NTIS # PB2003-104869

SSC-423

GREEN WATER LOADING ON SHIP DECK STRUCTURES

SHIP STRUCTURE COMMITTEE
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Technical Report Documentation Page

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SSC – 423
SR – 1416

May 2003

GREEN WATER LOADING ON SHIP DECK STRUCTURES

Green water is the term used to describe a significant mass of water coming onto the deck of a ship due to a combination of the motions of the sea and the ship. Once shipped, a mass of water can achieve significant velocities in the shallow-water environment on deck, and can exert significant pressure on deck structure and fittings. Green water incidents have a demonstrated potential for damage to deck structures including deck plating, breakwaters, external bulkheads, deck-mounted weapons, antennas and portholes.

This study integrates a shallow-water finite volume approach with the LAMP (Large Amplitude Motion Program) ship motions analysis to find the incidence of green water and the resultant forces and pressures on deck structures.

The results show expected trends in speed, sea state and ship size for the magnitude of loads and pressures.

PAUL J. PLUTA
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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1. Report No. SSC- 423	**2. Government Accession No.** PB2003-104869	**3. Recipient's Catalog No.**
4. Title and Subtitle Green Water Loading on Deck Structures		**5. Report Date** 31 January 2003 **6. Performing Organization Code** SR-1416
7. Author(s) Michael Meinhold Daniel Liut, Kenneth Weems, Thomas Treakle, and Woei-Min Lin		**8. Performing Organization Report No.** SAIC Report #03-1005
9. Performing Organization Name and Address SAIC Ship Technology Division 134 Holiday Court Suite 318 Annapolis, MD 21401		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address Ship Structure Committee U.S. Coast Guard (G-MSE/SSC) 2100 Second Street Washington, DC 20593-0001		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code** G-M
15. Supplementary Notes Sponsored by the Ship Structure Committee. Jointly funded by its member agencies.		
16. Abstract A method was developed to use the Large Amplitude Motions Program (LAMP) to determine incidence of green water on deck, and to estimate the pressure forces generated by shipped water on major deck structures. This method was applied to three ship types in a variety of loading conditions and sea conditions.		
17. Key Words Green Water, Sea Loads, Deck Structure, Ship Motions	**18. Distribution Statement** Distribution Unlimited, available from: National Technical Information Service Springfield, VA 22161 (703) 487-4650	

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	33	Paper $25.50 Electronic $8.95

Conversion Factors

(Approximate conversions to metric measures)

To convert from	to	Function	Value
LENGTH			
inches	meters	Divide	39.3701
inches	millimeters	multiply by	25.4000
feet	meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
$inches^2$ $feet^2$	$centimeters^2$ $meters^2$	multiply by	1.9665
$inches^2$ $feet^2$	$centimeters^3$	multiply by	196.6448
$inches^4$	$centimeters^3$	multiply by	16.3871
MOMENT OF INERTIA			
$inches^2$ $feet^2$	$centimeters^2$ meters	divide by	1.6684
$inches^2$ $feet^2$	$centimeters^4$	multiply by	5993.73
$inches^4$	$centimeters^4$	multiply by	41.623
FORCE OR MASS			
long tons	tonne	multiply by	1.0160
long tons	kilograms	multiply by	1016.047
pounds	tonnes	divide by	2204.62
pounds	kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
$pounds/inch^2$	$Newtons/meter^2$ (Pascals)	multiply by	6894.757
kilo $pounds/inch^2$	mega $Newtons/meter^2$ (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tons	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo $pound/inch^2$ $inch^{1/2}$(ksi$\sqrt{in}$)	mega Newton $MNm^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	$Joules/mm^2$	multiply by	0.1753
kilo pound/inch	kilo $Joules/m^2$	multiply by	175.3

Table of Contents

Table of Figures

List of Tables

Table of Nomenclature

h	Elevation of water at the control point of a given element
e	Green water volume element
q	Element adjacent to the given element e denoted are designated by the subscript q
m_{ij}^{k}	Mass where the superscript k is the time step index, the subscript i denotes each of the four sides of each element, and the subscript j is the iteration index
C	Characteristic area is defined by the projection of the base area of a given element onto a normal to the gravitational field surface at the geometric center of the base of each element
Q	Flow per unit of water elevation across any lateral wall of an element e
$\mathbf{v}$	Characteristic flow speed of a given element
D	Flow across a lateral side i of any element
$\mathbf{P}$	Hydrostatic and hydrodynamic forces
$\mathbf{R}$	Position vector
$\mathbf{b}$	Accelerations in the plane normal to the gravitational field
h	Submergence (Relative Motion at the Location)
a_z	Vertical Acceleration
a_y	Transverse Acceleration
ρ	Density of water
σ	Stress
k	Determined from the plate aspect ratio (Figure 9.6 in Hughes 1988)
P	Lateral pressure on the plate
t	plate thickness
M	Maximum moment on beam
w	Uniform loading per unit length along beam
l	Length of beam

Executive Summary

Green water is the term used to describe a significant mass of water coming onto the deck of a ship due to a combination of the motions of the sea and the ship. Once shipped, a mass of water can achieve significant velocities in the shallow-water environment on deck, and can exert significant pressure on deck structure and fittings. Green water incidents have a demonstrated potential for damage to deck structures including deck plating, breakwaters, external bulkheads, deck-mounted weapons, antennas and portholes.

This study integrates a shallow-water finite volume approach with the LAMP (Large Amplitude Motion Program) ship motions analysis to find the incidence of green water and the resultant forces and pressures on deck structures. Three ships are examined:

- A USCG 378-ft. High Endurance Cutter
- A USN CG-47 Ticonderoga Class Guide Missile Cruiser
- A Nominal Large Container Ship

The results show expected trends in speed, sea state and ship size for the magnitude of loads and pressures.

The scope of the calculation performed for this study did not provide sufficient data to statistically characterize the green water pressures and forces. In order to do that, a sufficient series to generate a stationary process in the peaks of the pressures and forces is required. Some changes to the process of making simulation runs and data analysis can be made to make much longer calculations (days instead of hours) more easily and make this further calculation practical.

A sample structural stress analysis for the CG-47 shows that the predicted green water pressure loading induces stresses in both the plate and the stiffeners that are larger than the yield stress of the aluminum bulwark. This finding correlates with damage reported on the CG-47 during large sea states when the shipping significant green water occurs.

The current formulation is a practical foundation for extensions to include nonlinear free-surface effects important to the deck loads problem. We recommend the development of a hybrid method that uses the shallow water formulation when possible and implement a nonlinear water-on-deck model when necessary.

1 Introduction

Green water is the term used to describe a significant mass of water coming onto the deck of a ship due to a combination of the motions of the sea and the ship. Once shipped, a mass of water can achieve significant velocities in the shallow-water environment on deck, and can exert significant pressure on deck structure and fittings. Green water incidents have a demonstrated potential for damage to deck structures including deck plating, breakwaters, external bulkheads, deck-mounted weapons, antennae and portholes.

In this study, a finite-volume method based on shallow water assumption for predicting the incidence and some of the impacts of green water incidents was formulated, implemented and applied. This report describes the technical approach for the determination of the ship motions, the incidence of green water, and the motion of and forces generated by the water on deck.

Any ocean-going vessel can ship water onto its decks, but Navy and Coast Guard vessels whose missions may require them to maintain course and speed in heavy seas are more likely to experience green water incidents more frequently than ordinary ships. Large container ships that carry stacks of containers well forward have also experienced damage under some conditions. In this study, we applied the green water analysis to three hull forms:

- A USCG 378-ft. High Endurance Cutter
- A USN CG-47 Ticonderoga Class Guide Missile Cruiser
- A Nominal Large Container Ship

Each ship was run for thirty minutes in 6 cases of speed, heading, and wave height. The cases were chosen to obtain approximately 3 occurrences of green water over the bow per minute. The forces and pressures due to the green water on each deck surface were measured and analyzed and are presented in graphical and tabular form. A sample calculation to determine the structural stress on the CG-47 bulwark was conducted from the predicted green water pressure loading.

