

# Structural Fatigue Life Assessment and Sustainment Implications for a New Class of US Coast Guard Cutters

Karl Stambaugh<sup>1</sup>, Ingo Drummen<sup>2</sup>, Chris Cleary<sup>1</sup>, Rubin Sheinberg<sup>3</sup>, Mirek Kaminski<sup>4</sup>

<sup>1</sup> US Coast Guard SFLC ESD, <sup>2</sup> MARIN, <sup>3</sup> US Coast Guard SFLC ESD ret., <sup>4</sup> TUDelft (formerly MARIN)

*The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant or of the U.S. Coast Guard.*

## ABSTRACT

*This paper presents an overview of the US Coast Guard's Fatigue Life Assessment Project (FLAP) and the application of the results in hull structure lifecycle management of the National Security Cutter class. One of the key measurements of the FLAP instrumentation included a radar based wave data measuring system. These measurements were used to determine the operational profile and wave statistics the Cutter encountered for the first five years of service. This information was compared to the design assumptions to understand the differences between design, actual operations, and impact on the long term fatigue damage forecasts. The influence of the operator is discussed. The model tests, dedicated trials and long term monitoring provided valuable insights into the limitations of analysis and predictions. A reliability based fatigue life prediction approach is discussed, along with how they may be used to evaluate options for life cycle management of fatigue and the Return on Investment (ROI) for considering fatigue early in the design. Finally, conclusions and recommendations are provided for the advancement of the spectral fatigue approaches for cost effectively managing fatigue in ship structure.*

## KEYWORDS

Ship structural fatigue, Fatigue life prediction, Fatigue reliability, Structural monitoring

## INTRODUCTION

The United States Coast Guard (USCG) initiated a project to assess fatigue design approaches for its new National Security Cutters (NSCs), which became known as the Fatigue Life Assessment Project (FLAP). Predicting the fatigue life of a ship hull structure involves the prediction of hull loading in a seaway, and comparison of this with the structural capacity. Especially the former is an effort requiring information from a multitude of disciplines. Therefore, MARIN was contracted to support FLAP and reached out to involve other subject matter experts and stakeholders. American Bureau of Shipping, BAE Systems, Bureau Veritas, Damen Shipyards, Defence R&D Canada, DGA Hydrodynamics, Lloyd's Register, Ingalls Shipbuilding and Office of Naval Research participated in the VALID Joint Industry Project (JIP). The broader goals of the project are to forecast structural maintenance needs of USCG Cutters, further improve the understanding of wave loading leading to fatigue damage, and increase the confidence level in predicting wave loading leading to fatigue damage on a naval frigate type hull form and structure. The broader goals of FLAP were achieved through a model test program supported by dedicated full scale trials.

Measurements taken during the trials have provided data for correlation with model experiments and numerical simulations. A long term monitoring campaign was performed on the USCGC BERTHOLF to evaluate fatigue life prediction methodologies and also forecast structural maintenance needs. A photograph of the USCGC BERTHOLF is shown in Figure 1. Characteristics are shown in Table 1.



Figure 1 – USCGC BERTHOLF instrumented as part of FLAP

This paper presents an overview of FLAP and the application of results in a reliability assessment and lifecycle cost implications.

## FATIGUE DESIGN APPROACH

Although the structural fatigue life assessment approach is well established for naval ships, there are operational, environmental and structural design considerations of this new Cutter that required further evaluation in the context of structural fatigue maintenance considerations in its service life. For example, this Cutter will operate more days at sea in high latitude climates than is typical for most naval ships. Furthermore, limitations and uncertainties in the fatigue analysis approach must be quantified especially in the context of reliability based approaches to make long term sustainment decisions. The FLAP program provided a unique opportunity to evaluate the fatigue design process for USCG Cutters, quantify uncertainties and investigate other approaches in order to improve the current state of practice.

Structural fatigue analysis is based on the ship's predicted operational profile combined with wave statistics and processed through specialized analysis programs to determine lifetime histograms of hull sectional forces such as vertical bending moments and resulting stress histories at fatigue sensitive locations. A graphical summary of the many activities included with fatigue life prediction being evaluated as part of FLAP is shown in Figure 2. This approach is also known as Spectral Fatigue Analysis (SFA).

Given a ship hull form and structural design, the following are the major elements of a fatigue life assessment of that design including environment and operational profile, ship data and loading, hull girder hydrodynamic loading, structural response and the fatigue life calculation described in more detail as:

1. Environment and operational profile – Historical environmental data are available for predictions. The accuracy of any fatigue analysis is highly dependent upon the accuracy of the operational profile and associated environmental data used to develop the environmental loads. In the case of the fatigue evaluations, the Bales *et. al.* (1981) North Pacific wave scatter diagram was used to describe the probabilities of wave height and period combinations. The operational profile provides probabilities of speed and heading combinations.
2. Ship data and hydrostatic loading – The process for calculating hydrostatic loads is well established. However, it requires careful attention as proper modeling and scaling of mass, buoyancy and stiffness distributions are needed to draw proper conclusions from comparing results of numerical calculations, model testing and full-scale measurements.
3. Hull Girder Hydrodynamic Loading – Hydrodynamic loading is the area of uncertainty due to complex physics, dynamics and random nature of wave action. These results are often accompanied by sectional forces in several transverse sections along a ship. Similar results can be obtained from model testing and full-scale measurements, and because they are required when structural response is calculated for a ship segment.

Table 1- Main particulars of USCGC BERTHOLF and displacement at the time of the dedicated trials.

