# RELIABILITY ASSESSMENT OF WATERTIGHT SHIP DECKS AND BULKHEADS

J. A. Pires, M. ASCE, R. H. Sues, M. ASCE, and Mark Cesare, M. ASCE
*Applied Research Associates, Inc., Albuquerque, NM, 87110*
jpires@ara.com, rsues@ara.com, mcesare@ara.com

B. Battacharya and R. I. Basu
*ABS Americas, Houston, TX 77060*
rbasu@eagle.org

Pradeep Sensharma
*Designers and Planners, Arlington, VA 22204*
psenshar@dandp.com

## Abstract

This research is developing a framework for reliability assessment of existing watertight boundaries of vital spaces of U.S. Navy ships. These structural components are essential for ship survival during flooding conditions that occur after damage caused by collisions that may take place as part of normal peacetime operations. The goal is to use this reliability assessment framework to establish reliability levels inherent in present design practices and then develop a reliability-based load and resistance factor design (LRFD) approach for the watertight boundaries of new ships. Work to date is presented and includes a probabilistic loading model, a probabilistic structural response and damage model, and reliability analysis techniques and corresponding software. The methodology is illustrated for an example bulkhead with the calculation of reliability indices implicit in the current design practice. While this work is being done for the U.S. Navy, it is applicable to commercial ships, which must meet similar damage stability criteria.

## Introduction

Reliability-based design codes and reliability assessment frameworks permit a systematic and rational treatment of uncertainties, direct and meaningful comparisons of safety levels, possible savings in structural steel weight, and risk assessment studies. These benefits lead the government and private sectors to emphasize implementation of reliability-based structural ship design (Mansour et al., 1997, Melton and Ayyub, 1999, Hughes et al., 1994, Hess, Bruchman and Ayyub, 1997). These efforts have dealt with the structural design of the main ship structure while the work reported here addresses the reliability and design of watertight boundaries (WTBs) of vital spaces of U.S. Navy ships. The primary objective of this work was the development and demonstration of a framework for the reliability assessment of these watertight boundaries. Its goal is the assessment of current design codes with the calculation of underlying reliability levels and then the development of a reliability-based load and resistance factor design (LRFD) approach for the WTBs of new ship structures. The major elements of the proposed methodology are a probabilistic load model, a structural response and damage model, which includes geometric and material uncertainties, and the reliability analysis techniques and corresponding software. These elements are briefly described in the following. Then, the methodology is illustrated with the calculation of underlying limit state probabilities for an example bulkhead designed following the current design codes. Given the space limitations only a summary of the developments and results produced is presented here. For complete descriptions the readers are referred to Pires et al. (2000).

## Probabilistic Load Modeling

A probabilistic model was developed to characterize internal seawater pressures on WTBs under the flooding conditions that may follow collision damage. The major attributes of this model are as follows: (1) it is mechanics-based which makes it applicable to ships of different sizes and classes and different damage-causing events; (2) relates hydrostatic pressures to readily available ship design parameters, which facilitates its integration into design practices; and (3) the loads have explicit functional dependence on the damage-related variables. For more details see also Battacharya and Basu (2000). A combination of mechanics- and simulation-based approaches is used in the derivation of the model, which consisted of the following steps:

1. Identify significant variables and select those for inclusion in the model.
2. Identify distinct load components on WTBs.
3. Develop a simplified description of the ship damage.
4. Establish predictive equations (mechanics-based) and functional forms (modified predictive equations that explicitly relate loads to design variables) for each load component. The functional forms will have undetermined coefficients to be determined as indicated in step 6 below.
5. Adopt an adequate but simple ship response model that includes the variables identified in step 1, and exercise it over the range of values of the basic variables.
6. Identify the undetermined coefficients in the functional models (step 4) using the results of step 5 and regression analysis.
7. Establish the probability distribution functions (PDFs) for the basic variables.
8. Use statistical simulation together with the functional forms determined in steps 4 and 6 and the PDFs of step 7 to obtain the necessary load statistics.

