SSC-208

SLAMMING OF SHIPS: A CRITICAL REVIEW OF THE CURRENT STATE OF KNOWLEDGE

This document has been approved for public release and sale; its distribution is unlimited.

SHIP STRUCTURE COMMITTEE

1970

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

UNITED STATES COAST GUARD
NAVAL SHIP SYSTEMS COMMAND
MILITARY SEA TRANSPORTATION SERVICE
MARITIME ADMINISTRATION
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C. 20591

1970

Dear Sir:

To assure the utility of data accumulated in a project that will measure strain caused by a ship's bow leaving and reentering the water, called "slamming," a critical review of existing knowledge and, hence, development areas required, was undertaken.

Herewith, is a report containing the review.

Sincerely,

W.F. Rea, III
RADM, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-208

Technical Report

to the

Ship Structure Committee

on

Project SR-172, "Slamming Studies"

SLAMMING OF SHIPS:
A CRITICAL REVIEW OF THE CURRENT STATE OF KNOWLEDGE

by

J. R. Henry and F. C. Bailey

Teledyne Materials Research
Waltham, Massachusetts

under

Department of the Navy
Contracts: NObs 94252
N00024-67-C-5312
N00024-69-C-5231

U.S. Coast Guard Headquarters
Washington, D.C.

1970

ABSTRACT

This critical review of the current status of the knowledge of bottom slamming phenomena was undertaken to assure that maximum value will be gleaned from recorded data obtained on the *SS Wolverine State*. The review covers experimental laboratory and ship data and their correlation with available theory; statistical considerations in slamming and in the ocean environment; and structural implications and possible design improvements. Although there are certain areas in the theory which require expansion, the most pressing need is for additional full-scale experimental data to provide confirmation of existing analytical techniques.

CONTENTS

SHIP STRUCTURE COMMITTEE

The SHIP STRUCTURE COMMITTEE is constituted to prosecute a research program to improve the hull structures of ships by an extension of knowledge pertaining to design, materials and methods of fabrication.

RADM W. F. Rea, III, USCG, Chairman
Chief, Office of Merchant Marine Safety
U. S. Coast Guard Headquarters

Capt. W. R. Riblett, USN
Head, Ship Engineering Division
Naval Ship Engineering Center

Capt. T. J. Banvard, USN
Maintenance and Repair Officer
Military Sealift Command

Mr. E. S. Dillon
Deputy Chief
Office of Ship Construction
Maritime Administration

Mr. C. J. L. Schoefer, Vice President
American Bureau of Shipping

SHIP STRUCTURE SUBCOMMITTEE

The SHIP STRUCTURE SUBCOMMITTEE acts for the Ship Structure Committee on technical matters by providing technical coordination for the determination of goals and objectives of the program, and by evaluating and interpreting the results in terms of ship structural design, construction and operation.

NAVAL SHIP ENGINEERING CENTER

Mr. J. B. O'Brien - Acting Chairman
Mr. J. B. O'Brien - Contract Administrator
Mr. G. Sorkin - Member
Mr. H. S. Sayre - Alternate
Mr. I. Fioriti - Alternate

MARITIME ADMINISTRATION

Mr. F. Dashnaw - Member
Mr. A. Maillar - Member
Mr. R. Falls - Alternate
Mr. W. G. Frederick - Alternate

AMERICAN BUREAU OF SHIPPING

Mr. S. G. Stiansen - Member
Mr. F. J. Crum - Member

OFFICE OF NAVAL RESEARCH

Mr. J. M. Crowley - Member
Dr. W. G. Rauch - Alternate

NAVAL SHIP RESEARCH & DEVELOPMENT CENTER

Mr. A. B. Stavovy - Alternate

MILITARY SEALIFT COMMAND

Mr. R. R. Askren - Member
Lt. J. G. T. E. Koster, USN - Member

U. S. COAST GUARD

LCDR C. S. Loosmore, USCG - Secretary
CDR C. R. Thompson, USCG - Member
LCDR J. W. Kime, USCG - Alternate
Capt. L. A. Colucciello, USCG - Alternate

NATIONAL ACADEMY OF SCIENCES

Mr. A. R. Lytle, Liaison
Mr. R. W. Rumke, Liaison
Prof. R. A. Yagle, Liaison

SOCIETY OF NAVAL ARCHITECTS & MARINE ENGINEERS

Mr. T. M. Buermann, Liaison

AMERICAN IRON AND STEEL INSTITUTE

Dr. J. R. LeCron, Liaison

BRITISH NAVY STAFF

Dr. V. Flint, Liaison

WELDING RESEARCH COUNCIL

Mr. K. H. Koopmen, Liaison
Mr. C. Larson, Liaison

I. INTRODUCTION

Bottom slamming has been recognized for many years as a source of damage to ships. The phenomenon results when the ship's bow emerges from the water and subsequently submerges at an attitude such that the angle between the bottom plates and water is small. This action produces large forces for short-time durations. The impulses so generated can cause vibratory motion of the entire ship to the extent that ships' masters intuitively reduce the forward speed and/or change the ship's heading resulting in an undesirable change in schedule. Minor or occasionally moderate slamming has been known to cause local buckling and plastic deformations in bottom plates in the forefoot region of the ship. These deformations increase the maintenance costs because of additional drydocking charges necessary to make repairs following the more severe cases of slamming. Hard slamming produces large impulses that set the entire ship into vibratory motions which persist for up to one minute. In summary, slamming can generate large bending stresses in the hull girders, deformations in bottom plates and bulkheads, damage to cargo, and loss or damage to shipboard equipment.

Much information has been collected on slamming effects on ships and the statistical motion of irregular seas. These data have had little or no impact on the design of future ships to withstand heavy, irregular seas with moderate to severe slamming. In the early stages of design, only rigid body motion is investigated and verified by model tests for regular sea conditions. The flexibility of the hull must be taken into account when it is subjected to irregular seas resulting in slamming. It is not sufficient to use the statistical maximum slamming load as a static force in the design of the hull.

Under Ship Structure Committee Project SR-172, "Slamming Studies," Teledyne Materials Research has installed instrumentation aboard the SS WOLVERINE STATE to measure the following: (1) slamming pressures on the forward bottom, (2) vertical accelerations, and (3) midship stresses. The purpose of this installation is to collect data which will assist in predicting the incidence of slamming and the resulting gross response of the vessel. In order to assure that maximum value will be gleaned from the recorded data, this critical review of the current status of the knowledge of bottom slamming phenomena was undertaken. This report summarizes the review and presents recommendations for future studies.

It is recognized that slamming can be induced by sudden bow flare immersion as well as bottom impact. Even though some of the theoretical and experimental work to be cited is applicable to both mechanisms, the report will be directed principally at bottom impact slamming, which is the mechanism most commonly encountered in merchant ships.

II. EXPERIMENTAL DATA

Because of the several random variables involved in both wave motion and wave-induced motion of ships, it is necessary to acquire actual data from shipboard measurements. From these data, one can establish the extent to which the responses can be described by theories of probability. If the data indicate that normal laws of probability hold true, then many parameters can be calculated which would have design implications.

This section contains a review of typical shipboard measurements (Section A) and laboratory model tests (Section B) that establish the significant parameters affecting slamming.

A. Ship Data

Several attempts to measure slamming effects on ships are described in the literature. Various pressure gages, accelerometers, and strain gages were placed throughout the ship to record external pressures on the hull, accelerations related to bow pitching and heaving forces, and bending strains of sections of the forefoot and mid-section. A typical example of these types of measurements is shown in Figure II-1. These data were acquired from the seakeeping trials of three Dutch destroyers [1], [2].* Note the flat portions in the pressure transducer records. These flat portions indicate that the bow has lifted completely out of the water and that the gages are sensing atmospheric pressure. At the ends of these flat portions, the sharp discontinuity in pressure results from a slam. In this particular test, the response of the pressure transducers is reasonably high. The carrier frequency in the amplifiers gives reliable pressure readings up to approximately 4000 Hz. It is interesting to observe that the accelerometer and stress recordings show a persistent vibratory response as described by Szebehely and Todd [3], occurring with negligible attenuation. Also, the pitch angle exhibits a divergence which is probably due to the apparent wave frequency approaching the ship's pitch-heave resonance.

Bledsoe, Bussemaker, and Cummins [2] published a report on the data taken from the same Dutch destroyer trials and showed a high-speed recording oscillograph trace of a single slam. Figure II-2, taken from their report, shows rather clearly a high frequency pressure fluctuation of approximately 300 Hz occurring after initiation of the slam. The initial pressure rise appears to be a step function response and could contain frequencies well above 1000 Hz. This report indicates the existence of pressures as high as 100 psi and of the order of .020 second duration. The rise time from Figures II-2 would appear to be only a fraction of a millisecond. The pressure decay is either constant or logarithmic in form with a very high frequency superimposed on it.

Greenspon [4] reports on pressure pulses recorded during the sea trials of the USCGC UNIMAK. The frequency response of both the transducer and signal conditioning system was linear to 500 Hz. The pressure gages, 2-6, are shown in Figures II-3 to II-5. Gages 3, 4, 5, and 6 were in a plane perpendicular to the keel with gage 3 near the keel and gage 6 at the turn of the bilge. Gage 2 was located forward of this plane and gage 8 is aft of this plane. Again, the pressure pulse has a duration of approximately .010 to .020 seconds, reaching peak amplitudes of 100 psi to 300 psi. From these curves it appears that a precursor wave develops before the main sharp-fronted pressure pulse arrives at the transducer. Because of the sharpness of the wave front, it is questionable whether the acquisition system was capable of recording the initial peak pressure. It is interesting to note that the relative angle between the keel and the wave surface could be estimated from these data. In Figure II-5, this angle could be obtained from the initiation times between pressure sensors 2 and 3; also, an estimate of the velocity could be obtained from integrating the output of the accelerometer, gage 9, in the vicinity of gages 2 and 3. The same approach could be used to compute the relative roll angle between gages 3 and 4. Greenspon's conclusion that high pressures are felt by

* Numbers in brackets refer to references listed after Section IX.

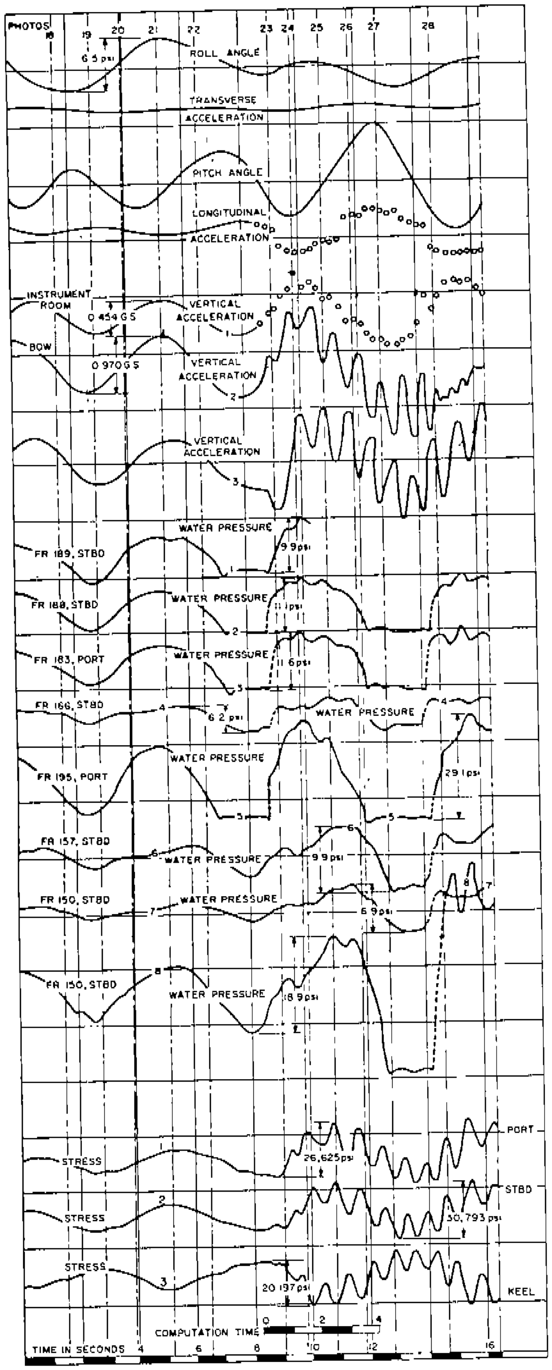


Fig. II-1. Experimental Data Acquired From Seakeeping Trials of Three Dutch Destroyers[1]

Water Pressure

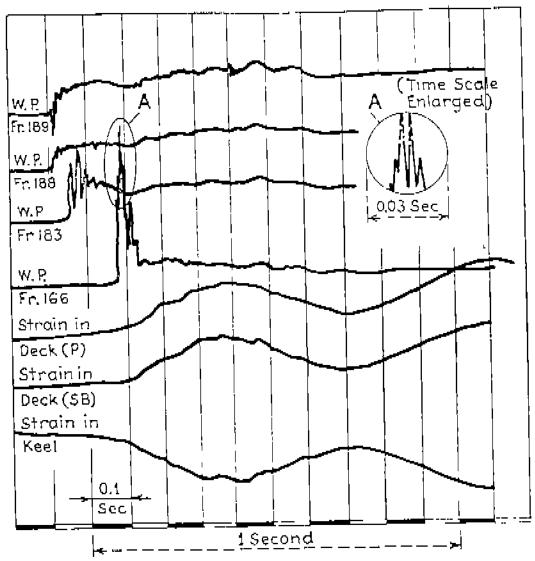


Fig. II-2. Sample of High Speed Slam[2]

