THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Suite 400, Jersey City, New Jersey 07306 USA
Paper presented at the Marine Structural Inspection, Maintenance and Monitoring Symposium
Sheraton National Hotel, Arlington, Virginia, March 18-19, 1991

Parametric Evaluation of Marine Structural Life Expectancy Using a Reliability-Based Methodology

B.M. Ayyub, University of Maryland, College Park, Maryland
G.J. White, U.S. Naval Academy, Annapolis, Maryland

ABSTRACT

The estimation of an absolute life expectancy is a complex process and the results are expected to have relatively large levels of uncertainty. In this study, a parametric sensitivity analysis of structural life expectancy due to variation in several variables that include the size of the plating panel, thickness, operational profile, failure criteria and loading conditions was performed. The sensitivity of the structural life expectancy of the forward bottom plating to variations in these parameters was evaluated. A brief comparative analysis was undertaken between three different patrol boats. The study is limited to the critical forward bottom plating and takes into account the differences in material, plate dimensions, operational profile, structure and loading of the vessels. Two failure modes, plastic plate deformation and fatigue, were considered and a novel approach to corrosion and wastage was included.

INTRODUCTION

The estimation of an absolute life expectancy is a complex process and the results are expected to have relatively large levels of uncertainty. In this study, a methodology for structural life expectancy was developed, validated and calibrated using the performance records of the Cape-Class patrol boat. The estimation of structural life expectancy can be based on selected failure modes. All possible failure modes of the Island, Heritage, Point and Cape-Class patrol boats were identified. The most critical failure modes, based on experiences of the U.S. Coast Guard and the fundamentals of naval architecture (9 to 24), were determined to be plate plastic deformation and fatigue (3,7,16,20). A novel approach to include plate corrosion and wastage was developed as a component of the methodology. Structural life expectancy based on these two failure modes was determined for the forward bottom plating of the four boat classes.

Many factors affect the structural life of a boat. They include structural type, operational profile, structural details, loads, inspection and maintenance, design methods, safety factors, corrosion, and environmental factors. These factors have four types of uncertainty; namely, physical randomness, statistical and model uncertainties, and vagueness. All can be addressed by a reliability-based structural life assessment methodology.

STRUCTURAL LIFE EXPECTANCY ASSESSMENT

A methodology for structural life assessment was developed. The methodology is based on probabilistic analysis using reliability concepts and the statistics of extremes. The methodology results in the probability of failure of the boat structural system according to the identified failure modes as a function of time, i.e., structural life. The results can be interpreted as the cumulative probability distribution function (CDF) of structural life. Due to the unknown level of statistical correlation between failure modes, limits or bounds on the CDF of the structural life the structural system were established. The limits correspond to the extreme cases of fully correlated and independent failure modes. An interactive computer program was developed to perform these calculations that allows parametric sensitivity analysis of structural life due to variations in several variables.

Structural reliability methods for determining the *exact (numerical value)* of probability of failure of a structural component or system according to a specified performance function can be classified into two types, closed-form solutions and simulation-based techniques. Consider the following performance function:

$$Z = g(X_1, X_2, ..., X_n) \qquad (1)$$

where the X_i's are the basic random variables. Equation 1 defines the failure surface, such that failure occurs where $g(.) < 0$. The probability of failure can be determined by solving the following integral:

$$P_f = \int\int\cdots\int f_{\underline{X}}(X_1,\ldots,X_n)\, dx_1\, dx_2 \ldots dx_n \qquad (2)$$

where $f_{\underline{X}}$ is the joint probability density function (PDF) of $\underline{X} = \{X_1, X_2, \ldots, X_n\}$ and the integration is performed over the region where $g(.) < 0$.

In closed-form solutions, Equation 2 is evaluated making use of the probabilistic characteristics of the basic random variables. This can be done if the joint PDF of the basic random variables is known and the integral of Equation 1 can be evaluated. In many practical problems, these conditions cannot be met.

In the classical use of the simulation-based methods, all the basic random variables are randomly generated and Equation 1 is evaluated. Failures are then counted depending on the sign of Equation 1. The probability of failure is estimated as the ratio of the number of failures to the total number of simulation cycles. Therefore, the smaller the probability of failure is, the larger the needed number of simulation cycles to estimate the probability of failure within an acceptable level of statistical error. In addition, direct simulation requires binary definition of failure according to the limit state equation. The level of computational effort in this method is relatively small. The fundamentals of this method are available in several references (1,2,4,25,26,27).