The Approach section below describes in detail the limits and capabilities of the LAMP System including the green water calculations method. The result section describes the sample ships used in this case study, the sequence of calculations, data analysis, and a structure analysis based on the pressure loadings on the deck structure caused by the green water.

2 Technical Approach

2.1 The LAMP System

Over the past fourteen years, LAMP (Large Amplitude Motion Program) has been developed as a multi-level time-domain simulation system for the prediction of motions, wave loads, and structural responses of ships and marine structures. As shown in Figure 1, this system consists of several closely integrated modules designed to perform specific tasks. The primary module computes time-domain ship motions, wave-frequency loads, and pressure distributions over the hull surface. The second module calculates the impact forces due to slamming. The third module computes the whipping responses using a non-uniform-section dynamic beam method. A fourth module provides an interface to detailed finite-element analysis by computing nodal load sets from the time-domain hull pressure distribution. Other tasks can be performed by the LAMP System, which further perfects its proficiency as a state-of-the-art modeling and simulation tool (see Weems *et al.*, 1998). The research described in this report has been focused on extending the capabilities of the first module to account for water-on-deck occurrences and the effects of green water on ship motions and wave loads. To this end, a green water model, capable of predicting the green water related pressures and forces, was developed. This section summarizes the current capabilities of the LAMP System and describes the basis of the newly developed green water model. Numerical examples of the green water calculations are also given.

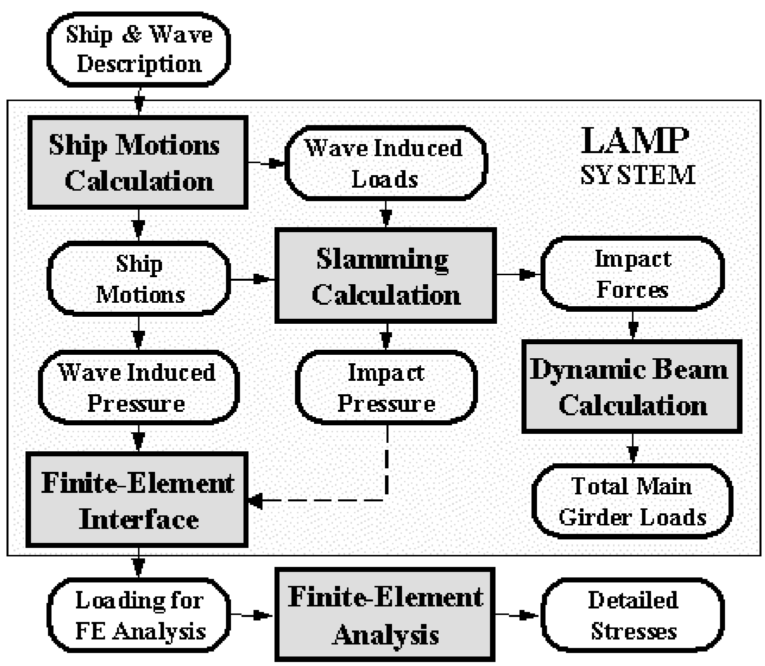


Figure 1: Components of the LAMP System

One of the most important capabilities of the LAMP System is its ability to solve for the three-dimensional time-domain nonlinear ship motions and the corresponding hydrodynamic loads. The computational model is based on a potential-flow "body-nonlinear" approach (Lin and Yue, 1990, 1993; and Lin *et al*., 1994). In contrast to the linear approach in which the body boundary condition is satisfied on the portion of the hull under the mean water surface, the body-nonlinear approach satisfies the body boundary condition exactly on the portion of the instantaneous body surface below the incident wave surface. It is assumed that both the radiation and diffraction waves are small compared to the incident wave so that the free surface boundary conditions can be linearized with respect to the incident wave surface. In this formulation, both the body motions and the incident waves can be large relative to the draft of the ship.

Several variations of Lin and Yue's original body-nonlinear approach have been developed and are currently available in the LAMP System. The body-nonlinear approach described above is designated as LAMP-4; in addition to 3-D large-amplitude hydrodynamics, LAMP-4 calculates nonlinear hydrostatic restoring and Froude-Krylov wave forces. A weakly nonlinear version of the code, LAMP-2, has also been developed to calculate 3-D linear hydrodynamics, but still uses nonlinear hydrostatic restoring and Froude-Krylov wave forces. In addition, a linear code, LAMP-1, is available for calculating 3-D linear hydrodynamics and linear hydrostatic restoring and Froude-Krylov wave forces.

2.1.1 Mixed Source Formulation

A hybrid numerical approach has been developed in the LAMP hydrodynamic formulation that uses both transient Green functions and Rankine sources (Lin *et al*., 1999). This approach has been implemented in the LAMP code as the "mixed source formulation." In the mixed source formulation, the fluid domain is split into two domains as shown in Figure 2. The outer domain is solved with transient Green functions distributed over an arbitrarily shaped matching surface, while the inner domain is solved using Rankine sources. The advantage of this formulation is that Rankine sources behave much better than transient Green functions near the body and free surface juncture, and that the matching surface can be selected to guarantee good numerical behavior of the transient Green functions. The transient Green functions satisfy both the linearized free surface boundary condition and the radiation condition, allowing the matching surface to be placed fairly close to the body. This numerical scheme has resulted in robust motion and load predictions for hull forms with non-wall-sided geometries.

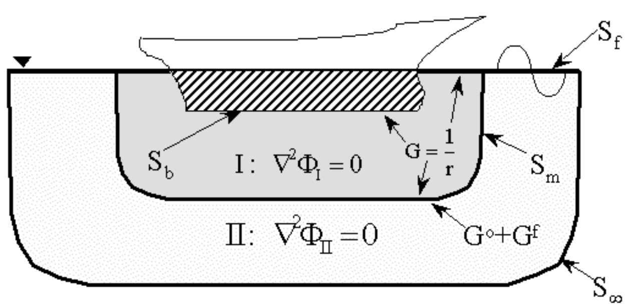


Figure 2: Mixed Source Formulation

Another advantage of the mixed formulation is that the local free surface elevation is part of the solution, and no additional evaluation is needed as in the case of the transient Green function approach. In addition, a nonlinear free surface boundary condition can be implemented at a modest computational cost. The capability to included the 2nd order free surface boundary conditions in the LAMP System is currently under development.

2.1.2 Non-Pressure Forces

In order to calculate the time-domain six-degree-of-freedom coupled motions for any ship heading and speed, LAMP also includes models for non-pressure forces including viscous roll damping, propeller thrust, bilge keels, rudder and anti-rolling fins, mooring cables, and other systems. For oblique-sea cases, a PID (Proportional, Integral, and Derivative) course keeping rudder control algorithm and a rudder servo model are implemented. Because of the time-domain approach, these non-pressure force models can include arbitrary nonlinear dependency on the motions, etc. Adjustable viscous roll damping models are available that allow the roll damping to be "tuned" to match experimental values by simulating roll decay tests.

2.1.3 Equations of Motions

Once the hydrodynamic and non-pressure forces have been computed, the general 6-DOF equations of motion are solved in the time domain by either a 4th-order Runge-Kutta algorithm or a predictor-corrector scheme. Since the forces on the right hand side of the equations of motion include the instantaneous added mass, an estimated added mass term is added to both sides of the equation of motion to achieve numerical stability. In addition to motion simulations, LAMP calculates the time-domain wave-induced global loads, including the vertical and lateral shear forces and bending moments, torsional moment, and compression force, at any cross-section along the length of the ship. Structural loads can be computed using rigid-body or finite-element beam models.

