# Uncertainties in Material and Geometric Strength and Load Variables

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## ABSTRACT

*Uncertainty in the basic load and strength variables of a ship structure can significantly affect structural performance and safety. Variations in strength, load and load effects greatly impact the reliability of a structural system. Understanding and including this variation, or uncertainty, in the design and analysis of ship structures requires the use of structural reliability-based design and assessment methodologies.*

*For example, the design strength is based on nominal values for variables such as yield stress of the material, plate thickness, modulus of elasticity, etc. The actual values of these variables are often different from the nominal, or design, values. These actual values tend to behave in a random manner, causing random behavior of the actual structural strength. Understanding the randomness of the basic strength variables allows the designer to account for this variability in the design strength of the structure.*


*The moment methods for calculating reliability-based, partial safety factors (Ang and Tang 1984 and Ayyub and White 1987) require probabilistic characteristics of both strength and load variables in the limit state equation. Relevant strength variables for ship plates are the material's yield strength (stress)($F_y$), modulus of elasticity (E), Poisson's ratio ($\upsilon$), thickness (t), and length (a) and width (b) of a plate. The relevant load variables are the external pressures due to stillwater bending moment, wave bending moment, and dynamic loads. Uncertainty, reliability, and risk measures are vital to the analysis and design of an engineering system. The reliability of the system can be stated in reference to some performance criteria. The need for reliability analysis stems from the fact that there is the presence of uncertainty in the definition, understanding, modeling, and behavior prediction of the model or models describing the system.*

*The objective herein is to compile statistical information and data based on literature review on both strength and load random variables relevant to ship structures for quantifying the probabilistic characteristics of these variables.*

## Introduction

The design strength of a structure is based on nominal values of basic strength variables, both material and geometric, such as yield strength of the material, plate thickness, modulus of elasticity, etc. Random behavior of the basic strength variables can cause the strength of the structure to vary beyond acceptable levels. The actual values of these variables are often different from the nominal, or design, values, and tend to behave in a random manner, causing random behavior of the actual structural strength. Quantifying the uncertainty, or randomness, found in the basic strength variables allows the designer to account for this variability in the strength of the structure. The uncertainty associated with the strength prediction may be calculated using simulation techniques, such as Monte-Carlo simulation, which allow the values for the basic strength variables to be generated based on their statistical distributions (probability density functions).

The objective herein is to compile statistical information and data based on literature review on both strength and load random variables for quantifying the probabilistic characteristics of these variables. Quantification of the probabilistic characteristics of these variables is needed for reliability analysis and design of ship structures. Quantification of random variables of load 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.

Also, the objective is to present statistical estimates of the uncertainty associated with geometric, material, and load basic strength variables used in the analysis and design of surface ship structures, with an emphasis on commercial and naval ships. The basic structural strength variables may be grouped into two classes, material variables (such as yield strength and ultimate strength) and geometry variables (such as plate thickness and stiffener height). The geometric variables may also be called construction variables. The load variables include external load effects because of stillwater, wave-induced, and dynamic bending moments.

The material strength variables considered in this paper are the mechanical properties of yield strength, ultimate strength, and elastic modulus. The steel types include ordinary steel, high strength (HS) steel, high-strength low-alloy (HSLA) 80 steel, high yield (HY) 80 steel, and HY-100 steel. The data presented are from previously published sources and testing undertaken for this study.

Statistical estimates of the uncertainty for the following geometric basic strength parameters are presented: plate thickness, stiffener length and spacing, stiffener web height, web thickness, flange breadth and flange thickness. The effect of the following factors on plate thickness uncertainty are considered: nominal thickness, steel type, data source, ordering specification, measurement technique, presence of a surface coating during measurement, and amount of local plate deformation.

The impact of the random uncertainty on structural strength prediction cannot be overemphasized, and it is a very important issue in reliability-based analysis of common surface ship structural components.

## Methodology

Data on basic strength and load variables were collected from a variety of sources, which can be classified in numerous ways. Sample sets have been created from measurements taken of materials prior to fabrication as well as from finished structures. These samples encompass both materials used in actual ship construction and in scaled-down models of ship components. The histories of these sample sets are maintained to preserve a means for tracking purposes, but the statistical analyses were conducted with rather general groupings of these sets.

A means of addressing the uncertainty inherent in geometric and material variables is to study the bias between the actual (measured) value and the value used for design and to create a statistical (probabilistic) model of this bias for use in reliability analysis and design methods.

## Bias

The uncertainty in basic strength variables can be quantified using two types of bias, the *ratio* bias and the *difference* bias. The ratio bias is the ratio between the measured value and the nominal (or design) value for strength variables as follows:

$$b_R = \frac{\text{measured value}}{\text{nominal value}} \tag{1}$$

The difference bias is the difference, or error, between the measured value and the nominal value:

$$b_D = \text{measured value} - \text{nominal value} \tag{2}$$

For geometric variables such as thickness, breadth, and height, variations from nominally specified values may not be dependent upon nominal values. For small nominal values of these variables, the ratio bias may overestimate the variability, while for larger variable values it may underestimate the variability. Therefore the error, or difference, between the measured and nominal values can be analyzed along with the ratio of these values.

Uncertainty in distortion, or eccentricity, can be described using a normalized value, which is the ratio of the distortion to a dimension of the distorted structural component. An example in this case is the normalization of stiffener distortion by the stiffener length.

### *BIAS ASSESSMENT OF STRENGTH MODELS*

The uncertainties that are associated with a numerical analysis are generally the result of experimental approximation or numerical inaccuracies, which 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 that 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 ones that are more accurate. An advanced prediction model should account for more variables than the one that is being assessed for use in reliability-based load and resistance factor design (LRFD) rules. For the purpose of evaluating and assessing the biases, these prediction models can be 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). These bias factors are given by

$$B_{21} = \frac{\text{Advanced predicted value}}{\text{Rules value}} \tag{3}$$

$$B_{32} = \frac{\text{Experimental value}}{\text{Advanced predicted value}} \tag{4}$$

$$B_{43} = \frac{\text{Real value}}{\text{Experimental value}} \tag{5}$$

$$B_{41} = \frac{\text{Real value}}{\text{Rules value}} = B_{21}B_{32}B_{43} \tag{6}$$

The bias and uncertainty analyses for these strength models are needed for the development of LRFD rules for stiffened panels of ship structures. The uncertainty and biases of these models can be assessed and evaluated by comparing their predictions with more accurate models or real values.

### *MEAN TO NOMINAL RATIOS AND TOTAL BIAS*

In order to develop reliability-based ship design codes, an additional source of uncertainty needs to be evaluated. This source of uncertainty stems from the fact that the basic strength parameters that are used in a design equation are random variables. The design strength is usually based on nominal values for parameters such as yield strength of the material, plate thickness, modulus of elasticity, etc. The actual values of these parameters are often different from the nominal, or design, values. These actual values tend to behave in a random manner, causing random behavior of the actual strength. When a design strength model is used to predict the strength of a structural component based on nominal values, its strength can be different from the actual one. For this reason mean to nominal ratios are needed to account for this uncertainty. The mean to nominal ratio of a strength model can be combined with the model bias (real value/mean predicted value) to produce the total bias $B_T$. The total bias is therefore defined as (Ayyub et al. 1997 and Assakkaf 1998)

$$B_T = \frac{\text{real value}}{\text{mean predicted value}} \times \frac{\text{mean predicted value}}{\text{nominal value}} = \frac{\text{real value}}{\text{nominal value}} \tag{7}$$

The total bias value is used to revise the mean strength reduction factor by multiplying it by this value.

## Probability Density Functions

The probability density function (PDF) is a curve for which probability density, the $y$-axis value, is plotted against possible values of a specific random variable. Integration of the area under this curve, between two bounds, gives a measure of the probability that a value will occur between the chosen bounds. The legitimacy of a PDF is dependent upon two properties:

1. Values of the PDF are always greater than zero or $f_X(x) \geq 0$.
2. The area of the PDF is always equal to one or $\int_{-\infty}^{+\infty} f_X(x)dx = 1$

Additional information about the PDF, and probability theory in general, is available in Ang and Tang (1990), Ayyub and McCuen (1977), and Thoft-Christensen and Baker (1982).

The computer program BestFit® (1995) was used to explore which probability density functions (PDF) were most representative of the sample data. BestFit® uses the LevenBerg-Marquardt Method to fit PDFs from a library of 21 continuous functions to the sample data. The ranking of the PDFs was done using Chi-squared, Kolomagorov-Smirnov, and Anderson-Darling goodness-of-fit tests.

The top two PDFs are presented for each variable. The calculated goodness-of-fit statistics show that very few of the cases satisfy any realistic level of significance ($\alpha$), usually violating the associated critical value and limiting the relevance of the tests. Therefore, the recommended PDFs are based on a subjectively weighted averaging of the numerical goodness-of-fit ranks.

The use of BestFit® requires an input of a bin (class or grouping) size for the histogram generation. The equations $1+3.3Log_{10}N$ suggested in Ayyub and McCuen (1997) and $(4N)^{2/5}$ suggested in BestFit® (1995) were used to gain an initial estimate of appropriate bin sizes. These numbers were varied and a selection was made that caused the histogram to approach a relatively smooth curve, which seemed to best represent the data. It should be noted that the Kolmagorov-Smirnov and Anderson-Darling goodness-of-fit tests are not dependent upon bin size.

## Basic Strength Random Variables

This section summarizes the probabilistic characteristics of strength basic random variables that are needed for the development of reliability-based LRFD design methods for hull structural components of ship structures.

### *DATA SOURCES*

### Material Variable Data Sources

#### *SSC-352 Report*

In 1990, the Ship Structures Committee (SSC) sponsored an effort to develop a data bank documenting the toughness of steels for marine applications (Kaufman and Prager 1990). In this data bank, the results of approximately 10,000 tests of 11 steels are recorded. Tensile, Charpy V-notch, fracture toughness (Jic), NDTT, and DT energies were focused on with the steel's composition and fabrication history included. In this study, only the tensile properties were analyzed.

#### *NSWCCD Tests*

Starting in 1993, the Naval Surface Warfare Center (NSWC), Carderock Division, performed approximately 500 tension and compression tests as a part of the effort to determine the variability in material properties of marine structural steels. The effects of parameters such as roll direction and tensile versus compressive properties for mild steels, high strength steels, and HSLA steels were investigated and reported (Sahay 1993).

The tension tests were conducted using a Tinius Olsen 60,000 lb capacity universal test machine. Specimens were fabricated and tested in accordance with guidelines given in the ASTM E8 standard. Specimens were secured in standard serrated-jaw type grips and were aligned in the fixture to insure application of a true axial load. An extensometer (2 inch gage length) was used to obtain real time load-elongation plots.

*Ingalls Shipbuilding*
Ingalls Shipbuilding, located in Pascagoula, Mississippi, also supplied an extensive amount of yield strength, ultimate strength, and Charpy data from tests conducted in 1993. The steel samples were primarily higher strength material reflecting the construction materials required during that time frame.

