{SW}$, $\phi_{SW}$, $\phi_{WD}$, $\phi_{WD}$</td>
<td>n/a, 0.36, n/a, 0.34, n/a, 0.44</td>
</tr>
</tbody>
</table>

\[
\left( \frac{f_{1x}}{\phi_{ax}} \right)^2 + \left( \frac{f_{1y}}{\phi_{ay}} \right)^2 - \eta_b \left( \frac{f_{1x}}{\phi_{ax}} \phi_{ay} \right) \left( \frac{f_{1y}}{\phi_{ax}} \phi_{ay} \right) \leq 1
\]
\[
\left( \frac{f_{2x}}{\phi_{ax}} \right)^2 + \left( \frac{f_{2y}}{\phi_{ay}} \right)^2 - \eta_b \left( \frac{f_{2x}}{\phi_{ax}} \phi_{ay} \right) \left( \frac{f_{2y}}{\phi_{ax}} \phi_{ay} \right) \leq 1
\]
\[
\left( \frac{f_{1x}}{\phi_{ax}} \right)^2 + \left( \frac{f_{1y}}{\phi_{ay}} \right)^2 + \left( \frac{f_{1x}}{\phi_{ax}} \right)^2 \leq 1
\]
\[
\left( \frac{f_{2x}}{\phi_{ax}} \right)^2 + \left( \frac{f_{2y}}{\phi_{ay}} \right)^2 + \left( \frac{f_{2x}}{\phi_{ax}} \right)^2 \leq 1
\]

Note: $f_1$ and $f_2$ are the magnified applied stresses in $x, y,$ and $z$ direction; the subscripts refer to limit states $1$ and $2$, respectively, according to Eqs. 44 and 45; n/a = not applicable

Table 24
Nominal Load Factors

<table>
<thead>
<tr>
<th>TARGET RELIABILITY INDEX</th>
<th>$\gamma_{SW}$</th>
<th>$\gamma_{WD}$</th>
<th>$\gamma_{WD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>1.05</td>
<td>1.40</td>
<td>1.10</td>
</tr>
<tr>
<td>3.5</td>
<td>1.05</td>
<td>1.55</td>
<td>1.10</td>
</tr>
<tr>
<td>4.0</td>
<td>1.05</td>
<td>1.70</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Determine these factors based on prescribed probabilistic characteristic of strength and load effects. Also, strength factors were computed for a set of load factors to meet selected target reliability levels for demonstration purposes. The resulting LRFD guidelines are demonstrated in this paper using design examples.

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REFERENCES


Author’s Biographies

PROFESSOR BILAL M. AYYUB is the general director of the Center for Technology and Systems Management at the University of Maryland, College Park, Maryland. Dr. Ayyub completed his B.S.C.E. (1980), M.S.C.E. (1981), and Ph.D. (1983) at the Georgia Institute of Technology in Atlanta. He joined the University of Maryland in 1983 and presently is a professor of civil and environmental engineering at the University of Maryland, College Park. He directed the structures programs and now directs the project management program at the University of Maryland. He is a consultant and board member of two corporations that provide services in the areas of risk and decision analysis. As a registered professional engineer with the State of Maryland, Professor Ayyub is the recipient of several awards, including the ASNE “Jimmie” Hamilton Award for the best papers in the Naval Engineers Journal in 1985 and 1992, the ASCE Outstanding Research Oriented Paper in 1987, the NAFIPS K. S. Fu Award in 1995, the ASCE Edmund Friedman Award in 1989, and the ASCE Walter L. Huber Civil Engineering Research Prize in 1997. He is a fellow of ASCE, ASME and SNAME. Professor Ayyub has completed several research projects funded by the National Science Foundation, the U.S. Coast Guard, the U.S. Navy, the U.S. Army Corps of Engineers, the Maryland State Highway Administration, ASME, and several engineering companies. He is a researcher and consultant in the reliability and risk analysis of engineering systems and in decision analysis. With an extensive background in uncertainty modeling and analysis, risk-based analysis and design, simulation, and marine systems, Professor Ayyub is engaged in research involving reliability, marine systems, uncertainty modeling and analysis, and mathematical modeling using the theories of probability, statistics, and fuzzy sets. His publications, which include edited books, textbooks, book chapters, refereed journal papers, reports, and papers in conference proceedings, number about 300. For more details about Professor Ayyub’s previous and ongoing activities, see the web site http://ctsm.umd.edu/ayyub.