The efficiency of simulation can be largely improved by using variance reduction techniques. However, the level of computational effort is increased. One of the commonly used methods is conditional expectation combined with antithetic variates variance reduction techniques (VRT's) for structural reliability assessment (1,2,25). These methods were determined to be highly efficient, and converge to the correct probability of failure in a relatively small number of simulation cycles. The methods are mathematically simple, do not require large spaces of computer memory and, therefore, can be programmed on small micro- and personal computers. A menu-driven computer program, "RASCS, Reliability Assessment of Structural Components and Systems," was developed based on these methods by Ayyub and White in 1988. In this study, conditional expectation with antithetic variates VRT were used for determining the probabilities of failure.

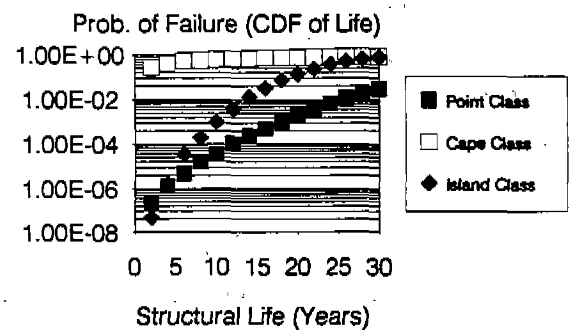

Figure 1. Comparative Results for Failure in Plate Deformation

The details of the methodology that was used in this study were described in detail by Ayyub, et al (5,6,7,8). Example results are comparatively shown in Figures 1 and 2 for the Point, Cape and Island-Class patrol boats.

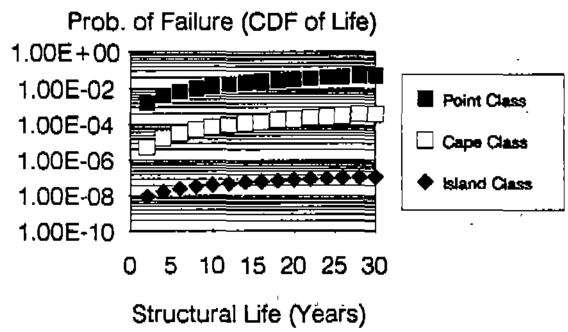

Figure 2. Comparative Results for Failure in Fatigue

PARAMETRIC ANALYSIS

A parametric sensitivity analysis of the developed analytical model was performed on the Island-Class patrol boat. In order to perform the analysis, a reference set of values for the analytical model parameters needs to be defined. This set is used to assign values for all the parameters except the parameter being investigated. The value of the parameter under investigation is varied to cover a selected range, and the variation of the estimated structural life expectancy according to the two failure modes due to this parametric variation is plotted. The reference set is selected such that all the parameters are at the normal levels of the strength, loading and operational profile characteristics. The reference set of parameters will be defined in the paper.

The parameters that are considered in this sensitivity analysis include the simulation cycles, size of the plating panel, thickness of the plating, operational profile, number of operational hours per year, loading profile, fatigue details, and plate failure criteria. The selected parameters are summarized in Table 1. The sensitivity of the structural life expectancy of the forward bottom plating to variations in these parameters was evaluated. The evaluation was performed for both the plastic plate deformation and fatigue failure modes. The treatment and presentation of the two failure modes were maintained separate in order to keep track of the sensitivity of each failure mode to the variation in the parametric values. The resulting probabilities of failure as a function of time are summarized in figures that correspond to the reference case and the cases with each varied parameter.

Table 1 Definition of Parameters

Parameter	Plate Deformation	Fatigue	Figure Number
Simulation Cycles	x	x	Not shown
Plate thickness	x		3-a & 3-b
Plate size	x		Not shown
Wastage	x		4
Annual use	x	x	5-a & 5-b
Plate failure criteria	x		6 & 7
Speed and sea state combinations	x		Not shown
Percent use in combination 8	x		Not shown
Fatigue loading cycles		x	8
Fatigue local details		x	9-a, 9-b & 9-c

Results

In this section, the results of the parametric analysis are summarized. A brief discussion of the results is provided. These results can be used to study the effects of future design changes.