## GEOMETRIC VARIABLE DATA SOURCES

### Measurements Taken from Plates Before Construction

*NSWCCD Model Tests*
The Naval Surface Warfare Center, Carderock Division, has performed various scale model tests to investigate failure mechanisms and strength behavior. Measurements were taken of the thickness of the uncoated plating used in these tests using a micrometer.

*Newport News Shipbuilding*
Newport News Shipbuilding measured plating for thickness variability, as part of a quality assurance program, using UT and micrometer measurements. The plates are assumed to be without any surface coating. For this study, each measurement is considered to be a data point unto its own, even though numerous data points were taken from the same plate. This is considered appropriate based on the variability found in the measured thickness of each plate.

*U.S. Coast Guard*
Plate thickness measurements were taken of material destined for use in Coast Guard vessels. The specified (nominal) thickness used in ordering this material is less than the equivalent Navy nominal thickness. An example of this would be the use of 10.0# (0.2451 inch thickness) plating by the U.S. Coast Guard, as opposed to 10.2# (0.25 inch thickness) as used by the Navy. The Coast Guard specified nominal value is used in the calculation of the bias, matching the data trends found in other sample sets.

### Measurements Taken from Plates and Sections After Construction

*NSWCCD Shipboard Measurements*
In support of this study, measurements were taken on board currently active ships in areas readily accessible for study. Limitations to accessibility due to equipment and insulation caused the most frequently measured panel types to be longitudinal and transverse bulkheads. All measured areas were coated with paint of unknown thickness. The nominal values were found from the ship structural drawings on hand.

Stiffener height, web thickness, flange breadth, and flange thickness were measured at three locations on each stiffener, when no interferences were present. Each of these independent measurements is considered a data point in the analysis even though they come from the same member.

*SC-364 Report*
The Ship Structures Committee published a report (Jennings et al. 1991) on the maximum inelastic plate distortions found in a ship hull. Plate thickness data were gathered around the deformed region using a UT measuring device. The measurements were taken primarily on the shell, with unknown amounts of paint coating the material. The reported distortion data are not used in this study, as they are the result of extreme environmental loads or impacts, and as such should be considered damaged.

*NSWCCD Bending Model*
Unstiffened plating distortion measurements were taken from a large-scale model of a prismatic ship midsection prior to testing at NSWCCD. These panels were components of an advanced double hull design and so not bounded by stiffeners, but by plating of similar thickness. The mode shapes were recorded, but only the maximum deflection values from these measurements are reported in Hess and Ayyub (1997).

## PROBABILISTIC CHARACTERISTICS OF STRENGTH VARIABLES

This section provides detailed statistical data

**Table 1**

*Statistical Information on Yield Strength of Ordinary Strength (OS) Steel*

| STEEL TYPE | # OF TESTS | $\overline{F}_y$ (ksi) | COV OF $F_y$ | $\overline{F}_y / F_y$ RATIO | COMMENTS | REFERENCES |
|---|---|---|---|---|---|---|
| ABS A | 33 | 36.091 | 0.059 | 1.062 | 1948 tests, 7/16 and 1/2-in plates | Mansour et al. (1984) and Atua et al. (1996) |
| ABS B | 79 | 34.782 | 0.116 | 1.023 | 1948 tests, 9/16, 5/8, 11/16, 3/4,13/16, 7/8, 15/16, and 1-in plates | Mansour et al. (1984) and Atua et al. (1996) |
| ABS C | 13 | 33.831 | 0.081 | 0.995 | 1948 tests, plates 15/8, 13/16, 11/4, 13/8, and 11/2-in plates | Mansour et al. (1984) and Atua et al. (1996) |
| ABS B | 39 | 34.850 | 0.044 | 1.025 | normal distribution, 3/4-in plates | Mansour et al. (1984) |
| ABS C | 36 | 35.000 | 0.069 | 1.029 | 11/4-in plates | Mansour et al. (1984) and Atua et al. (1996) |
| ASTM A7 | 3974 | 40.000 | 0.087 | 1.212 | mill tests, lognormal distribution, upper yield point | Galambos and Ravindra (1978), Mansour et al. (1984), and Lay (1965) |
| ASTM A7 and A 36 | 3124 | 39.360 | 0.078 | 1.210 | ASTM mill tests | Galambos and Ravindra (1978), Mansour et al (1984), and AISICPS (1972) |
| A7 and A36 | 400 | 44.000 | 0.110 | 1.220 | mill tests | Galambos and Ravindra (1978), Mansour et al. (1984), and AISICPS (1972) |
| ASTM A7 | 120 | 35.080 | 0.038 | 1.063 | 55T, beams and flanges | Mansour et al. (1984) |
| ASTM A7 | 58 | 39.079 | 0.044 | 1.184 | 55T, beams and webs | Mansour et al. (1984) |
| ASTM A7 | 54 | 38.000 | 0.026 | 1.152 | 55T, beams and cover plates | Mansour et al. (1984) |

for strength variables of steel used in ship structures. These data are collected from various sources with the objective of identifying strength uncertainties. The data includes the mean ($\mu$), standard deviation ($\sigma$) or coefficient of variation (*COV*), and wherever available the distribution type for each strength basic random variable. The moment methods that are used in reliability design and assessment of ship structural components require these information types. Statistical data on strength variables that are considered relevant to ship structures are provided in this section under separate headings. The material strength variable data addresses steel properties.

The types of steel included in the data are as follow: ordinary steel, yield strength ($F_y$) = 34 ksi, ultimate strength ($F_u$) = 60 ksi); high strength steel ($F_y$) = 51 ksi, $F_u$ = 72 ksi); HY 80 steel ($F_y$ = 80 ksi, $F_u$ =115 ksi); HSLA 80 steel ($F_y$ =80 ksi, $F_u$ = 87 ksi); HY 100 steel ($F_y$ =100 ksi, ($\sigma_{Ult}$=115 ksi); and HSLA 100 steel ($F_y$ =100 ksi, $F_u$ =115 ksi).

The material properties that were emphasized in this study are primarily yield strength, ultimate strength, and Young's modulus (modulus of elasticity). Poisson's ratio is generally considered to be a deterministic value and was not investigated in this study because of lack of available data. Charpy V-notch data were collected but are not considered herein. These data will be analyzed at a later date in future work.

## Material Properties

Tabulated statistical data on the yield strength ($F_y$), ultimate strength ($F_u$), modulus of elasticity (or Young's modulus) ($E$), and Poisson's ratio ($\upsilon$) are provided in the following sections.

**Table 2**

*Statistical Information on Yield Strength of High Strength (HS) Steel*

| STEEL TYPE | # OF TESTS | $\overline{F}_y$ (ksi) | COV OF $F_y$ | $\overline{F}_y / F_y$ RATIO | COMMENTS | REFERENCES |
|---|---|---|---|---|---|---|
| SA36 | n/a | 39.6 | 0.100 | 1.100 | assumed lognormal distribution | Mansour et al. (1994) |
| SA537 Grade B | n/a | 66.0 | 0.091 | 1.320 | assumed lognormal distribution | Mansour et al. (1994) |
| SA516 Grade 70 | n/a | 41.8 | 0.100 | 1.100 | assumed lognormal distribution | Mansour et al. (1994) |
| SA516 Grade 70 | n/a | 51.1 | 0.066 | 1.345 | assumed lognormal distribution | Mansour et al. (1994) |

*n/a = not available*

*Yield Strength*

Statistical information on yield strength ($F_y$) of shipbuilding steel is summarized in **Tables 1** and **2**. These tables also show data summarized by Mansour et al. (1984) and others. Some of these reported data were discarded because either (1) the steel type was not reported and indicated as an unknown steel type or (2) steel strength was reported in the form of ranges (e.g., 40 to 50 ksi) rather than steel type with known nominal (or design) value. The steel types were needed in this study in order to compute the yield strength ratio that is defined as the mean to nominal ratio of yield strength. The tables also provide information on ordinary and higher strength steel, respectively, such as number of tests, yield strength ratio, coefficient of variation (*COV*), and wherever available probability distribution types. The same information was published by Mansour et al. (1984) who suggested that the weighted average of the *COV* values for data of more than 60,000 samples is 0.089. Galambos and Ravindra (1978), in reviewing much the same data, suggested that any numerical or statistical analysis is probably worthless, since the measurement methods are so varied. Based on judgment, they recommended that for rolled shapes the mean yield strength could be taken as 1.05 $F_y$ for flanges and 1.10 $F_y$ for webs with *COVs* of 0.10 and 0.11, respectively.

Studies of the effect of various independent variables such as production year, temperature, orientation (tension or compression), steel type, and plate thickness on material properties show that only the steel type and plate thickness have a significant role in the determination of the yield strength ratio (Hess and Ayyub 1997). The result of these studies was based on analyzing data provided in the SSC-352 report (Kaufman and Prager 1990). The yield strength ratio for both ordinary strength (OS) and high strength (HS) steels tend to be significantly higher than that of high strength low alloy (HSLA) steel and high yield (HY) steel. Also, the yield strength ratio tends to increase as the plate thickness $t$ decreases, particularly below 1.5 in. The influence of the other variables was concluded to be insignificant because of lack of a clear trend under normal operational conditions of typical ships. Other studies (Mansour et al. 1984) suggest that a lognormal distribution is appropriate for the yield strength. Therefore, based on these studies and on the available information, a lognormal distribution is recommended for the yield strength for both ordinary and higher strength steels. **Table 3** provides information on the calculated values and ranges of $\overline{F}_y$, coefficient of variation of yield strength, and the yield strength ratio for ordinary steel (OS). **Table 4** provides similar information for high strength steel (HS). The averages calculated

**Table 3**

*Averages and Ranges for Statistics of Yield Strength for Ordinary Strength (OS) Steel*

| | $\overline{F}_y$ (ksi) | COV OF $F_y$ | $\overline{F}_y / F_y$ RATIO | DISTRIBUTION |
|---|---|---|---|---|
| Average | 37.3 | 0.068 | 1.11 | Lognormal |
| Minimum | 33.8 | 0.026 | 1.00 | Lognormal |
| Maximum | 44.0 | 0.116 | 1.2 | Lognormal |

**Table 4**

*Averages and Ranges for Statistics of Yield Strength for High Strength (HS) Steel*

| | $\overline{F}_y$ (ksi) | COV OF $F_y$ | $\overline{F}_y / F_y$ RATIO | DISTRIBUTION |
|---|---|---|---|---|
| Average | 49.6 | 0.089 | 1.22 | lognormal |
| Minimum | 39.6 | 0.066 | 1.10 | lognormal |
| Maximum | 66.0 | 0.100 | 1.35 | lognormal |

**Table 5**

*Results of the Statistical Analysis for the Yield Strength Data*

| | INPUT DATA | LOGNORMAL | WEIBULL | EXTREME VALUE TYPE I |
|---|---|---|---|---|
| Mean | 0.1746 | 0.2055 | 0.1791 | 0.1745 |
| Standard Deviation | 0.1214 | 0.1831 | 0.1223 | 0.1214 |
| Mode | 0.105 | 0.08549 | 0.094 | 0.1199 |
| Skewness | 1.218 | 3.382 | 0.9993 | 1.1395 |
| Kurtosis | 4.539 | 28.580 | 3.8779 | 5.4 |

**Table 6**

*Yield Strength Bias Statistics by Steel Type*

| | COMBINED | MILD | HIGH STRENGTH | HY 80 | HSLA 80 | HSLA 100 |
|---|---|---|---|---|---|---|
| Mean | 0.1746 | 0.3000 | 0.1903 | 0.1958 | 0.0761 | 0.0783 |
| Standard Deviation | 0.1214 | 0.1606 | 0.0989 | 0.1010 | 0.0368 | 0.0318 |

in Tables 3 and 4 were based on the data reported in Tables 1 and 2, respectively.