Main particular		
Length Overall	418.60 ft	127.59 m
Length Between Perpendiculars	390.00 ft	118.87 m
Beam, Waterline	48.89 ft	14.9 m
Beam, Maximum	54.00 ft	16.46 m
Design Draft	14.40 ft	4.39 m
Block Coefficient	0.492	0.492
Displacement (fully appended)	4430 LT	4500 ton

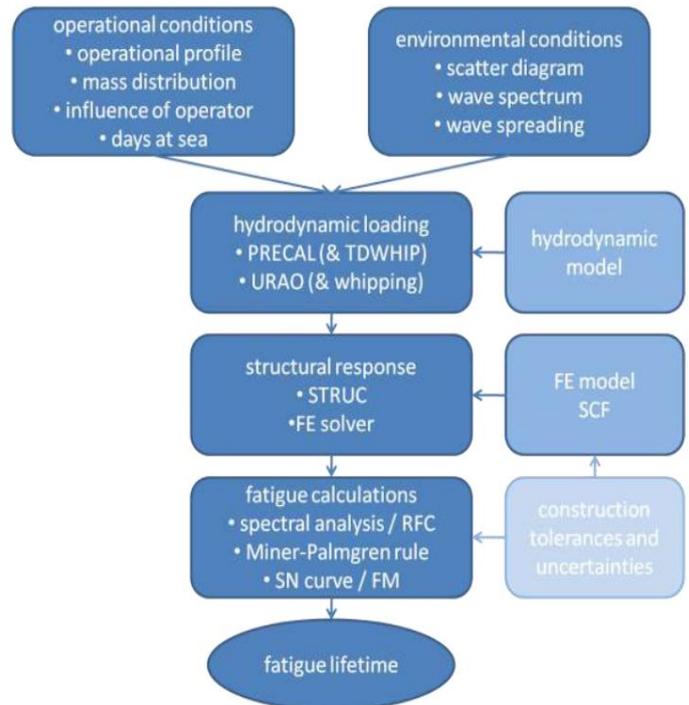
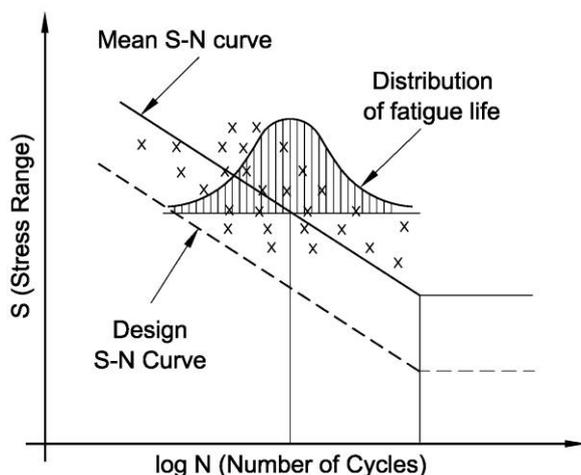


Figure 2 – Structural Fatigue Analysis approach evaluated as part of FLAP

4. Structural Response– The FEA and structural response process is well established in general; however, FEA modelling assumes ideal structure without geometric and fabrication imperfections. The focus of the approach is on the nominal stresses which are free of geometric stress concentrations. In this way, the full scale measurement can be compared with FEA results and extrapolations to hotspots can be further evaluated using other approaches.
5. Fatigue Life Calculation - The application of S-N data and the cumulative damage approach process is relatively well established for ship and other large structure systems; however, it is not free of uncertainties. The use of design or characteristic curve as illustrated in Figure 3 with fatigue response presented on a logarithmic scale obscures the magnitude of this uncertainty. This process also assumes the validity of rain-flow counting methods and linear Palmgren-Miner

accumulation law. The mean stress effect, the sequence effect, the distribution type effect, the effect of standing/hanging strain cycles, multiaxial stress and the uncertainty of the linear accumulation law are disregarded. While not within the scope of this effort originally, many of these aspects were considered where their impact was thought to be present.

The construction quality, tolerances and imperfections, such as misalignments are very important aspects of structural fatigue life but not included as part of this validation study. Their uncertainties in the context of structural reliability analysis are documented by Hess *et. al.* (1998). The validation effort presented here focused on quantifying the uncertainties in the operational environment, hydrodynamic loading and fatigue damage calculation. While hydrodynamic calculations are widely used, the quantification of their uncertainties has not been well documented, especially in the context of measured environments.



**Figure 3 Illustration of characteristic design curve and test data (redrawn from Hughes *et. al.* 2010)**

### FLAP Overview

The traditional approach used to design naval ship structures relies on a prescriptive quasi-static wave approach with safety factors developed from previous experience. Fatigue is not considered explicitly in the design process. Current naval ships (including USCG Cutters) have significantly different house structure, are operated at an increased tempo in more harsh environments and are being used well beyond their original service life requirements. These factors have increased the occurrences of fatigue cracking in older USCG cutters and are problematic in naval ship structures in general. Therefore, it became necessary to evaluate the current practices in naval ship structures as applicable to the USCG operational environments, profiles and structural configurations associated with the new class of NSCs.

Structural fatigue was not a specific consideration in the initial NSC design; however, given the structural arrangement and planned operational tempo, the USCG initiated an effort to evaluate the fatigue life of the NSCs.

This was supported by Naval Systems Warfare Center Carderock Division (NSWCCD) and their Spectral Fatigue Analysis (SFA) approach (Sikora *et. al.* 1983 and Sieve *et. al.* 2000). The USCG used this fatigue life prediction approach to design enhanced structure in specific locations to improve the fatigue life of the NSCs.

In order to evaluate these elements of the SFA design approach for a new NSC class, the USCG recognized this validation effort would require an extensive program of testing, measuring, simulation and analysis. A long term wave measurement sample was needed to assess the operational profile and environment encountered by the Cutter. Understanding that measuring waves from a moving ship was new technology, it was decided to conduct dedicated trials with a deployed wave buoy to calibrate the wave measurement system and to measure the dynamic response of the hull structure required to perform hydroelastic model tests and calculations. Segmented model tests were conducted in a controlled environment and correlated to full scale trials data.

Key elements of FLAP include:

- Full scale trials on a fully instrumented ship
- Segmented structural model tests
- Monitoring campaign for five years
- Analysis efforts by JIP members

Companion papers by Drummen *et. al.* (2014) present the details of the model test and full scale programs and Hageman *et. al.* (2014) presents the simulation and predictions of loading and response relative to the fatigue problem.

## RESULTS

### Measured Speed Heading Probabilities

Using the data available from the instrumentation system, measured speed heading probabilities for sea state ranges are shown in Table 2. The range of speeds reflects the various missions performed by the USCG including lower speeds for Launch and Recovery (L&R), patrol, transit and Search and Rescue (SAR) response. For the most part, these probabilities are similar to those used in early evaluations with the noted preferences for bow quartering seas in the 5 and 15 knot speeds. This preference for bow quartering seas does have a small effect to increase fatigue life relative to other parameters investigated.