1. Simulation Cycles: In order to select the least number of simulation cycles that gives results with acceptable levels of statistical accuracy, the resulting failure probabilities for the analytical model were determined as a function of the number of simulation cycles. The statistical accuracy is measured in terms of the convergence of the estimated probability of failure and the magnitude of its coefficient of variation (COV). The selected numbers of simulation cycle is based on satisfying the convergence criterion and maintaining a level of COV less that 0.1. By inspecting the resulting figures, 2000 simulation cycles and 500 simulation cycles for plastic plate deformation and fatigue failure modes, respectively, yield in statistically accurate results. Therefore, these numbers of simulation cycle were selected and used in all the program runs in this study.

2. Plate Thickness: The plate thickness of the forward bottom plating of the Island-Class patrol boat was varied from its current value of 0.161 in (7#) plate to 0.171 in (7.5#), 0.224 in (9#) and 0.236 in (10#) plate sizes. Based on the results as shown in Figures 3-a and 3-b, the structural life expectancy of the forward bottom plating of the Island-Class patrol boat in this critical failure mode can significantly be improved by increasing the plate thickness to 7.5# or 9#. The effect of plate thickness variation on fatigue life expectancy of the critical region is minimal, therefore, was not considered.

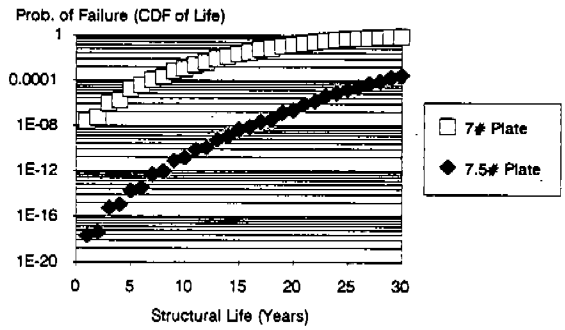

Figure 3-a. Effect of Plate Thickness on P_f Plate Deformation for the Island-Class

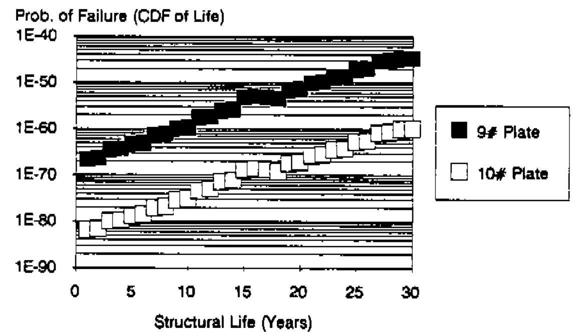

Figure 3-b. Effect of Plate Thickness on P_f Plate Deformation for the Island-Class

3. Plate Aspect Ratio: The current aspect ratio of a plate in the forward bottom part of the boat is 2. This aspect ratio is based on the plate size, length x width, of 23.5 in x 11.75 in. In this analysis, the aspect ratio was changed to 1, which corresponds to change in the plate size to 11.75 in x 11.75 in. The structural life expectancy of the forward bottom plating of the Island-Class patrol boat in this critical failure mode can significantly be improved by reducing the plate size. It will be shown that this approach is more effective than increasing the plate thickness. The effect of this change on fatigue is in the form of increasing the number of fatigue details.

However, since the failures of fatigue detail are considered to be statistically highly correlated, the effect of this change on fatigue life expectancy is minimal.

4. Rate of Plate Wastage: The probabilities of failure in plastic plate deformation were estimated for a mean value of wastage rate of 0, 1, 1.5 and 2 mpy. Unquestionably, the inclusion of a wastage allowance in the structural life expectancy model is vital for a realistic prediction of life. However, the model is slightly sensitive to the selection of the plate wastage rate within the range 1 to 2 mpy as shown in Figure 4. In this study, a wastage rate of 1 mpy was used.