DR. IBRAHIM A. ASSAKKAF is an instructor of civil engineering at the University of Maryland, College Park, Maryland. He is the director of reliability research at the Center for Technology and Systems Management (CTSM) at the University of Maryland. He completed both his B.S. degree (1990) and M.S. degree (1993) in civil engineering at the George Washington University in Washington D.C. and his Ph.D. degree (1998) from the University of Maryland. Before 1985, Dr. Assakkaf was employed as a general manager for six years by Assakkaf Establishment, a major construction company in Saudi Arabia. This company was awarded a number of the public and private projects in Saudi Arabia. Some of these projects were part of the multimillion dollar infrastructure construction projects awarded to the public by the government in the nineteen seventies and eighties. Because of his position as a vice president and general manager, Dr. Assakkaf gained unique administrative experience in planning, designing, and construction of buildings, waterways, and roads. Dr. Assakkaf’s most recent experience was with the CTSM working on projects funded by the U.S. Navy, University of New Orleans (UNO), and other government organizations to develop Load and Resistance Factor Design (LRFD) for ship structures. His involvement in these projects provided him with unique academic and practical experience for reliability-based design of different steel components of ship structures. Dr. Assakkaf is the author and co-author of 50 papers and reports relating to reliability-based designs and analyses. For more information about Dr. Assakkaf’s activities, see the web site http://ctsm.umd.edu/assakkaf

MR. ROBERT MCCARTHY is a member of the Senior Executive Service and is director of the Platform Systems Group, SEA 05P, within the
Integrated Warfare Systems Directorate of the Naval Sea Systems Command. The Platform Systems Group is responsible for structures, survivability, weights and stability, weapons handling and aircraft support, submarine mechanical systems, underway replenishment systems, and deck systems. Mr. McCarthy is a member of the NAVSEA People Team and a member of the Navy Civilian Leadership Board. Also, as chairman of the People Team of the Engineering Directorate for several years, he led initiatives on development, retention, and recruitment to ensure sustained engineering workforce quality. Mr. McCarthy has a B.S. degree in civil engineering from the University of Maine, a masters degree in structural engineering from Cornell University, and is a registered professional engineer.

DR. JEFFREY E. BEACH is the head of the Structures and Composites Department at the Carderock Division of the Naval Surface Warfare Center, where he has been employed since 1969. He received B.S. and M.S. degrees in aerospace engineering from the University of Maryland and received his D.Sc. in engineering management and systems engineering from George Washington University in 2001. He has devoted much of his 30-year career to the evaluation and management of structural reliability and risk. He currently manages a diverse program of exploratory, advanced, and engineering development research aimed at the application of composite and advanced metallic structures to marine systems and the advancement of surface ship and submarine naval platforms. He is active nationally and internationally in professional societies, organizations, and exchanges and has published and presented numerous technical papers in the international community. Mr. Beach received the 1984 ASNE Solberg Award for outstanding and exceptional achievements in structural research and the 1998 ASNE Gold Medal Award for his contributions to naval engineering in advanced structural design technology.

MR. WILLIAM MELTON has been at NSWCCD since receiving his M.S. degree in naval architecture from the University of California, Berkeley, in 1984. Mr. Melton has been heavily involved conducting reliability and risk studies, and double-hull studies. He has authored many technical reports and publications dealing with these issues.

MR. W. THOMAS PACKARD is the division director for the Surface Ship Structural Integrity Division of the Naval Sea Systems Command, NAVSEA 05P1. Mr. Packard has been employed at NAVSEA, or its predecessor organizations, since 1970. He received a B.S. degree in mechanical engineering and an M.S. degree in solid mechanics from The George Washington University. He has devoted much of his 30-year career to the structural design, maintenance, and construction support of naval surface ships. He manages an organization responsible for establishment of design criteria for all naval surface ships and ensuring proper implementation of these criteria during construction and life-cycle maintenance activities with the primary purpose of assuring hull girder safety. He is active nationally in professional societies, organizations, and exchanges and has been a strong proponent of reliability based design and maintenance criteria.