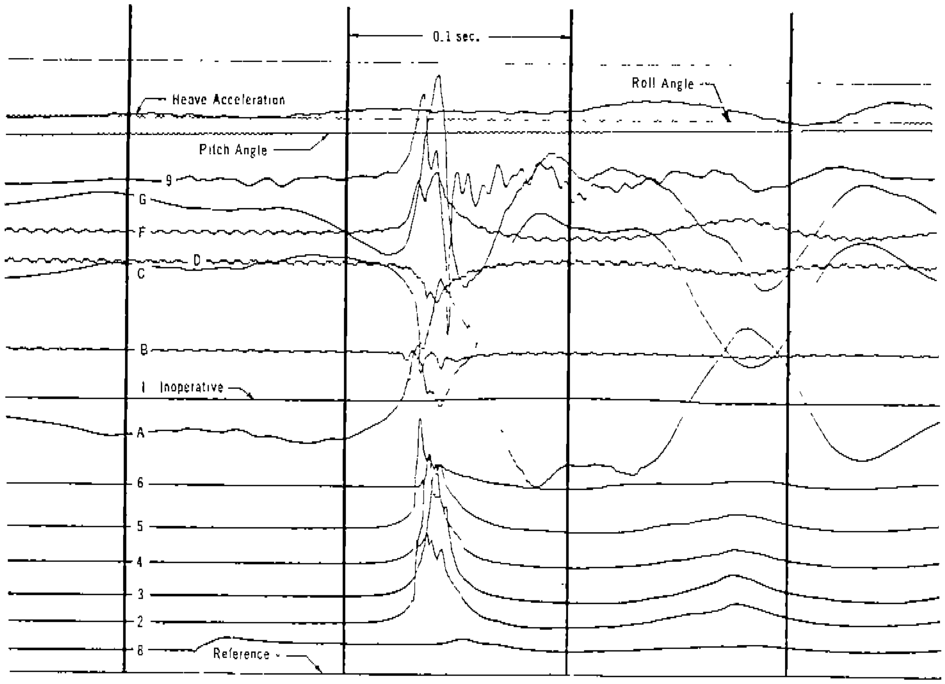


Fig. II-3. Record 4064, UNIMAK[4]

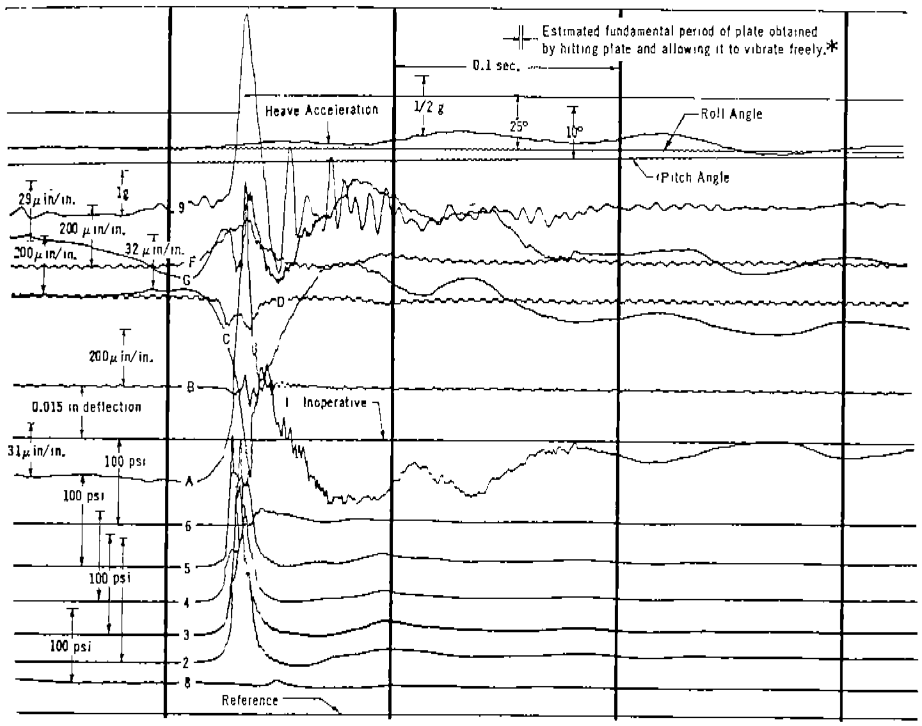


Fig. II-4. Record 4098, UNIMAK[4] (Ordinate Scales Apply to Figs II-3 & II-5)

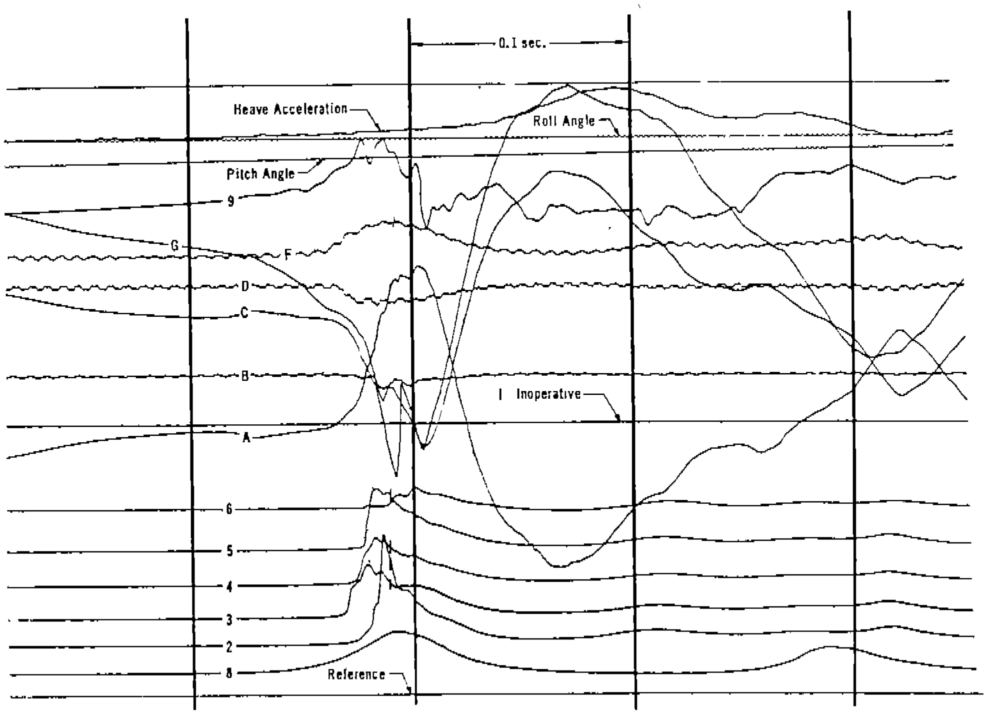


Fig. II-5. Record 4104B, UNIMAK[4]

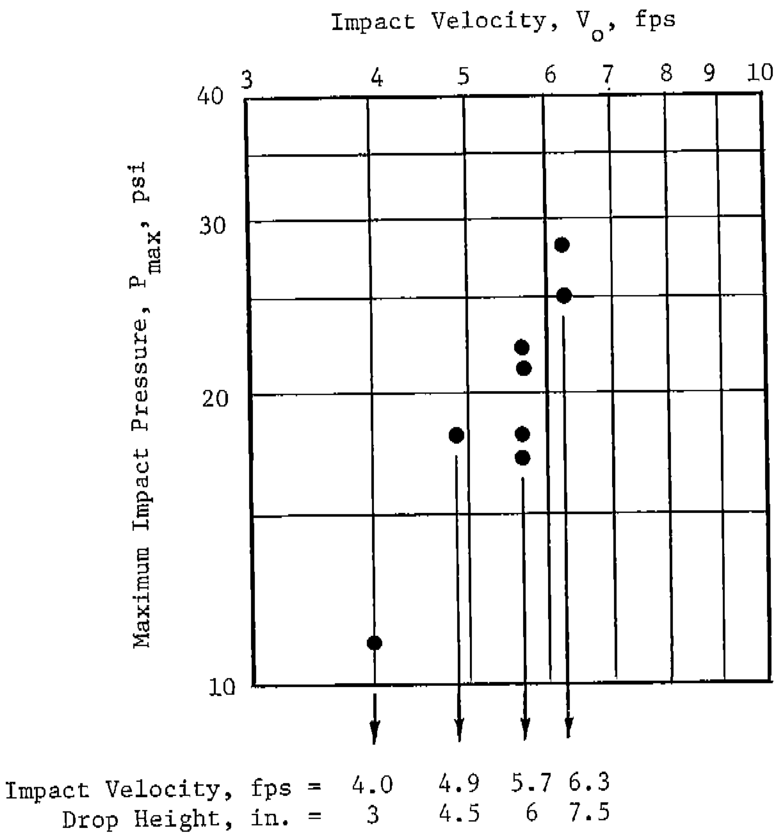


Fig. II-6. Sheng-Lun Chuang's Test Results[5] relatively limited areas of the bottom plates at any one time seems reasonable. However, he should qualify the assumption that the response of the bottom plates is essentially static because the duration of the pressure pulse is much longer than the period of the lowest plate bending mode. Since the pressure rise time is relatively short, one should always consider the possibility of the lower plate bending modes being excited by the higher harmonics in the pulse. In the present case, the energy content of these harmonics would probably be quite small.

B. Laboratory Test Data

In March 1966, Sheng-Lun Chuang [5] performed drop tests on a flat plate. The purpose of these tests was to establish if the acoustic pressure, $p = \mu c V$ could be obtained or whether the air between the flat plate and water was acting as a cushioning device. He indicated that his recording system had a flat response to 200 KHz, which was adequate for detecting the acoustic wave. The results of his tests are shown in Figure II-6. The data indicate that the maximum pressure was nowhere near the acoustic pressure. It is unfortunate that higher-velocity impacts were not used to compare with actual ship slamming velocities of the order of 12 to 25 ft/sec. He concluded that the presence of air between the falling body and the water surface does substantially reduce the pressure in comparison to the expected $p = \mu c V$. He indicated that pressure rise time is increased due to the entrapped air, and a nonhomogeneous air-water mixture is formed which would also reduce the acoustic pressure. He states that these conclusions might not hold for high-velocity impacts, and the scaling laws which apply to this type of impact have to be determined and verified. Also, from the high speed underwater photographs it is not apparent whether this nonhomogeneous air-water mixture is produced by air entrapment or by cavitation.

Ochi and Schwartz [6] performed some very comprehensive two-dimensional drop tests on V-Forms, UV-Forms (Mariner), and U-Forms. They measured pressure-time histories at the keel and at various half breadths. They also measured velocity versus time, wetted width as a function of time, and rigid body deceleration. Unfortunately, their overall instrumentation system response was only 1200 Hz for the piezoelectric pressure gages located at the keel and 600 Hz for all other pressure transducers. They quoted rise times of .0007 seconds for the piezoelectric gages and 0.001 seconds rise time on the other diaphragm-type pressure gages. Because of the low frequency response, these numbers are questionable. They show a general trend of highest peak pressure for the U-Forms and lowest for the V-Forms. There appears to be some inconsistency when one estimates the impulse from their velocity-time histories and compares these impulse values with their calculated impulse-versus-time plots. Also, the velocity of impact was lower than what is usually experienced in actual ship slamming. For these reasons, the results cannot be scaled in an attempt to find forces and pressures on ships. The authors concluded that the most significant forces were evident in the first instant of water contact. However, present theories in this time regime are not accurate. Peak pressure was found to be approximately proportional to the square of the velocity.

Verhagen [7] in December 1967, reported impact data of a flat plate which was in general agreement with Chuang [5]. However, he concluded that if the peak pressure occurs in the time interval $\Delta \tau = \frac{\ell}{c_a}$, (where c_a is the sound velocity in air and ℓ is the half breadth of the plate), then the compressibility of the air may be neglected. When the time to develop significant pressures is small or approaching $\frac{\ell}{c_e}$ (where c_e is the sound velocity in water), then the time-dependent term in the wave equation cannot be neglected. Compressibility of the water and possibly the elasticity of the structure have to be considered.

In September 1967, Sheng-Lun Chuang [8], reported drop test data on a wedge with varying dead-rise angle. In a similar fashion, as with his flat plate tests [5], he had very low impact velocities and recommended that analytical theories consider compressibility of entrapped air. He showed underwater, high-speed photographs which indicated that above a 3° dead-rise angle, no air was entrapped. He made the observation that the impulse pressure at the keel has a time duration of .05 milliseconds, and he concludes that the impulse pressure is not important and should be ignored in the design of ship bottoms. The impulse occurred at the beginning of the impact pressure record. It is worth noting that if the pressure duration is .05 milliseconds, then the pulse characteristic is made up of frequencies of 10,000 Hz and higher. Present day shipboard measuring systems do not usually have the high frequency response required to measure this short-duration pulse. Furthermore, local high pressures of short duration can produce dynamic elastic-plastic buckling of bottom plates and, if present, should definitely be considered in their design.

Lewison and Maclean [9], reported drop test data on flat plates of large areas and mass. The purpose of this series was to perform a more realistic test simulating the actual ship slamming phenomenon and to evaluate the consideration of a compressible layer of air. The frequency response of their data acquisition system was flat only to 1000 Hz. Therefore, initial high-pressure, short-time-duration pulses may not have been recorded. They found that as the mass of the plate and plate stiffness increased, the peak pressure also increased; but, with any one mass, the peak pressure varied as the square of the velocity.

Ochi [19] measured keel pressures on a 1/40 scale model of a MARINER cargo ship under conditions which generated slamming. His data fit the relationship

$$p = .086\, V^2$$

which, as will be noted in a later section, bears an interesting similarity to the expressions which best describe drop test results.

Many other investigators performed similar experiments. They concluded essentially that air entrapment tends to reduce the peak pressure during a slam as compared to the calculated acoustic pressure. Based on laboratory and full-scale test data obtained to date, it appears that:

1. The pulse width during a slam varies from a small fraction of a millisecond (0.05 ms.) to 20 or 30 milliseconds.
2. The peak pressures of significant slams ranged from 300 psi to 1000 psi.
3. The pressure rise times measured are in the range of fifty to several hundred microseconds depending on the frequency response characteristic of the recording equipment.
4. Results of laboratory drop tests cannot be scaled for analytical application to full-scale ships.
5. In all these tests, both full-scale and laboratory, a damaged forefoot or test panel was not demonstrated.

III. THEORIES

Attempts have been made to explain analytically the mechanism whereby a large pressure is developed as a result of a blunted or flat body entering a water surface. These analyses fall into three general categories: (1) expanding wedge theories;

(2) compressible flow theory; and (3) consideration of a compressible finite air density between the impacting body and the fluid medium.