### Measured Wave Environment

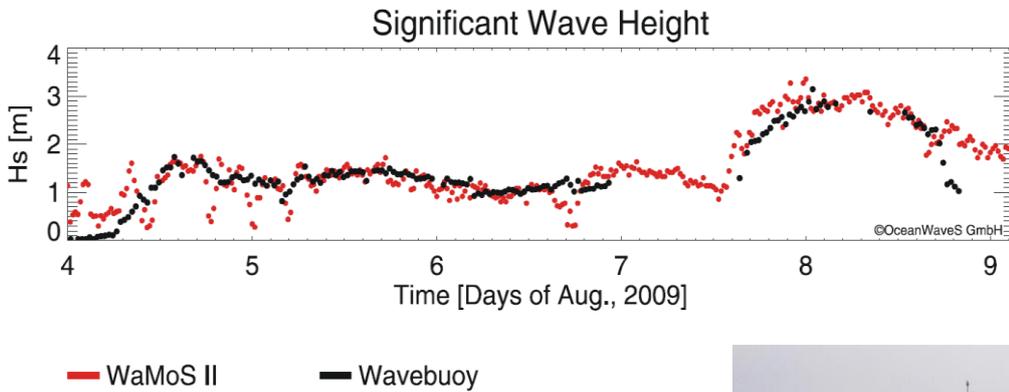
The wave environment was measured using the WAMOS II radar mounted on the Cutter's mast. This measurement was considered early on and has proven to be a necessary element of the total program throughout the assessment process. The WAMOS II radar system measures the wave period and direction. The amplitude of the measured

**Table 2 – Measured Speed and Headings Probabilities**

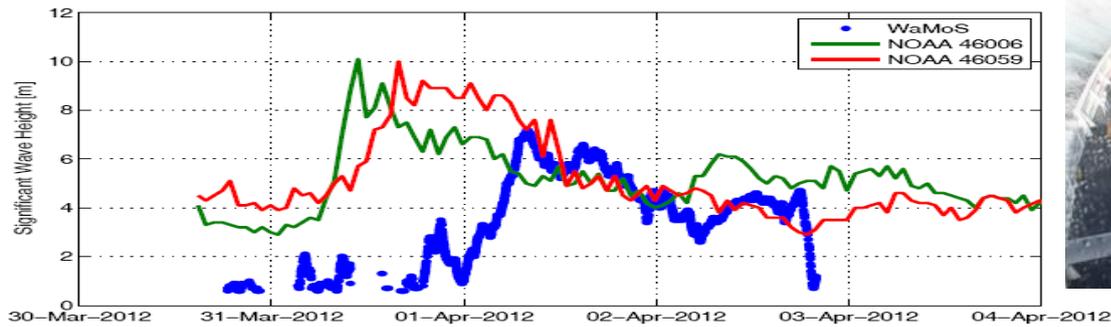
		Speed[knots]					
Heading		0	5	15	18	21	28
LowSeaStates(0-3meters)							
Head		0.01107	0.05676	0.03218	0.00425	0.00824	0.00026
Bow Qtr		0.04749	0.14414	0.19833	0.04505	0.03153	0.00245
Beam		0.01596	0.09820	0.10360	0.00991	0.00438	0.00090
StrnQtr		0.01133	0.06152	0.04633	0.00515	0.00180	0.00000
Following		0.00515	0.02870	0.01544	0.00940	0.00051	0.00000
MediumSeaStates(3-6meters)							
Head		0.00000	0.09756	0.09758	0.01626	0.00000	0.00000
Bow Qtr		0.00000	0.31707	0.011382	0.05691	0.00000	0.00000
Beam		0.00000	0.04065	0.08130	0.04878	0.00000	0.00000
StrnQtr		0.00000	0.00813	0.02439	0.02439	0.00000	0.00000
Following		0.00000	0.04878	0.00813	0.01626	0.00000	0.00000
HighSeaStates(6-meters)							
Head		0.00000	0.00000	0.00000	1.00000	0.00000	0.00000
Bow Qtr		0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Beam		0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
StrnQtr		0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Following		0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

spectrum must be scaled based on calibration factors. These are obtained from the system supplier and need to be further confirmed using alternate means. In this case, the wave radar was calibrated by a wave buoy at sea during dedicated trials as shown in Figure 4. To further calibrate the wave height statistics of the measured seaway, a wave fusion approach was employed by DRDC (Thornhill *et. al.* 2010).

The highest significant wave heights were measured when the Cutter responded to a Search and Rescue (SAR) of over 6 meters as shown in Figure 5. The time offset in measured data is from the ship encountering a storm at a different location as they approached the SAR location and NOAA buoys at 20knots. While these conditions produced the highest hull girder loading, they occur over a relatively short amount of time and limit the overall impact on fatigue damage. However, their influence must not be ignored because fatigue damage accumulated is proportion to the third power of stress range. This reinforces the need to monitor these events by either measuring wave height or hull response.



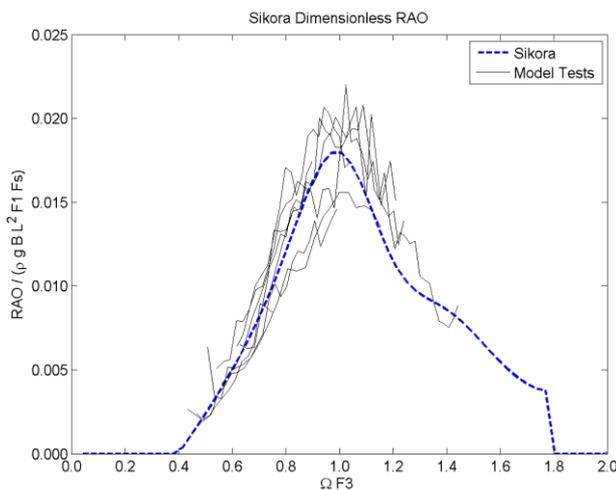
**Figure 4 – Example wave heights measured during dedicated trials**