At each time step, LAMP calculates the relative motion of the ship and the wave configuration as well as the hydrodynamic pressure distribution over the instantaneous wetted hull surface below the incident wave surface. The relative motion, which can include the local wave disturbance, is used as input for the impact load and green water-on-deck calculations. The pressure distribution is used to generate an input data set for finite-element structural analysis.

2.1.4 Impact Forces and Whipping Responses

In the LAMP System, a post-processor is used for either symmetrical or non-symmetrical impact load predictions. It is assumed that the impacts do not affect the global ship motions. The previously computed global ship motions are used to compute relative motion of the ship bow and identify events where impact forces may be significant. The relative ship motion is then used to compute impact loads on 2-D cross sections of the ship for impact occurrences. The forces from such impact events are then assimilated into an impact-force history, which can be used to evaluate whipping loads.

Once the sectional impact forces are computed, the main girder responses are computed in LAMP using a non-uniform-section dynamic beam method in order to get high-frequency global loads associated with whipping. The ship is modeled as either a uniform or a variable-mass beam. The total bending moment is obtained by combining the wave-frequency and the high-frequency bending moments with proper phasing.

2.1.5 Interface to Structural Finite-Element Analysis

The LAMP System calculates the pressure distribution over the instantaneous hull surface below the incident wave surface. The hull pressure information, combined with the acceleration data, can be used for finite element (FE) structural analysis. A generic interface between LAMP motion and load calculations and structural FE codes has been developed. The interface program reads nodal point coordinates and connectivity information (only surface nodes are needed) used in the FE code and computes the forces acting on the nodal points. At specified time steps, the interface program writes the nodal point forces and ship acceleration information as outputs for the finite element structural analysis program. Other outputs from the LAMP/FE interface include nodal pressure history, sectional main girder loads for FE analysis of partial ship configurations, and external forces (*e.g.* control surfaces) that were modeled in the LAMP simulation but were not included in the pressure distribution. The latter forces must be accounted for so that forces and accelerations are properly balanced in any subsequent structural analysis.

2.2 Green Water Formulation

This report describes the implementation of an effort that has been directed to extend the LAMP computational capabilities to account for water-on-deck or green water effects. To this end, a finite-volume model has been developed, in which the equations of conservation of mass and momentum are solved in the time domain. Shallow-water assumptions are made and viscous effects are ignored. In this formulation, the driving forces parallel to the gravity field are predominantly of a hydrostatic nature (*e.g.* Stoker, 1957).

As shown in Figure 3, in the green water computation, the computational domain is discretized in parallelepipedal volumes of water with height h, where h is the elevation of water at the control point of a given element. In Figure 3, a particular element e is shown with elements adjacent to the given element e denoted by the subscript q. All finite-volume elements are kept parallel to the gravitational field during the calculations. For each element, three characteristic variables are computed: water elevation, and the two components of the flow velocities normal to the gravitational field.

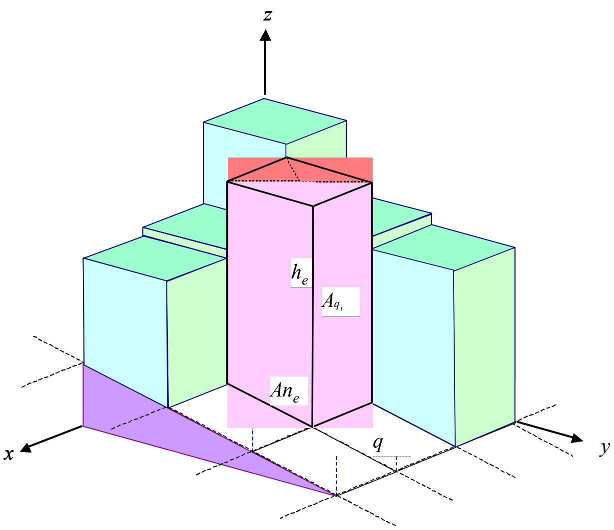


Figure 3: Finite Volume Discretization

The finite-volume implementation of the equations of conservation of mass can be expressed as:

$$m_{ee} \; h_e^{k_j+1} + \sum_{i=1}^{4} m_{eq_i}^{j} \; h_{q_i}^{k_j+1} = w_e^j \tag{1}$$

with

$$\begin{aligned} m_{ee} &= \left(\Delta C + \; \overline{C}^{k_{j-1}+1}\right)_e \\ m_{eq}^{j} &= \frac{\Delta t}{4} Q_{eq_i}^{k_{j-1}+1} \\ w_e^j &= \frac{\Delta t}{4} \sum_{i=1}^{4} \left(Q_{ee_i}^{k_{j-1}+1} \; h_e^{k_{j-1}+1} \right) \\ &+ \frac{\Delta t}{2} \sum_{i=1}^{4} \left(Q_{eq_i}^{k} h_{q_i}^{k} + Q_{ee_i}^{k} h_e^{k} \right) + h_e^k \; \overline{C}^{k_{j-1}+1} \end{aligned} \tag{2}$$

where *m* is mass, the superscript *k* is the time-step index, the subscript *j* is the iteration index, and the subscript *i* denotes each of the four sides of each element. The characteristic area *C* is defined by the projection of the base area of a given element onto a normal-to-the-gravitational-field surface at the geometric center of the base of each element (in Figure 3, *C* is denoted by *An*). The size of each element is arbitrarily determined based on the desired resolution for the green water solution. *Q* is defined as the flow per unit of water elevation across any lateral wall of an element *e*. On each boundary wall of any element, the terms *Q* are split into two components corresponding to the contributions from the characteristic flow velocity of element *e* and from an adjacent element *q*. Bars on top of variables indicate average values during a given time step.

The corresponding implementation of the momentum equations can be expressed as:

$$\mathbf{R}_{ee}^{j} \quad \mathbf{v}_{e}^{k_j+1} \quad + \sum_{i=1}^{4} \mathbf{R}_{eq_i}^{j} \quad \mathbf{v}_{q_i}^{k_j+1} = \mathbf{S}_{e}^{j} \qquad (3)$$

with

$$\mathbf{R}_{ee}^{j} = \begin{pmatrix} \overline{C}_{e}^{k_{j-1}+1} \quad \overline{h}_{e}^{k_j+1} \quad + \quad \overline{h}_{e}^{k_j+1} \quad \Delta C_{e}^{k_{j-1}+1} \\ + \overline{C}_{e}^{k_{j-1}+1} \quad \Delta h_{e}^{k_j+1} \end{pmatrix} \bullet \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\mathbf{R}_{eq_i}^{j} = \frac{\Delta t}{2} \quad \overline{D}_{eq_i}^{k_j+1} \bullet \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad (4)$$

$$\mathbf{S}_{e}^{j} = \overline{C}_{e}^{k_j+1} \quad \overline{h}_{e}^{k_j+1} \quad \left(\mathbf{v}_{e}^{k} - \overline{\mathbf{b}}_{e}^{k_{j-1}+1} \Delta t \right)$$

$$- \frac{\Delta t}{2} \sum_{i=1}^{4} \mathbf{v}_{q_i}^{k} \quad \overline{D}_{i}^{k_j+1} - \overline{\mathbf{P}}_{e}^{k_j}$$

where bold-face letters represent vector quantities, **v** is the characteristic flow speed of a given element, D is the flow across a lateral side i of any element, and **P** is the hydrostatic and hydrodynamic forces. Analogously as with Q, the D terms are also split into two contributions: one from the given element e and the other from the element adjacent to the boundary i being considered. Vector **b** denotes accelerations in the plane normal to the gravitational field. Accelerations parallel to the gravitational field are added through the term **P**. The nonlinearity in flow velocities comes through the products of **v** by **R**, since the latter contains velocities through the term D. This, plus the fact that the water elevations (which are also computed at each time step) are contained in the terms **R**, contributes to the nonlinear nature of the problem. Analogously, nonlinearity exists in the equations of mass as the velocities present in the terms Q are multiplying the elevations h.