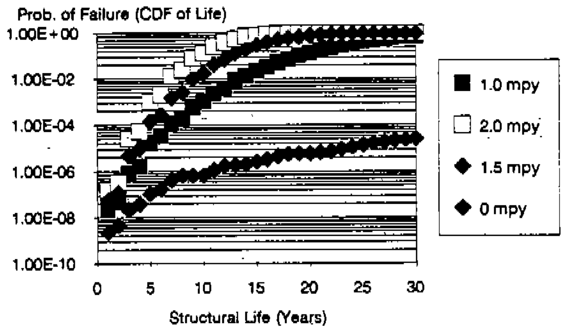

Figure 4. Effect of Plate Wastage on P_f for Island-Class

The effect of plate wastage on fatigue life expectancy is in the form of slightly shifting the location of the neutral axis of the cross section at the fatigue details. The effect of this neutral axis location change on the structural life expectancy of fatigue details is relatively small. It can be shown that after 30 years with a plate wastage rate of 1 mpy, this effect results in detail-stress transfer function values that are 10 to 20% less than the case of no wastage allowance.

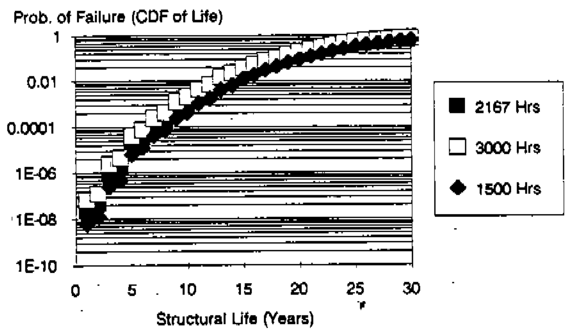

Figure 5-a. Effect of Annual Use on P_f for Island-Class

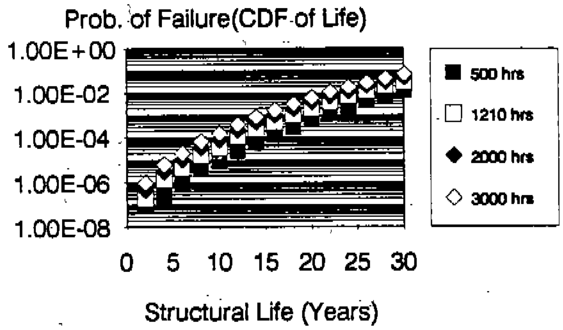

Figure 5-b. Effect of Annual Use on P_f for Point-Class

5. Annual Use: The current average annual use of the Island-Class patrol boat is 2167 hours/year. These results are based on varying the annual use from 2167 to 1500 and 3000 hours/year. The effect of increasing the annual use of a boat is greater on fatigue than plastic plate deformation structural life expectancy. However, the analytical model is slightly sensitive to the selection of the average value of annual use.

6. Plate Failure Criteria: The plate failure criteria are defined by mainly two parameters, the deformation ratio wp/th and the total number of failed plates within the critical region n_p/N_p. The effect of variation in these parameters on structural life expectancy is studied in this section.

a. Deformation Ratio. The deformation ratio wp/th for the Island-Class patrol boat was selected to take the value of at least 3. The effect of varying this ratio on the probability of failure in plastic plate deformation is shown in Figure 6. In this figure, the ratio takes the values of 2.5, 3.0 and 3.5. Evidently, structural life expectancy based on plastic plate deformation is sensitive to variations in this parameter. However, this ratio was carefully selected to take the value 3 in the reference cases for the Island and Heritage-Class patrol boats based on the model calibration process.

b. Number of Plates. The total number of failed plates within the critical region n_p/N_p for the Island-Class patrol boat was set to take the value of at least 6/28. The effect of varying this criterion on the probability of failure in plastic plate deformation is shown in Figure 7. The criterion was changed to take the values of 3/28, 6/28 and 9/28. Evidently, structural life expectancy based on plastic plate deformation is sensitive to this parameter. However, this criterion was carefully selected to take the value 6/28 in the reference case for the Island-Class patrol boat based on the current practices of the U.S. Coast Guard.

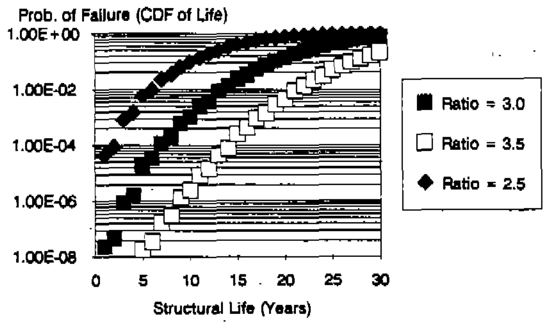

Figure 6. Effect of Plate Deformation on P_f

7. Speed/Sea State: As was discussed by Ayyub et al (7,8), combination 8 of the speed and sea state condition represents the most critical case of the operational profile. This case corresponds to the medium speed and high sea state. It results in significant values for the probabilities of failure in plastic plate deformation. For other speed/sea state combinations, the resulting probabilities of failure are insignificant; virtually zero.