## Yield Strength Data Analysis

The past sources of yield strength data are extremely important. They form a strong foundation to build upon. In this study, these data were supplemented with further testing, recent information from shipbuilders, and data from recent Ship Structure Committee reports (Kaufman and Prager 1990). The more recent data were used as a primary source to update yield strength statistics and to investigate the influences of various parameters on the yield strength.

The ratio bias was used to normalize the yield strength data. A value of one was subtracted from each sample so that a steel sample that exhibited yield strength identical to its design value would now have a yield strength ratio of 0.0, or be 0% greater than the design value. Similarly, a yield strength ratio of 0.5 would signify a steel specimen, which exhibited 50% greater yield strength than its design value. The biases ranged from 0.0 to 0.7, with a sample size of 749 divided into 10 bins or classes. **Table 5** shows the statistical analysis results.

The large values of mean and standard deviation were influenced by the large yield strength ratio and variation of the mild steel tests. Higher grades of steels did not exhibit these large values. The large values can be attributed to a common practice of downgrading higher strength steels that do not meet the specifications and also because the Navy designation for mild steels include various commercial grades which often have higher design values than the minimum specified by the Navy for mild steels. The goodness-of-fit tests suggest that the lognormal, Weibull, and extreme value distributions are all equally valid choices for describing the yield strength of steel. The parameters of the Weibull are $\beta$ =1.49 and $\alpha$ =0.20, and for the Extreme Value Type I the location parameter is 0.12 and the scale parameter is 0.0946.

## Factors That Influence Yield Strength

The effects of the following factors on the yield strength bias and uncertainty were investigated: loading direction, roll direction, temperature, production year, steel type, and plate thickness. The steel type was the dominant influence on the bias. Plate thickness played a slightly lesser role and the other factors proved negligible for this sample population. The amount of samples for each plate thickness for a steel type did not allow a breakdown of the sample set beyond steel type. The statistics for the yield strength bias of different steel types are shown in **Table 6.** The lognormal PDF may be used to represent each of the individual steel types with their accompanying statistics.

### *Ultimate Strength*

Ultimate strength properties are also of significant interest to the designer and analyst. They are often used in allowable stress deter-

## Table 7

*Statistical Information on Ultimate Strength of Shipbuilding Steel*

| STEEL TYPE | # OF TESTS | $\overline{F}_y$ (ksi) | COV OF $F_y$ | $\overline{F}_y / F_y$ RATIO | COMMENTS | REFERENCES |
|---|---|---|---|---|---|---|
| ABS A | 33 | 59.27 | 0.044 | 1.022 | 1948 tests, 7/16 and 1/2-in plates | Mansour et al. (1984) |
| ABS B | 79 | 60.99 | 0.091 | 1.052 | 1948 tests, 9/16, 5/8, 11/16, 3/4, 13/16, 7/8, 15/16, and 1-in plates | Mansour et al. (1984) |
| ABS C | 13 | 60.25 | 0.051 | 1.039 | 1948 tests, 15/8, 13/16, 11/4, 13/8, and 11/2-in plates | Mansour et al. (1984) |
| ABS B | 39 | 62.57 | 0.044 | 1.079 | normal distribution, 3/4-in plates | Mansour et al. (1984) |
| ABS C | 36 | 63.22 | 0.047 | 1.090 | normal distribution, 11/4-in plates | Mansour et al. (1984) |
| ASTM A7 | 120 | 62.64 | 0.0226 | 1.044 | 55T, WF beams, and flanges | Mansour et al. (1984) |
| ASTM A7 | 58 | 64.33 | 0.0341 | 1.072 | 55T, WF beams, and webs | Mansour et al. (1984) |
| ASTM A7 | 54 | 60.64 | 0.0241 | 1.011 | 55T, beams, and cover plates | Mansour et al. (1984) |
| ASTM A7 | 22 | 60.41 | 0.0719 | 1.007 | structural steel plates | Mansour et al. (1984) |

minations and also give the analyst an idea of the post yielding material strength. There are limited studies relating to the ultimate strength behavior of various steels. Minnick and St. John (1987) have presented an extensive summary of the work in this area. Many of the tests noted above took place prior to 1950 and focused on the lower strength materials. These data are valuable but more recent data are needed.

Statistical information on ultimate strength ($F_u$) for shipbuilding steel is provided in **Table 7** (Mansour et al. 1984). The information in this table includes number of tests, mean to nominal ratio of ultimate strength (ultimate strength ratio), coefficient of variation (*COV*), and wherever available probability distribution type. Since the steel type is needed for the determination of ultimate strength ratios as was performed in the case of yield strength ratios, not all the data reported by Mansour et al. (1984) are shown in Table 7. Data that do not show steel type or data that give only ultimate strength ranges (e.g., 40 to 50 ksi) were not used herein. Mansour et al. (1984), in reviewing the same data, estimated the weighted average of the *COV* values of more than 4200 samples to be 0.068. Conclusions reached by other researchers (Atua and Ayyub 1996 and Hess and Ayyub 1997) regarding the effect of the various indepen-

## Table 8

*Averages and Ranges for the Statistics of Ultimate Strength of Shipbuilding Steel*

| | $F_y$ (ksi) | COV OF $F_y$ | $\overline{F}_y / F_y$ RATIO | DISTRIBUTION |
|---|---|---|---|---|
| Average | 61.6 | 0.04774 | 1.046 | normal |
| Minimum | 59.3 | 0.023 | 1.007 | normal |
| Maximum | 64.3 | 0.09 | 11.090 | normal |

dent variables such as production year, temperature, orientation (tension or compression), steel type, and plate thickness on yield strength ratio held true for the ultimate strength ratio. Only steel type and plate thickness has a significant effect on the ultimate strength ratio. The ultimate strength ratio for both ordinary and high strength steels tends to be significantly higher than that of HSLA and HY steels. Also, the ultimate strength ratio tends to increase as the plate thickness *t* decreases. **Table 8** summarizes calculated ultimate strength averages and their ranges, coefficients of variation, and ultimate strength ratios for both ordinary and higher strength steels. The averages that are shown in Table 8 were based on the data provided in Tables 7.

### Ultimate Strength Data Analysis

Ultimate strength was analyzed in a similar manner to the yield strength using the ratio

**Table 9**

*Results of the Statistical Analysis for the Combined Ultimate Strength Data*

| | INPUT DATA | NORMAL | WEIBULL |
|---|---|---|---|
| Mean | 0.06169 | 0.06169 | 0.23503 |
| Standard Deviation | 0.07546 | 0.07546 | 0.07899 |
| Mode | 0.01480 | 0.06169 | 0.2345 |
| Skewness | 0.3702 | 0 | 0.07165 |
| Kurtosis | 4.692 | 3 | 2.624 |

**Table 10**

*Ultimate Strength Bias Statistics by Steel Type*

| | COMBINED | MILD | HIGH STRENGTH | HY 80 | HSLA 80 | HSLA 100 |
|---|---|---|---|---|---|---|
| Mean | 0.0561 | 0.0660 | 0.0854 | 0.0796 | -0.0618 | -0.0134 |
| Standard Deviation | 0.0790 | 0.1363 | 0.0545 | 0.0633 | 0.0385 | 0.0261 |

bias minus one. The available number of data points decreased substantially, however, because many of the steel coupon tests did not supply ultimate strength values. Data consisted of the tension tests performed in-house at Ingalls Shipbuilding and found in SSC 352 (Kaufman and Prager 1990). **Table 9** shows the results of the statistical analysis of the combined data. The data ranged from -0.1747 to 0.3667 with 701 samples separated into 10 bins. There is no significant difference between using either a Weibull or a normal distribution to represent the ultimate strength of steels, except for the lower truncation of the Weibull. In typical design situations it would be appropriate to use the normal distribution in lieu of the steel particular distribution to model ultimate strength behavior without introducing significant error. The parameters of the Weibull distribution are $\beta$ =3.27 and $\alpha$ =0.26 with the PDF shifted to accommodate the data range by subtracting 0.17.

### Factors That Influence Ultimate Strength

The effects of the following factors on the ultimate strength bias and uncertainty were investigated: loading direction, temperature, production year, steel type, and plate thickness. As with the yield strength, the steel type and plate thickness were the dominant influences on the bias. The data provided more justification for breaking down the samples by steel type yet was insufficient to carry the subdivision further to account for plate thickness. The other factors proved negligible for this sample population. The statistics for the ultimate strength bias of different steel types are shown in **Table 10.** The use of the normal PDF is appropriate to represent each of the individual steel types with their accompanying statistics.

### *Modulus of Elasticity*

The modulus of elasticity (Young's modulus or elastic modulus) of a given material is also of particular interest to the structural engineer. Instability failure modes rely heavily on this value. Young's modulus is often treated deterministically even in studies which deal with variability in mechanical properties. Galambos and Ravindra (1978) did, however, address variability in elastic modulus values and discovered significant studies in this area. Based on the information available at that time, Galambos and Ravindra (1978) chose a mean value of 29 x 106 psi with a *COV* of 0.06 to describe both the tension and compression elastic modulus behavior.

Variability of modulus of elasticity, *E,* was investigated and the results were plotted as shown in **Figure 1** (Aua et al. 1996). The mean value was found to be 28,901 ksi with a *COV* value of 0.105. Statistical information on the modulus of elasticity of shipbuilding steel was summarized by Galambos and Ravidra (1978), Manour et al. (1984), and others as shown in **Table 11**. Generally, the reported data do not include steel types and are given in terms of general types of steels, noticeably, general structural steels. Since the nominal elastic modulus is commonly specified as 29,000 ksi (Galambos and Ravindra 1978) in tension and compression, this value was used in the computation of the modulus of elasticity ratio (i.e., mean to nominal ratio of the modulus of elasticity).