At each time step, the finite-volume implementation of equation of conservation of mass and the two components of the momentum equations are solved simultaneously, and the corresponding green water effects are computed. An optimal time step size to obtain fast computations, while at the same time guaranteeing convergence, can be computed automatically in the current method and is typically $1/10^{th}$ the size of a LAMP time step or approximately $1/100^{th}$ of a second. In this regard, a minimum water elevation is prescribed. Elements with water elevation below a given threshold are ignored when computing the equations of motion. A maximum water elevation is also computed beyond which the shallow-water assumptions would not be valid.

The next two sections provide several green water related validation cases and numerical examples. In particular, the general procedure of including green water effects on ship motions and global loads calculations are presented.

2.3 Validation Of The Green Water Approach

The current green water approach has been tested thoroughly. In this section, two particular validation examples are discussed. The first example is the “dam break” problem described in Stoker (1957). In this problem, Stoker used a linear theory to solve the water profile of a suddenly removed dam. Similar conditions to those presented by Stoker were set in the current model. The water initial height is 10 meters, and the water profile is observed one second after the dam is removed. The finite-volume grids used for this calculation contained 41 elements. As can be seen in Figure 4, generally good agreement was obtained between Stoker’s linear results and those computed with the present approach. The primary difference is seen in the smoother manner in which the free surface transitions to the asymptotic water depth near the dam with the finite-volume approach.

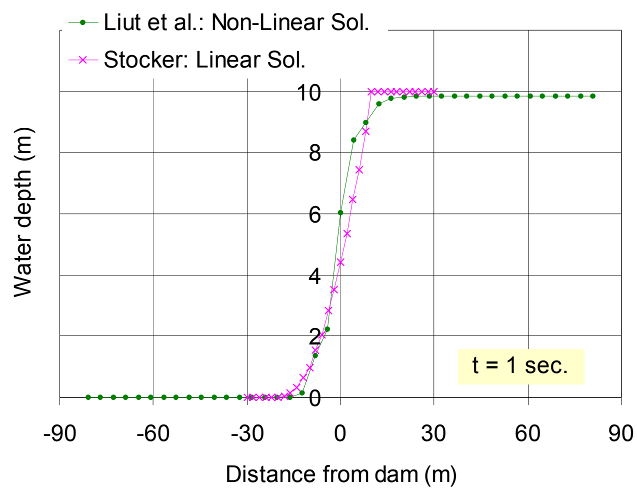


Figure 4: Comparison with Stoker’s Linear Theory

The second validation example is a comparison with a series of shallow-water experiments results presented by Buchner (1995). Buchner studied the effects of the sudden opening of a flap in a tank with one side initially filled with water. The dimensions of the tank and the position of the flap in his experiments are described in Figure 5. One of these experiments (experiment Nr. 4487001) is used in the current study. In this experiment, a sensor was positioned 1.525 meters away from the back of the tank. When the flap was removed, the water moved forward, and the water elevation was measured at the sensor location. In addition to the experiments, Buchner (1995) also developed a shallow-water model based on Glimm’s method (Glimm, 1965). The time history comparison of the experimental measurements of the water height, the results based on Buchner’s method, and the results from the current approach are shown in Figure 6. In general, the comparison is very encouraging. The finite-volume grids used for the calculation contained 21 elements.

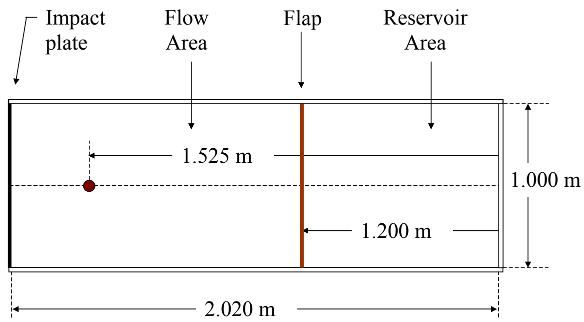


Figure 5 Experimental Geometry Setup- Bucher (1995)

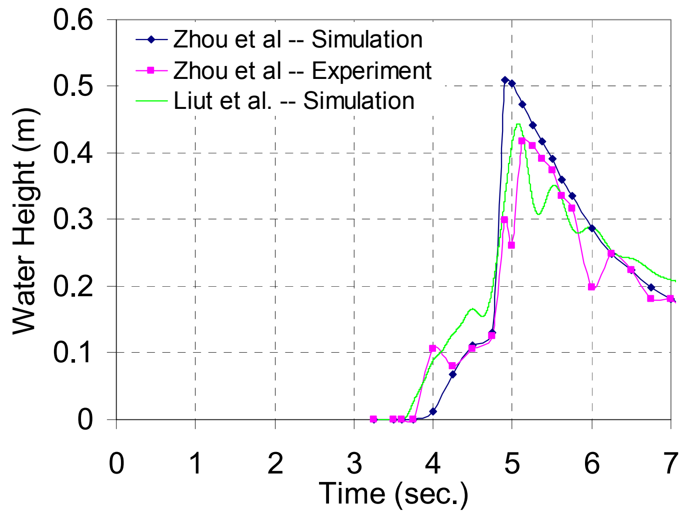


Figure 6 Validation Case – Buchner (1995)

2.4 Green Water Calculation Procedure

The green water method is now fully integrated in the LAMP System, but can also function as a standalone code. In the work described in this report, the Green water calculation was run separately from LAMP. While considering the green water effects, the following procedures are followed:

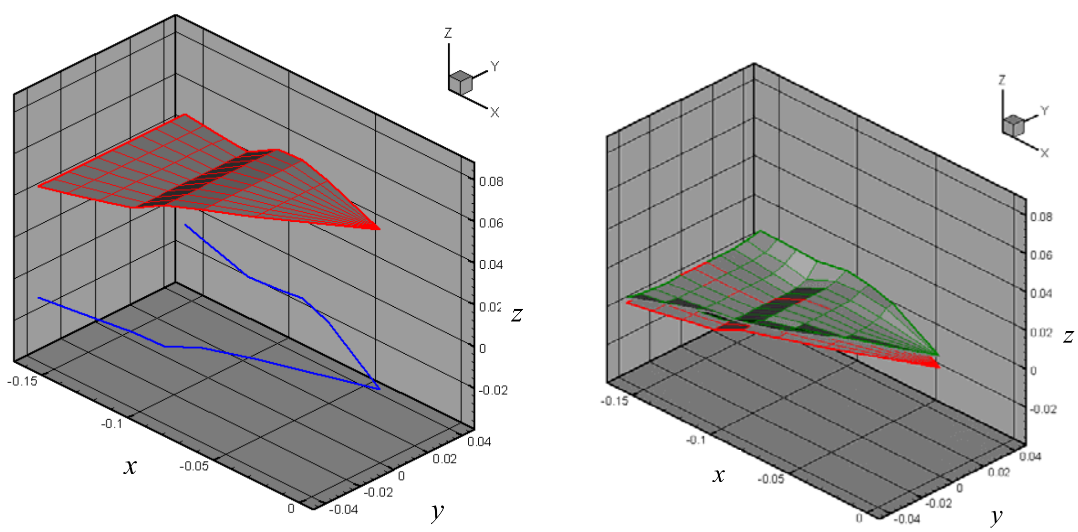
1. Run the LAMP code, compute the deck-edge sea-water elevation and the motions of each point on the deck. The ship motion computations in LAMP provide the relative location of the water surface and the deck edge. The water surface computed in LAMP includes the radiation and diffraction wave components.
2. In the Green water code, compute the amount of water entering the ship deck. A water-entry model based on the water head and a semi-empirical formula are used to determine the amount of water that enters the ship deck.
3. Apply the appropriate boundary conditions on the ship deck. The 3-D shallow-water finite-volume approach described in this paper is used to calculate the water movement on deck.

Appropriate boundary conditions are applied to account for the presence of incoming water, deck edges, partially submerged elements, and the presence of possible obstacles on deck (*e.g.* forecastle).