**Figure 5 – Example wave heights measured during SAR**

### Hydrodynamic Load Predictions

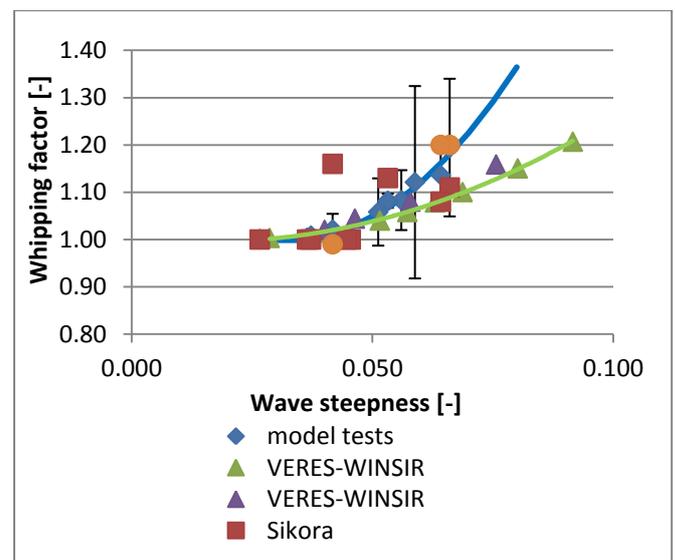
Hydrodynamic load prediction evaluations were conducted using a number of prediction techniques including empirical Universal Response Amplitude Operators (RAOs) (Sikora *et. al.* 1983). Sikora developed Universal RAOs for vertical bending moment, horizontal bending moment and torsional bending moment from model tests and full-scale data for a variety of ship types. Sectional loads predicted using Sikora’s method were found to be between 5% and 10% less than sectional loads inferred from measured strains in full scale and model tests, respectively. An example comparison between predictions and model tests of vertical wave bending moment is presented in Figure 6. Additional comparisons between monitoring data and PRECAL and Hydrostar panel codes and VERES strip theory code were made with results presented by Hageman *et. al.* (2014).



**Figure 6 - Comparison of RAOs from Model tests and Sikora URAOs**

The fatigue loading from slamming and whipping was investigated using several approaches including Sikora *et. al.* (1983), VERES-WINSR (Wu *et. al.* 2005) and NLOAD 3D (Kim *et. al.* 2006) as compared to model tests as shown in Figure 7. A whipping factor was calculated as the ratio of fatigue damage with whipping divided by the fatigue damage without whipping. These predictions show there is room for

improvement in accuracy of the dynamic hull structure response and fatigue damage; however, the overall contribution to fatigue damage is relatively small because of the infrequent occurrence of slamming in the fine hull form of the NSC and the relatively infrequent encounter of conditions that produce slamming (i.e. higher speeds and higher wave heights). Impact load and whipping response relevant to fatigue estimates is under predicted by the approaches considered as shown in Figure 7. However, the predictions are best compared on a total load basis from an engineering perspective. Hageman *et. al.* (2014) correctly state “Good tool accuracy is at least partly related to a favorable combination of over and under prediction”.

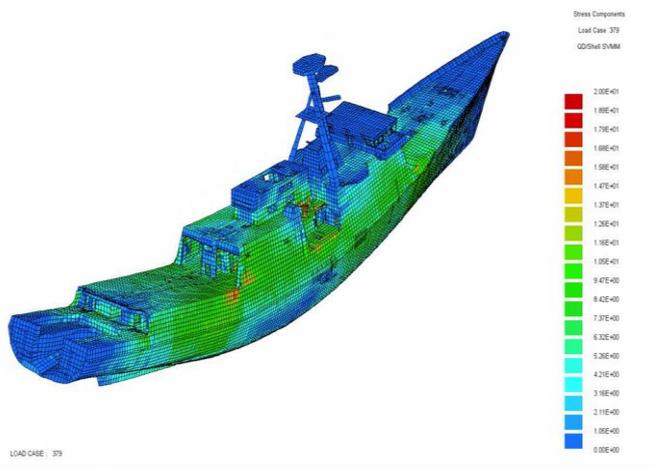


**Figure 7 – Comparisons of fatigue damage factor from whipping contribution**

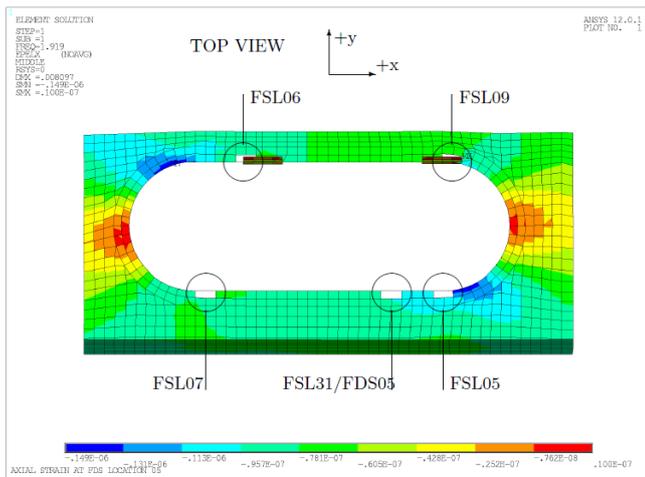
### Structural Response

FEA models were developed to support the structural fatigue life calculations. This model of the NSC was constructed to calculate the structural response and fatigue sensitive locations where measurements were obtained, see Figure 8. This type of detailed FEA is especially beneficial to model the dynamic modal shapes as presented by Drummen *et. al.* (2014) and inferred stress in the numerous structural details that are prone to structural fatigue. There were 25 structural

detail locations monitored by strain gauges including the termination details of the O2 Level connection between the forward house and the hanger, openings in the O1 Level, and ends of the fashion plate transitions at the ends of the house. Figure 9 shows an example FEA model of an opening in the O1 Level. This is one of over 25 fatigue critical details identified by FEA and monitored by strain gauges.