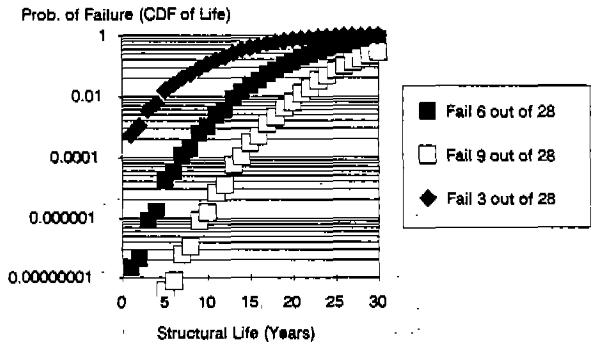

Figure 7. Effect of Number of Failed Plates on P_f

8. Percent Use in Speed/ Sea State Case 8: The effect of varying the percent use in the speed/sea state combination that corresponds to case 8 on the probabilities of failure in plastic plate deformation will be discussed. This case corresponds to the medium speed and high sea state. The percent use is considered to take the values 0.5, 1, 1.5 %. Evidently, structural life expectancy based on plastic plate deformation is moderately sensitive to variations in this parameter. The magnitude of this parameter was selected based on a survey that was sent to operators of the Island-Class patrol boats.

9. Fatigue Loading Cycles: Based on the study performed by Ayyub and White in 1988 on the Island-Class patrol boat, the number of fatigue loading cycles was determined to be on the average 1402 cycles/hour based on the strain time-history records. The effect of varying this number on the probabilities of failure in fatigue is shown in Figure 8s in this figure are 1200, 1402, 1600 and 1800 cycles/hour. Clearly, structural life expectancy based on fatigue is slightly sensitive to variations in this parameter.

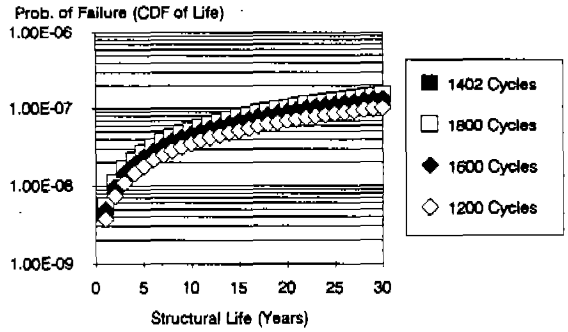

Figure 8. Effect of Fatigue Loading Cycles on P_f

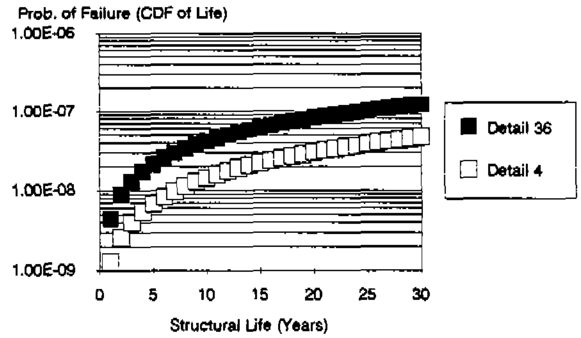

Figure 9-a. Effect of Local Fatigue Detail on P_f for the Island-Class

10. Fatigue Local Details: According to this study and other previous studies (5,7,8), fatigue local detail 36 was determined to be the most critical one in the forward bottom plating of the Island-Class patrol boat. The effect of eliminating this detail and using in its place local fatigue detail 4 in the form of a continuous weld between the longitudinals and the shell on the structural life expectancy in fatigue is shown in Figure 9-a. Obviously, structural life expectancy based on fatigue can be greatly improved by using local fatigue detail 4 in place of local fatigue detail 36. Similar results are shown for the Point-Class in Figures 9-b and 9-c.