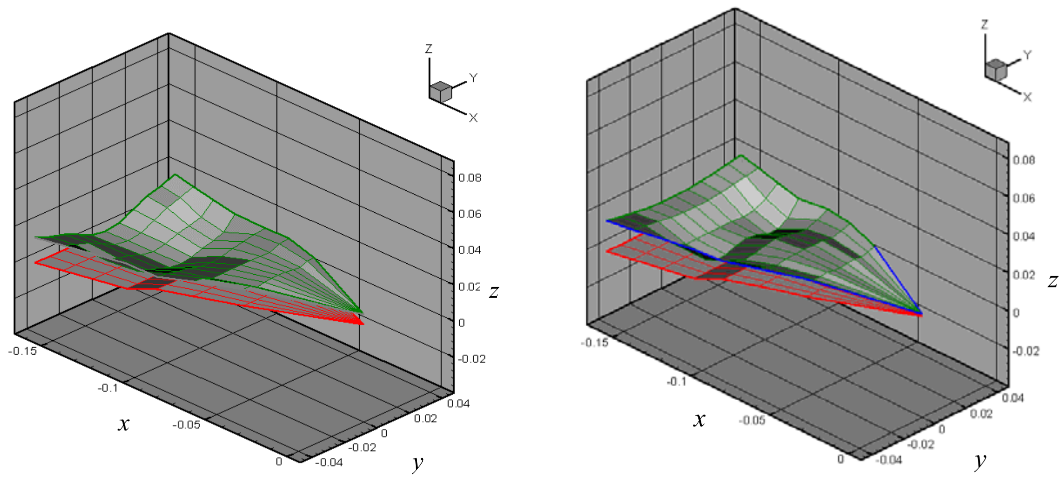
4. Apply the deck-edge boundary conditions on the ship deck. The water exit at deck edges is taken as a free fall condition.

In general, the green water computations require finer time-step sizes compared to those used in the ship motion calculations, typically on the order of ten to one. The time-step size in the green water calculations can be adjusted automatically during the calculations, and the green water effects are evaluated only at the required "ship-motion" time steps.

An example of the integrated ship motion and green water computation is given in Figure 7. The results are shown for a deck area close to the bow at x = 0.0 where y = 0.0 is at the centerline of the ship and z = 0.0 is at the initial undisturbed deck level. At the backside of the computational domain, a boundary condition was set to simulate the presence of a forecastle. The sides of the deck are free for water flow in and out. In this example, the ship speed is 20 knots and has a dominant non-regular pitching motion. The ship is operating in a head sea, long-crested sea-state 6 condition. The computational grid was comprised of 70 finite-volume elements (seven length-wise by ten beam-wise). In Figure 7(a), the deck is completely out of the water. The line below the deck is the vertical projection of the deck edge onto the water surface below it. In Figure 7(b), the deck is below the free surface, and water is pouring into it. Different stages of the subsequent green water distribution are shown in Figure 7(c) and Figure 7(d). Although the example shows a head-sea symmetrical computation, the current capability can handle the unsymmetrical green water computations as well.



(a) (b)



(c) (d)

Figure 7 Green Water Effects on Ship Motions

2.5 Green Water Loads Statistics and Processing

The present study is an exercise that shows how the green water calculation can show sensitivity to parameters of geometry, environment and operational conditions. The green water calculation can provide free-surface elevations over the deck surfaces, velocities, and total force, which can be converted to average pressure.

In this study, three ships, CG47, USCG 378-ft. WHEC, and a containership were selected. For each ship, three surfaces on which to track force and pressure were selected.

1. A Bow Bulwark
2. A Forward Deck
3. A Forward Bulkhead

For the CG47 the AEGIS deckhouse provided the vertical bulkhead; for the USCG WHEC the bulkhead was the forward deckhouse structure's forward face, and its port and starboard faces; for the containership the bulkhead was the forward container stack.

In this study we varied ship geometry, sea state, heading and speed. For each condition the LAMP-2 method was used to simulate the motions of the ship for thirty minutes of real time. Using the LAMP post-processing tool, LMPOST, the relative motions along the deck were measured to find cases in which sufficient submergences occurred. For these selected cases, the green water program was run. It simulated the incidence of water-on-deck, tracked its motion on deck, and measured the force on the discrete panels defining the surface. This normal force was integrated over all the panels – note that this force is integral of the local normal force, and for highly curved surfaces does not represent the magnitude of the total force. At each panel, a pressure was calculated by dividing force by the panel area.

It must be noted that even with some submergence, the green water calculation did not always find sufficient water-on-deck to generated significant pressures and forces, so the final results show some of the green water cases with no force or pressure results.

At each time step the pressure records were analyzed to find the largest pressure for all of the panels on each of the three surfaces. This peak pressure was then analyzed along with total force. Ideally the desire would be to characterize the pressure and force statistically in a manner sensitive to changes in geometry and operating conditions. Rigorous analysis requires that enough peak values of the process be found to plot a probability density function, then determine a representative mathematical distribution and find its parameters. In this limited study, no simulations with a long enough time record to carry out this analysis were generated.

The following analyses on each record of integrated normal force and peak pressure were completed:

1. Local Maxima were determined
2. The Maxima were sorted by magnitude
3. The Highest 33.33 % of magnitudes were averaged.

In practice, very few of the thirty-minute simulations generated sufficient peaks to find this average 1/3 highest value. Therefore it was decided to find the maximum of all the peaks and associated this value with the specified conditions. While this maximum value cannot represent the process statistically, it can be used anecdotally to illustrate the green water analysis process.

3 Definitions of Case Studies

3.1 Ship Geometries and Particulars

Three ships were nominated for this study, as follows:

- A USCG 378-ft. High Endurance Cutter
- A USN CG-47 Ticonderoga Class Guide Missile Cruiser
- A Nominal Large Container Ship

Figure 8 shows a photograph of the USCG C. Hamilton. In this analysis the forward deckhouse was modeled without the gun and the bow bulwarks. The geometry used in the LAMP and green water analysis is shown in Figure 9. Note that in the green water calculation the vertical surfaces – bulwarks and bulkheads – are defined parametrically and not via the panel model shown here. The geometry shown does closely match the parametric definition. The geometric particulars for this ship as modeled for the calculation are shown, along with those for the other two ships, in Table 1. Figure 10 shows a photograph of the US Navy CG47, USS Lake Champlain underway. Figure 11 shows the surface panelization used in the LAMP and green water calculations for this ship. Again, note that the bulwarks and the AEGIS forward bulkhead are defined parametrically to the green water code, and are not represented in the panelization. Figure 12 shows a shaded model of the nominal containership, showing the container stack and the bulwarks that were modeled in the calculation. Figure 13 shows the panelized geometry.