The force vector on a WTB (**F**) is a function of time and space and is, generally, the sum of two loading sources: $\mathbf{F}_{liquid}$ and $\mathbf{F}_{hull}$. $\mathbf{F}_{liquid}$ represents the effects of liquids, either ingressed or liquid cargo, in direct contact with the bulkhead, and $\mathbf{F}_{hull}$ represents loads that derive from the hull girder response. Loads from $\mathbf{F}_{liquid}$ act mostly normal to the WTB and have static as well as dynamic components. The dynamic components include wave action, roll action and sloshing while the static components include draft, parallel sinkage and trim. $\mathbf{F}_{hull}$ represents loads from the hull girder response, which are mostly in plane forces, *e.g.*, shear forces caused by bending and torsion of the hull girder, as well as dynamic effects caused by environmental loads, *e.g.*, springing and whipping. In this project, the focus is on the survivability of WTBs under flooding conditions and it is assumed that $\mathbf{F}_{liquid}$ is the result of seawater ingress ($\mathbf{F}_{flood}$). It is also assumed that $\mathbf{F}_{hul}$ is weakly dependent on the damage variables and that under flooding conditions the flooding forces govern the WTBs performance. For these reasons, $\mathbf{F}_{hull}$ is not considered in this study.

For convenience, the loading terms were separated in those that vary longitudinally, *i.e.*, with the distance $x_b$ from amidships, and those that vary transversely (roll), *i.e.*, with the distance $y$ from the centerline as follows: $h(x_b, y) = h_x(x_b) + h_y(y)$. Functional forms for the various loading terms were derived (steps 4 and 7 above) for a military Sealift ship and the following equation was obtained for the water pressures:

$$h_{x_{actual}}(x_b) = T + \left\{ \alpha_{11} \frac{\mu LBT}{A_w} \left( \frac{l}{L} \right)^{\alpha_{12}} \cdot \exp[\varepsilon_{fit_1}] \right\} B_1$$

$$x_b \sin \left[ \left\{ -\alpha_{21} \frac{\mu \rho g BT}{(MTm)} (LCF) + \alpha_{22} \frac{\mu \rho g LBT}{(MTm)} \left( \frac{x_D}{L} \right) + \varepsilon_{fit_2} \right\} B_2 \right] + \varsigma_a \tag{1}$$

$$h_{y_{actual}}(y) = y \sin \phi^*_{actual} \; = y \sin \left\{ \frac{\exp(-kT/2)}{\sqrt{(1-\Lambda^2)^2 + \nu_\phi^2 \Lambda^2}} k \varsigma_a \right\} B_3 \tag{2}$$

where μ = volume permeability for damaged compartments, $A_W$ = waterplane area, → = seawater density, g = acceleration of gravity, L= ship length, B = breadth at midsection, T = draft at midsection, *l* = flooded length (depends on damage location and ship subdivision), ↦→, $↦→_{11}$, $↦→_{12}$ = regression coefficients, $x_D$ = distance of center of damage from amidships, (LCF) = longitudinal center of flotation, MTm = moment to trim, Λ = frequency ratio $\omega/\omega_0$, ω = wave frequency, $\omega_0$ = natural roll frequency of the ship, *k* = wave number, $\nu_\phi$ = damping factor (between 0.1 and 0.2) and $\zeta_a$ = wave amplitude. Equations 1 and 2 contain terms that account for curve fitting errors ($⊙_{fit1}$ and $⊙_{fit1}$) and modeling errors ($B_1$, $B_2$ and $B_3$). In the derivation of these equations, symmetric flooding is assumed which removes the heel term. It is also assumed that a damaged ship will stop and take a beam configuration (regular sea state), which eliminates the pitch term. Finally, the variation of roll and wave with time are not considered and only their amplitudes are included in the model. These assumptions can be relaxed with future developments.

Statistical simulation was used together with Equations 1 and 2 to calculate the statistics of $h_{x_{actual}}$ and $h_{y_{actual}}$. Random variables included in the simulation were those for the curve fitting and modeling errors, the geometric and ship variables T, $A_W$, ∓, $↼_0$, and MTm, the independent damage variables $l_D$ (damage length) and $x_D$ , and the dependent damage variable *l*. The calculated statistics are shown in Table 1 below. Goodness-of-fitting tests suggest a lognormal PDF for $h_{x_{actual}}$. However, no PDF was found for $h_{y_{actual}}$ that would pass goodness-of-fitting tests at acceptable significance levels. On the basis of its very large coefficient of variation, a Weibull distribution was adopted for $h_{y_{actual}}$ .