A. Expanding Wedge

Von Karman's original work, [10], considered a rigid wedge having a small wedge angle crossing over a fluid boundary. For small angles of β, (See Figure III-1.), he assumed the wedge was equivalent to a flat plate of width b moving in an infinite laminar medium. If irrotational flow of an incompressible fluid is assumed, the added (or apparent) mass due to an energy transfer to the fluid particles is $\frac{\pi}{4}\mu b^2$ [11]. Since the added mass is related to the velocity potential, ϕ, according to

$$m = \frac{2T}{V^2} = \frac{\mu}{V^2}\iint_S \phi \frac{\partial \phi}{\partial n} dS \tag{1}$$

the surface integral around the entire plate has no value for the surface of the plate above the fluid boundary. The reason for this is that in the case of a flat plate moving in a fluid medium, particles of the fluid in front of the plate as well as behind the plate are given added momentum. However, a flat plate just entering the fluid medium will transfer momentum to the fluid particles in front of the plate only, since the plate is not fully immersed in the fluid. Therefore, the added mass becomes one half the value in the usual flat plate problem:

$$m = \frac{\pi}{8}\mu b^2 = \frac{\pi \mu r^2}{2} \tag{2}$$

Wagner's linearized theory [12] considers the pile-up of water at the free surface as shown in Figure III-1. By taking the potential of an inclined plate [13], subjected to sudden movement in an infinite medium and by utilizing the

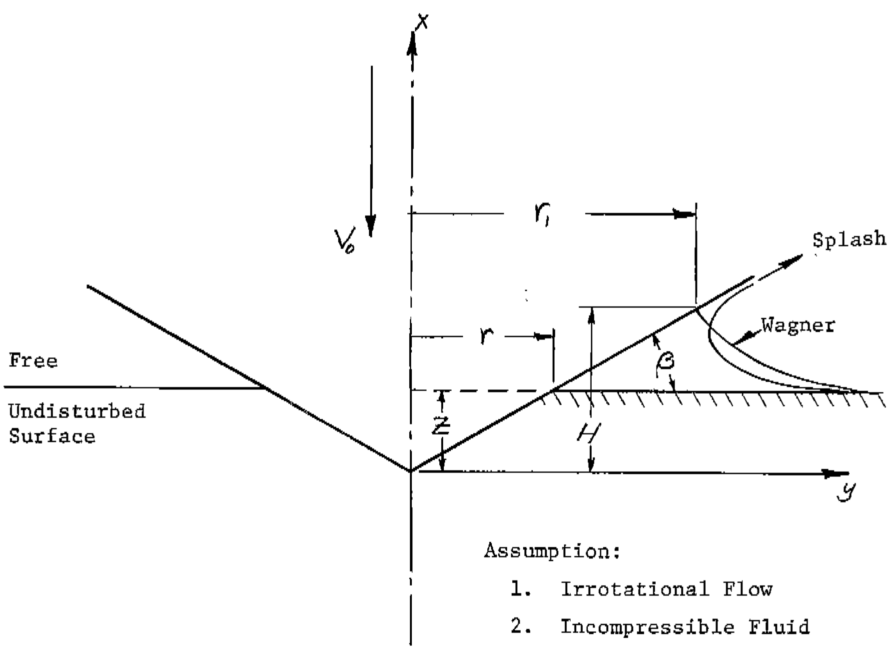


Fig. III-1. Wedge Entry Into Fluid Medium linearized free surface boundary conditions, he obtains a normal particle velocity distribution along the unknown surface. By a time integration of this distribution and a power series expansion of H and $\frac{dv}{dr_1}$ in y and r_1, respectively, he was able to compute the instantaneous height of the free surface as a function of time and distance y. When Wagner used r_1 for the half breadth of the flat plate, the added mass was $\frac{\pi^2}{4}$ times that of Von Karman's.

Many investigators have since used Wagner's approach of "fitting" and correcting the free surface shape, with questionable results. One notable approach was performed by Hillman [14]. He assumes a polynomial trial fit to the free surface and a polynomial for the potential. Using the "continuity condition," the "arc-length condition," other geometric considerations, and the integral equations for the potential on the free surface at several appropriate points, he is able to solve for the coefficient in the polynomials and readjust the surface shape such that all conditions are satisfied within a specified accuracy. This type of approach, with high speed computers, seems to offer some hope for analyzing arbitrary shapes.

In all of these theories, as the dead-rise angle, β , tends towards zero, the pressure becomes infinite. For example, in Wagner's solutions, the average pressure is,

$$\left(p_{ave}\right)_{max.} \simeq \frac{3V_0^2}{\beta} \tag{3}$$

The greatest single criticism of these theories is the neglect of the effects of compressibility of both air and water.

B. Compressibility Considerations

Von Karman noted a singularity in his approach as the dead-rise angle tends toward zero. He placed a finite band on the pressures by assuming the particle velocity at the water surface instantaneously acquired the body velocity, V, of the wedge, thereby producing the sonic pressure,

$$p = \mu c V \tag{4}$$

To include compressibility effects of the water, Trilling [15] linearized the continuity equation and Bernoulli's equation.

$$\nabla \cdot q = \nabla^2 \phi \simeq \frac{1}{\mu c^2} \cdot \frac{\partial p}{\partial t} \quad , \tag{5}$$

$$p \simeq -\mu \frac{\partial \phi}{\partial t} \quad , \tag{6}$$

$$\nabla^2 \phi = \frac{1}{c^2} \cdot \frac{\partial^2 \phi}{\partial t^2} \; , \quad \text{(wave equation)} \tag{7}$$

With the appropriate free surface linearized boundary conditions, the solution for the upward force is

$$P = 2r_1(\mu c V)\left\{1 - \frac{ct}{2r_1}\right\} \tag{8}$$

For small values of ct, equation (8) reduces to the limiting case of Von Karman. Equation (8) also indicates that pressure and force go to zero when $ct = 2r_1$. A conceptual view of this rapid decrease in pressure is that initially the μcV pressure is developed due to the sudden velocity rise of the surface water particles. At the two ends of the plate of finite length, a rarefaction wave develops and moves toward the center of the plate as the compressive wave propagates downward at the sonic velocity, since c is usually orders of magnitude greater than V.

In summary, the singularity for incompressible flow theory that appears for a blunt-body can be bounded by the sonic pressure developed at the instant of water impact.

C. Air Density

One important consideration that has been left out of most theoretical approaches to the slamming problem is the compressibility of the air. The significant feature of this air-cushioning effect is that the compressed air between the hull and the water brings the velocity of the water particles on the surface up to the hull velocity by a relatively gradual process. This mechanism eliminates the abrupt velocity change when considering a compressible fluid with no air cushion.

Lewison and Maclean [9], recently published an analysis of the two-dimensional compressible flow of the air-cushioning effect. Their mathematical model is shown in Figure III-2 where the air gap is $w(z, t) = y(z, t) - x(t)$. They assume that the air is an ideal gas, and with the continuity, momentum, and energy relation, they are able to compute the pressure on the body and added mass as a function of time. A typical plot of pressure versus time is shown in Figure III-3, where b is the initial air gap in feet and t_o is the time at which the calculation is started. For such an outwardly simple approach, they obtained exceptionally good results.

IV. THEORETICAL AND EXPERIMENTAL CORRELATION

Since most ships have a relatively flat forefoot, it is essential to determine the comparison between the actual pressure and the sonic pressure $\mu c V$. Chuang's experimental data [5] do not correlate with the sonic pressure that would be developed if no air were present for low drop velocities. The maximum pressures he measured were more than three orders of magnitude less than the calculated sonic pressures. If one considers the very high-response recording equipment Chuang used in his experiments, it is quite apparent that for an inatmospheric flat body water impact, the maximum pressure cannot be calculated using wave theory. From previous Model Basin data, he finds that the maximum pressure is

$$p_{max.} = 4.5\,V \tag{9}$$

This relationship is shown in Figure IV-1 as compared with other identifiable data in reference [5] and with Ochi's result [19].

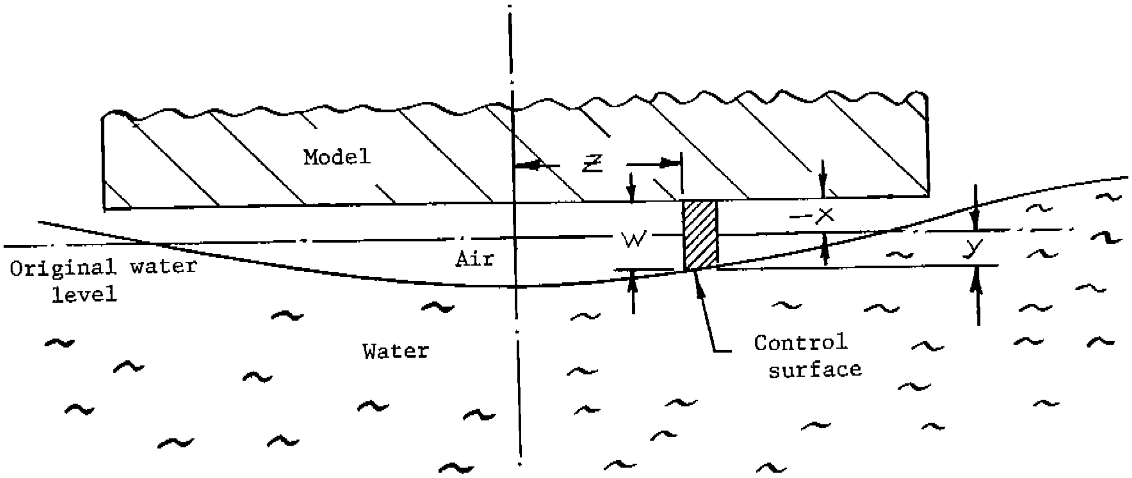


Fig. III-2. Impact Model and Control Surface[9]

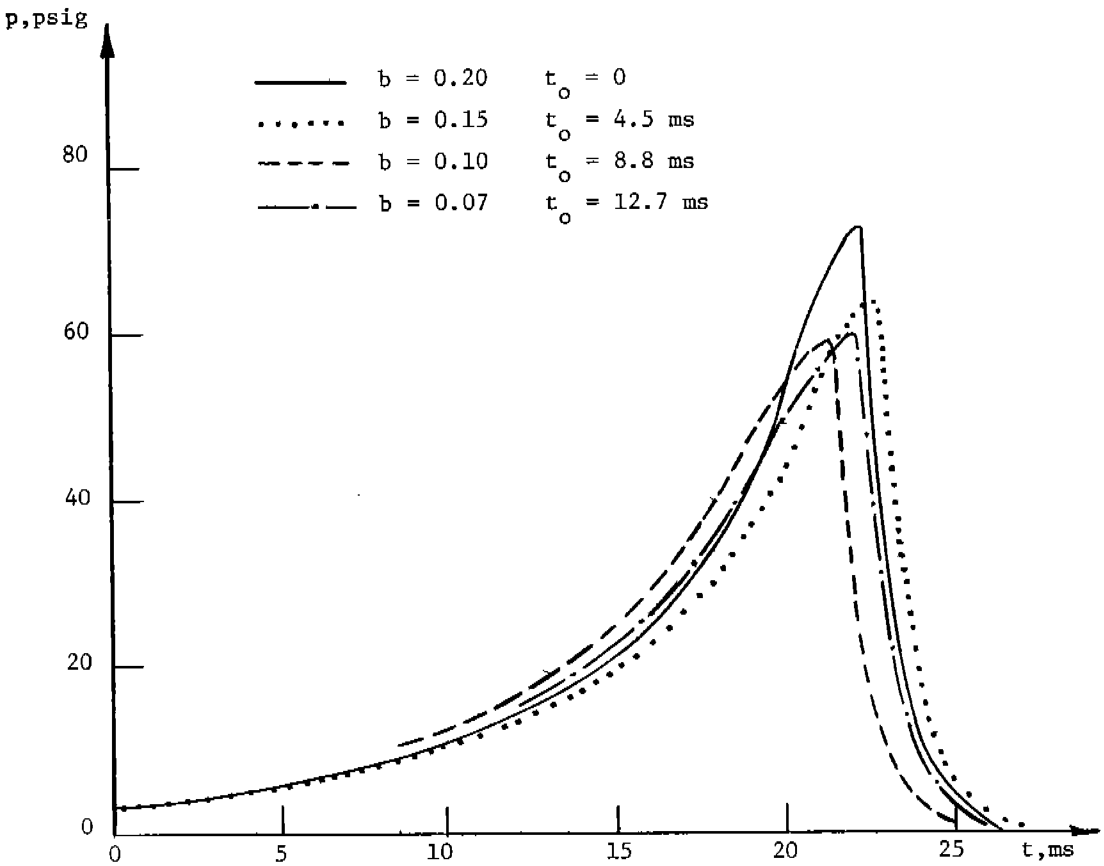


Fig. III-3. Pressure Versus Time at the Centerline of the Model[9]