Table 1 Principal Particulars

Particular	Symbol	Units	378	CG47	Container
Wetted Surface Area	S	M^2	1522.2	3263.7	21219
Submerged Volume	V	M^3	3131	9160	180310
Longitudinal Center of Buoyancy	LCB	M	-55.81	-3.25	-11.32
Vertical Center of Buoyancy	VCB	M	-1.73	-2.73	-7.63
Waterplane Area	Awp	M^2	1041	2007	13480
Longitudinal Center of Flotation	LCF	M	-59.48	-12.41	-20.15
Longitudinal Metacentric Height	BML	M	229.27	333.22	565.86
Transverse Metacentric Height	BMT	M	3.38	3.84	11.91
Vertical Center of Gravity (input)	VCG	M	0.73	0.48	1.00
Longitudinal Metacentric Height	GML	M	226.81	330.01	557.23
Transverse Metacentric Height	GMT	M	0.92	0.63	3.28
Waterline Length	LWL	M	107.18	161.52	335.60
Waterline Maximum Beam	BWL	M	12.78	16.58	45.60
Maximum Draft	T	M	4.61	9.87	17.82
Overall Length	LOA	M	115.21	170.07	345.16
Maximum Beam	B	M	12.84	16.68	45.60

Figure 8 Photo of the USCG WHEC 378' Cutter Hamilton

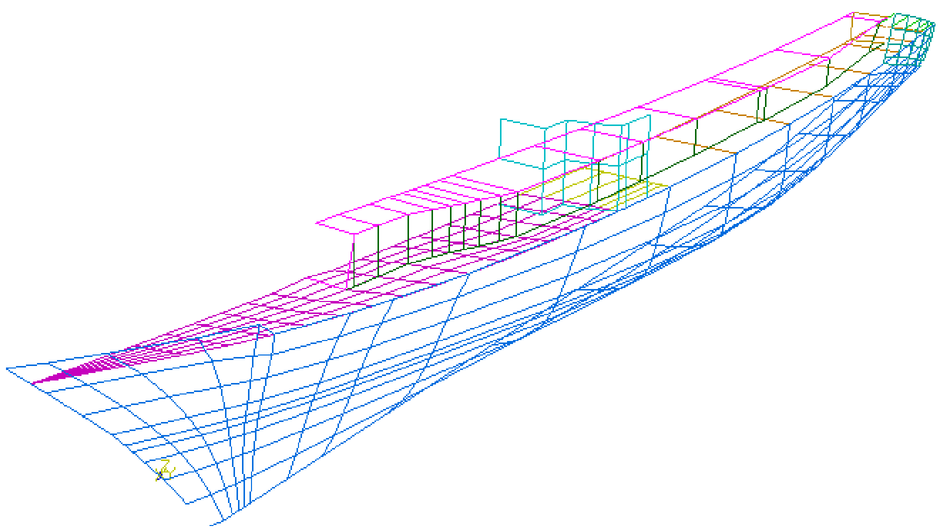


Figure 9 USCG 378 Panel Geometry for LAMP and Green Water Modeling

Figure 10 Photo of USN Ticonderoga-Class Guided Missile Cruiser Lake Champlain

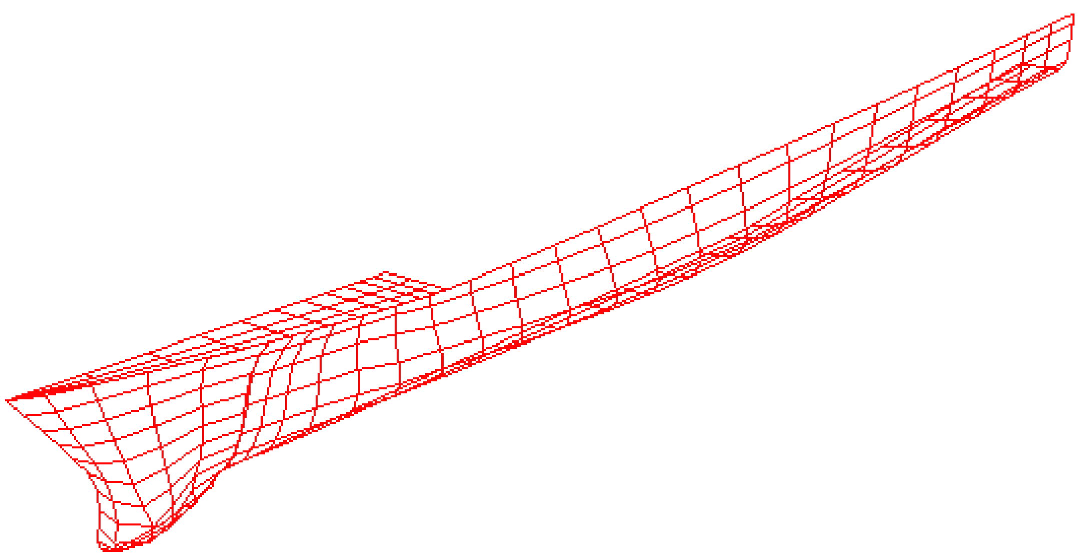


Figure 11 USN CG47 Panel Geometry for LAMP and Green Water Modeling

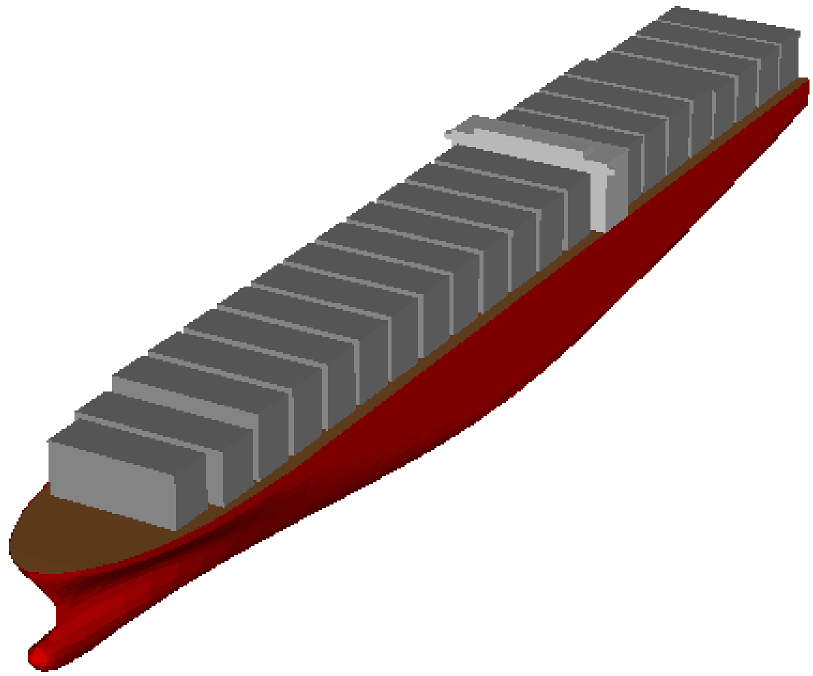


Figure 12 Containership Visualization Model

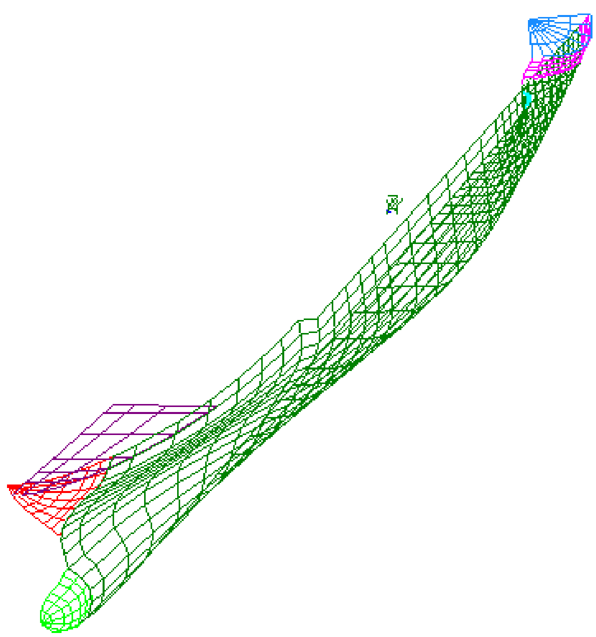


Figure 13 Containership Panel Geometry for LAMP and Green Water Modeling

3.2 Environmental Conditions

Each of the three ships was run in LAMP-2 for a set of 18 conditions, varying speed, heading, and sea state as defined in Table 2 where a heading of 180 degrees denotes the head sea condition. The sea states wave heights are defined by NATO standards for the "center" of the sea state range, as shown in Table 3. The modal periods were chosen as the closest integer value in seconds to the NATO standard. In the process of determining the cases, consideration was given both to using a consistent set for all three ships, and to obtaining a standard number of submergences. The container ship is much larger and has a much larger freeboard than the other two ships, so it was run in Sea States 7 and 8. The smaller ships were run in Sea States 6 and 7. In all cases the ships were run for 30 minutes, with a time step of 0.17 seconds, or 10,588 time steps. Once the motions calculations were complete, the submergences were counted at a set of points along the deck edge forward of the bulkhead. Cases in which the submergence rate was less than 10 in 30 minutes, or 20 per hour, were not further processed. Table 4 shows the submergence rates for each run. Bold text indicates which runs had sufficient submergences to warrant further analysis, no simulations were performed in light gray shaded regions, and dark gray shading indicates a simulation without sufficient submergences to warrant further analysis.