**Figure 8 - Finite Element Modeling (FEM) of strains measured during dedicated full scale trials August 2009 using modal analysis**



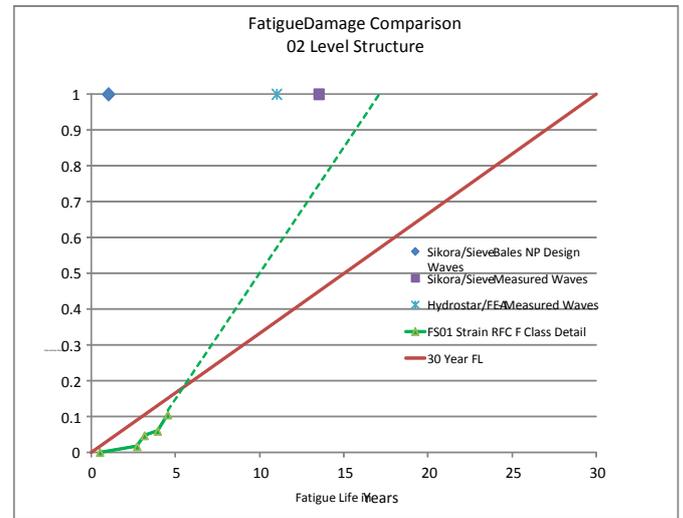
**Figure 9 - Finite Element Modeling (FEM) of an opening in the O1 Level near midship**

### Fatigue Life Estimates

By combining the load predictions and structural response from strain conversion and FE stress conversion with the S-N data from AASHTO in accordance with the SFA (Sikora *et al.* 1983, and Sieve *et al.* 2001), it is possible to make fatigue life predictions based on the initial design and measured environmental conditions. The fatigue life estimates are shown in Figure 10 along with fatigue damage calculated from measured data using rain flow counting.

The predicted fatigue life using the design wave environment is less than calculated from the measured data for the most fatigue critical locations which are located in the O2 level of the superstructure.

The measured fatigue damage shows a clear difference between the lower fatigue damage occurring early in the service life and the rapidly increasing damage occurring in later Northern deployments. The dashed green line is an extrapolation of fatigue damage from the last three deployments that were considered more representative of service life in comparison to earlier deployments.

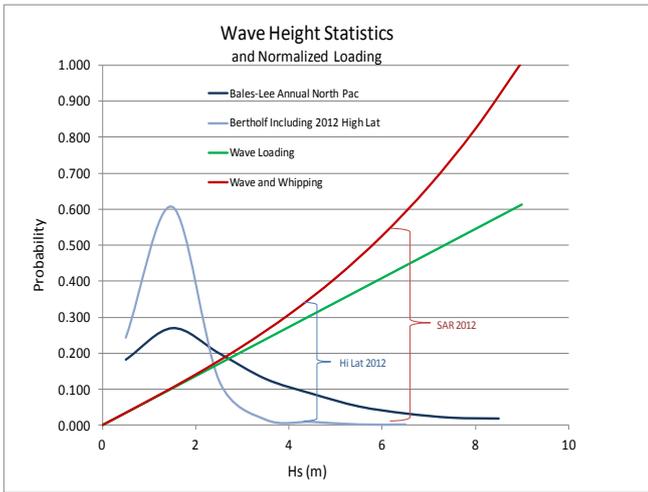


**Figure 10 – Example fatigue life estimate using spectral fatigue analysis and measure data**

The effects of the measured environment produces a higher calculated fatigue life than that based on the Bales *et al.* (1981) wave environment used in design evaluations shown in Figure 11. The effects of measured wave conditions on fatigue loading are significant as compared to the wave statistics used in design.

Figure 11 shows a comparison of the annual North Pacific wave height probability distribution from Bales *et al.* (1981) and those from measured data over five years. The probabilities show higher probabilities in lower wave heights than compared to those measured during the monitoring campaign. Two factors influence this difference including more southern deployments in milder weather early in the service life and the practice of heavy weather avoidance when possible. Although the instrumented Cutter did respond to a SAR in heavy weather at high speed, this was a onetime occurrence over this time period when measurements were taken. The effects of impact loading increased significantly during a high speed SAR as shown in Figure 10. This impact loading is damaging because fatigue is proportional to stress to the third power. However, their relatively low frequency of occurrence limits the overall lifetime effects. It is possible that the frequency of these events will increase as the Cutters perform routine patrols in the future. In general, it is desirable to manage these effects by continuous monitoring and make the needed lifecycle decisions

Analysis of the measured and model test data also indicate a rather large effect of wave energy directionality in the lower wave height conditions. The effects of wave directionality are likely to become smaller when the Cutter operates in higher significant wave height conditions expected in future service.



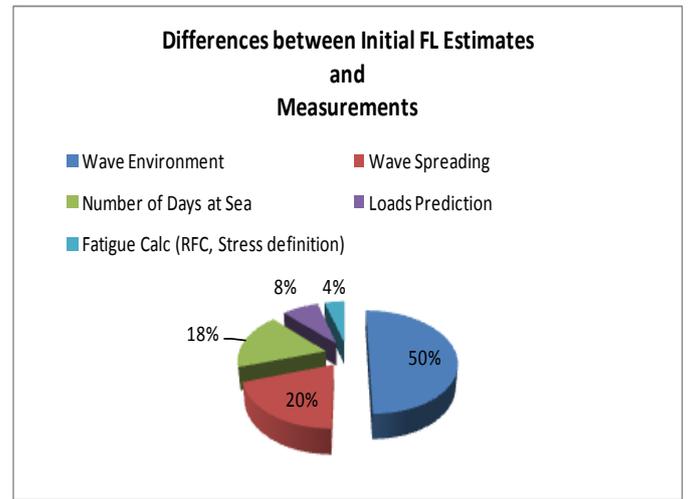
**Figure 11 –Measured and design marginal probabilities and effects of measured wave environment on load prediction**

This evaluation confirms the importance of the following:

- Fatigue life is proportional to the number of encountered stress cycles which is proportional to time (days) at sea.
- Fatigue life is proportional to the third power of stress range and is strongly influenced by wave conditions encountered while at sea.

With this knowledge and measured effects of wave environment, it is possible to separate these rather large effects from other uncertainties in the process elements described in Figure 1. The relative differences between calculated design fatigue life and measured fatigue damage are introduced by the differences in design and measured wave environment at approximately 50% and directional wave conditions at 20% difference. The actual number of days at sea is 18% less than in design and the load prediction contributes to approximately 8% less fatigue life than measured. These relative percentages are illustrated in Figure 12. Given these differences, the conclusion applicable to fatigue design isn't to reduce the magnitude of design wave conditions or under prediction of fatigue damage will result. However, for sustainment maintenance support decisions, the measured data may be used if considered representative of typical operations. It is anticipated the NSCs will be more heavily utilized; therefore, increasing the exposure to heavy weather. The only way to confirm this with a higher degree of confidence is to continue a monitoring campaign on a smaller scale and investment. A smaller monitoring system combined with smart and consistent data analysis will provide a significant return on investment given the maintenance costs of these expensive and operationally valuable assets.