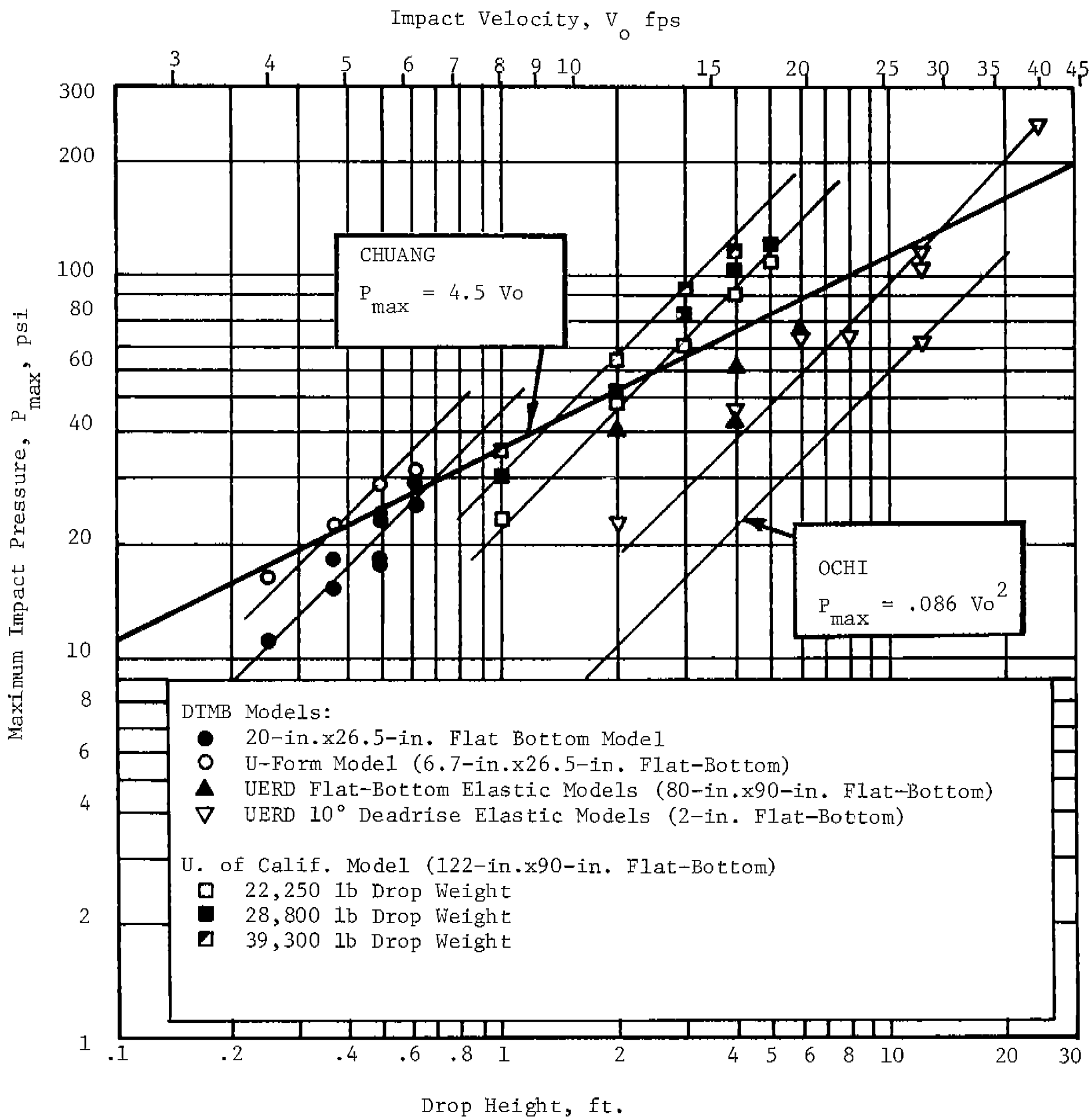


Fig. IV-1. Comparison of Test Data

An evaluation of each specific group of data in Figure IV-1 indicates that a square-law relationship

$$p_{max.} = (Const.)\, V^2$$

is more appropriate, as shown by the lines drawn in the figure with a slope of 2. This type of expression would bring the flat plate data more into line with the low angle wedge data presented in Figure IV-2. Ochi's data in Figure IV-1 illustrate the commonly observed reduction in slamming pressure as the real situation is more closely simulated.

The flat plate drop test data of Verhagen [7] as compared to his two-dimensional compressible flow theory shows excellent correlation for small values of entry body mass, $\left(\frac{M}{\mu \ell^2} = .5\right)$. However, his maximum pressure calculations do not compare very well with Chuang's data [5], $\left(\frac{M}{\mu \ell^2} = 2\right)$. Therefore, one is led to believe that no correlation could be expected for hull impacts, where $\frac{M}{\mu \ell^2} \gg 1$.

The wedge drop-test pressure data obtained by Chuang [8] compared reasonably well with Wagner's and Von Karman's wedge-impact theories [12], [10], as shown in Figure IV-2. The data indicate that the maximum pressure can be predicted analytically for dead-rise angles above three degrees. He also shows a large difference between theory and experiment for a one degree dead-rise angle, pointing out the air-cushioning effect.

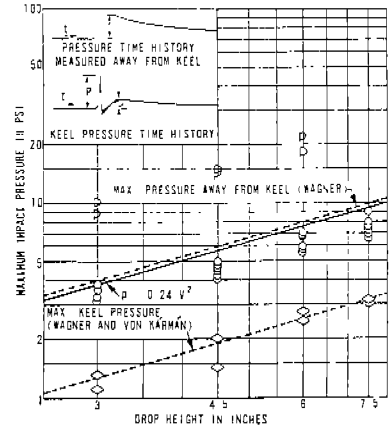
The data of Ochi and Bledsoe [16] indicated close agreement with the theory [3] that the highest pressures after initial impact occur in the spray-root. They also found that the added mass was reasonably close to $\frac{\pi}{2} \mu\, r^2$, for U, U-V, and V-form hulls.

The most striking correlation between experiment and theory was demonstrated by Lewison and Maclean [9]. By assuming a compressible air layer and an incompressible fluid, they were able to obtain very close agreement between experimental and analytical results as shown in Figure IV-3. They predict that the compressed air tends to decelerate the impacting body while accelerating the surface particles of the water in a downward direction. The relative velocity between the impacting body and the water surface would tend, therefore, to be reduced. They also introduce the concept of "coalescences" between the compressed air and water. As the pressure increases, the air is dissolved in the water over a finite time interval. They did not observe the high pressures predicted by Ogilvie's theory, [17]. Some evidence of this concept was presumed to take place in Ochi's and Chuang's experiments [6], [5]. However, the question of the presence of cavitation is still unresolved.

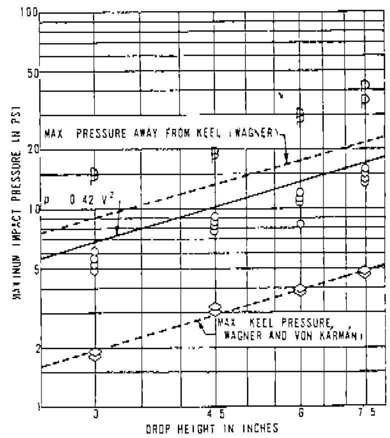
In summary, the designer has two methods for conservatively estimating the loading on the hull bottom plates. For equivalent dead-rise angles over three degrees, Wagner's theory [12] gives reasonable results, and for less than three degrees, Lewison and Maclean's approach [9] should be taken.

V. STATISTICAL APPROACH TO SLAMMING

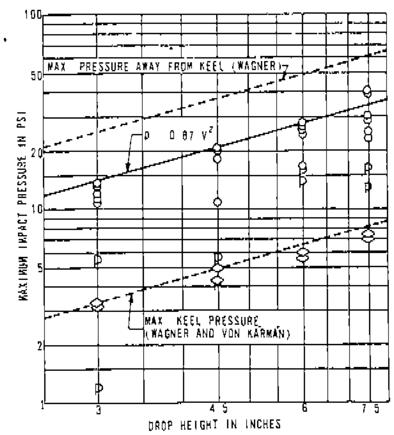
The previous section was concerned with the analysis of the single impact of a fixed geometry in a static water surface. Since the motion of the sea surface is statistical in nature, ship motions are also statistical. Therefore, since slamming depends on both of these, it is reasonable to expect that slamming has



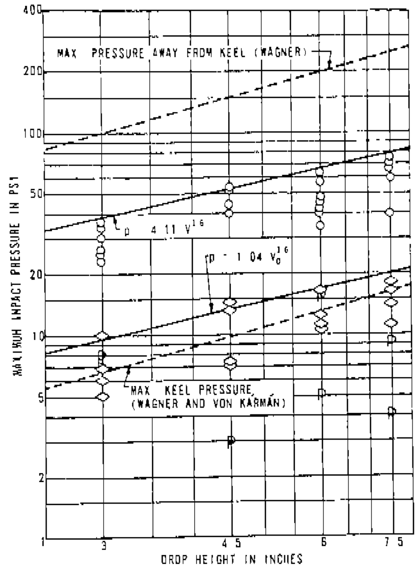
(*a*) Model with 15-deg deadrise angle



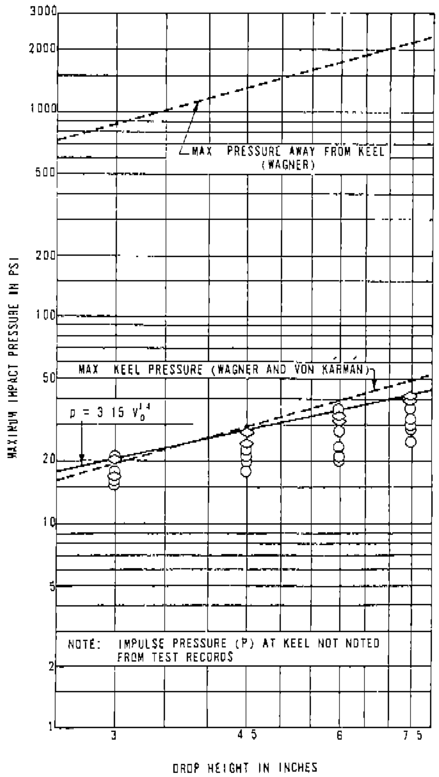
(*b*) Model with 10-deg deadrise angle



(*c*) Model with 6-deg deadrise angle



(*d*) Model with 3-deg deadrise angle



(*e*) Model with 1-deg deadrise angle

Fig. IV-2. Experimental Results of Rigid Wedge-Shaped Models[8]

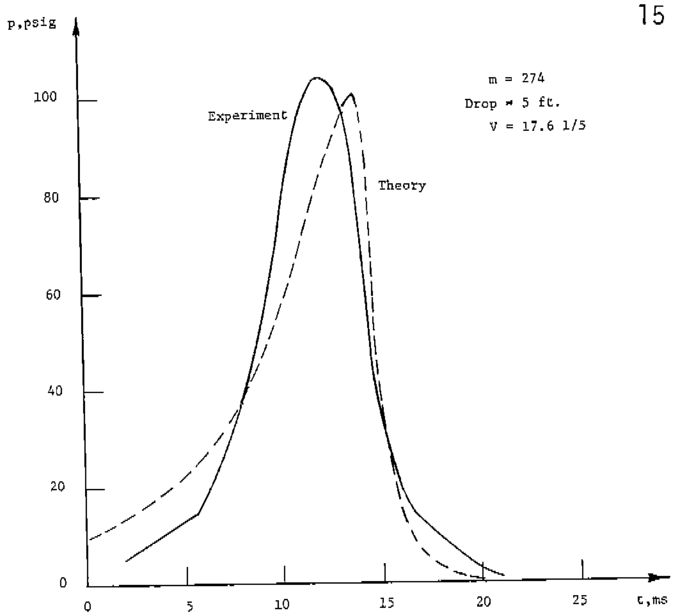


Fig. IV-3. Pressure-Time Curves by Two-Dimensional Theory[9]

some statistical basis; hence, a new dimension to the problem is introduced.

It is important for the designer to have some estimate of the frequency of slamming and the statistical averages and deviations of the pressure magnitudes as a result of irregular sea states. Having this information allows him to design the essential main load-carrying members and bottom plates to sustain the loading conditions for the design speed of the ship for a given sea state.

It is the purpose of this section to cite the assumptions that are made in these analyses and the variables, correlated and uncorrelated, that are considered. There are two outstanding papers published on the statistical characteristics of slamming. One is by L.J. Tick [18], 1958, and the other by M.K. Ochi [19], 1964.

Tick's approach is to obtain the joint probability density function for the occurrence of a slam. He then integrates this function between the limits of the variables and arrives at the expected number of slams per second.

He first assumes the Pierson model [20] for long-crested waves to describe the surface motion as being made up of the sum of a large number of independent random processes. In this case, he assumes that these independent sources of disturbance consist of an infinite sum of sines and cosines where the amplitudes are uncorrelated and their frequencies and phase angles are unspecified in time. The spectrum of wave elevation can thus be computed. With the coupled equations of motion developed by Korvin-Kroukovsky and Jacobs [21], [22], the steady-state solution is obtained. Since this is a system of linear equations of motion, the pitch and heave response spectra are obtained by [23],

$$S_z(\omega) = \text{HEAVE SPECTRUM} = T_{z\eta}^2\, S_\eta(\omega)$$

$$S_\theta(\omega) = \text{PITCH SPECTRUM} = T_{\theta\eta}^2\, S_\eta(\omega)$$

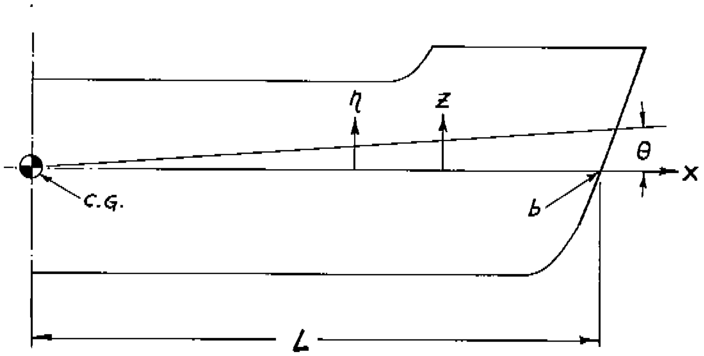


Fig. V-1. Coordinate System

where Z and θ are the heave and pitch motion of the center of gravity. The submergence is defined as

where $T_{z\eta}$ and $T_{\theta\eta}$ are the amplitude operators and $S_{\eta}(\omega)$ is the sea elevation spectrum.

He then computes the bow submergence and emergence variance starting with the following relation (Figure V-1),

$$Z_b(t) = Z(t) + L\,\theta(t) \;, \tag{10}$$

$$\zeta(t) = \eta_b(t) - Z_b(t) \;, \tag{11}$$

where η is the surface elevation of the sea. Since η is made up of a linear combination of Gaussian processes, then η will also be a Gaussian process. Therefore, assuming a zero mean, one computes the autocorrelation function, power spectral density function, and finally the variance, σ_ζ^2 . This procedure has to be done for all variances and covariances of the variables to be considered in the probability analysis.