In reviewing much of the same data, Mansour et al. (1984) reported that the weighted averages of the mean value and *COV* of the modulus of elasticity are 30,070 ksi and 0.031, respectively. However,

## Table 11

*Statistical Information on Modulus of Elasticity*

| STEEL TYPE | # OF TESTS | $\overline{E}$ (ksi) | *COV* OF *E* | $\overline{E}/E$ RATIO* | COMMENTS | REFERENCES |
|---|---|---|---|---|---|---|
| general structural steel | 7 | 29,360 | 0.0100 | 1.0124 | tension coupon | Lyse and Keyser (1934), Galambos and Ravindra (1978) |
| general structural steel | 56 | 29,437 | 0.0140 | 1.0151 | tension coupon | Rao et al (1964), steel Galambos and Ravindra (1978) |
| general structural steel | 67 | 29,540 | 0.0100 | 1.0186 | tension coupon | Julian (1957), steel Galambos and Ravindra (1978) |
| general structural steel | 67 | 29,550 | 0.0100 | 1.0190 | compression coupon | Julian (1957), Galambos and Ravindra (1978) |
| general structural steel | 50 | 29,774 | 0.0380 | 1.0267 | tension and compression coupon | Johnson and Opila (1941), Galambos and Ravindra (1978) |
| general structural steel | 94 | 31,200 | 0.0600 | 1.0759 | tension coupon and standard column | Tall and Alpsten (1969), Galambos and Ravindra (1978) |
| general structural steel | 104 | 30,000 | 0.0327 | 1.0345 | tension, structural steel from bridges | Mansour et al. (1984) |
| various types | 19 | 28,980 | 0.0269 | 0.9993 | tension, steel alloys, annealed and quenched | Mansour et al. (1984) |
| general structural steel | 22 | 29,500 | 0.0072 | 1.0172 | tension | Mansour et al. (1984) |
| general structural steel | 22 | 29,490 | 0.0146 | 1.0169 | compression | Mansour et al. (1984) |
| low alloy (LA) steel | 20 | 29,590 | 0.0056 | 1.0203 | tension | Mansour et al. (1984) |
| low alloy (LA) steel | 20 | 29,640 | 0.0070 | 1.0221 | compression | Mansour et al. (1984) |
| low alloy (LA) steel | 10 | 29,560 | 0.0064 | 1.0193 | tension | Mansour et al. (1984) |
| low alloy (LA) steel | 10 | 29,610 | 0.0111 | 1.0210 | compression | Mansour et al. (1984) |
| general structural steel | 38 | 29,420 | 0.0157 | 1.0145 | tension, 1/4, 1/2, and 1-in plate samples | Mansour et al. (1984) |
| ASTM A710-10 | *n/a* | 30,210 | *n/a* | 1.0417 | tension | Montemarano et al. (1986) |
| ASTM A710-10 | *n/a* | 29,980 | *n/a* | 1.0338 | compression | Montemarano et al. (1986) |

*n/a = not available, *Computed based on a nominal value of 29,000 ksi*

Galambos and Ravindra (1978) assumed a mean value of 29,000 ksi and a coefficient of variation (*COV*) of 0.06 for the elastic modulus. In their judgment, the *COV* value is to account for the variation due to different shapes, heat, mills, etc. They also pointed out that the most carefully performed and controlled tests on Young's modulus is probably that of Johnson and Opila (1941) which give a mean value of 29,774 ksi. This is probably the most accurate value according to Galambos and Ravindra (1978). As it can be seen from Table 11 all cited references failed to report the probability distribution type for *E*, and thus a lognormal distribution is assumed herein on the basis of its limitation to nonnegative value. A normal distribution can be also used. **Table 12** provides information on the calculated averages and ranges of the modulus of elasticity, its coefficient of variation, and the elastic modulus ratio for both ordinary and high strength steels. The averages calculated in Table 12 are based on the data shown in Table 11.

## Table 12

*Averages and Ranges for the Statistics of Modulus of Elasticity*

| | E (KSI) | COV OF E | $\overline{E}/E$ RATIO | DISTRIBUTION |
|---|---|---|---|---|
| Average | 29,696 | 0.0179 | 1.024 | lognormal or normal |
| Minimum | 28,980 | 0.0056 | 1.000 | lognormal or normal |
| Maximum | 31,200 | 0.0600 | 1.076 | lognormal or normal |

## Table 13

*Results of Statistical Analysis for Young's Modulus Data*

| | INPUT DATA | NORMAL | WEIBULL |
|---|---|---|---|
| Mean | -0.01325 | -0.01325 | 0.2757 |
| Standard Deviation | 0.07520 | 0.07520 | 0.07293 |
| Mode | 0.01392 | -0.01325 | 0.2757 |
| Skewness | -0.3557 | 0 | -0.1159 |
| Kurtosis | 3.483 | 3 | 2.677 |

### Elastic (Young's) Modulus Data Analysis

For the analysis of modulus data all the steels were combined into one data set because of a lack of data across the range of steel specimens. The data ranged from -0.2804 to 0.1724, consisted of 149 samples, separated into 10 bins. The statistical analysis and goodness-of-fit tests conclude that the normal and Weibull distributions most closely approximated the data. As shown in **Table 13**, the mean value of Young's Modulus for all of the steels is 29.2 x 106 psi, i.e., 1.3% lower than the nominal value. The data appears to be best described by a normal distribution with a standard deviation of 0.075. The parameters for the Weibull are $\beta = 4.13$ and $\alpha = 0.29$ with the PDF shifted by subtracting 0.28.

#### *Poisson's Ratio*

The Poisson's ratio of steel is considered non-random with a deterministic value of 0.3.

### Fabricated Dimensions of Shipbuilding Steel

In this section, statistical data for plate thickness $t$ and plate dimensions $a$ and $b$ are collected from various sources. The data for each variable were analyzed and tabulated as provided under its own heading. This section includes the recent field measurement and statistical analysis of fabricated dimensions of shipbuilding steel provided by Hess and Ayyub (1997). The new results are in agreement with previously recommended values by Ayyub and Assakkaf (1997).

#### *Plate Thickness*

Plate thickness is considered a rather important variable in ship structural design. Variations in the thickness can play an important role in the uncertainty of the strength of the final product, as shown in Hess et al. (1994). There is also the potential for significant variation in the weight and cost of the structure. The uncertainty in the

**FIGURE 1:**
*Test Results of Modulus of Elasticity as Reported by Hess and Ayyub (1997)*

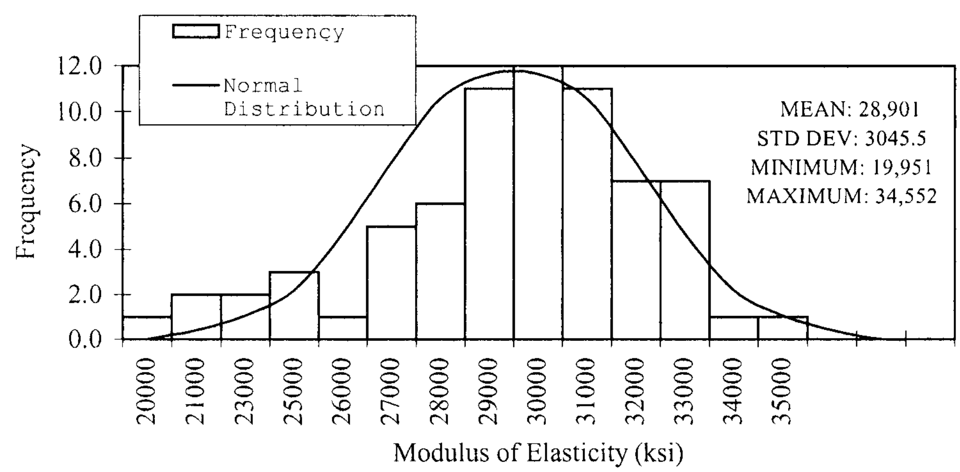

plate thickness may be described using a variety of classifications. The total population, as well as assorted subsets, are discussed below to explore factors influencing the uncertainty.

Statistical information on plate thickness *t* of shipbuilding steel was summarized by Daidola and Basar (1980) as given in **Tables 14a** and **14b**. These tables provide tolerances and statistical information on variation of plate thickness used in shipbuilding. Mansour and Faulkner (1973) reported that the coefficient of variation of plate thickness is greatest for thin plates. Calculation of the standard deviation for a plate thickness *t* based on its tolerance can be performed by dividing the tolerance by 3 (Daidola and Basar 1980). This is true if the underlying probability distribution of *t* is normal and 99.7 percent of the measurements generally fall within the tolerance limit. The mean value of *t* can be chosen from its reporting context, and hence the *COV* can be computed by dividing the standard deviation by *t*. The calculated values for the standard deviations and *COVs* of *t* are shown in Tables 14a and 14b. Table 15 summarizes the calculated averages and ranges for the standard deviation and the coefficient of variation of *t*. The calculated averages in **Table 15** were based on the data provided in Tables 14a and 14b.

### Plate Thickness Data Analysis

The statistics and PDFs representing the overall uncertainty of the total plate thickness sample population are presented in **Table 16** and account for 2,252 measurements. The ratio bias and difference bias were both measured. The range of ratio biases in the analysis is from 0.9068 to 1.376 and for the difference biases from -0.0233 to 0.141.

For the plate thickness ratio bias, the bin size was chosen as 37 in order to achieve an adequate detail level and to create the smoothest empirical distribution. The logistic PDF was considered the best fit for the data (parameters are 1.0485 and 0.02515), while the lognormal PDF may be used in its place should a simpler model be required (1.0480 and 0.04499).