MR. NATALE NAPPI, JR. is a naval architect in the Surface Ship Structural Integrity Division of the Platform Systems Group in the Naval Sea Systems Command and has been with the command since 1989. His career started in 1980 in the Structures Department at the David Taylor Research Center (NSWCCD). In 1988 he assisted in the SWATH T-AGOS 23 structural design while detailed to NAVSEA. He was the lead structural engineer for the T-AGS SWATH preliminary design. He provided technical support on both SWATH T-AGOS 19 and T-AGOS 23 during their construction. Mr. Nappi was a member of the Standards and Criterias Committee for the Mobile Offshore Base program and was also a technical member on various Ship Structure Committee panels. He also served as the structure's technical advisor for the Arsenal Ship. During the past five years, he has been extensively involved in the Navy's ONR-sponsored 6.3/6.4 structural reliability R&D efforts, which included arranging and organizing a structural reliability workshop with representatives from ABS, the SSC, academia and industry. He is presently the SBIR Chairman for several ship structures R&D projects and is providing techni-
cal guidance in the development of ABS naval vessel rules. He is a guest speaker at MIT on ship structural design issues and trends. He is author and coauthor of several research papers in the area of structural survivability and SWATH design. He received his B.S. degree in civil engineering from the University of Maryland in 1983 and his M.S. degree in structural engineering from The George Washington University in 1987. Mr. Nappi is a member of ASCE, The Structural Engineering Institute, and is a licensed professional engineer in the state of Maryland.

**DR. JOHN C. ADAMCHAK** has been at NSWC-CD since he received his Ph.D. in naval architecture from the Massachusetts Institute of Technology in 1969. He is internationally recognized as a technical expert in the areas of structural analysis and instability of stiffened panels. His experiences in structural systems include NASTRAN and MAESTRO analyses, instability of grillage structures, and ship structural design. Dr. Adamchak has been involved in the design and analysis of a wide variety of vessels including SWATH ships, aircraft carriers, advanced double hull ships, and all of the Navy's current combatants. He is the author of the ship ultimate strength program, ULSSTR. He has published numerous papers and government reports.

**DR. KHALED ATUA** is a senior reliability engineer at KLA-Tencor Inc., Milpitas, California. Dr. Atua is currently on a sabbatical leave for two years as a lecturer at Alexandria University, Alexandria, Egypt. He also worked as a reliability and risk management consultant for Scotsman Ice System, IL USA. He was a visiting scholar at the University of Maryland on the development of new reliability-based design rules for the systems and structural design of naval ships. He is the coauthor of the new Navy ship structural design guidelines. Dr. Atua developed risk assessment models for newly designed engine room systems aboard a new generation of naval ship for the U.S. Navy at Carderock. Dr. Atua taught at the American University in Cairo as a visiting professor in the Industrial Engineering Department from 1998 through 2000. Dr. Atua has published in journals and presented at symposia and conferences. He teaches reliability classes in industry, and provides consulting services to government and private companies. He obtained his B.S. and M.S. in naval architecture and marine engineering from Alexandria University, Egypt, in 1988 and 1992 and obtained his Ph.D. in reliability engineering from the University of Maryland at College Park, Maryland, in 1998.

**DR. JUDY A. CONLEY** is the head of the Structural Reliability Branch at the Carderock Division of the Naval Surface Warfare Center, where she has been employed since 1982. She received a B.S. degree in civil engineering from Michigan State University and both her M.S. and D.Sc. degrees in civil engineering from The George Washington University. She manages an extensive program of development, evaluation and application of a holistic approach to structural reliability and risk-based technology for ship and submarine structural systems. Dr. Conley was a member of the Mobile Offshore Base (MOB) Standards and Criteria Working Group, representing NAVSEA/NSWCCD in the role of structural design, Navy ship LRFD, and DoD requirements.