The general slamming criteria he uses are (1) forefoot emergence, (2) relative velocity between keel and water surface and (3) relative angle, ϕ between the keel and the surface of the wave. More precisely, he states that to produce a slam the following conditions have to be met.

$$\zeta = \eta - Z = -K \quad \text{(vessel draft)}$$

$$\dot{\zeta} > v_0 > 0$$

$$|\phi| \geq \phi_0 \;,$$

where v_0 and ϕ_0 are critical values above which slamming is possible. Note that K , the vessel draft, is implicitly included in the expressions defining the limiting conditions. The joint probability density function (third order), having zero means, is

$$p(\zeta, \dot{\zeta}, \phi) = \frac{Exp\{\ \}}{\sqrt{8\pi^3}\;\sigma_\zeta\;\sigma_{\dot{\zeta}}\;\sigma_\theta\sqrt{1-\gamma_{\dot{\zeta}\phi}^2-\gamma_{\phi\zeta}^2}} \;,$$

$$Exp\left\{-\frac{1}{2(1-\gamma_{\dot{\zeta}\phi}^2-\gamma_{\phi\zeta}^2)}\left[\frac{(1-\gamma_{\dot{\zeta}\phi}^2)}{\sigma_\zeta^2}\zeta^2+\frac{\gamma_{\phi\zeta}\,\gamma_{\dot{\zeta}\phi}}{\sigma_\zeta\,\sigma_{\dot{\zeta}}}\zeta\dot{\zeta}-\frac{\gamma_{\phi\zeta}}{\sigma_\zeta\,\sigma_\phi}\zeta\phi\right.\right.$$

$$+\frac{\gamma_{\varsigma\phi}\,\gamma_{\dot{\varsigma}\phi}}{\sigma_{\varsigma}\,\sigma_{\dot{\varsigma}}}\varsigma\dot{\varsigma} + \frac{(1-\gamma_{\varsigma\phi}^2)}{\sigma_{\dot{\varsigma}}^2}\dot{\varsigma}^2 - \frac{\gamma_{\phi\dot{\varsigma}}}{\sigma_{\dot{\varsigma}}\,\sigma_{\phi}}\dot{\varsigma}\phi - \frac{\gamma_{\varsigma\phi}}{\sigma_{\varsigma}\,\sigma_{\phi}}\varsigma\phi$$

$$-\frac{\gamma_{\dot{\varsigma}\phi}}{\sigma_{\dot{\varsigma}}\,\sigma_{\phi}}\dot{\varsigma}\phi + \frac{1}{\sigma_{\phi}^2}\phi^2\Big]\Big\} \qquad (12)$$

where σ and γ are defined as the standard deviations and correlation coefficients, respectively [23].

Tick proceeds to integrate equation (12) and presents the very general form of f_s, (slams per second). In order to make a comparison with experimental data, he assumes the process in ς and $\dot{\varsigma}$ to be stationary, Gaussian, and uncorrelated. Equation (12) now becomes a second order probability density function in ς and $\dot{\varsigma}$ with the remaining correlation coefficients equal to zero. Completing his integration in the similar manner for the general case, he expresses the frequency of slamming by the following form:

$$f_s = \frac{1}{2\pi}\left(\frac{\sigma_{\dot{\varsigma}}}{\sigma_{\varsigma}}\right) e^{-\frac{1}{2}\left\{\frac{K^2}{\sigma_{\varsigma}^2} + \frac{v_o^2}{\sigma_{\dot{\varsigma}}^2}\right\}} \qquad (13)$$

It was necessary for him to do this because the experimental data [24] gave estimates of the first two conditions of slamming; namely, bow emergence and that a critical velocity v_o is a condition of slamming. A large amount of data have been acquired to substantiate the conclusion that a critical velocity is a condition of slamming. It appears that the experimental data indicated this. Sharp pressure increases were obtained by Lewison and Maclean [9] and Chuang [5] in laboratory experiments at low velocity impacts. Other investigators have also observed that slamming can take place on board ship without any of the usual characteristic effects present such as whipping. Of equal, if not more, importance is the relative angle between the keel or bottom plates and the surface of the water at time of impact. The importance of this angle was brought forth in Sections II and III of this report. If equation (12) is reduced to a usable form and if ϕ is retained as a random variable, it is evident that Tick's implicit assumptions are justified; i.e., that the random processes of ς , $\dot{\varsigma}$ and ϕ are stationary, Gaussian, and uncorrelated. Therefore, equation (12) becomes

$$p(\varsigma,\dot{\varsigma},\phi) = \frac{1}{\sqrt{8\pi^3}\,\sigma_{\varsigma}\,\sigma_{\dot{\varsigma}}\,\sigma_{\phi}}\cdot \mathrm{Exp}\left\{-\frac{1}{2}\left[\frac{\varsigma^2}{\sigma_{\varsigma}^2} + \frac{\dot{\varsigma}^2}{\sigma_{\dot{\varsigma}}^2} + \frac{\phi^2}{\sigma_{\phi}^2}\right]\right\} \qquad (14)$$

If equation (14) is integrated [25] between the appropriate limits of the variables ς , $\dot{\varsigma}$ and ϕ, the frequency of slamming becomes

$$f_s = \frac{1}{\sqrt{2\pi^3}}\left(\frac{\sigma_{\dot{\varsigma}}}{\sigma_{\varsigma}}\right)\left(\frac{\phi_o}{\sigma_{\phi}}\right) e^{-\frac{1}{2}\left\{\frac{K^2}{\sigma_{\varsigma}^2} + \frac{v_o^2}{\sigma_{\dot{\varsigma}}^2}\right\}} \qquad (15)$$

If the asymptotic expansion of $P\left(\frac{\phi_o}{\sigma_\phi}\right)$ for $\left(\frac{\phi_o}{\sigma_\phi}\right) > 0$ is used, [26], equation (15) takes the form

$$f_s = \frac{1}{\sqrt{2\pi^3}}\left(\frac{\sigma_{\dot\rho}}{\sigma_\rho}\right)\left(\frac{\phi_o}{\sigma_\phi}\right) e^{-\frac{1}{2}\left\{\frac{K^2}{\sigma_\rho^2} + \frac{v_o^2}{\sigma_{\dot\rho}^2} + \frac{\phi_o^2}{\sigma_\phi^2}\right\}} \tag{16}$$

If we assume that $\frac{\phi_o}{\sigma_\phi}$ = 0.1 in equation (16), then the frequency of slamming that Tick computed would be equal to 0.047. This value is reasonably close to the experimental data (0.05 slams per second) that he used [24].

Although Tick did an excellent job of describing mathematically the statistical characteristic of slamming beginning with Pierson's [20] model of the sea spectrum, he realizes certain inadequacies of his theoretical approach. One significant failure is the inability to account for the nonlinear motion of the ship during emergence and the nonlinear transients during submergence. Also the assumptions that go into describing the sea spectrum have not been fully explored. The significant parameters and values thereof should exhibit reasonable correlation with test data to be meaningful for theoretical applications and impact on future designs of ships.

Ochi, in his approach, assumes that for all practical purposes the variables ρ and $\dot\rho$ are Gaussian, random variables with a narrow-band frequency distribution. He immediately accepts the first two criteria of Tick as definitive of the occurrence of a slam, (i.e., $\rho = -K, \dot\rho \geq v_o \geq 0$). He points out that smallness of the keel-line angle with respect to the sea surface is reflected in his concept of a threshold velocity. He presents experimental data from ship model tests as evidence of the existence of a threshold velocity as a prerequisite for slamming.

His proposition that the two pertinent variables are narrow-band Gaussian leads to the conclusion that a possibility for slam exists once per cycle of expected frequency,

$$f_s = \frac{1}{2\pi}\left(\frac{\sigma_{\dot\rho}}{\sigma_\rho}\right) \tag{17}$$

and that the probability for a slam in one of these cycles is

$$P\left(\frac{\text{ONE SLAM}}{\text{CYCLE}}\right) = \mathrm{Exp}\left\{-\frac{1}{2}\left[\frac{K^2}{\sigma_\rho^2} + \frac{\dot\rho_o^2}{\sigma_{\dot\rho}^2}\right]\right\} \tag{18}$$

Thus, the expected number of slams per unit of time is merely the product of equations (17) and (18), which leads directly to Tick's result, equation (13).

Since there is evidence to support the thesis that the maximum slamming pressure is directly proportional to the square of the relative velocity at impact [9], he then proceeds to find the probability density function for the relative velocities at impact and develops an expression that gives the expected distribution of the maximum pressures to be encountered in slamming. That is, he gives an expression for what fraction of the maximum recorded pressures might lie above some value p_o. This expression is

$$P(p > p_o) = Exp\left\{-\frac{1}{4C\sigma_{\dot{\zeta}}^2}\left(p_o - p_*\right)\right\} \tag{19}$$

where C is the constant of proportionality between the pressure and the square of the relative velocity, and p_* is the impact pressure resulting from the threshold velocity.

This pressure statistic is now carried one step further. He derives an expression for the average value of the 1/mth highest pressures. If a set of n pressures measured on a slamming ship are ordered, the top 1/mth of these can be expected to have pressures equal to or greater than

$$p_{1/m} = p_* + 4C\sigma_{\dot{\zeta}}^2 \ln(m) \tag{20}$$

Further, Ochi computes the average value of these pressures to be given by

$$\bar{p}_{1/m} = 2C\left\{v_o^2 + 2\sigma_{\dot{\zeta}}^2\left(1 + \ln(m)\right)\right\} \tag{21}$$

which becomes, for m equaling 3 and 10,

$$\bar{p}_{1/3} = 2C\left\{v_o^2 + 4.2\,\sigma_{\dot{\zeta}}^2\right\} \tag{22}$$

$$\bar{p}_{1/10} = 2C\left\{v_o^2 + 6.61\,\sigma_{\dot{\zeta}}^2\right\} \tag{23}$$

It would seem that these types of statistics could be of value from the design point of view. For experimental data, one could integrate similarly the distribution functions and write an expression for the number of slams in which the pressures exceed some triggering value to which the recording instrumentation could be set. Ochi presents graphs of data which substantiate these predictions quite reasonably. In his final section on slam statistics, he develops a criterion for predicting the time interval between successive slams. The argument rests on an assumption that the time interval between successive slams is a random variable [27] whose distribution can be approximated by a Poisson distribution. He then develops formulas for the probability of the time interval between successive slams and finally for the time interval between successive severe slams. He presents experimental evidence that supports the theoretical results.

In the realm of statistical analysis of slamming many fundamental questions arise that are not answered in the literature. It should be determined if the occurrence of slamming is weakly stationary or actually nonstationary. There are three random variables:

1. Relative displacement between the ship's keel and the sea surface.
2. Relative velocity.
3. Relative angle between the keel and the tangent to the sea surface.

These variables should be scrutinized very carefully as to the nature of their spectral densities, cross spectral and covariance correlation coefficients. These statistical characteristics should be evaluated before one can assume that these variables are stationary, ergodic, Gaussian, and uncorrelated.

VI. STATISTICAL APPROACH TO WAVE CHARACTERISTICS

Wave motion, an integral part of the analytical approach to slamming, deserves special treatment here. Its importance is related to the computed values of the variance and the standard deviation of the relative motion between the ship and the waves. Given the wave spectrum and the response amplitude operators of the ship in regular waves at various frequencies, one can compute the heave and pitch response spectra. The relative response can then be statistically computed and ultimately used in the analysis of the occurrence of slamming.

Longuet-Higgins, in 1952 [28], assumed that waves were generated by statistically independent, uncorrelated sources of nearly the same frequency, but phased in a random fashion. Assuming a Rayleigh frequency distribution which is suitable when the spectrum is narrow-band, he was able to compute the probability distribution and the statistical averages of the wave height. Many assumptions must be justified for this approach to be valid. The significant consideration is that the wind-generated waves are produced by one storm. The effects of other storm centers and local winds are assumed to be negligible, and independent source contributions to the wave-height within a storm are linear and can be superimposed. This assumption is not reasonable for large waves because wave height becomes a nonlinear function of wind velocity. He computes ratios of the average heights of the highest 10% and 30% of the wave heights to the average height of all the waves and obtains very good correlation with previously accumulated sea data. He does not, however, attempt to establish whether or not these collected wave data confirm his basic assumptions. One of the fundamental approaches is to examine the autocorrelograms to establish the underlying nature of the source. Since these are wind-generated waves, the statistical properties of the local and source wind-velocities should be investigated for the existence of coherence, and cross correlation with the wave height parameters.

In 1953, St. Denis and Pierson [29] published an analysis of the rigid body motion of a ship in a confused sea. Based on Lamb's [13] hydrodynamic description of the propagation of a surface disturbance, they assumed for small wave heights that the seaway elevation is of the following form:

$$Z(t) \cong \sum_{n=0}^{\infty} \sqrt{S(\omega)\cdot\Delta\omega}\; \cos(\omega_n t + \alpha) \tag{24}$$

where $S(\omega)$ is the power spectral density of the wave height and the quantity under the square root is the average wave height associated with ω_n . This equation says that the wave height is comprised of the contributions of many independent uncorrelated sources of various amplitudes and a randomly varying phase angle α .

They also assume that the probability of Z at any particular time being equal to or less than certain values is based on the Gaussian probability law. To obtain the wave height of each component, they assumed a Neumann spectrum [30] for a fully-developed sea as a function of wind velocity, U .

$$S(\omega) = \frac{C}{\omega^6} e^{-\frac{2g^2}{U^2\omega^2}} \tag{25}$$

where C is a constant based on experimental data and g is the gravity constant. By randomly choosing values of α , they are now in a position to describe completely the wave height for any sea state. They examine the shortcomings of these assumptions and attempt to explain departures from theory. Nonlinear effects at large wave heights will produce significant differences, and winds above certain velocities and of short duration will not produce fully developed seas. St. Denis and Pierson did an excellent job of taking existing theories (verified or not) and developing an approach to analyze the rigid body response of a ship subjected to wave motion. Many investigators [31, 32, 33] have since utilized, corrected, refined, and expanded this same approach resulting in reasonable-to-questionable correlation with actual data. Pierson's comments on Cartwrights and Rydill's paper [34] which uses this theory cautiously advises that this theory has not been fully verified. Even Michel's review of sea spectra analysis [35] indicates that all these theories generate unexplained differences. Michel selects Bretschneider's formulation [36] because it is an easy form to use.

As mentioned previously in this section, further effort should be made to investigate the basic fundamentals of the statistical relations leading to the formulation of sea spectra. By doing so, a better understanding of this random process may explain the differences between the various theories advanced and test data.