The bin size was chosen as 18 for the plate thickness difference bias. The lognormal PDF

**Table 14a**

*Uncertainty in Plate Thickness t Based on Tolerance (Receipt Inspection)*

| DATA POINT | TOLERANCE (IN) | STANDARD DEVIATION OF *t* (IN) | MEAN OF *t* (IN) | *COV* OF *t* |
|---|---|---|---|---|
| 1 | 1/8 | 0.0417 | *t* | 0.0417/ *t* |
| 2 | 1/32 | 0.0104 | *t* | 0.0104/ *t* |
| 3 | 1/64 | 0.0052 | *t* | 0.0052/ *t* |
| 4 | 1/8 | 0.0417 | *t* | 0.0417/ *t* |

*t = plate thickness in inches*

**Table 14b**

*Uncertainty in Plate Thickness Based on Tolerance (Undercut)*

| DATA POINT | TOLERANCE (IN) | STANDARD DEVIATION OF *t* (IN) | MEAN OF *t* (IN) | *COV* OF *t* |
|---|---|---|---|---|
| 1 | 1/32 | 0.0104 | *t* | 0.0104/*t* |
| 2 | 1/16 | 0.0208 | *t* | 0.0208/*t* |
| 3 | 1/32 | 0.0104 | *t* | 0.0104/*t* |
| 4 | 1/32 | 0.0104 | *t* | 0.0104/*t* |
| 5 | 1/32 | 0.0104 | *t* | 0.0104/*t* |
| 6 | 1/32 | 0.0104 | *t* | 0.0104/*t* |
| 7 | 1/16 | 0.0208 | *t* | 0.0208/*t* |
| 8 | 1/32 | 0.0104 | *t* | 0.0104/*t* |
| 9 | 1/16 | 0.0208 | *t* | 0.0208/v |

*t = Plate thickness in inches*

*Undercut = further cutting of plate by the recipient after delivery*

**Table 15**

*Averages and Ranges of Standard Deviation and COV for Plate Thickness t*

| | STANDARD DEVIATION OF *t* (IN) | *COV* OF *t* |
|---|---|---|
| Average | 0.0172 | 0.0172/*t* |
| Minimum | 0.0052 | 0.0052/*t* |
| Maximum | 0.0417 | 0.0417/*t* |

**Table 16**

*Plate Thickness Statistical Analysis*

| | RATIO BIAS | | | DIFFERENCE BIAS (IN.) | |
|---|---|---|---|---|---|
| | *INPUT* | *LOGISTIC* | *LOGNORMAL* | *INPUT* | *LOGNORMAL* |
| Mean | 1.04849 | 1.04849 | 1.04796 | 0.01473 | 0.01568 |
| Standard Deviation | 0.04592 | 0.04562 | 0.04499 | 0.02100 | 0.02226 |
| *COV* (%) | 4.38 | 4.35 | 4.30 | n/a | n/a |
| Median | 1.04370 | 1.04849 | 1.0470 | 0.0061 | 0.01055 |
| Mode | 1.04323 | 1.04849 | 1.0451 | 0.0046 | 0.00222 |
| Skewness | 1.524 | 0 | 0.1289 | 1.979 | 1.900 |
| Kurtosis | 5.804 | 4.2 | 3.0295 | 4.201 | 10.04 |

*n/a = not available*

## Table 17

*Correlation Coefficients of Factors Which Influence Plate Thickness*

| | NOMINAL THICKNESS | STEEL TYPE | SOURCE | ORDERING SPECIFICATION | MEASUREMENT TECHNIQUE | COATING | PLATE SHAPE |
|---|---|---|---|---|---|---|---|
| Nominal Thickness | 1 | | | | | | |
| Steel Type | 0.163 | 1 | | | | | |
| Source | 0.746 | 0.233 | 1 | | | | |
| Ordering Specification | 0.690 | 0.294 | 0.902 | 1 | | | |
| Measurement Technique | 0.655 | 0.566 | 0.846 | 0.748 | 1 | | |
| Coating | 0.146 | 0.477 | 0.649 | 0.606 | 0.844 | 1 | |
| Plate Shape | -0.437 | -0.045 | -0.795 | -0.626 | -0.775 | -0.791 | 1 |

was agreed upon by each goodness-of-fit test and is recommended for use in modeling the data. The parameters are 0.03898 and 0.022264 with an adjustment of -0.0233 added to allow values less than zero.

### Factors That Influence Plate Thickness Uncertainty

The effects of the following factors on the plate thickness uncertainty are investigated: nominal thickness, steel type, data source, ordering specification, measurement technique, presence of a surface coating, and amount of plate deformation. The correlation coefficients of these factors were calculated and are shown in **Table 17**. The interdependencies between the variables are quite high with correlation coefficients approaching unity for multiple factors.

The influence of each of these factors on the two bias types was investigated. The nominal plate thickness of the sample population ranged from 0.0819 to 0.875 inches. There was no discernible impact on either bias because of the nominal thickness of the sample. Three types of steel were in the sample set: OS, HTS, and HY-80. The mean ratio bias increased with material yield strength, while the standard deviation decreased. A similar increasing trend was found in the difference bias mean, but the uncertainty increased as well.

The source of the data had a large impact on the results with greater uncertainty associated with the NSWCCD test and on-ship data, and the data reported in SSC-364. The Newport News data and the U.S. Coast Guard data appear to have less associated variability. The higher bias of the on-ship measured thickness values (NSWCCD and SSC-364) may have resulted from the conditions under which the measurements were made. These conditions include the presence of paint on the surface through which ultrasonic measurements were taken. The measurements taken of materials before construction (Newport News, NSWCCD tests, and U.S. Coast Guard data) were made with either a micrometer or ultrasonic measuring device without the impact of layers of surface treatments.

The bias of the plate thickness appears to be influenced by the manner in which it is ordered. The U.S. Navy pays for material based on its weight, so it would benefit the manufacturer by allowing the thickness to be skewed toward the higher tolerance limit. This would be the reverse for customers who order per piece, where the minimum amount of material necessary would be used and the plate thickness would tend to be closer to the specified tolerance lower bound. This influence may also be because of measurement methods and conditions such as whether the data are from a built and painted structure (as is the case with the Navy and commercial data) or from material measured before fabrication.

The techniques used in gathering the data were dependent upon access to the material. If a free edge of the plate was available, a micrometer could be used. If the plate was part of an existing structure, without an accessible free edge or opening, ultrasonic techniques (UT) were the only option. The NSWCCD on-board ship data were obtained through the use of UT. Micrometers and UT were both used to find thickness values of plating measured prior to construction. The ratio bias *COVs* of the micrometer and UT data are 2.8% and 11.7%, respectively, with means of 1.04 and 1.11. The presence of a surface coating also noticeably influenced the ratio and difference bias uncertainties. The ratio bias *COVs* were 3.4% for no coating and 12.2% with coating.

### *Plate Dimensions*

The literature search revealed that statistical data on plate dimensions a and b are limited. The same information source tends to be repeatedly used and referenced by other sources. The original source of information is the Japanese Shipbuilding Quality Standards. The studies by Basar and Stanley (1978), Daidola and Basar (1980), and others refer to this source. The steps necessary to estimate the coefficient of variations for the plate dimensions $a$ and $b$ are outlined in these references. The following equations were used for this purpose:

$$COV(a) = \frac{\sigma_a}{\mu_a} = \frac{0.106}{a - 0.037} \quad (8)$$

$$COV(b) = \frac{\sigma_b}{\mu_b} = \frac{0.093}{b - 0.013} \quad (9)$$

where $\sigma_a$ = standard deviation of $a$ equal to 0.106 in, $\sigma_b$ = standard deviation of $b$ equal to 0.093 in, $\mu_a$ = mean of $a$, $\mu_b$ = mean of $b$. In the above equations, it is assumed implicitly that the variances are not functions of plate dimensions (Daidola and Basar 1980). The dimensions of plates are assumed to follow normal distributions.

The plate dimensional uncertainty can also be framed as a direct function of stiffened spacing and length. Ship survey data analysis results for stiffener length and spacing can be considered to represent the plate length and width respectively. The following section provides uncertainty information appropriate for determining unstiffened panel strength uncertainty.

### *Stiffener Dimensions*

Stiffener geometry includes length, spacing, web height, web thickness, flange breadth, and flange thickness. The stiffener cross-sectional properties (web and flange dimensions) are dependent upon the supplier's tolerances, while the length and spacing are a result of construction techniques. Stiffeners are manufactured by either cutting an I-beam or channel to the desired size of tee or angle stiffener or building the stiffener from plating. Higher strength steels require the stiffener to be built up, while lower strength steels may be cold rolled. The analysis, which follows, lumps the various types together into one sample population. Future efforts may decide that the cold-rolled sections possess their own set of properties, and the built-up sections should be treated separately. The plate thickness statistics would then be applicable to the flange and web thickness values of the section, and the flange breadth and web height could be considered the same as the cold-rolled values.

The steps necessary for estimating the *COV's* for breadth of the flange and depth of the web of a stiffener were outlined by Daidola and Basar (1980) as follows:

$$\mathrm{COV}(f_w) = \frac{\sigma_{\Delta f_w}}{\bar{\Delta} b_f + f_{wn}} \text{ for flanges} \quad (10)$$

and

$$\mathrm{COV}(d_w) = \frac{\sigma_{\Delta d_w}}{\bar{\Delta} d_w + d_{wn}} \text{ for webs} \quad (11)$$

where $\sigma_\Delta$ = standard deviation of variability in flange breadth or web depth, $\bar{\Delta}$ = variability mean value of flange breadth or web depth, $f_w$ = flange breadth, $d_w$ = web depth, and the subscript $n$ denotes nominal or design value.

The variability of the stiffener web depth, flange breadth, web thickness, and flange thickness is quantified using two types of bias (Hess and Ayyub 1997): (1) ratio bias and (2) difference bias. The ratio bias is the ratio between the measured value and the nominal (or design) value for each specific strength parameter. On the other hand, the difference bias is the difference, or error, between the measured value and the nominal value.

**Table 18**

*Stiffener Length Data Statistical Analysis*

| | RATIO BIAS | DIFFERENCE BIAS (IN.) |
|---|---|---|
| Mean | 0.9882 | -1.264 |
| Standard Deviation | 0.04670 | 4.819 |
| *COV* (%) | 4.73 | *n/a* |
| Median | 0.9920 | -0.5000 |
| Mode | 1 | 0 |
| Skewness | 0.7870 | 0.4465 |
| Kurtosis | 1.7917 | 0.6921 |

*n/a = not available*

**Table 19**

*Stiffener Spacing Data Statistical Analysis*

| | RATIO BIAS | DIFFERENCE BIAS (IN.) |
|---|---|---|
| Mean | 0.9921 | -0.2514 |
| Standard Deviation | 0.02816 | 0.8669 |
| *COV* (%) | 2.84 | *n/a* |
| Median | 0.9969 | -0.1875 |
| Mode | 1 | 0 |
| Skewness | -0.9313 | -0.6187 |
| Kurtosis | 6.0535 | 6.0423 |

*n/a = not available*

With dimensional parameters such as thickness, breadth, and height, the variation from the nominally specified value may not be dependent upon the nominal value. For small nominal values of these parameters, the ratio bias may underestimate the variability, while for larger parameter values, it may overestimate the variability. Therefore, the error, or difference, between the measured and nominal values will be analyzed along with the ratio of these values.

### Stiffener Length

The stiffener length data were measured from U.S. Navy ships currently in service. Design values were garnered from drawings, which did not always accurately correspond to the measured values. These extreme values were filtered out as they could not be explained by pure randomness. The statistics of the filtered data are shown in **Table 18.** The stiffener length ratio bias data were analyzed using bin sizes 4 and 6 and consisted of 89 samples ranging in value from 0.9074 to 1.1597. The lognormal distribution is recommended for use with the normal distribution being acceptable should an even simple model be needed.

The stiffener length difference bias data were analyzed using bin sizes of 4, 5 and 6, with a sample size of 89 and a range from -10 to 11.5 inches. The logistic distribution is recommended with parameter values of -1.2641 and 2.6394. For simplicity the normal distribution may be used.

### Stiffener Spacing

The stiffener spacing data were collected from current U.S. Navy ships and are primarily from bulkheads and decks, which is due to the irregularity of the spacing on the side shell and the lack of accessible regions to survey. The measurements were taken from flange edge to flange edge. This method does not reflect the effects of stiffener distortion or flange tilting. The nominal values of the spacing were taken from design drawings. The statistics of the sample are shown in **Table 19** for a sample size of 261.