**MR. PAUL E. HESS, III** is a lead researcher in the Structural Reliability Branch within the Survivability, Structures, and Materials Directorate of NSWCCD. He completed both his B.S. (1989) and M.S. (1994) in aerospace and ocean engineering at the Virginia Polytechnic Institute and State University and is currently a doctoral candidate in reliability engineering at the University of Maryland. Mr. Hess has 12 years of experience as a naval architect (structures) in both surface ship design applications and structural reliability. His masters thesis was “Uncertainty in Marine Structural Strength with Application to Compressive Failure of Longitudinally Stiffened Panels.” Mr. Hess has been heavily involved conducting reliability and risk studies. His areas of expertise include structural reliability analysis and tool/process development (metallic and composite), development of reliability-based design criteria, probabilistic and statistical data analysis, and ship structural failure analysis.

**DR. DAVID P. KIHL** has been at NSWCCD since receiving his B.S. degree in civil engineering from the State University of New York at Buffalo in 1978. He has received his M.S. and D.Sc. (1991).
degrees in structural engineering from The George Washington University. He has been involved in numerous surface ship structural integrity projects, structural evaluations, model tests, and full-scale trials. Dr. Kihl has been heavily involved conducting fatigue tests and developing fatigue design criteria for structures operating in a seaway environment. As a result of these endeavors, he is an internationally recognized expert in the fields of stochastic damage evaluation. He has authored many technical reports and publications dealing with life prediction and failure criteria of surface ships.

PROFESSOR SHAHRAM SARKANI is a member of the engineering management and systems engineering faculty at The George Washington University (GW). He earned the B.S. (1980) and the M.S. (1981) degrees from Louisiana State University and his Ph.D. (1986) from Rice University, all in civil engineering. Professor Sarkani joined GW's faculty in 1986. He served as chair of the Civil, Mechanical, and Environmental Engineering Department from 1994 to 1997 and joined the School of Engineering and Applied Sciences (SEAS) Department of Systems Engineering and Engineering Management in 1998. Since 1997 he has been the SEAS Interim associate dean for Research and Development. He was awarded the Walter L. Huber Civil Engineering Research Prize by the American Society of Civil Engineers in 1999. The broad areas of stochastic methods of structural dynamics and fatigue, fatigue and fracture reliability, structural safety and reliability, and smart infrastructure systems for natural hazard mitigation constitute his research specialties. In 1993 he founded, and still directs, GW's Center for Infrastructure Safety and Reliability, whose main objective is to formulate and solve problems that require application of the most up-to-date and powerful theories of reliability and structural analysis. His current research investigations include modeling damage accumulation in materials made from advanced composites, modeling fatigue and fracture in welded joints, understanding extreme responses of structures to nonstationary vibratory loadings, using smart materials and dampers to control and reduce structural vibration, and testing large-scale structural models under stochastic loadings. Professor Sarkani's research activities are funded by the NSF, U.S. Navy, the National Aeronautics and Space Administration, and the U.S. Agency for International Development. His research has also been supported by the Department of the Interior, Department of Transportation, Office of Naval Research, and the National Institute of Standards and Technology. Professor Sarkani is the author of more than 100 technical publications and presentations.

MR. JEROME P. SIKORA has been with NSWCDD since he received his B.S. degree in physics from the University of Detroit in 1969. He is the head of the eighteen member Design Applications Branch (Code 6510), which is responsible for developing structural design criteria and design tools for Navy surface ships and submarines. In addition, it performs large-scale numerical analyses and experimental studies of whole ship and structural component behavior. Mr. Sikora began his career specializing in the field of static and dynamic holographic and other optical measurements of such structural parameters as stress, deformations, and vibration modes. Over the past two decades, he has developed probability-based load criteria for conventional and SWATH ships. He is the author of the lifetime, seaways load program, SPECTRA. Recently, he has been involved in developing structural design criteria and design methods for the cellular structure of no-frame, double hull ships; large floating structures, such as the Mobile Offshore Base; and high-speed sealift ships. He has written 100 government reports and published 30 refereed papers.