Table 1. Statistics of $h_{x\,actual}$ and $\phi_{actual}$ calculated with the Monte Carlo simulation

| Sample Size | $h_{x\,actual}$ |  | $\phi_{actual}$ |  | Correlation coefficient ($h_{x\,actual}$ and $\phi_{actual}$) |
|---|---|---|---|---|---|
|  | mean (ft) | sd (ft) | Mean (deg) | sd (deg) |  |
| 1,000,000 | 51.7 | 9.3 | 3.8 | 4.0 | 0.35 |

## Response and Damage Model

This model includes the definition of the failure modes or limit states for the WTBs, the algorithms for the calculation of load effects and the uncertainty model for the geometric and material properties of watertight boundaries. In its current form, the model considers strength and stability failure modes of stiffened bulkheads and uses closed-form methods for the calculation of load effects. The failure modes or limit states considered in this study are as follows:

1. Axial loading and bending of the stiffener-plate beam-column.
   1.1 Limit State 1 – Compressive stresses in the stiffener flange.
      1.1.1 **Limit State 1a** – Defined by the design code equations for limit state 1.
      1.1.2 **Limit State 1b** – Defined in Chapter 14 of Hughes (1988).
   1.2 **Limit State 2** – Plate buckling
2. Stiffener tripping (**Limit State 3**) – Defined in Chapter 13 of Hughes (1988).

Uncertainty models for the geometric and material properties of stiffened bulkheads already published were used for this study. Specifically, the uncertainty model proposed by Hess, Bruchman and Ayyub (1997) and a simplified form of it were used. The variables considered in these models are: the ultimate and yield strength of steel, the Young's modulus of steel, the thickness of the deck plating, stiffener flange and stiffener web, the width of the stiffener flange, and the height of the stiffener. In the example applications, it was assumed that the same steel was used for the deck plating and stiffener. It is noted that the coefficients of variation for these properties are significantly smaller than the coefficient of variation for the load.

## Reliability Analysis Algorithms and Software

Reliability assessments were performed using first-order reliability methods (FORM) and Monte Carlo simulations to verify the accuracy of the FORM algorithms. FORMs were chosen because of their computational efficiency and because they yield sensitivity coefficients useful to interpret the results and identify significant random variables. A commercial software tool called ProFES (Probabilistic Finite Element Software) (Cesare and Sues, 1999) was used for all reliability assessments. ProFES is a user-friendly software that links a probabilistic mechanics engine with either finite element codes or with user defined software that executes the algorithms that calculate the response variables needed to evaluate the limits state functions. Currently, the proposed reliability assessment framework for the WTBs uses closed-form expressions to calculate these response variables and assumes linear-elastic structural response. Future developments of this framework will use finite element analysis (including nonlinear inelastic analyses) to calculate the load effects. This will take full advantage of ProFES' capabilities.

## Illustrative Application

The proposed methodology is illustrated with the preliminary calculation of underlying limit state probabilities for an example bulkhead designed using current design codes. Schematic representations of the ship and bulkhead cross-sections are shown in Figure 1. The ship dimensions and compartments are compatible with those used for the derivation of the probabilistic load model. A limited sensitivity analysis was conducted to assess the effect of the ratio of the dead load to the hydrostatic flooding pressures. Accordingly low, medium and high load ratios (dead load to hydrostatic load) were considered. A summary of the reliability indices calculated for bulkhead DE is shown in Table 2.