The stiffener spacing ratio bias data were analyzed using bin sizes of 14 and 29 resulting in a close agreement. The values ranged from 0.8620 to 1.0953. The logistic distribution is ranked highly by all three goodness-of-fit methods with parameter values of 0.9922 and 0.01542. Should simplicity be needed, the normal distribution may provide an adequate description of the bias.

The stiffener spacing difference bias data were analyzed using bin sizes of 14 and 25 with good agreement in the results. The data values ranged from -4.4375 to 3.8125 inches. Like the ratio bias, the logistic distribution is recommended as all three goodness-of-fit methods ranked it highest, with parameters of -0.2514 and 0.4748. The normal distribution is an acceptable substitute for simple applications.

### Stiffener Depth (Height)

The measurements of the height of the stiffeners on board ships were conducted by measuring the height of the stiffener flange from the supporting plate. A pair of measurements was done on both flange edges at three locations on each stiffener. The average of each pair of measurements was used to represent one data point. The resulting data set may be affected by localized distortion in the plating, tilting of the stiffener web and flange, and variations in the surface coating.

The data set as analyzed contained 547 points. Three extreme data points were filtered out of the analysis, as they appear to be the result of inaccurate nominal values. The statistics of the data are summarized in **Table 20**.

**Table 20**

*Stiffener Depth Data Statistical Analysis*

| | RATIO BIAS | DIFFERENCE BIAS (IN.) |
|---|---|---|
| Mean | 0.9955 | -0.0281 |
| Standard Deviation | 0.01859 | 0.1171 |
| *COV* (%) | 1.87 | *n/a* |
| Median | 0.9968 | -0.01625 |
| Mode | 1.003 | 0.01563 |
| Skewness | -0.3475 | -1.432 |
| Kurtosis | 1.620 | 8.994 |

*n/a = not available*

The stiffener ratio bias data range was from 0.9353 to 1.0698. BestFit® was used to analyze the bias data using bin sizes of 10, 14, and 27. As all three methods rank the logistic PDF as the first choice, it is recommended when representing the variability of the stiffener depth ratio bias. The parameters for the logistic distribution are 0.9954 and 0.01018. It is appropriate to use the normal distribution should a simplified model be required.

The stiffener depth difference bias was analyzed using bin sizes of 22 and 40 with a range from -0.84 to 0.41 inches. As with the ratio bias, based on the goodness-of-fit tests, the recommended PDF for the difference bias is the logistic distribution, with parameter values of -0.02812 and 0.06413. The normal distribution provides a better match of fundamental statistics, and may be appropriate for most purposes.

### Stiffener Web Thickness

The ease of access to the stiffener webs influenced whether they were measured using ultrasound techniques or a micrometer. Which method was used was not noted on the data collection sheets. Some of the samples were found to vary quite a bit from the thickness specified in the stiffener catalog. As the discontinuity in the frequency density was quite pronounced, these points were filtered out of the final analysis. An example of this would be a 5x4x6#T stiffener whose web was measured to be 0.134 in. thick, but whose nominal value is 0.190 in. The converse also occurs with measured values being 50% greater than the specified value. Such disparity was not seen in the other dimensions (height, flange breadth, and flange thickness) on the same stiffeners. As these stiffeners were designed to be rolled sections, there may be another explanation besides pure randomness in the thickness. The amount of paint covering the sample is an unknown quantity, but would tend to skew the bias upward, depending upon the sensitivity of the UT tools. The statistics of the web thickness bias are shown in **Table 21** for a sample size of 262.

**Table 21**

*Stiffener Web Thickness Data Statistical Analysis*

| | RATIO BIAS | DIFFERENCE BIAS (IN.) |
|---|---|---|
| Mean | 1.2550 | 0.0503 |
| Standard Deviation | 0.1134 | 0.0180 |
| *COV* (%) | 9.04 | *n/a* |
| Median | 1.229 | 0.04900 |
| Mode | 1.2059 | 0.035 |
| Skewness | 0.8991 | 0.2573 |
| Kurtosis | 0.3548 | -0.3874 |

*n/a = not available*

The web thickness ratio bias data were analyzed using a bin size of 11. The data ranged was from 1.0522 to 1.5603. The closeness of the test statistics for the different PDFs makes a clear recommendation difficult. The logistic distribution (parameters are 0.9385, 0.2721, and 4.4047) is recommended as it is ranked first by the K-S and A-D tests, and the lognormal may be used should a simple model of the randomness be required. The Extreme Value Type I distribution (parameters of 1.1977 and 0.0805) appeared to visually fit the best, but this is not backed up by the ranking methods.

The web thickness difference bias data ranged from 0.012 to 0.1 inches. BestFit® was used to

**Table 22**

*Stiffener Flange Breadth Data Statistical Analysis*

| | RATIO BIAS | DIFFERENCE BIAS (IN.) |
|---|---|---|
| Mean | 1.0144 | 0.0587 |
| Standard Deviation | 0.01634 | 0.0649 |
| *COV* (%) | 1.61 | *n/a* |
| Median | 1.0139 | 0.05000 |
| Mode | 1.031 | 0.1225 |
| Skewness | 0.2122 | 0.3186 |
| Kurtosis | -0.009167 | -0.2056 |

*n/a = not available*

**Table 23**

*Stiffener Flange Thickness Data Statistical Analysis*

| | RATIO BIAS | DIFFERENCE BIAS (IN.) |
|---|---|---|
| Mean | 1.1321 | 0.0293 |
| Standard Deviation | 0.1038 | 0.0212 |
| *COV* (%) | 9.17 | *n/a* |
| Median | 1.101 | 0.02500 |
| Mode | 1.1 | 0.03 |
| Skewness | 1.236 | 1.0118 |
| Kurtosis | 1.315 | 0.8388 |

*n/a = not available*

analyze the bias data with bin sizes 6 and 13, with good agreement between the results. The Weibull distribution is ranked highly by each method and is recommended for use with parameter values of 3.0468 and 0.05637. Should a simpler PDF be needed, the normal distribution would be an adequate representation of the web thickness difference bias, as the test statistics are relatively good and it matches quite well visually.

### Stiffener Flange Breadth

Measurement of the stiffener flange breadth was done onboard current U.S. Navy ships using a ruler and measuring to the nearest 32nd of an inch (0.03125). The accuracy of the measurements generally lacks the resolution found in other measurements because of the magnitude of the measured values relative to the level of precision. The statistics of the data are presented in **Table 22** for a sample size of 495.

The flange breadth ratio bias data ranged from 0.9678 to 1.0628 and were grouped into bin sizes of 5 and 9. The recommended distribution is the logistic distribution (parameters of 1.0144 and 0.00895) as it is ranked highly by the C-S and A-D tests and visually fits the histogram quite well. For a simpler model, the lognormal distribution is a valid second choice.

The flange breadth difference bias data ranged from -0.125 to 0.2475 inches and were analyzed by BestFit® using bin sizes of 5 and 6. The logistic distribution (parameters of 0.05649 and 0.04659) is recommended as the best model of the randomness of the flange breadth stiffener difference bias, as it visually matches quite well, and is ranked highly by both the C-S and A-D tests. The normal distribution also has a very good visual fit, was ranked highly by the C-S test, and is much simpler to use.

### Stiffener Flange Thickness

The stiffener flange thickness was measured with a micrometer. Factors influencing the measurement were the amount of paint on the flange and the degree of taper of the flange from the centerline to the edge. The measurements were meant to be taken at the midpoint between the centerline and the edge of the flange, giving an average thickness across the breadth. The statistics of the biases are reported in **Table 23** for 480 samples.

The flange thickness ratio bias data ranged from 0.9400 to 1.490. The BestFit® analysis of the flange thickness ratio bias was conducted using bin sizes of 10 and 14 with close agreement. The goodness-of-fit tests all rank the Extreme Value Type I distribution as the best, and it is recommended for use with parameters of 1.0854 and 0.0809. The lognormal would be suitable for simple applications.

A bin of 10 was used to analyze the flange thickness difference bias data, which ranged from a value of -0.012 to 0.098 inches. The goodness-of-fit tests and visual inspection agree on the Extreme Value Type I distribution as the best match for the flange thickness difference bias with parameters of 0.01974 and 0.01653. A simpler model may be found in the lognormal distribution.

## Fabricated Dimensions of Ships

### *Ship's Length*

The literature review did not reveal any information on uncertainties in the length (LBP) of ships, but it can be assumed that the length variability in the form of a standard deviation does not exceed one or two inches with a normal probability distribution. In addition, it is assumed that the standard deviation is not a function of length.

### *Ship's Depth*

Statistical information on ship's depth ($D$) was summarized by Daidola and Basar (1980) as given in **Table 24**. This table provides statistical information on variation of ship's depth based on average tolerance. As in the case of plate thickness ($t$), the calculation of standard deviation for $D$ based on its tolerance can be performed by dividing the tolerance by three. This calculation leads to correct results, if the underlying probability distribution for $D$ is normal and 99.7 percent of the measurement fall within the tolerance limit. The *COV* of $D$ can be simply computed by dividing the standard deviation by the mean of $D$ as shown in **Table 24**. Daidola and Basar (1980) outlined the necessary steps for the calculation of the *COV* of $D$ from measured data. Based on four measured depths, their computed value for the *COV* is 0.001365. **Table 25** provides averages and ranges for the mean, standard deviation, and *COV* of $D$. The calculated averages and ranges in Table 25 were based on the data shown in Table 24.

### *Ship's Breadth*

The coefficient of variation of ship's breadth ($B$) that is based on fabrication tolerances is given in **Table 26** (Daidola and Basar 1980). The coefficient of variation was computed to be 0.000181. **Table 27** provides averages and ranges for the mean, standard deviation, and *COV* of $B$.

### *Section Modulus*

**Table 28** provides the ratio of actual ($Z_a$) to minimum (or rules required, $Z_r$) section modulus (i.e., $Z_a/Z_r$) for selected ships from different countries and various classification societies (Guedes Soares and Moan 1985 & 1988). The computed mean value and coefficient of variation for this ratio were found to be 1.04 and 0.05, respectively. Mansour et al. (1993) assumed a lognormal distribution with mean to nominal ratio and coefficient of variation of 1.0 and 0.04, respectively (nominal value was taken to be the section modulus as required by ABS rules).