VII. STRUCTURAL IMPLICATIONS

Slamming can produce transient local loading of sufficient magnitude to cause serious damage to the ship. The nature of this damage is characterized by Church [37]. Briefly, the damage is logically divided into two areas of concern: 1) damage brought about by high-intensity local forces, 2) damage due to gross hull structure response. Response due to the high-pressure and short-time-duration pulse can produce local plate bending deformations in the nonlinear plastic range. If the time duration is short enough, the inertia of the plate and its initial imperfections must be considered in the problem of elastic-plastic instability. Otherwise, the stress analyses are quasi-static. The overall response of the ship as a free-free beam is an initial boundary valued problem. The stresses in the hull girder due to this first flexural mode can be much greater than the normal operating stresses. Serious damage can be avoided by reducing speed at the first indication that slamming is producing this mode of vibration.

A. Local Failure Analysis

Greenspon [4] performed an analysis of the bottom plating of the USCGC UNIMAK subjected to slamming. His forcing function was the actual pressure measurement, examples of which are shown in Figures II-2 through II-5. He assumed that the forcing function spectrum involved much lower frequencies than the first plate bending mode; therefore, he was able to treat the solution as a statically loaded, uniform pressure case with reasonably good correlation with strain gage data.

His assumption that the loading is static may be questionable in light of the very fast rise times. It is possible that there is an instability problem, rather than a stress problem. He assumes a classical small deflection flat plate solution, but the photographs in reference [4] indicate some cylindrical curvature. If this is the case, his solution is definitely not adequate, and the methods developed by Roth and Klosner [38] on the nonlinear response of cylindrical shells would be applicable. Also, finite element techniques as applied by Witmer, Balmer, Leech, and Pian [39] to the elastic-plastic solutions of beams, rings, and plates subjected to impulsive loading are applicable to ship structures.

B. Ship Flexural Modes

The application of linear dynamic vibration analysis as applied to ship slamming was presented in 1957 by McGoldrick [40]. He utilized a lumped parameter technique by assuming the ship structure to be made up of discrete masses and springs. In the calculation of the springs, he accounts for transverse shear energy, and in his equation of motion he includes rotary inertia. He then solves the coupled equations by a finite difference method. His piece-wise rectangular approximation to a continuously varying (in time) forcing function is poor because at each step approximation, transients of all frequencies will be generated obscuring the true response.

Leibowitz [1] applied the same approach as McGoldrick [40] in the analysis of the hull girder stresses on the Dutch destroyers, except that he deduced his forcing function from the measured rigid body motion data during the sea-keeping trials. He computed the slamming force from wedge theory and included the added mass. He solved the equations of motion by an implicit finite difference formula. If one ignores the phase shift, he obtained very good correlation with the measured keel stress. It would have been of interest to see the acceleration response at stations closer to the bow section. Generally, when a structure is subjected to impulsive loading at a point, the response decreases as a logarithmic function of the distance from the loading point.

These types of analyses are reasonably good for computing the overall response of the ship, but usually for a complex structure the detailed load paths are obscured. Leibowitz [41] realized this and attempted to superimpose three types of stresses to arrive at the total local plate stresses. These were: (1) beam bending stresses of the ship due to slamming forces, (2) dynamic stresses in a plate having orthotropic stiffness, and (3) the dynamic stresses developed in the plate between the stiffeners. Many questionable assumptions are made in these analyses, such as the use of membrane solutions and the lack of time phasing between these three types of responses. However, it does establish the need to evaluate the local plate response and other structural details normally neglected in gross structural response methods.

What is needed at this time is a three-dimensional, finite-element, idealized model of the entire ship, as shown in Figure VII-1. The external plating of the ship including the deck plates are idealized as being made up of small triangular plates connected at the nodal points. (See Figure VII-2.) The first step is to develop the element stiffness matrix. This is obtained by minimizing the total element potential energy with respect to each prescribed generalized nodal displacement $(\delta)^e$ as shown in the equation (26).

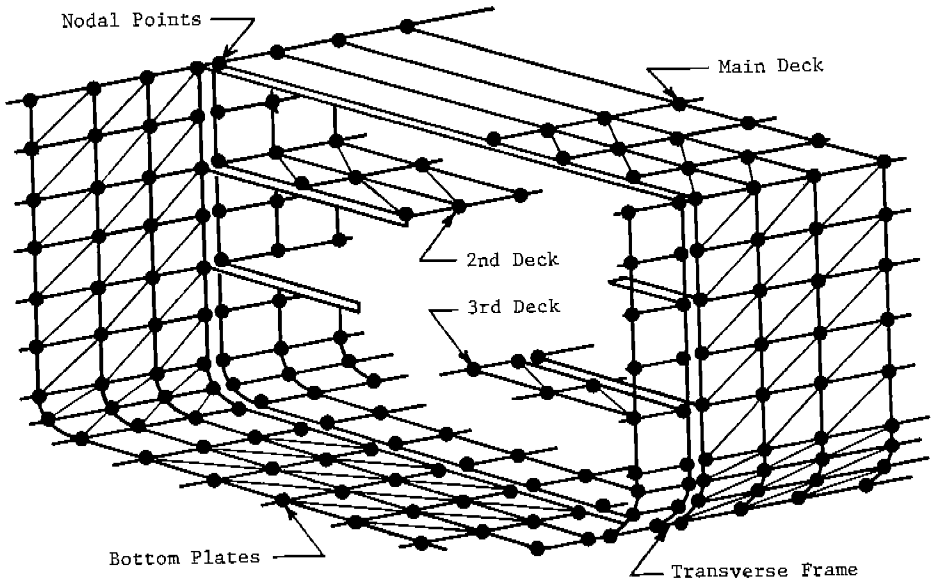
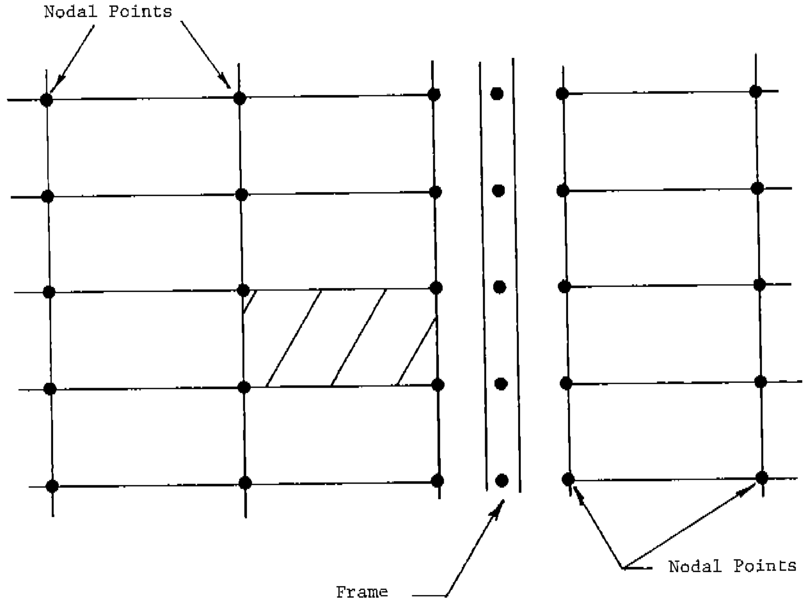


Fig. VII-1. Finite Element Break Down of Typical Ship Segment



$$\delta_i = \begin{Bmatrix} u_i \\ v_i \\ w_i \end{Bmatrix}$$ Nodal Displacement

Fig. VII-2. Idealized Element

$$\frac{\partial \phi^e}{\partial \delta^e} = \begin{Bmatrix} \frac{\partial \phi^e}{\partial(\delta_i)} \\ \frac{\partial \phi^e}{\partial(\delta_j)} \\ \frac{\partial \phi^e}{\partial(\delta_m)} \\ \frac{\partial \phi^e}{\partial(\delta_k)} \end{Bmatrix} = [K]^e(\delta)^e - \{F_p\}^e = 0 \qquad (26)$$

where ϕ^e is the total potential energy [42], $[K]^e$ is the element stiffness, and $\{F_p\}^e$ is the nodal force due to the distributed load. The complete stiffness matrix is a logical superposition of all the element stiffness matrices with the torsional and bending stiffness of the frames properly accounted for. The consistent force and inertia matrices are computed on the basis of the virtual work done by the nodal force and the inertia being equal to the work done by the distributed force and inertia. Initial strains due to thermal gradients, and forces due to dead-weight or wave-induced loads can be taken into account. Extensions of this method can include large-deflection theory and approximations to elastic-plastic solutions of structural response.

Once the inertia, stiffness, damping and the force matrices are provided, the dynamic response can be computed by a number of routines such as Milne's method and the Runge Kutta series solution which have been used successfully. These routines are classified as forward or direct integration schemes. Their disadvantage lies in the fact that they can become unstable, and diverge or oscillate about the true answer. Implicit or explicit finite difference routines such as Houbolt's scheme [43] are inherently stable. However, they display convergence problems, and one must develop an approach in selecting an appropriate time-step to provide the desired accuracy. If one can make generalities about these methods, it can be said that the implicit finite difference routine for solving large matrix sizes requires less time on the computer, and reasonable accuracies can be achieved by properly selecting the integration time step, Δt .

Another approach commonly used is the normal mode method. The equations of motion become uncoupled by making the transformation to generalized coordinates and by utilizing the orthogonality relationships. Each second-order differential equation is now solved independently for the modal displacement. The total desired response is the summation of all the modal contributions. Since this approach depends upon the accurate computation of the eigenvalues and eigenvectors, methods such as modified Givens-Householder Method [44, 45] have been used successfully for large matrices. The modal method is not the most desirable approach to use for transient dynamic response analyses due to the sharp discontinuity in the forcing function and the large number of modes necessary to provide reasonable accuracy.

C. Possible Damage Modes

The possible modes of failure caused by slamming in heavy seas can be divided into two groups: primary failures, where the ship's survival is threatened; and secondary failures, where the continuance of the voyage in the normal mode of operation is impaired.

Primary damage modes consist of the following:

1. Local yielding of forefoot plates due to excessive

bending at hard points and rupture of welded joints, causing intake of sea water.

2. Plastic buckling of bow and forefoot plates.
3. Yielding of frames in the highly-loaded areas of the hull.
4. Yielding and possible rupture of hull girder plates caused by the severe vibratory motion of the entire ship.
5. Low-cycle fatigue in the highly stressed locations.

The possible secondary modes of failure can be characterized as

1. Shock damage to navigational and communication systems, rendering them inoperative or unreliable due to calibration requirements.
2. Shock damage to piping and electrical transmission systems.
3. Damage to cargo due to high vibratory or shock loading.

D. Vulnerability Assessments

Up to now specific hydrodynamic theories and inadequacies thereof approximate analytical structural response methods and possible failure modes that are not associated with correct failure criteria have been discussed. With the advancement of analytical techniques, designers can be supplied with reasonable loading information and environmental criteria. The next step is to convey to the ship's captain the designers' confidence in the design of the ship to withstand the environments to which it will be subjected. As the size and speed of cargo carriers increases, the judgment of the ship's master is placed at a great disadvantage. He tends to be conservative in order to avoid damage to his ship, and when he is not, damage usually occurs. An analogous situation is found in the early stages of aircraft development. As the transition to larger and faster jet airliners took place, the pilots could no longer depend on their "feel" of the controls. Similarly, the ship's captain, in the future, will have to be assisted by instruments and charts to evaluate properly, with some degree of confidence, the vulnerability of his ship and cargo to a particular sea state.

Usually, as the sea state becomes more severe the ship's captain will reduce the forward speed as shown in Figure VII-3. The drag due to increased head seas will account for some reduction. If the analyst has done his job correctly, there is an upper limit on what the ship structure can take and that is designated as the "allowable" curve in Figure VII-3 for a constant heading.

Another, more general way of describing the limitations of a ship are shown in Figure VII-4. The sure "safe" contour could be based on 0.8 of the yield strength of the material. The sure "failure" line corresponds to exceeding the ultimate strength of the material based on an elastic-plastic large deflection analysis of the bottom plates, for instance. This information can then be plotted as a function of relative heading angle, and the failure envelope of all the combined failure modes can be determined, (See Figure VII-5.) A more meaningful plot for the captain would be typical of Figure VII-6, where maximum speed, heading, and severity of sea state are accounted for. The implicit features of a plot like this are that each control speed contour is based first on several modes of failure along its length, and second on a probability-of-success factor attached