Table 2 Run Cases

Speed, Knots	Headings, Deg.	Sea States
10	180	5
15	165	6
18	150	7

Table 3 Sea State Definitions

Sea State	Significant Wave Height, feet	Modal Period, seconds
5	10.7	10
6	16.4	12
7	24.6	15
8	37.7	17

Table 4 LAMP Cases and Green Water Incidence

Speed, knots	Heading, Degrees	Sea State	Green Water Incidents		
			378	CG47	Container
10	150	6	1	1	
15	150	6	2	4	
18	150	6	**14**	3	
10	165	6	2	1	
15	165	6	**10**	1	
18	165	6	**22**	2	
10	180	6	2	0	
15	180	6	7	1	
18	180	6	**10**	2	
10	150	7	4	**15**	0
15	150	7	9	**19**	0
18	150	7	**12**	**44**	0
10	165	7	9	6	0
15	165	7	**18**	**18**	0
18	165	7	**28**	**16**	0
10	180	7	9	9	0
15	180	7	**27**	9	0
18	180	7	**34**	**20**	0
10	150	8			4
15	150	8			9
18	150	8			5
10	165	8			7
15	165	8			7
18	165	8			9
10	180	8			**10**
15	180	8			**10**
18	180	8			**13**

4 Results

4.1 Pressure and Loading on Foredeck Surfaces

As described in Section 2.5, the final result of the calculation is a maximum pressure and maximum force on a Deck, Bulwark and Bulkhead for each ship, for each condition. The force is the sum of the Normal Force, or the integration of the pressure, and the maximum is the largest value for all time steps. The pressure is the largest for any component panel of that surface for each time step of the calculation. The maxima are each for a thirty-minute simulation of the motions and green water.

In Table 5 the force is presented in Mega Newtons (Newtons * 10^6). In Table 6 the pressure is represented in standard atmospheres, (1.01 * 10^5 pascal). Note that this pressure does not include the atmospheric pressure.

Table 5 Maximum Force on Foredeck Surfaces

				FORCE, MN		
Ship	**Heading, Deg.**	**Speed, Knots**	**Sea State**	**Deck**	**Bulwark**	**Bulkhead**
378	150	18	6	0.000	-	-
378	150	18	7	-0.003	-	-
378	165	15	6	0.000	-	-
378	165	15	7	0.000	-	-
378	165	18	6	-0.098	0.044	-
378	165	18	7	-0.067	0.039	-
378	180	15	7	-0.271	-	-0.026
378	180	18	6	-0.417	-	-0.007
378	180	18	7	-0.473	-	-0.924
CG47	150	10	7	-0.240	2.469	-
CG47	150	15	7	-2.903	7.464	-
CG47	150	18	7	-6.066	19.851	0.000
CG47	165	15	7	-0.162	0.174	-
CG47	165	18	7	-5.893	11.301	-
CG47	180	18	7	-1.700	-	0.000
Container	180	10	8	-0.698	0.000	-
Container	180	15	8	-13.267	-0.023	0.000
Container	180	18	8	-19.322	-0.019	-0.002

(white)	378 Forward Bulkhead	(green)	Stbd Bulwark
(yellow)	378 House Side	(pink)	Port Bulwark
(orange)	378 Aft Bulkhead		

Table 6 Maximum Pressures on Foredeck Surfaces

Ship	Heading, Deg.	Speed, Knots	Sea State	PRESSURE, Atmospheres Deck	Bulwark	Bulkhead
378	150	18	6	-	-	-
378	150	18	7	-0.015	-	-
378	165	15	6	-	-	-
378	165	15	7	-	-	-
378	165	18	6	-0.126	0.183	-
378	165	18	7	-0.118	0.292	-
378	180	15	7	-0.309	-	-0.084
378	180	18	6	-0.500	-	-0.153
378	180	18	7	-0.386	-	-1.715
CG47	150	10	7	-0.152	4.173	-
CG47	150	15	7	-0.939	5.925	-
CG47	150	18	7	-0.992	15.603	-
CG47	165	15	7	-0.136	0.409	-
CG47	165	18	7	-1.089	2.783	-
CG47	180	18	7	-0.939	-	0.000
Container	180	10	8	-0.210	-0.003	-
Container	180	15	8	-0.995	-0.010	0.000
Container	180	18	8	-1.505	-0.016	-0.002

Legend	
378 Forward Bulkhead	Stbd Bulwark
378 House Side	Port Bulwark
378 Aft Bulkhead	

The largest pressure is about 16 atmospheres, for the CG47 bulwark in Sea State 7 at 150 degrees, or 30 degrees off the bow, and 18 knots. The pressure is composed of hydrostatic head, inertial load, and hydrodynamic pressure. It is useful to examine the relative magnitudes of the component pressures for this extreme case. At the time this large pressure was measured and the following data extracted:

1. Submergence (Relative Motion at the Location) =h= 4.5 m
2. Vertical Acceleration = a_z= 0.98 g's
3. Transverse Acceleration = a_y=1.25 g's

The hydrostatic pressure is then given as

$$rho*g*h = (1025\ kg/m^3)*(9.81 m/s^2)*4.5m\ /\ 1.01E5\ atm/(N/m^2) = 0.45\ atm$$

The inertial component of the pressure as

$$rho*g*\ (a_z\hat{}2+a_y\hat{}2)\hat{}1/2\ *\ h =$$
$$(1025\ kg/m^3)*(9.81 m/s^2)*(0.98^2+1.25^2)*4.5m\ /\ 1.01E5\ atm/(N/m^2) = 0.71\ atm$$

The remaining pressure is due to the hydrodynamic effects, and is

$$15.603 \text{ atm} - (0.45 \text{ atm} + 0.71 \text{ atm}) = 14.443 \text{ atm}$$

A good measure of the scale of this force is the velocity required to provide this dynamic head, where the pressure is ½*ρ*V^2. The velocity is then;

$$Vdyn = (2*P/\rho)^{½} = (2*14.44 \text{ atm} * (1.01E5 \text{ N/m}^2/\text{atm})/1025 \text{ kg/m}^3) = 53.35 \text{ m/s}$$

$$Vdyn / Vship = (53.35 \text{ m/s})/(18 \text{ knots} * 0.5148 \text{ m/knot*s}) = 5.76$$

This indicates the relative importance of the hydrodynamic solution in providing fluid velocity as well as depth of fluid.

We can observe an expected trend of increasing loads with speed for each ship. Interestingly, the USCG 378 had smaller loads than the larger USN CG47 in most cases. This may be due to larger deck accelerations on the CG47, but further analysis would be required to confirm this. The containership had very small loads relative to the other two (see Table 5 and Table 6) as it required very high seas to get water on the foredeck. The scope of this study (as discussed in Section 2.5) did not provide a sufficient number of peaks in the deck loads time history to characterize it statistically. The results can be viewed as anecdotal evidence of the performance of each ship in the specified conditions.

4.2 Structural Stresses on CG-47 Bulwark

A sample structural stress analysis was performed on an approximated bulwark section on the CG-47. The bulwark section, shown in Figure 14, is approximate in size and composition as there is significant variation along the longitudinal axis of the ship. The sample analysis is broken down into two separate calculations. The first calculation looks at the lateral pressure loading on the plate sections between the stiffeners. It is assumed that the plate is clamped on all sides. Following Hughes (1988), the plate stress σ is given by:

$$\sigma = kP(\tfrac{b}{t})^2$$

Where k is determined from the plate aspect ratio (Figure 9.6 in Hughes 1988), P is the lateral pressure on the plate, b is width of the short side of the plate, and t is the plate thickness.