**Table 24**

*Uncertainty in Ship Depth (D) Based on Tolerance*

| DATA POINT (IN) | TOLERANCE (IN) | STANDARD DEVIATION OF D (FT) | MEAN OF *D* | *COV* OF *D* |
|---|---|---|---|---|
| 1 | 1/4 | 0.00694 | 20.0 | 0.000347 |
| 2 | 1/2 | 0.01390 | 36.0 | 0.000386 |
| 3 | 0.1% | 0.01200 | 36.0 | 0.000333 |
| 4 | 1/2 | 0.01390 | 26.0 | 0.000535 |
| 5 | 3/8 | 0.01040 | 91.0 | 0.000114 |
| 6 | 1/2 | 0.01390 | 50.0 | 0.000278 |

**Table 25**

*Averages and Ranges for the Statistics of Ship Depth D*

| | MEAN OF *D* (FT) | STANDARD DEVIATION OF *D* (FT) | *COV* OF *D* |
|---|---|---|---|
| Average | 43.2 | 0.01180 | 0.0003255 |
| Minimum | 20.0 | 0.00694 | 0.0001140 |
| Maximum | 91.0 | 0.01390 | 0.0005350 |

**Table 26**

*Uncertainty in Ship Breadth (B) Based on Tolerance*

| DATA POINT | TOLERANCE (IN) | STANDARD DEVIATION OF *B* (FT) | MEAN OF *B* | *COV* OF *B* |
|---|---|---|---|---|
| 1 | 0.1% | 0.002 | 6 | 0.0003333 |
| 2 | 1/2 in | 0.0139 | 200 | 0.0000695 |
| 3 | 1/2 in | 0.0139 | 75 | 0.0001853 |
| 4 | 1/2 in | 0.0139 | 96 | 0.0001450 |

**Table 27**

*Averages and Ranges for the Statistics of Ship Breadth B*

| | MEAN OF *B* (FT) | STANDARD DEVIATION OF *B* (FT) | *COV* OF *B* |
|---|---|---|---|
| Average | 94.25 | 0.01093 | 0.0001833 |
| Minimum | 6.00 | 0.00200 | 0.0000695 |
| Maximum | 200.00 | 0.01390 | 0.0003333 |

## Load Random Variables

This section provides statistical data of load variables for ship structures. These data were

## Table 28

*Ratio of Actual ($Z_a$) to Minimum (Rules Specified, $Z_r$) Section Modulus for Selected Ships*

| SHIP | $Z_a / Z_r$ | SHIP | $Z_a / Z_r$ | SHIP | $Z_a / Z_r$ | SHIP | $Z_a / Z_r$ |
|---|---|---|---|---|---|---|---|
| CS 3 | 1.04 | OBO 3 | 1.00 | TK7 | 1.00 | TK31 | 1.02 |
| CT 2 | 1.00 | OBO 4 | 1.00 | TK8 | 1.00 | TK32 | 1.02 |
| CT 3 | 1.00 | OBO 5 | 1.06 | TK18 | 1.12 | TK33 | 1.02 |
| BC 5 | 1.00 | OBO 6 | 1.00 | TK19 | 1.12 | TK34 | 1.02 |
| BC 9 | 1.01 | CH 1 | 1.00 | TK20 | 1.12 | TK35 | 1.02 |
| BC 10 | 1.00 | CH 2 | 1.15 | TK21 | 1.12 | TK36 | 1.02 |
| BC 14 | 1.01 | CH 3 | 1.15 | TK22 | 1.00 | TK37 | 1.02 |
| BC 15 | 1.01 | OO2 | 1.02 | TK23 | 1.00 | TK38 | 1.04 |
| | | OO3 | 1.02 | TK24 | 1.07 | | |

*CS = cargo ship, CT = containership, BC = bulk carrier, OBO = ore/bulk/oil carrier, CH = chemical tanker, OO = ore/oil carrier, and TK = oil tanker*

## Table 29

*Summary of Statistics for Stillwater Bending Moment MSW*

| $\overline{M}_{SW}/M_{SW}$ | *COV* OF $M_{SW}$ | DISTRIBUTION TYPE |
|---|---|---|
| 0.4 to 0.6 | 0.3 to 0.9 | Normal |

collected from various sources with the objective of identifying the load uncertainties. The random variables of interest in this section are stillwater bending moment, wave bending moment, and dynamic load effects. Therefore, the load random variables are not basic ones, but rather bending moments as would be used in reliability-based design formats. The data includes the mean $\mu$, standard deviation ($\sigma$) or coefficient of variation (*COV*) and wherever available the distribution type for each load random variable. The moment methods that are used in reliability-based design and assessment require these types of information. Statistical information on load variables that are considered to be relevant to ship structures is provided in this section under separate headings.

## Stillwater Bending

Statistics on stillwater bending moment ($M_{SW}$) were summarized by Atua et al. (1996). This summary is provided in **Table 29** and applies to commercial ships. The table provides information on the mean to nominal ratio ($\overline{M}_{SW}/M_{SW}$), the coefficient of variation (*COV*), and distribution type. The nominal value is taken as the value required by the classification societies rules, while the distribution type is assumed to be normal (Mansour et al. 1996).

## Wave-Induced Bending Moment

Statistical data on wave-induced bending moment was collected from different sources as shown in **Table 30**. Extreme Value Type I distribution was used to model the lifetime extreme wave bending moment with mean to nominal ratio of 1.0 (Mansour 1987). Mansour et al. (1996) used a *COV* value of 0.2 for extreme wave-induced bending moment to demonstrate the calculation of partial safety factors, and used a value of 0.1 in the development of a prototype load and resistance factor design (LRFD) format for hull girder collapse for both cruisers and tankers. In a previous study, a *COV* value of 0.09 was set for extreme wave-induced bending moment for cruisers and tankers.

Guedes Soares (1992) used the Weibull distribution to fit extreme wave-induced bending moment ($M_W$) expressed in the form of its cumulative distribution function as

$$F_{M_w}(x) = 1 - e^{-(x/\sigma)^q} \tag{12}$$

where $\sigma$ = standard deviation and $q$ = exponent of Weibull distribution.

Kaplan et al. (1984) reported that the coefficient of variation of wave-induced bending moment was taken to be 0.149 in

## Table 30

*Models Used for Life-time Extreme Wave-induced Bending Moment*

| $\overline{M}_{sw}/M_{sw}$ | COV OF $M_{sw}$ | DISTRIBUTION TYPE | COMMENTS | REFERENCES |
|---|---|---|---|---|
| n/a | n/a | Exponential (long term) Rayleigh (short term) | | Boe et al. (1974) |
| 1.0 | 0.09 | Extreme | COV varies with number of wave moment peaks | Mansour (1993) |
| n/a | n/a | Weibull | For long term wave loads | Guedes Soares (1992) |
| n/a | 1.0 | Exponential | Exponential fits better in the Pacific and general usage cases, and Weibull fits for the Atlantic case | Mansour et al. (1984) |

*n/a = not available*

many studies without any close investigation. The uncertainties in wave-induced bending moment were attributed to three major sources (Atua and Ayyub 1996): (1) uncertainty because of the effect of sea state, (2) uncertainty because of the effect of theoretical response amplitude operators (RAOs), and (3) uncertainty because of the effect of extrapolation methods for lifetime maximum. The *COV* value of wave-induced bending moment because of the first category was found to be equal to 0.2 for Bretschneider spectrum and equal to 0.1 for the 6-parameter spectra (Ochi 1978). Kaplan et al. (1984) recommended an average value for this *COV* of 0.15 to be used in design cases. The *COV* value because of the second category was found to equal 0.1. The *COV* value because of the third category was found to be equal 0.065 for an extreme value that correspond to 10,000 load repetitions. Treating the three sources as uncorrelated random variables, the combined *COV* for lifetime extreme wave-induced bending moment was computed as follows (Kaplan et al 1984):

$$COV(M_W) = \sqrt{(0.15)^2 + (0.10)^2 + (0.065)^2} = 0.192 \tag{13}$$

**Table 31** provides a summary of statistical data for lifetime extreme wave-induced bending.

## Table 31

*Summary of the Statistics for Lifetime Extreme Wave-induced Bending Moment $M_W$*

| $\overline{M}_w/M_w$ | COV of $M_w$ | DISTRIBUTION TYPE |
|---|---|---|
| assumed to be 1.0 | 0.1 to 0.2 | extreme value (type I) |

### *DYNAMIC LOADS*

The dynamic loads that are considered in this section are: (1) the whipping bending moment and (2) springing loads. The two kinds of loading are provided under separate headings.

### Whipping Bending Moments

The literature review revealed no statistical information on dynamic loads on hull girders including whipping. Mansour et al. (1996) considered the values provided by classification societies as default design values in cases with no information. As an alternative to the default values, Mansour et al. (1996) suggested values of $0.2M_W$ for commercial ships and $0.3M_W$ for naval vessels as design (or nominal) values. In their study, they assumed an extreme value distribution with a mean to nominal ratio of 1.0 and a coefficient of variation of 0.3 for both tankers and cruisers.

Kaplan et al. (1984) reported results of studies performed to investigate uncertainties associated with whipping bending moment. A *COV* of 0.21 was recommended for short-term probability representation (Kaplan et al 1984). The exponential distribution was also recommended to model whipping (Kaplan et al. 1984; Dalzell et al. 1979; and Clarke 1982). A *COV* in the range of 0.05 to 0.1 was recommended for long-term probability representation (Kaplan et al. 1984).

## Table 32

*Summary of Life-time Extreme Vertical Midship Whipping Bending Moment $M_{WH}$*

| $\overline{M}_{WH}/M_{WH}$ | COV of $M_{WH}$ | DISTRIBUTION TYPE |
|---|---|---|
| Assumed to be 1.0 | 0.2 to 0.3 | extreme value (type I) or exponential |

## Table 33

*Summary of Life-time Extreme Vertical Midship Springing Bending Moment $M_{SP}$*

| $\overline{M}_{SP}/M_{SP}$ | COV of $M_{SP}$ | DISTRIBUTION TYPE |
|---|---|---|
| Assumed to be 1.0 | 0.3 | extreme value (type I) |

**Table 32** provides a summary of the statistics for lifetime extreme vertical midship whipping bending moment ($M_{WH}$).

### Springing

The variability associated with springing loads (MSP) can be attributed to three types of uncertainties (Kaplan et al. 1984). The first type is the uncertainty due to the effects of the wave spectral variability, which can be expressed as a *COV* value of 0.2. The second uncertainty is associated with the error in the theoretical RAO values, which can be approximately estimated to be 0.2. The third type of uncertainty is due to the extreme value variability that is represented as a *COV* value of about 0.05. The resulting *COV* for springing was estimated to be 0.287 according to the following equation

$$COV(M_{SP}) = \sqrt{(0.2)^2 + (0.2)^2 + (0.05)^2} = 0.287 \tag{14}$$

**Table 33** provides a summary of the statistics for lifetime extreme vertical midship springing bending moment $M_{SP}$.

#### *HYDROSTATIC PRESSURE*

Hydrostatic pressure on plates (panels) is due to several sources that include (1) stillwater, (2) wave and dynamic effects, (3) green seas, and (4) liquids in tanks. Only the first two types are considered in this paper. Mansour et al. (1996) assumed coefficients of variation (*COVs*) of 0.2 and 0.1 for stillwater and wave-induced pressures. In this study, the *COV* for stillwater pressure is assumed to be 0.15, the *COV* for wave-induced pressure is 0.15, the *COV* for dynamic-induced pressure is 0.25, and the *COV* for the combined wave and dynamic-induced pressure is 0.25. These values were selected based on judgment.