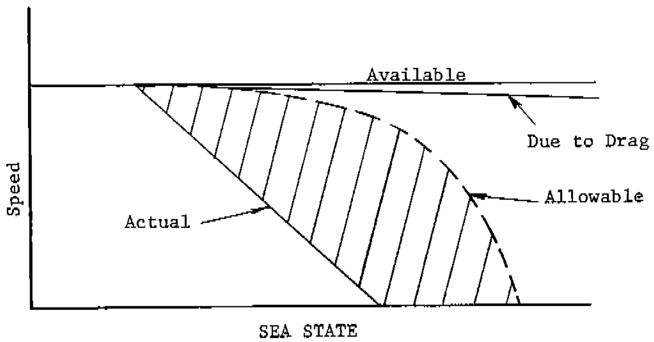


Fig. VII-3. Speed vs Sea State

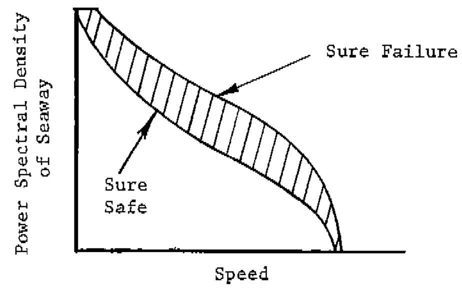


Fig. VII-4. Power Spectral Density of Sea State vs Speed

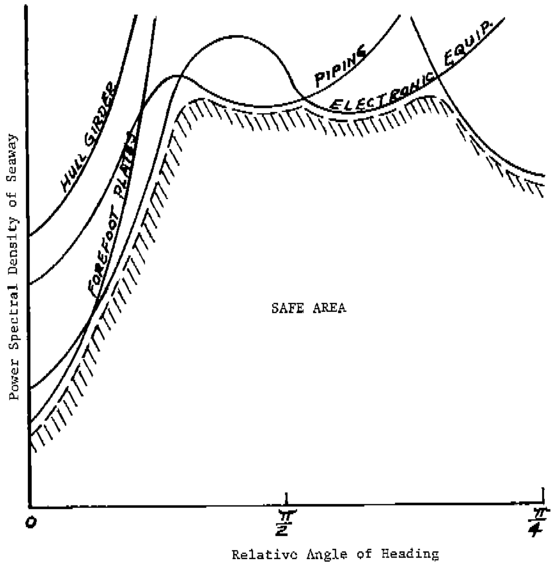
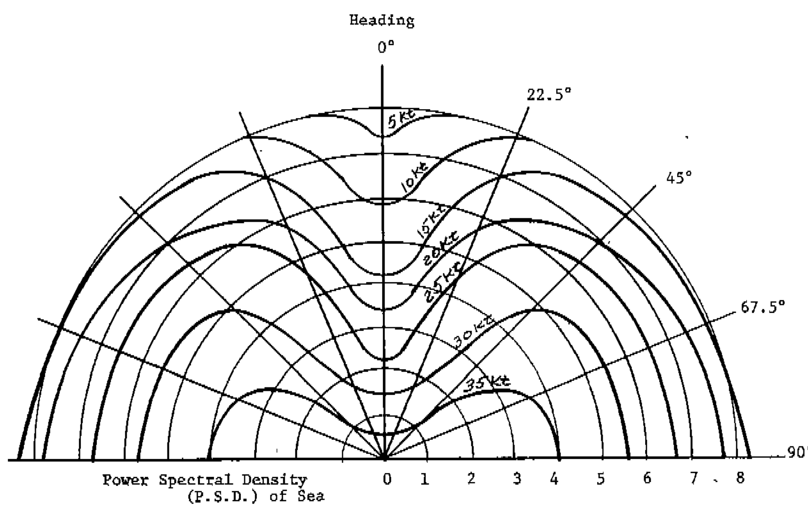


Fig. VII-5. Failure Envelope at Constant Speed

Fig. VII-6. Failure Curves at Constant Speed vs P.S.D. of Sea



to each contour, (The probability might be the same for all contours.) These contours would also vary for different deadweight conditions, and the failure mechanisms of Figures VII-4 and-5 might be different. The utilization of this approach presupposes that the captain knows the Power Spectral Density of the immediate sea he is experiencing. A reliable bow sensing unit has to be developed to record the continuous absolute surface elevation. A small computer would comprise part of the signal conditioning equipment to compute the autocorrelation function and integrate the Fourier transform to obtain the Power Spectral Density in terms of the surface elevation. With this information, the captain can operate his ship in optimum fashion even though he is experiencing some degree of hull vibration (whipping).

VIII. DESIGN IMPROVEMENTS

To alleviate slamming loads on the hull structure certain low-cost efforts can be accomplished for existing ships. Obviously, the best approach to this problem should be employed in the early stages of hull design. An extensive review of structural design criteria to account properly for these severe loading conditions would be required. At the risk of over-generalizing the solutions to slamming, the following design improvement will be considered.

A. Local Stiffening

Increased bottom plate thickness could reduce the amount of damage. However, a judicial placement of edge gusset plates and interstitial stiffeners could be employed to reduce the local out-of-plane bending moments.

B. Energy Dissipation

Bottom plates could be designed as sandwich structures with a high-durometer neoprene rubber as a core material. The shock loading on the structure would be greatly attenuated. In the past five years other versions of the concept have been developed that are having wide usage in industry. One of these versions consists of laminated layers of metal and viscous polymers.

C. Bulb Design

The primary reason for having a bulb [46] is to produce a secondary wave which has a trough near the bow, thereby reducing the bow wave and resultant drag. A secondary effect is to reduce pitching in heavy seas with the reduction of the occurrence of slamming. Design effort should be directed toward making the bulb more efficient in reducing pitch.

D. Dead-Rise Angle

Increasing the dead-rise angle reduces the slamming forces [47]. This increase in dead-rise angle should be considered in the forebody design of future ships.

E. Stability

Hydraulically-actuated automatic fins could be utilized to reduce pitching. Increased amounts of green water over the bow would be expected with this approach.

Concurrent improvements would have to be made in supporting and isolating shipboard equipment from higher shock loading. Whenever this could not be done, the equipment itself would have to be hardened to the environment.

IX. SUMMARY AND RECOMMENDATIONS

The theoretical and experimental study of slamming and its effect can be divided into five areas as shown in Figure IX-1.

1) sea state predictions in measurements
2) response amplitude operators
3) rigid body response
4) structural dynamic response
5) structural vulnerability assessment

Each area could be investigated in depth, independent of the others. However, understanding the slamming phenomenon and effects thereof requires sufficient knowledge in all sections of the overall problem. It is recognized that there are some weak areas in the theoretical approach that could stand further refinements. These refinements in the analytical approach should be verified by measurements taken at sea on full-scale ships. The following recommendations are made in order of importance.

A. Pressure-Time Histories

The most immediate problem when one considers slamming and its effects is the acquisition of reliable pressure-time histories. The fundamental reason why structural damage cannot be predicted on a consistent basis is that the force applied to the forefoot as a function of sea state is not known. Data from a sufficient number of pressure sensors would provide the analyst input to develop a three dimensional least square envelope of the pressure distribution as a function of time. From this the total force of the slam could be calculated along with the total impulse, and equivalent static pressure for each bottom plate. It is recommended that the WOLVERINE STATE or other ships similarly instrumented provide this basic information. The installation must be operated by professional-level engineering personnel with recording equipment having a frequency response flat up to 10 KHz or higher to obtain more accurate pressure-time data. These data would then be analyzed statistically to obtain the pressure power spectra for various sea states. A rational environmental design criteria could then be developed which the designers would employ in reducing the incidence of damage through better design practice.

B. Measurement of Statistical Parameters

Other important parameters to be included in shipboard measurements are relative velocity and displacement between the ship hull and the sea surface, and relative angle during slamming. Their effect on slamming forces and on the occurrence of slamming are shown in laboratory tests and statistical analyses. The WOLVERINE STATE has pressure transducers adequate to examine the distribution of pressure in the forefoot area, but lacks instrumentation capable of accurately measuring the relative velocity or measuring relative displacement or angle.

The initial intent of instrumenting the WOLVERINE STATE, however, was to measure midship hull stresses and the occurrence of slamming. If the Tucker wavemeter data were considered reliable, it would be possible to calculate relative displacements between keel and wave surface by comparing wave data with vessel displacement data obtained by combining and integrating the output of the fore and aft vertical accelerometers. This is not considered to be a promising approach, however.

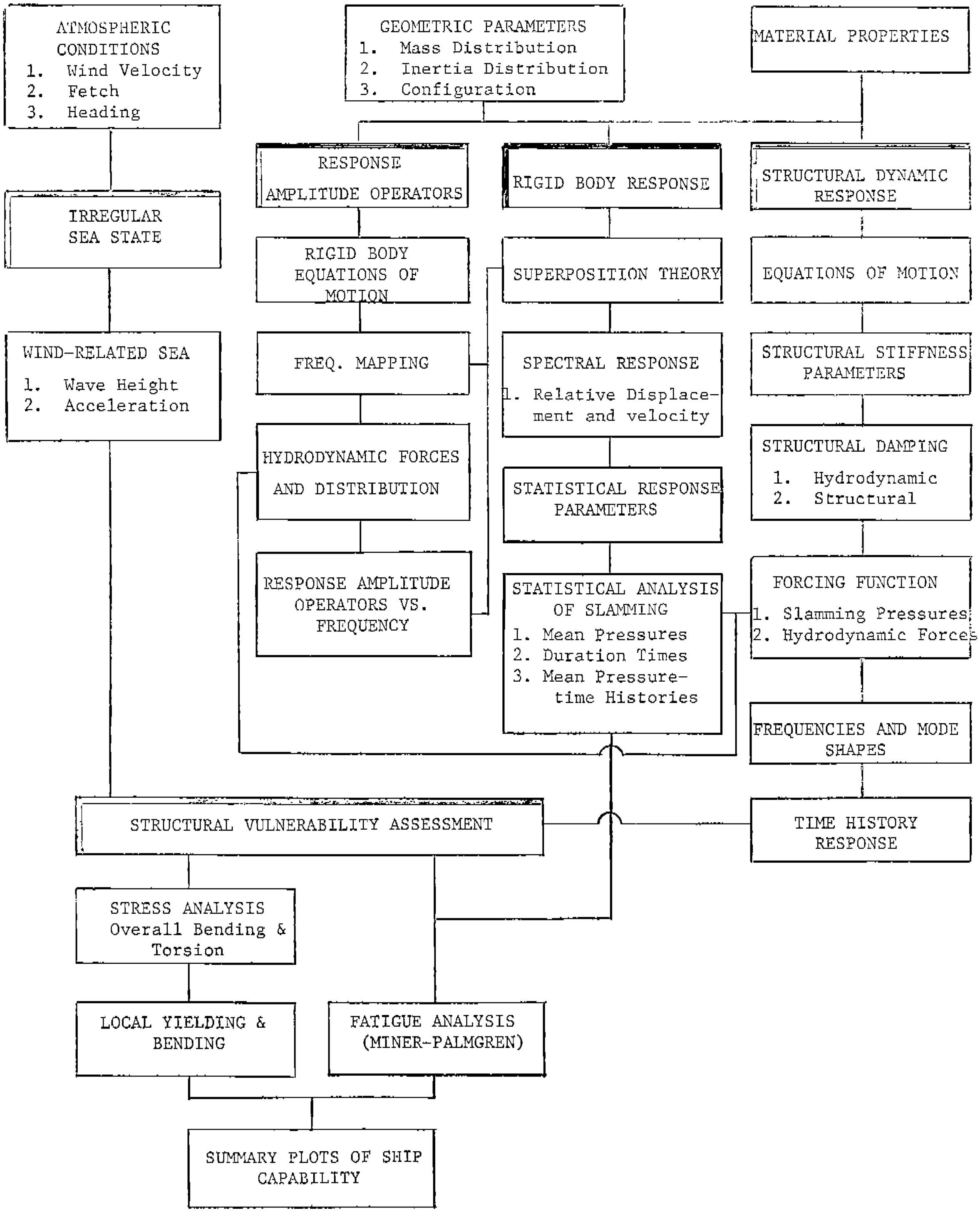

ATMOSPHERIC CONDITIONS
1. Wind Velocity
2. Fetch
3. Heading
GEOMETRIC PARAMETERS
1. Mass Distribution
2. Inertia Distribution
3. Configuration
MATERIAL PROPERTIES
RESPONSE AMPLITUDE OPERATORS
RIGID BODY RESPONSE
STRUCTURAL DYNAMIC RESPONSE
IRREGULAR SEA STATE
RIGID BODY EQUATIONS OF MOTION
SUPERPOSITION THEORY
EQUATIONS OF MOTION
WIND-RELATED SEA
1. Wave Height
2. Acceleration
FREQ. MAPPING
SPECTRAL RESPONSE
1. Relative Displacement and velocity
STRUCTURAL STIFFNESS PARAMETERS
HYDRODYNAMIC FORCES AND DISTRIBUTION
STATISTICAL RESPONSE PARAMETERS
STRUCTURAL DAMPING
1. Hydrodynamic
2. Structural
RESPONSE AMPLITUDE OPERATORS VS. FREQUENCY
STATISTICAL ANALYSIS OF SLAMMING
1. Mean Pressures
2. Duration Times
3. Mean Pressure-time Histories
FORCING FUNCTION
1. Slamming Pressures
2. Hydrodynamic Forces
FREQUENCIES AND MODE SHAPES
STRUCTURAL VULNERABILITY ASSESSMENT
TIME HISTORY RESPONSE
STRESS ANALYSIS Overall Bending & Torsion
LOCAL YIELDING & BENDING
FATIGUE ANALYSIS (MINER-PALMGREN)
SUMMARY PLOTS OF SHIP CAPABILITY

Fig. IX-1.

C. Sea State Measurements

Most full-scale testing efforts have ignored the direct measurement of sea state, depending only on visual observations. It is suspected by most investigators that in heavy seas, when slamming is prevalent, wave motions are a linear function of wind velocity. It is important, therefore, to measure the power spectral density of the sea in the immediate vicinity of the ship such that the correlation between power input of the sea and the response power spectral density of the ship can be assessed for linearity. If nonlinear effects are present, then the theoretical approach to wave-induced motion and slamming will have to be changed. The power spectral density of the sea is obtained by measuring the surface elevation of the sea. There are several methods by which this could be accomplished such as wave buoys, bow-mounted wave staffs, and other devices.

In this connection, it should be noted that vessel draft has a powerful influence on slamming. For a given vessel, it should be possible to develop a correlation between sea state and draft at the slamming threshold.

D. Mode Shapes

Recent data from the WOLVERINE STATE indicate that higher ship bending modes may be excited. It is difficult to identify these higher modes since only the bow and stern were instrumented with accelerometers. It is estimated that ten accelerometer locations along the length of the ship would be necessary to measure adequately the first three mode shapes.

E. Laboratory Tests

Some additional tests in the laboratory should be performed on flat plates, V-, and U-forms at higher velocities with high-frequency recording equipment. Simulation in much of the testing to date has not been considered too strongly with the intent to develop scaling laws applicable to full-scale ships. These models should be strain gaged and the possible modes of failure identified and demonstrated.

F. Theoretical Pressure Calculations

To enhance the capability of calculating the wedge entry pressure loading several things can be done. By fitting a polynomial curve to the free water surface in Wagner's basic approach to a wedge-water entry problem, Hillman [14] was able to approximate better the free surface potential. This approach should be fully explored utilizing digital computers. Air compressibility and structural elasticity effects should also be included.

G. Vulnerability Analyses

Analytical efforts should be initiated to establish the severity of slamming conditions that will cause various degrees of damage. It is recommended that these analyses be accomplished by the use of finite element techniques. Appropriate information, as described in Section VIII-D, should be provided to the ship's captain so that he can control his ship in an optimum fashion with some degree of confidence.