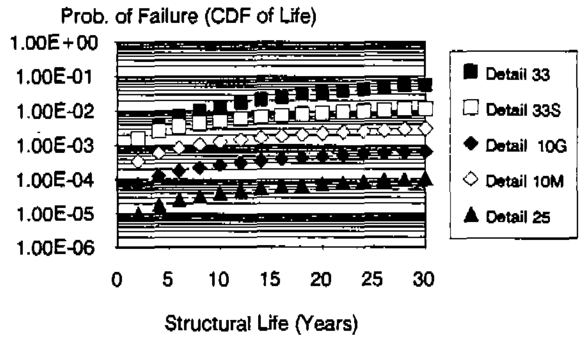

Figure 9-b. Effect of Local Fatigue Detail on P_f for the Point-Class

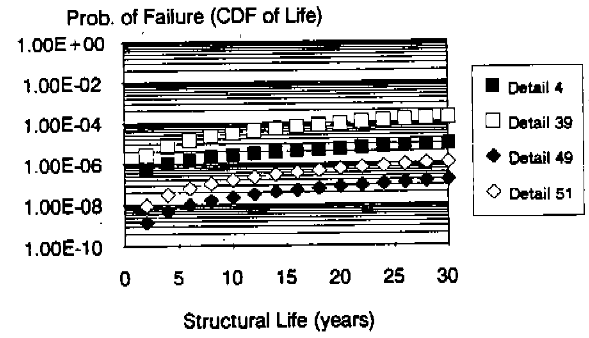

Figure 9-c. Effect of Local Fatigue Detail on P_f for the Point-Class

Summary and Conclusions

The estimation of an absolute life expectancy is a complex process and the results are expected to have relatively large levels of uncertainty. In this study, a parametric sensitivity analysis of structural life expectancy due to variation in several variables that include the size of the plating panel, thickness, operational profile, failure criteria and loading conditions was performed. The sensitivity of the structural life expectancy of the forward bottom plating to variations in these parameters was evaluated. A summary of this analysis is shown in Table 2. A brief comparative analysis was undertaken between three different patrol boats. The study is limited to the critical forward bottom plating and takes into account the differences in material, plate dimensions, operational profile, structure and loading of the vessels.

Table 2. Summary of Parametric Analysis

Variation of Parameter	Effect on Plate Deformation	Effect on Fatigue
Plate thickness	Large	Not considered
Plate size	Very large	Not considered
Plate wastage	Moderate	Not considered
Annual use	Very small	Small
Plate failure criteria	Moderate	Not considered
Percent use in high speed and medium sea state combination	Small	Not considered
Wave encounters	Not applicable	Very small
Type of fatigue details	Not applicable	Moderate to large

Two failure modes, plastic plate deformation and fatigue, were considered and a novel approach to corrosion and wastage was included.

References

1. Ang, A.H-S. and W.H. Tang, (1983), *Probability Concepts in Engineering Planning and Design*, Vol. 2 - Decision, Risk and Reliability. John Wiley and Sons, New York.
2. Ayyub, B.M., and A. Haldar, (1984), "Practical Structural Reliability Techniques," *Journal of Structural Engineering*, American Society of Civil Engineers, Vol. 110, No. 8, Paper No. 19062, August 1984, pp. 1707-1724.
3. Ayyub, B.M., and G.J. White, (1987), "Reliability Analysis of the Island-Class Patrol Boat," *Report* Submitted to U.S. Coast Guard R&D Center, Avery Point, August 1987.
4. Ayyub, B.M., and G.J. White, (1987) "Reliability-Conditional Partial Safety Factors," *Journal of Structural Engineering*, American Society of Civil Engineers, Vol. 113, No. 2, Paper No. 21241, February 1987, pp.279-294.
5. Ayyub, B.M., G.J. White, and E.S. Purcell, (1989) "Estimation of the Structural Service Life of Boats," *Naval Engineers Journal*, American Society of Naval Engineers, Vol 101, No. 3, May 1989, pp.156-166.
6. Ayyub, B.M., and G.J. White, (1988), "Life Expectancy Assessment and Durability of the Island-Class Patrol Boat Hull Structure," Report Submitted to U.S. Coast Guard R&D Center, Avery Point, September 1988.
7. Ayyub, B.M., G.J. White, T.F. Bell-Wright, and E.S. Purcell (1989), "Reliability-Based Comparative Life Expectancy Assessment Patrol Boat Hull Structure," Report Submitted to U.S. Coast Guard R&D Center, *Report No. CG-D-02-90*, Avery Point, 1990.
8. Ayyub, B.M., G.J. White, T.F. Bell-Wright, and E.S. Purcell (1990), "Comparative Structural Life Expectancy Assessment of Patrol Boat Bottom Plating," *Naval Engineers J.*, American Society of Naval Engineers, Vol. 102, No. 3, May 1990.
9. Fridsma, G., (1971), "A Systematic Study of the Rough-Water Performance of Planing Boats (Irregular Waves - Part II)," Report, Stevens Institute of Technology, March 1971.
10. Heller, S.R. and N.H. Jasper, (1960), "On the Structural Design of Planing Craft," *Quarterly Transactions of the Royal Institution of Naval Architects*, July, 1960.
12. Hoggard, M.M. and M.P. Jones, (1980), "Examining Pitch, Heave and Accelerations of Planing Craft Operating in a Seaway," *High-Speed Surface Craft Exhibition and Conference*, 24-27 June 1980, Metropole, Brighton, Sussex, UK.