The percentages shown in Figure 12 pertain to the uncertainties in operational profile, wave environment and hydrodynamic load prediction. Characterization of the statistics of this information combined with the uncertainties in fatigue response facilitates the application of reliability based approaches.

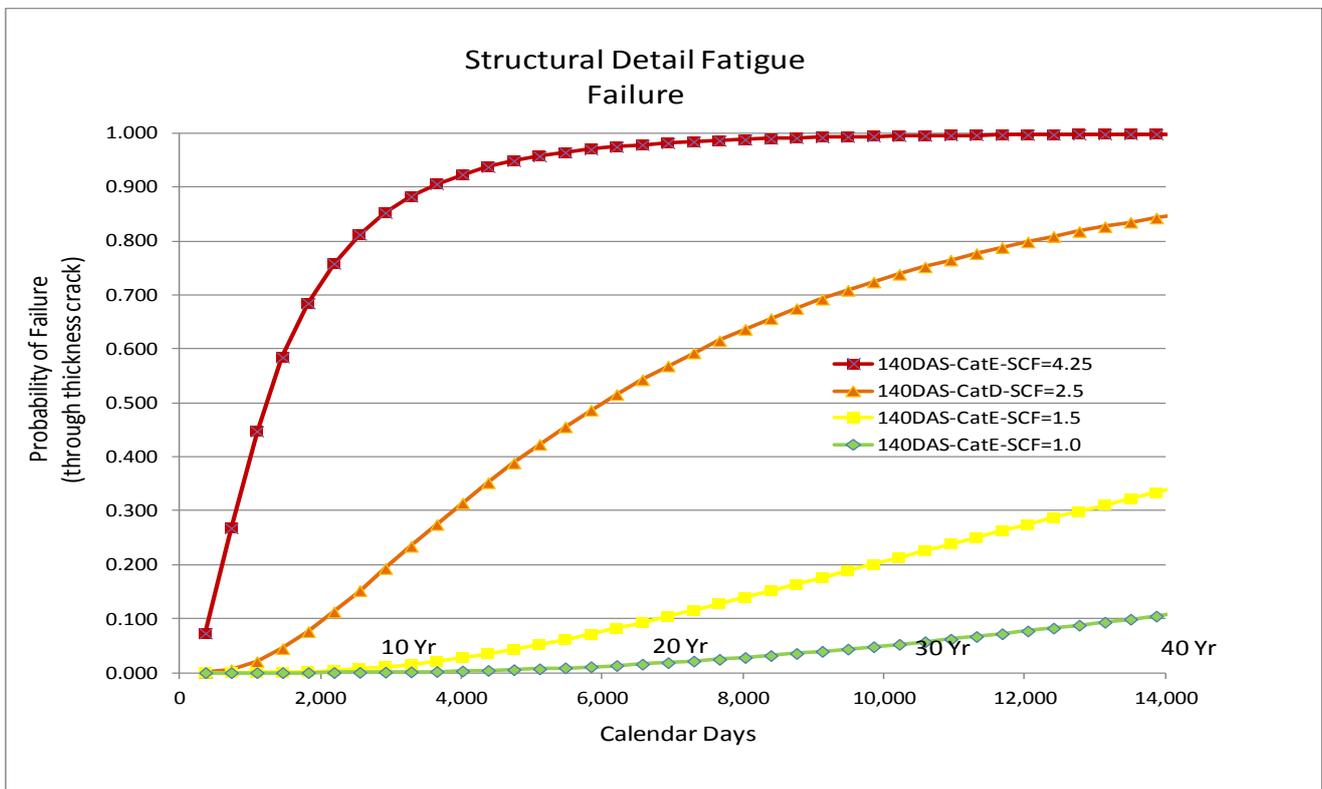


**Figure 12 – Relative magnitude of key differences in the SFA process used for the NSC structural design as compared to fatigue damage calculated from measured data**

Initial efforts have begun to characterize the statistical uncertainties of the structural loading for application in reliability based fatigue evaluations. One such fatigue reliability approach has been in development by Ayyub *et. al.* (2014) for the USCG. It is possible to determine the time dependent probability of fatigue failure and the system reliability by using a stochastic based reliability approach. Table 3 presents the bias and Coefficient of Variation (COV) for the load prediction techniques that are used in fatigue reliability calculations. The bias and COV were obtained by calculating the fatigue life for each cell in the measured wave scatter diagram, including all speeds and headings, dividing this by the measured fatigue damage and then calculating a weighted average for the entire wave scatter diagram based on the probabilities of the wave encountered. Results of this calculation are presented in Table 3 for the empirical Sikora URAOs, Hydrostar potential flow, PRECAL potential flow, and VERES strip theory loads prediction programs. More information about these programs and results of the hydrodynamic loads predictions are presented by Hageman *et. al.* (2014).

**Table 3 – Vertical Bending Moment (VBM) prediction comparisons with measured data**

	VBM Prediction Bias Correction with Directional Seas	VBM Prediction COV with Directional Seas
URAO	.92	.38
Hydrostar	.88	.35
PRECAL	.80	.35
VERES	.67	.25



**Figure 13 - Time based probability of fatigue failure for 140 Days at Sea per year (DAS), AASHTO fatigue categories (i.e. Cat E) and Stress Concentration Factors (SCF) relative to midship bending stress in the deck.**

### Structural fatigue reliability based approach

A traditional SFA copes with fatigue accumulation in a deterministic way. Uncertainties are not explicitly calculated by the procedure, but instead safety factors are relied upon to ensure structural integrity. However, explicit modelling of uncertainties allows the calculation of reliability levels. The following section discusses how the reliability based approach may contribute towards structural integrity management.

With the knowledge of the statistical uncertainties shown in Table 3 and the uncertainties of the S-N diagram from Ayyub *et al.* (2014), it is possible to make a time dependent reliability prediction for various details in the Cutter without structural fatigue enhanced modifications. This approach uses a Monte Carlo simulation approach to solve the time varying limit state. Conditional expectation with variance reduction is used to determine convergence of the simulations. The bias and coefficient of variation are obtained from measured PAF data described by Hageman *et al.* (2014) and presented in Table 3.