## Summary of Probabilistic Characteristics of Random Variables

In this section, the probabilistic characteristics of strength and load random variables for ship structures are summarized and tabulated based on the data collected in previous sections. These characteristics include the mean $\mu$, standard deviation ($\sigma$)or the coefficient of variation, (*COV*), and the underlying probability distribution type for each random variable. The results herein can be used in reliability-based design and assessment for ship structural elements. However, since these results can be revised as new data and research on the subject emerge, caution must be taken when using these results in reliability assessment and reliability-based design of ship structures. Also, these results might not be appropriate for special situations where thorough and rigorous analyses are required, because they represent only the ranges and the weighted averages of the statistical values collected in previous sections. For such situations, the user or reader must consult these sections for further detailed statistical information. Summaries of the probabilistic characteristics of the random variables are provided in this section under two headings, one for the strength variables and the other for the load variables. The strength and load random variables required for performing reliability-based design for ship panels are shown in **Tables 34** and **35**, respectively.

## Summary of Strength Variables

**Table 36** gives a summary of the probabilistic characteristics of strength basic random variables. It includes weighted averages for means, coefficients of variation, standard deviations, and probability distributions of basic random variables. The bias in this table is defined as the ratio of mean to nominal (or design) value.

## Summary of Load Variables

**Table 37** shows recommended statistical characteristics of basic load components for ship structures. The statistical characteristics consist of mean to nominal ratio or mean value, coefficient of variation (*COV*), and distribution type. Stillwater bending moment can be modeled using a normal distribution with a mean to nominal ratio ranging from 0.4 to 0.6, and a *COV* value ranging from 0.3 to 0.9. Lifetime extreme wave-induced bending moment can be modeled using an Extreme Value Type I distribution with a mean to nominal ratio of 1.0 and a *COV* value ranging from 0.1 to 0.2. Whipping bending moments can be modeled using either an Extreme Value Type I distribution or exponential distribution with a mean value calculated as a function of the ship principal dimensions and a *COV* ranging from 0.2 to 0.3. Springing bending moment can be modeled using Extreme Value Type I distribution with a mean to nominal ratio of 1.0 and a *COV* of 0.3. In this study, the *COV* for stillwater pressure is assumed to be 0.15, the *COV* for wave-induced pressure is 0.15, the *COV* for dynamic-induced pressure is 0.25, and the *COV* for the combined wave and dynamic-induced pressure is 0.25. These values were selected based on judgment.

## Conclusions

The use of surface ship structural strength predictions in a reliability-based design format requires accurate characterization of the uncertainty inherent in the basic strength variables and their impact on the resulting strength. Preceding the development of any reliability-based design procedure, relevant variables must be identified and their statistical characteristics need to be defined.

The design strength of a ship structural component is based on nominal values of basic strength variables, both material and geometric, such as yield strength of the material, plate thickness, modulus of elasticity, etc. Random behavior of the basic strength and load variables can cause the strength of the structure to vary beyond acceptable levels. For example, the strength prediction of a longitudinally stiffened panel may be shown to have coefficients of variation ranging as high as 10% (Hess et al, 1994). Quantifying the uncertainty, or randomness, found in the basic strength and load variables allows the designer to account for this variability in the strength of the structure. The uncertainty associated with the strength prediction may be calculated using simulation techniques,

**Table 34**

*Strength Random Variables*

| VARIABLE | NOTATION |
|---|---|
| steel thickness for plates | $t$ |
| length or span of steel plate | $a$ |
| width of steel plate | $b$ |
| stiffener web depth | $d_w$ |
| stiffener flange breadth | $f_w$ |
| stiffener web thickness | $t_w$ |
| stiffener flange thickness | $t_f$ |
| ship length | $L$ or $LBP$ |
| ship depth | $D$ |
| ship breadth | $B$ |
| yield strength of steel | $F_y$ |
| ultimate strength of steel | $F_u$ |
| Modulus of elasticity of steel | $E$ |
| Poisson's ratio | $\nu$ |
| section modulus | $Z$ |
| initial yield bending capacity of a hull girder | $M_y$ |
| plastic bending capacity of a hull girder | $M_p$ |

**Table 35**

*Load Random Variables*

| VARIABLE | NOTATION |
|---|---|
| stillwater bending moment | $M_{SW}$ |
| wave-induced bending moment | $M_W$ |
| slamming and whipping bending moment | $M_{WH}$ |
| springing bending moment | $M_{SP}$ |
| hydrostatic pressure due to stillwater | $P_{SW}$ |
| hydrostatic pressure due to waves | $P_W$ |
| hydrostatic pressure due to dynamic effects | $P_D$ |
| hydrostatic pressure due to combined waves and dynamic loads | $P_{WD}$ |

## Table 36

*Recommended Probabilistic Characteristic of Strength Basic Random Variables*

| VARIABLE | NOMINAL VALUE | STATISTICAL INFORMATION MEAN | COV | DISTRIBUTION TYPE |
|---|---|---|---|---|
| $t$ (in) | $T$ | 1.05 $t$ | 0.044 | Lognormal |
| $a$ (in) | $A$ | 0.988 $a$ | 0.046 | Lognormal |
| $b$ (in) | $B$ | 0.992 $b$ | 0.028 | Normal |
| $dw$ (in) | $dw$ | 0.996 $dw$ | 0.019 | Normal |
| $fw$ (in) | $fw$ | 1.014 $fw$ | 0.016 | Lognormal |
| $tw$ (in) | $tw$ | 1.255 $tw$ | 0.083 | Extreme Type I |
| $tf$ (in) | $tf$ | 1.132 $tf$ | 0.092 | Extreme Type I |
| $L$ (ft) | $L$ | $L$ | 0.08 | Normal |
| $D$ (ft) | $D$ | $D$ | 0.01 | Normal |
| $B$ (ft) | $B$ | $B$ | 0.01 | Normal |
| Ordinary Strength (OS) $F_y$ (ksi) | $F_y$ | 1.3 $F_y$ | 0.124 | Lognormal |
| High Strength (HS) $F_y$ (ksi) | $F_y$ | 1.19 $F_y$ | 0.083 | Lognormal |
| $F_u$ (ksi) | $F_u$ | 1.05 $F_u$ | 0.075 | Normal |
| $E$ (ksi) | $E$ | 0.987 $E$ | 0.076 | Normal |
| $\upsilon$ | $\upsilon$ | $\upsilon$ = 0.3 for steel | 0 | Deterministic |
| $Z$ | $Zr$ | 1.04 $Zr$ | 0.05 | Lognormal |
| $My$ | $F_yZ$ | $\bar{F}_y\bar{Z}$ | 0.15 | Lognormal |
| $Mp$ | $F_yZ_p$ | $\bar{F}_y\bar{Z}_p$ or $c\bar{F}_y\bar{Z}$ | 0.18 | Lognormal |
| | | | 0.18 | Lognormal |

such as Monte-Carlo simulation, which allow the values for the basic strength variables to be generated based on their statistical distributions (probability density functions).

Statistical estimates of the uncertainty associated with geometry and material basic strength variables used in the analysis and design of surface ship structures were presented with an emphasis on U.S. Navy ships. The basic structural strength variables may be grouped into two classes: material variables (such as yield strength and ultimate strength) and geometric variables (such as plate thickness and stiffener height). The geometric variables may also be called construction variables.

Statistics and recommended probability density distributions for characterizing the uncertainty in material strength variables were presented. The material strength variables considered are the mechanical properties of yield strength, ultimate strength, and elastic modulus. The steel types included in the sample population are ordinary steel, high strength (HS) steel, high-strength low-

## Table 37

*Recommended Probabilistic Characteristics of Load Random Variables*

| RANDOM VARIABLE | DISTRIBUTION TYPE | MEAN TO NOMINAL RATIO | COV |
|---|---|---|---|
| Stillwater Bending Moment $M_{SW}$ | Normal | 0.4 to 0.6 for commercial ships and 0.7 for naval vessels | 0.3 to 0.9 for commercial ships and 0.15 for naval vessels |
| Life-time Extreme Wave-induced Bending Moment $M_W$ | Largest Extreme value (type I) | 1.0 | 0.1 to 0.2 |
| Whipping Bending Moment $M_{WH}$ | Extreme value (type I) exponential | Mean value can be determined using formulae based on spectral analysis | 0.2 to 0.3 |
| Springing Bending Moment $M_{SP}$ | Extreme value (type I) | 1.0 | 0.3 |
| Hydrostatic Pressure Because of Stillwater, $P_{SW}$ | Normal | 0.4 to 0.6 for commercial ships and 0.7 for naval vessels | 0.15 |
| Hydrostatic Pressure Because of Waves, $P_W$ | Largest extreme value (type I) | 1.0 | 0.15 |
| Hydrostatic Pressure Because of Dynamic Effects, $P_D$ | Largest extreme value (type I) | 1.0 | 0.25 |
| Hydrostatic Pressure Because of Combined Waves and Dynamic Loads, $P_{WD}$ | Weibull | 1.0 | 0.25 |

alloy (HSLA) 80 steel, high yield (HY) 80 steel, and HY-100 steel. The data presented are from previously published sources and testing undertaken for this study.

Statistical estimates and probability density functions representing the uncertainty in the following geometric basic strength parameters were presented: plate thickness, stiffener length and spacing, stiffener web height, web thickness, flange breadth, and flange thickness. The effect of the following factors on the plate thickness uncertainty were investigated: nominal thickness, steel type, data source, ordering specification, measurement technique, presence of a surface coating during measurement, and amount of local plate deformation. Geometric basic strength variable data used in this study were from previously published sources, on-board ship measurements, and raw material measurements (before use in ship construction). The bulk of the data is for U.S. Navy ships with additional data provided for Coast Guard and commercial vessels. The results of this study can be used in the development of reliability-based design criteria, tolerance limits, and the assessment of random uncertainty in strength predictions.

Reliability analysis and design requires accurate representation of the uncertainty associated with the strength and the loading of the structure. A summary of probabilistic characteristics of strength and load random variables for ship structures was presented These characteristics include the mean ($\mu$), standard deviation ($\sigma$) or the coefficient of variation, ($COV$), and the underlying probability distribution type for each random variable. The results can be used in reliability-based design and assessment for ship structural elements. However, since these results can be revised as new data and research on the subject emerge, caution must be taken when using these results in reliability assessment and reliability-based design of ship structures. Also, these results might not be appropriate for special situations where thorough and rigorous analyses are required, because they represent only the ranges and the weighted averages of the statistical values collected in previous sections.

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**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

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**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 it's 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 Criteria 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 technical 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, ULTSTR. 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.

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**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)

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**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 NSWCCD 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. ■