The second calculation determines the stiffener stress from the same lateral pressure loading in the section. The stress is given as:

$$\sigma = \frac{-My}{I}$$

Where y is the maximum distance from the neutral axis of the stiffener cross section shown in

Figure 15, I is the section moment of inertia (pp. 287 Hughes, 1988), and M is the maximum moment on a clamped-clamped beam under uniform loading which is given by:

$$M = \tfrac{-1}{12} w l^2$$

Where w is the uniform loading per unit length and l is the length of the beam.

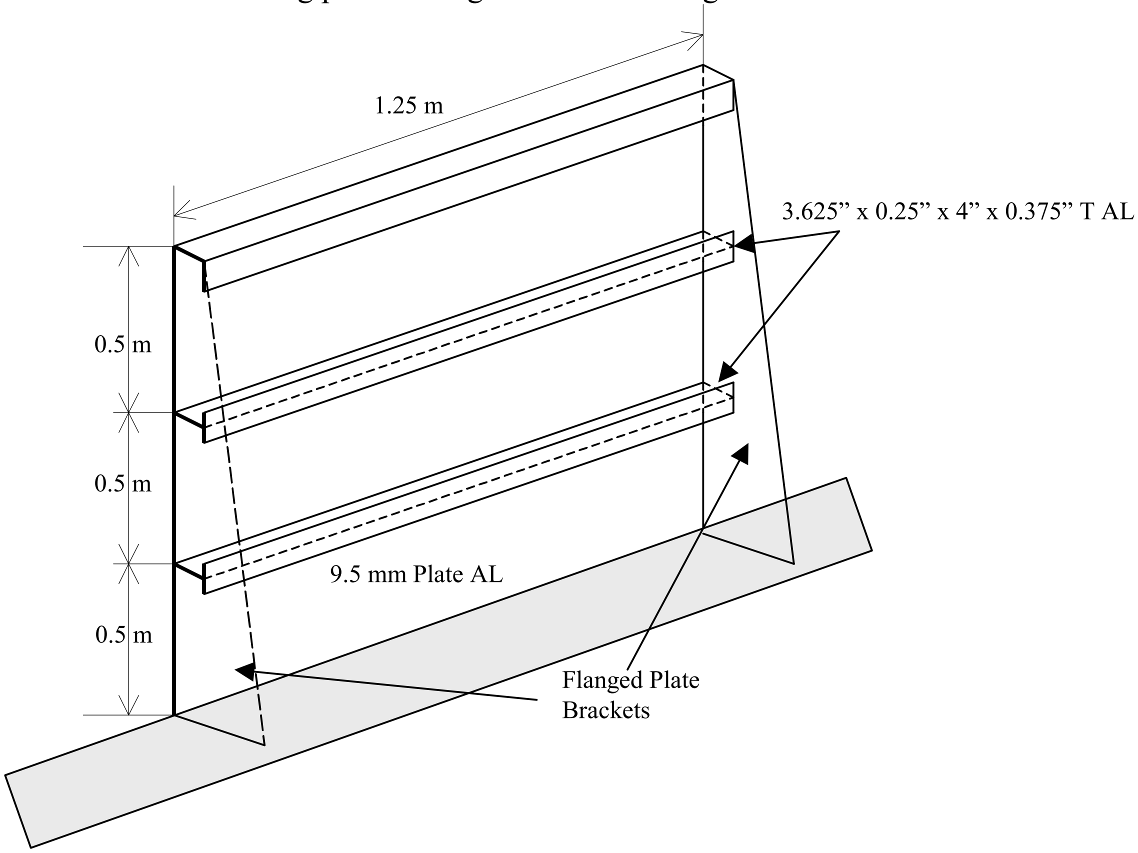


Figure 14 Sample Bulwark Section on CG-47

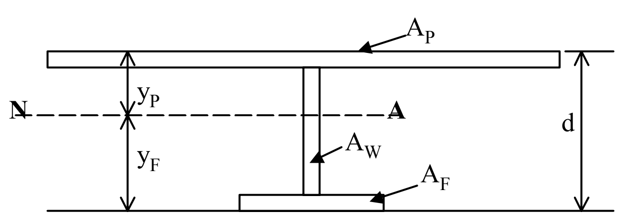


Figure 15 Cross Section of Beam Stiffened Panel

Results for the stress analysis in the plate and the stiffeners under the green water pressure loading for the CG-47 (see Table 6) are shown in Table 7. The type of Aluminum used in the actual bulwark is not specified in the presently available drawings so type AL 5383-H116 is assumed which has a yield stress of 220 MPa. The results in Table 7 show that there are several heading/speed combinations in sea state 7 where the plate stress and/or the stiffener stress exceed the assumed yield stress. This suggests that there may be significant structural damage in the bulwark as a result of the predicted pressure loading from the green water calculation. This finding correlates with damage reported on the CG-47 during large sea states when the shipping significant green water occurs.

Table 7 Stress in Sample CG-47 Bulwark Section

				Plate Analysis	Stiffener Analysis		
Heading, Deg.	**Speed, Knots**	**SS**	**Green Water Pressure, MN**	**σ_{Max}, MPa**	**M_{max}, MN-m**	**σ_{Max}, MPa Using y_f**	**σ_{Max}, MPa Using y_p**
150	15	7	0.421	**584**	-0.027	**253**	74
150	18	7	0.598	**829**	-0.039	**360**	105
165	15	7	1.576	**2183**	-0.103	**947**	**275**
165	18	7	0.041	57	-0.003	25	7
180	18	7	0.281	**389**	-0.018	169	49

Note: Stresses in bold type exceed the yield stress for Aluminum 5383-H116 (σ_{yield} = 220Mpa)

5 Conclusions and Recommendations

This study was intended to show the capability of the combined LAMP and green water analysis for examining the green water loads on deck structures. The study was also intended to determine if green seas loading, as modeled, is sufficient to result in damaged structure as indicated by real world cases. As described in Section 3, the analysis is based on a comprehensive set of calculations for 3 ships in a wide variety of conditions. The results show expected trends in speed, sea state and ship size for the magnitude of loads and pressures.

The calculations showed expected reasonable scale in pressure, as shown by Table 6. The pressures are shown scaled by standard atmospheric pressure, and the maximum value is about 16 atmospheres. A breakdown of the components of pressures shows the hydrodynamics contribution to be predominant for this particular condition.

As discussed in Section 2.5, the scope of the calculation performed for this study did not provide sufficient data to statistically characterize the green water pressures and forces. A sufficient series to generate a stationary process in the peaks of the pressures and forces is required. Some changes to the formulation can be made to make much longer calculations more easily and make this further calculation practical.

The containership did not show large amounts of green water on deck. Other studies have shown ships of this form to be potentially subject to the parametric roll phenomenon. Under the proper conditions, synchronous roll and pitch can produce very large relative motions at the bow, shipping green water and providing very large local accelerations. A study combining parametric roll and green water deck loads is recommended.

The sample structural stress analysis for the CG-47 (discussed in section 4.2) shows that the predicted green water pressure loading induces stresses in both the plate and the stiffeners that are larger than the yield stress of the aluminum bulwark. This finding correlates with damage reported on the CG-47 during large sea states when the shipping significant green water occurs.

We note again that the current green water calculation has no viscous effects and no impact or jet effects. It cannot therefore calculate the very highest local impact pressures, which are important in many actual ship structural damage cases. The current formulation is a practical foundation for extensions to include nonlinear free-surface effects important to the deck loads problem. We recommend the development of a hybrid method that uses the shallow water formulation when possible and implements a nonlinear water-on-deck model when necessary.

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