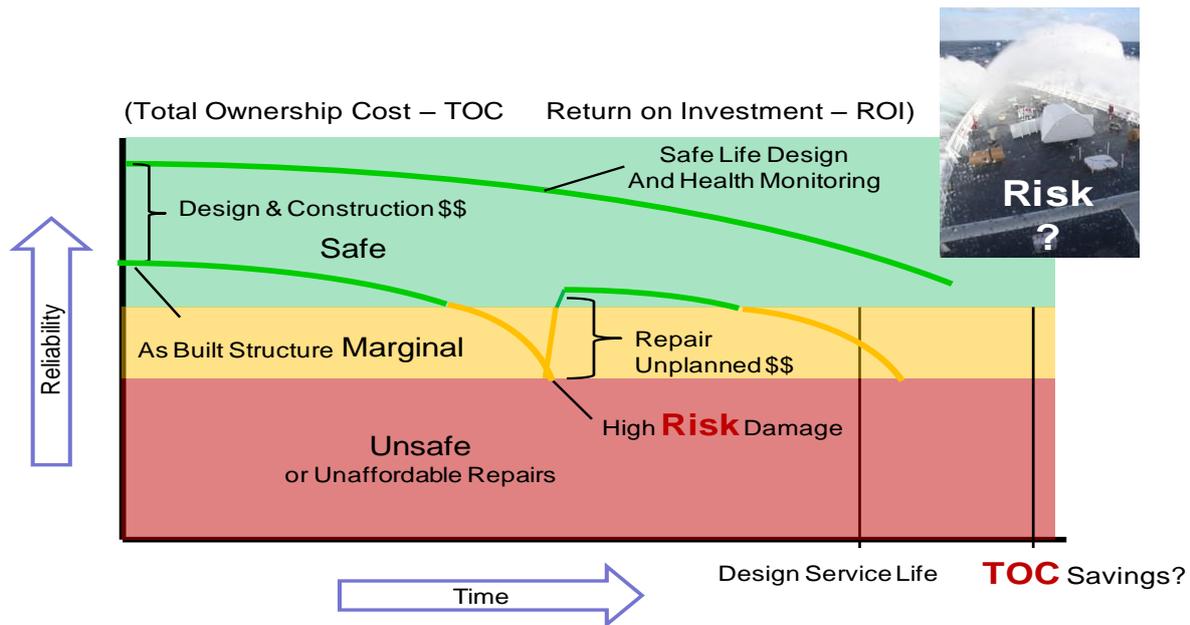
The fatigue calculations shown in Figure 13 include Stress Concentration Factors (SCFs) for the various fatigue sensitive locations, were obtained from FEA described by Drummen *et al.* (2014). The AASHTO fatigue categories and their application to ship structures are further described by Sieve *et al.* (2000). For ship structure that was designed without explicit SFA, shown in Figure 13, the variability in the range of fatigue response is striking. The fatigue life is dominated by the magnitude of SCF with fatigue damage being proportional to stress range to the third power. The

time required to accumulate a probability of failure of 1 is dominated by the uncertainties in the fatigue response of the material as shown in Figure 3. The time varying accumulation of numerous failed details becomes significant and unmanageable in repair cost and time out of service.

### Total Ownership Cost and Return on Investment for design and sustainment approaches

The validation of analysis tools, including the Sikora *et al.* (1983) and Sieve *et al.* (2000) and the statistical quantification in terms of bias correction and Coefficient of Variation (COV) according to Ayyub (2014) facilitates time dependent fatigue reliability evaluations from preliminary design through lifecycle maintenance decisions as illustrated in Figure 14. In this example, the reliability is calculated as one minus the probability of failure shown in Figure 13. Figure 14 shows two scenarios, one without explicit SFA and another with SFA and additional structure added in design and construction

In this illustrative example, the cost implications of this time dependent fatigue failure accumulation is significantly different than if fatigue is considered early in the cutters life as illustrated in Figure 14. Furthermore, the ability to extend the End of Service Life (ESOL) of a Cutter produces a significant savings in Total Ownership Costs (TOC), not only from a maintenance avoidance standpoint, but significant cost savings from not having to acquire a new Cutter because the structural life is limited.



**Figure 14 - Illustrative example of Total Ownership Cost considerations related to fatigue design approaches**

**ROI for various fatigue life approaches**

With the knowledge of the time varying structural fatigue reliability, it is possible to evaluate the cost of alternative design and maintenance strategies and the Return on Investment (ROI) of these alternatives. Table 4 provides example ROI estimates showing the benefits of considering SFA early in the design process, prior to construction, during construction, and in the ship's service life. In this example, the cost per Cutter is a relative Rough Order of Magnitude (ROM) for structural design, modifications and life cycle repairs. The estimates are from a combination of shipyard costs and repair estimates. ROI is defined as net cost savings (cost avoidance) divided by the cost invested by considering fatigue in a preliminary design shown as a baseline in Table 4. Because fatigue damage is proportional to the third power of stress range, the benefits of increased fatigue life and cost savings may be realized with small increases in steel weight required to reduce stress range. The associated construction cost is a minimal investment with very high ROI relative to the alternative of greater costs of repair when in service. The base ROI considers SFA early in a design as compared with the alternatives of managing the effects from not including SFA early in structural design. In the current example, a 30 year fatigue life can be achieved with additional steel as determined by SFA. This is in contrast to prescriptive rules that do not consider fatigue life explicitly. In this case, the additional steel weight required to achieve a 30 year fatigue life is on the order of 1.5% of the full load displacement. The effects of this additional weight on lifecycle cost are minimal as compared to the added maintenance cost and lost days of service due to unplanned repairs if SFA is not considered at all. In this example, the ROI is achieved by avoiding repair cost when utilizing SFA

early in the ship design rather than more expensive alternatives as presented in Table 4.

Without explicit SFA, fatigue damage will accumulate through service life and will lead to unplanned, unbudgeted and unaffordable repairs and potentially loss of the asset at high additional cost.