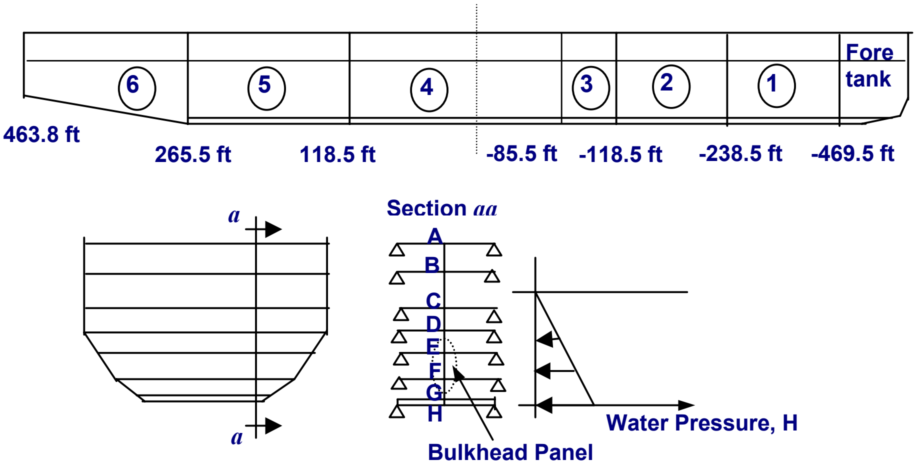

Figure 1. Schematic models of longitudinal and transverse ship cross-section

Examination of the results in Table 2 indicates that for limit state 1, the reliability indices are smaller when the design equations are used to represent the limit state than when the more accurate equations of limit state 1b are used. It is interesting to notice that the critical failure mode appears to be limit state 2 (buckling of the deck plating). This is somewhat unexpected because the design margins for this limit state were somewhat greater than those for limit state 1. Sensitivity of the limit state reliabilities to various random variables was investigated by comparing the sensitivity coefficients (director cosines squared) calculated with FORM. These coefficients are shown in Figure 2 for bulkhead DE, limit states 1b, 2 and 3 as defined above and for the a medium dead load intensity.

Table 2. Reliability indices for bulkhead DE

| Dead Load | Limit State | | | |
|---|---|---|---|---|
| | 1a | 1b | 2 | 3 |
| Low | - | 2.982 | 2.248 | 4.133 |
| Medium | 2.498 | 2.920 | 2.125 | 4.078 |
| High | - | 2.897 | 1.899 | 4.398 |

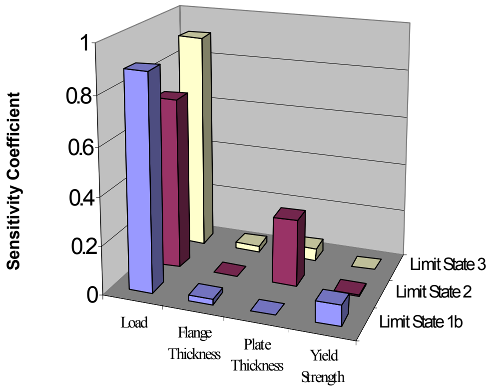

Figure 2. Sensitivity coefficients (bulkhead DE)

Examination of these results indicates the higher significance of the loading for all limit states. However, for limit state 2, the reliability is also quite sensitive to the bulkhead plate thickness. This seems to be a consequence of the fact that the allowable stress for this limit state is proportional to the square of the bulkhead plate thickness.

## Conclusions

A framework for the reliability assessment of the watertight boundaries of vital spaces of U.S. Navy ships was described. This framework was illustrated with the preliminary calculation of underlying reliability indices for an example bulkhead designed using the current allowable stress design codes. The goal of the proposed framework is the assessment of current design codes, in terms of underlying reliabilities, and the development of a reliability-based load and resistance factor design approach for the watertight boundaries of new ship structures.

### Acknowledgements

The work reported here was performed as part of the U.S. navy Phase I SBIR contract number N00024-99-C-4143. The technical monitor for this contract was Mr. Nat Nappi. His many contributions to this study are also gratefully acknowledged.

### References

Mansour, A., *et al.,* (1997), "assessment of Reliability of Existing Ship Structures," Ship Structures Committee, Report SSC-398.

Melton, W. M. and B. Ayyub, (1999), "LRFD Rules for Naval Surface Ship Structures: Reliability-Based Load ad Resistance Factor Design Rules," Report No. NSWCCD-65-TR-1998/4.

Huges, O., E. Nikolaidis, B. Ayyub and P. Hess, (1994), "Uncertainty in Strength Models for Marine Structures," Ship Structures Committee, Report SSC-375.

Hess, III, P. E., D. Bruchman and B. Ayyub, (1997), "Uncertainties in Material and Geomteric Strength variables in Marine Structures," Chapter 14 in Probability, Statistics & Reliability for Engineers, Bilal M. Ayyub and Richard H. McCuen, editors, CRC Press, Boca Raton, Florida.

Battacharya, B., and R. I. Basu, (2000), "Reliability of Watertight Boundaries," ABS Project ID: P39934R4.

Pires, J. A., M. Cesare, R. H. Sues, B. Battacharya, R. I. Basu and P. Sensharma, (2000), "Reliability Assessment of Watertight Boundaries," Final Report, Navy SBIR Topic N99-088, Contract No. N00024-99-C-4143, Prepared by Applied Research Associates, Inc., for Naval Sea Systems Command.

Hughes, O.F., (1988), Ship Structural Design – A Rationally-Based, Computer-Aided Optimization Approach, Society of Naval Architects and Marine Engineers (SNAME), Jersey City, New Jersey.

Cesare, M. A. and R. H. Sues, (1999), "ProFES, Probabilistic Finite Element Software – Bringing Probabilistic Mechanics to the Desktop," American Institute of Aeronautics and Astronautics, paper AIAA99-1607.