13. Hughes, O.F., (1981), "Design of Laterally Loaded Plating - Uniform Pressure Loads," *Journal of Ship Research*, SNAME, Vol. 25, No. 2, June, 1981, pp. 77-89.
14. Hughes, O.F., (1983), *Ship Structural Design*: A Rationally-Based, Computer-Aided, Optimization Approach, John Wiley and Sons , New York, NY.
15. Jones, N., (1971), "A Theoretical Study of the Dynamic Plastic Behavior of Beams and Plates with Finite Deflections," *Int. J. Solids Structures,* Vol. 7, 1971, pp. 1007-1029.
15. Jones, N., (1973), "Slamming Damage," *Journal of Ship Research,* SNAME, Vol. 17, No.2, June, 1973, pp. 80-86.
16. Jones, N., (1977), "Damage Estimates for Plating of Ships and Marine Structures," PRADS-*International Symposium on Practical Design in Shipbuilding,* Tokyo, October, 1977.
17. M. Rosenblatt & Son, Inc., (1985), "Final Report: Structural Evaluation of U.S. Coast Guard's 95 FT. WPB Class Cutters," *Report Prepared for Commandant (G-FCP-4/HW),* U.S. Coast Guard, 2100 Second Street, SW, Washington, D.C.
18. Mansour, A.E., (1967), "Ship Bottom Structure Under Uniform Lateral and In-plane Loads," *Schiff und Hafen*, Heft 5/1967, 19, Jahrgang.
19. Mansour, A.E., H.Y. Jan, C.I. Ziegelman, Y.N. Chen and S.J. Harding, (1984), "Implementation of Reliability Methods to Marine Structures," *Trans.* SNAME, Vol. 92, 1984.
20. Munse, W.H., T.W. Wilbur, M.L. Tellalian, K. Nicoll, and K. Wilson, (1982), "Fatigue Characterization of Fabricated Ship Details for Design," Ship Structure Committee *Report SSC-318*, 1982.
21. Purcell, E.S., S.J. Allen, and R.J. Walker, (1988), "Structural Analysis of the U.S. Coast Guard Island Class Patrol Boat," *Trans.*, SNAME, Vol. 96, 1988.
22. Savitsky, D., (1964), "Hydrodynamic Design of Planing Hulls," *Marine Technology*, Vol. 1, No. 1, Oct. 1964, pp.71-95.
23. Savitsky, D. and P. Ward Brown, (1976), "Procedures for Hydrodynamic Evaluation of Planing Hulls in Smooth and Rough Water," *Marine Technology*, Vol. 13, No. 4, Oct. 1976, pp. 381-400.
24. Silvia, P.A., (1978), "Structural Design of Planing Craft, A State of the Art Survey," SNAME Chesapeake Section meeting, March 1978.
25. White, G.J., and B.M. Ayyub, (1985), "Reliability Methods for Ship Structures," *Naval Engineers Journal*, ASNE, Vol. 97, No. 4, May, 1985, pp. 86-96.
26. White, G.J., and B.M. Ayyub, (1987), "Reliability-Based Fatigue Design of Ship Structures," *Naval Engineers Journal*, ASNE, Vol. 99, No. 3, May, 1987.
27. White, G.J., and B.M. Ayyub, "Probability-Based Design Formats for Marine Structures," *Journal of Ship Research*, Society of Naval Architects and Marine Engineers, Vol. 31, No. 1, March 1987, pp. 60-69.