**Table 4 – Example Return on Investment (ROI) of SFA in Preliminary Design as compared to incurred repair costs in service.**

Life Phase	Relative Cost/Cutter	ROI of fatigue design	Lost Op Days	Comments
Preliminary design	0.5	Base Option	0	Essentially the cost of added steel
Detail design	1.0	1.5:1	85 +	Including design rework
Construction	4	7:1	170	One year delay in delivery
After delivery	20	39:1	85	Half year Dry Dock
Repair through 30 year service life	10-30	>19.5:1	340 +	6 -2 week EDS+ 2 – 1 month EDD

EDD is Emergency Dry Dock EDS is Emergency Dock Side

Additionally, lifecycle repair costs are significant with much greater risk of significant failure. A Service Life Extension Program (SLEP), illustrated in Figure 13, will increase repair

costs for the through service life option and ROI on fatigue design will increase significantly by cost avoidance as compared to added structure during initial design and construction.

## CONCLUSIONS

The USCG FLAP and VALID JIP has produced a significant step in understanding the uncertainties of the Spectral Fatigue Analysis approach used for naval ships down to a high degree of fidelity by measuring the wave environment from the instrumented ship. The measured wave data facilitated the quantification of a relatively large uncertainty that would otherwise have been difficult to differentiate and fully evaluate other uncertainties in the SFA process. The key findings from the FLAP project relevant to the USCG and long term sustainment of the NSC class include:

- Fatigue life predictions using the Sikora *et. al.* 1983 approach under predicts wave induced fatigue loading by approximately 7%. Improvements are recommended for the Sikora *et. al.* 1983 approach to fatigue damage from impact loading and whipping response.
- The wave environment encountered by the instrumented Cutter was found to have lower probabilities of occurrence in significant wave heights (Hs) greater than 4m as compared to the wave probabilities used in early fatigue evaluations. The measured wave environment encountered by the Cutter was invaluable in quantifying the uncertainties in the SFA process.
- Uncertainties in the SFA process have been quantified on a sufficient level required for use in time varying fatigue reliability based assessments and sustainment evaluations.
- Conservative fatigue life estimates based on 2.3% probability of failure used in the S-N design curves are useful in fatigue design; however, forecasts of fatigue life must consider the large uncertainties in the operational environment, influence of the operator and most significantly the wide scatter of S-N data. The latter uncertainty associated with data scatter is best considered in time dependent fatigue reliability calculations for long term fatigue life assessments.
- Because fatigue damage is proportional to the third power of stress range and influence of the operator in avoiding heavy weather when possible, it is beneficial to monitor the fatigue damage accumulation. This can be done with a simple system calibrated to key locations using FEA.
- Given the large capital investments and lifecycle costs of ships, small investments in fatigue life reductions produce large improvements in TOC and significant ROI in applying SFA early in the ship design process.
- Using the Sikora *et. al.* (1983) and Sieve *et. al.* (2001) or similar spectral fatigue approach early in the design produces significant returns investment when compared

to modifications required late in the design process, unplanned ship repairs and sustainment costs.

Remaining work includes further statistical characterization of the uncertainties for improved structural reliability evaluations and presence of sub-visible fatigue cracking using fracture mechanics approaches as applied by Tammer and Kaminski (2013) for offshore floating structures and acoustic emission technology. Continued structural health monitoring provides quantified information on the long term condition of the hull structure and forms the basis for life cycle maintenance and decisions requiring knowledge of the remaining service life of these high valued assets.

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## REFERENCES

- Ayyub, B., Stambaugh, K., McAllister, T., de Souza, G., Webb, D., “Structural Life Expectancy of Marine Vessels: Ultimate Strength, Corrosion, Fatigue, Fracture and Systems,” ASCE-ASME *Journal on Risk and Uncertainty Analysis*, 2014 Submitted
- Bales, S., Lee, W., Voelker, J. “Standardized Wave and Wind Environments for NATO Operational Areas”, David W Taylor Naval Ship Research And Development Center Bethesda MD Ship Performance Dept, JUL 1981
- Drummen, I., Schiere, M., Dallinga, R., Thornhill, E., Stambaugh, K., “Full Scale Trials, Monitoring and Model Testing Conducted to Assess the Structural Fatigue Life of a New US Coast Guard Cutter”, to be presented at the Ship Structures Committee Symposium held in Linthicum Heights, Maryland, May 18-20, 2014
- Fathi, D., “ShipX Vessel Responses (VERES)”, user’s Manual, Marintek, 2005
- Hageman, R., Schiere, M., Drummen, I., Derbanne, Q., Le Guen, J., Shin, Y., Kim, P., Stambaugh, K., “Structural Fatigue Loading Predictions and Comparisons with Test Data for a New Class of US Coast Guard Cutters”, to be presented at the Ship Structures Committee Symposium held in Linthicum Heights, Maryland, May 18-20, 2014
- Hess, P., Bruchman, D., Ayyub, B., (1998), “Uncertainties in Material and Geometric Strength Variables in Marine Structures,” *Uncertainty Modeling and Analysis in Civil Engineering*, Edited by Bilal M. Ayyub, CRC Press.
- Hughes, O., Piak, J., “Ship Structural Analysis and Design” SNAME Publications 2010

Kim, S., Shin, Y., Liu, D., “Advanced ‘Dynamic Loading Approach’ for Ultra Large Container Carriers Based on Nonlinear Time-Domain Seakeeping Analysis”, *International Society of Offshore and Polar Engineers (ISOPE) 2006*

Rychlik, I., “A New Definition of the Rainflow Cycle Counting Method”, *International Journal of Fatigue*, 1987

Sieve, M., Kihl, D., and Ayyub, B., 2000, “Fatigue Design Guidance for Surface Ships”, NSWCCD-65-TR-2000/25, Naval Surface Warfare Center, Carderock Division, West Bethesda, Maryland

Sikora, J., A. Dinsenbacher, and J. Beach.. A Method for Estimating Lifetime Loads and Fatigue Lives for SWATH and Conventional Monohull Ships. *Naval Engineers Journal*, 1983

Tammer, M. and Kaminski, M.L., “Fatigue oriented risk based inspection and structural health monitoring of FPSOs”, *Proceedings of the International Offshore and Polar Engineering Conference*, 2013

Thornhill, E., “Real Time Local Sea State Measurement Using Wave Radar and Ship Motions”, *SNAME Transactions*, 2010

Wu, M., Moan, T., “Efficient Calculation of Wave-induced Ship Responses Considering Structural Dynamic Effects”, *Journal of Applied Ocean Research*, 2005