H. Conceptual Redesign Effort

Several design changes incorporating energy dissipation techniques, bulb redesigns, increased dead-rise angles, and stability mechanisms have been suggested in Section IX. It would seem prudent to explore the feasibility and comparative merits of possible design changes to alleviate the undesirable effects of slamming.

The WOLVERINE STATE in its present configuration appears to have a good chance of fulfilling many of the above recommendations. The pressure transducer locations in the forefoot area still appear to be suitable for the intended purpose. However, the acquisition system is a 14-channel tape recorder, which is not large enough to record all transducers simultaneously. The frequency response of the recording system is flat only to 50 Hz, and thus will probably not record the true peak slamming pressure. There has been sufficient data acquisition on this system to satisfy the initial intent of establishing the occurrence and gross nature of slamming. The value of the WOLVERINE STATE system can be enhanced by replacing the recorder with a high-frequency (10 kHz or higher) recording system with the capacity to record all channels simultaneously. Skilled personnel would have to be present on the voyages to operate, maintain and calibrate such equipment. Additional sensors would have to be installed for measuring relative velocity, displacement, and angle between the keel and water surface.

REFERENCES

1. Leibowitz, R. C., "Comparison of Theory and Experiment for Slamming of a Dutch Destroyer." David Taylor Model Basin Report 1511, June 1962.

2. Bledsoe, M. D., Bussemaker, O. and Cummins, W. E., "Seakeeping Trails on Three Dutch Destroyers." David Taylor Model Basin Report 1559, November 1961.

3. Szebehely, V. G. and Todd, M. A., "Ship Slamming in Head Seas." David Taylor Model Basin Report 913, February 1955.

4. Greenspon, J. E., "Sea Tests of the USCGC UNIMAK, Part 3, Pressure, Strains, and Deflections of the Bottom Plating Incident to Slamming." David Taylor Model Basin Report 978, March 1956.

5. Chuang, S.-L., "Experiments on Flat-Bottom Slamming." Journal of Ship Research, SNAME, Vol. 10, No. 1, March 1966.

6. Ochi, M. D. and Schwartz, F. M., "Two-Dimensional Experiments on the Effect of Hull Form on Hydrodynamic Impact." David Taylor Model Basin Report 1994, May 1966.

7. Verhagen, J. H. G., "The Impact of a Flat Plate on a Water Surface." Journal of Ship Research, SNAME, Vol. 11, No. 4, December 1967.

8. Chuang, S.-L., "Experiments on Slamming on Wedge-Shaped Bodies." Journal of Ship Research, SNAME, Vol. 11, No. 3, September 1967.

9. Lewison, G. and Maclean, W. M., "On the Cushioning of Water Impact by Entrapped Air." Journal of Ship Research, SNAME, Vol. 12, No. 2, June 1968.

10. Von Karman, T., "The Impact of Seaplane Floats During Landing." NACA TN 321, 1929.

11. Flügge, W., "Handbook of Engineering Mechanics." McGraw-Hill Book Co., Inc., New York, N. Y. 1962.

12. Wagner, H., "Landing of Seaplanes." NACA TM 622, May 1932.

13. Lamb, H., "Hydrodynamics," Sixth Edition, 1945, New York, Dover Publications.

14. Hillman, A., "Vertical Impact on a Water Surface by a 60° cone." Math. Tables Project, New York University, 1946.

15. Moran, J. P., "On the Hydrodynamic Theory of Water-Exit and Entry." Therm Advanced Research, Inc., TAR-TR-6501, March 1965, Fluid Dynamics Branch, Office of Naval Research.

16. Ochi, K. M. and Bledsoe, M. D., "Hydrodynamic Impact with Application to Ship Slamming." Fourth Symposium on Naval Hydrodynamics, Ship Propulsion and Hydroelasticity, Office of Naval Research, U. S. Dept. of the Navy, Vol. 3, ACR-73, 1962.

REFERENCES (Continued)

17. Ogilvie, T. F., "Compressibility Effects in Ship Slamming." Schiffstechnik, Vol. 10, No. 53, 1963.

18. Tick, L. J., "Certain Probabilities Associated with Bow Submergence and Ship Slamming in Irregular Seas." Journal of Ship Research, SNAME, Vol. 2, No. 1, June 1958.

19. Ochi, M. K., "Prediction of Occurrence and Severity of Ship Slamming at Sea." Fifth Symposium of Naval Hydrodynamics, Office of Naval Research, 1964.

20. Pierson, W. J., "Wind Generated Gravity Waves." Advances in Geophysics, Vol. 2, Academic Press, New York, N. Y., 1955.

21. Korvin-Kroukovsky, B. V., "Investigation of Ship Motions in Regular Waves." Trans. SNAME, Vol. 63, 1955, pp. 386-435.

22. Korvin-Kroukovsky, B. V. and Jacobs, W. R., "Pitching and Heaving Motions of a Ship in Regular Waves." Trans. SNAME, Vol. 65, 1957.

23. Bendat and Piersol, "Measurement and Analysis of Random Data." John Wiley and Sons, Inc., New York, N. Y. 1966.

24. Lewis, E. V., "Ship Speeds in Irregular Seas." Trans. SNAME, Vol. 63, 1955.

25. Burington, R. S., "Handbook of Mathematical Tables and Formulas." Handbook Publishers Inc., Third Edition, 1949.

26. Abramowitz, M. and Stegun, I. A., "Handbook of Mathematical Functions." U. S. Dept. of Commerce, National Bureau of Standards, Applied Mathematics Series 55, June 1964.

27. Bendat, J. S., "Principles and Application of Random Noise Theory." John Wiley and Sons, Inc., New York, N. Y. 1958.

28. Longuet-Higgins, M. S., "On the Statistical Distribution of the Heights of Sea Waves." Journal of Marine Research, Vol. 11, No. 3, 1952.

29. St. Denis, M. and Pierson, W. J., Jr., "On the Motion of Ships in Confused Seas." Trans. SNAME, Vol. 61, 1953.

30. Neumann, G., "Ocean Wave Spectra and a New Method of Forecasting Wind-Generation Sea." Beach Erosion Board, Tech. Memorandum No. 43, 1953.

31. Cartwright, D. E., "On Estimating the Mean Energy of Sea Waves from the Highest Wave in a Record." Proceedings from the Royal Society, National Inst. of Oceanography, Series A, Vol. 247, 1958.

32. Jasper, N. H., "Statistical Distribution Patterns of Ocean Waves and of Wave-Induced Ship Stresses and Motion, with Engineering Application." Trans. SNAME, Vol. 64, 1956.

REFERENCES (Continued)

33. Korvin-Kroukovsky, B. V., "Theory of Seakeeping." The Society of Naval Architects and Marine Engineers, 1961.

34. Cartwright, D. E. and Rydill, L. H., "The Rolling and Pitching of a Ship at Sea." Trans. Royal Institute of Naval Architects, London, Vol. 99, 1957.

35. Michel, W. H., "Sea Spectra Simplified." Presented at the April 1967 Meeting of the Gulf Section of the Society of Naval Architects and Marine Engineers.

36. Bretschneider, C. L., "Wave Variability and Wave Spectra for Wind-Generated Gravity Waves." Beach Erosion Board, T. M. No. 118, 1959.

37. Church, J. W., "Ship Response to Transient Forces." Presented at First Conference on Ship Vibration Laboratory, David Taylor Model Basin and Davidson Laboratory, Stevens Inst. of Technology, 25-26 January 1965.

38. Roth, R. S. and Klosner, J., "Nonlinear Response of Cylindrical Shells with Initial Imperfections Subjected to Dynamic Axial Loads." AIAA Journal, Vol. 2, No. 10, 1964.

39. Witmer, E. A., Balmer, H. A., Leech, I. W. and Pian, T. H. H., "Large Dynamic Deformations of Beams, Rings, Plates, and Shells." AIAA Journal, Vol. 1, No. 8, August 1963.

40. McGoldrick, R. T., "Calculations of the Response of a Ship Hull to a Transient Load by a Digital Process." David Taylor Model Basin Report 1119, March 1957.

41. Leibowitz, R. C., "A Method for Predicting the Plate-Hull Girder Response of a Ship Incident to Slam." David Taylor Model Basin Report 1706, October 1964.

42. Zienkiewicz, O. C. and Cheung, Y. K., "The Finite Element Method in Structural and Continuum Mechanics." McGraw-Hill Book Company, Inc., New York, N. Y. , 1967.

43. Houbolt, J. C., "A Recurrence Matrix Solution for the Dynamic Response of Elastic Aircraft." J. Aeronaut Sci. 17, 1950.

44. Ortega, J., "The Givens-Householder Method for Symmetric Matrices." Published in Math. Methods for Digital Computers, 2, edited by Ralston, A. and Wilf, H. S., John Wiley & Sons, Inc., New York, N. Y., 1967.

45. Parlett, B. N., "The LU and QR Algorithms." Published in Math. Methods for Digital Computers, 2, edited by Ralston, A. and Wilf, H. S., John Wiley & Sons, Inc., New York, N. Y., 1967.

46. Comstock, J. P., Editor, "Principles of Naval Architecture." Published by the Society of Naval Architects and Marine Engineers, 1967.

47. Townsend, H. S., "Some Observations on the Shape of Ship Forebodies with Relation to Heavy Weather." Presented at the April 1960 meeting of the New York Section of SNAME.

ADDITIONAL REFERENCES FOR SLAMMING

King, J. Foster. "Heavy Weather Damage," Trans. N.E.C.I.E.S., Vol. 51 (1934-35), pp. 151-160, (Discussion on pp. D51-D66).

Adam, J.L. "Some Notes on Damage to Ships," Trans. N.E.C.I.E.S., Vol. 45 (1928-29), pp. 400-410.

Hansen, Knud E. "Pounding of Ships and Strengthening Forward," Ship Building and Shipping Record, June 1935, pp. 656-658.

Kent, J.L. "The Cause and Prevention of Slamming on Ships in a Seaway," Trans. N.E.C.I.E.S., Vol. 65 (1948-49), p. 451.

Jasper, N.H. "Study of the Strains and Motions of the USCGC Casco at Sea." David Taylor Model Basin Report 781, May 1953.

Jasper, N.H., and Church, J.W. "Structural Seaworthiness Studies," Trans. S.N.A.M.E., Vol. 71 (1963).

Akita, Y., and Ochi, K. "Model Experiments on the Strength of Ships Moving in Waves," Trans. S.N.A.M.E., Vol. 63 (1955), pp. 203-236.

Warnsinck, W.H., and St. Denis, M. "Destroyer Seakeeping Trials." Proceedings of the Symposium on Behavior of Ships at Sea, Wageningen, 1957.

Lewis, E.V., and Gerard, G. "A Long Range Research Program in Ship Structural Design." Ship Structure Committee Report SSC-124, Washington, D.C., November 30, 1959.

Howard, J.L. "The Effect of Hull Shape on Dynamic Loading of Ship's Bottoms Due to Slamming." M.S. Thesis, Massachusetts Institute of Technology, May 1961.

McGoldrick, R.T. "Ship Vibrations." David Taylor Model Basin Report 1451, December 1960.

Greenspon, J.E. "Stresses and Deflections of Flat Rectangular Plates Under Dynamic Lateral Loads Based on Linear Theory." David Taylor Model Basin Report 774, April 1955.

Jasper, N.H. "Sea Tests of the USCGC Unimak, Part I. General Outline of Tests and Test Results." David Taylor Model Basin Report 976, March 1956.

Kosugi, T., Suenaga, I., and Miyamoto, Y. "Recording of Slamming on Board M/S Hodakasan Mar-," Journal of S.N.A.J., Vol. 105, July 1959.

Fabula, A.G. "Ellipse-Fitting Approximation of Two-Dimensional Normal Symmetric Impact of Rigid Bodies in Water." Fifth Midwestern Conference on Fluid Mechanics, University of Michigan Press, Ann Arbor, Michigan, pp. 299-315, 1957.

Egorov, I.T. "Udar o Szhimaemuiu Zhidkost." ("Impact on a Compressible Fluid.") Published in the Russian, Applied Mathematics and Mechanics, Vol. 20, No. 1, 1956, Translated in N.A.C.A. TM 1413, February 1958.

Leonard, R.W. "On Solutions of the Transient Response of Beams," N.A.C.A. TM 4244, June 1958.

ADDITIONAL REFERENCES FOR SLAMMING (Continued)

Borge, S.F. "The Analysis of Ship Structures Subject to Slamming Loads, J.S.R., Vol. 4, No. 3, December 1960, pp. 11-27.

Keil, A.H. "The Response of Ships to Underwater Explosions." David Taylor Model Basin Report 1576, November 1961 and Trans. S.N.A.M.E., Vol. 69, 1961.

Ochi, K.M. "Ship Slamming in Rough Seas." David Taylor Model Basin Report in Review.

Chu, W.H. and Abramson, H.N. "Hydrodynamic Theories of Ship Slamming - Review and Extension," J.S.R., Vol. 4, No. 4, March 1961, pp. 9-21.

Crane, C.L., Jr. "A Photographic Study of Water Impact Parameters and Flow." M.S. Thesis, Stevens Inst. of Technology, Hoboken, N.J., 1961.

Schwartz, F.M. "Two-Dimensional Experiments on the Effect of Hull Forms on Hydrodynamic Impact." David Taylor Model Basin Report in preparation.

Nagai, T. "Elastic Response of a Stiffened Plate Under a Slamming Load," University of California, Inst. of Engr. Res., Series 186, Issue 1, April 1962.

Nagai, T. "Permanent Set of Bottom Shell Plate Due to Slam Loads," University of California, Inst. of Engr. Res., Series 186, Issue 2, August 1962.

Nagai, T. "large Permanent Set of Ship Bottom Plating Due to Slam Loads," University of California, Inst. of Engr. Res., Series 186, Issue 5, December 1962.

"Design Charts for Bottom Shell Plate Scantlings to Withstand Slam Loads." University of California, Inst. of Engr. Res., Series 186, Issue 6, January 1963.

Clevenger, R.L., and Melberg, L.C. "Slamming of a Ship Structural Model." M.S. Thesis, Massachusetts Institute of Technology, May 1963.

Goodwin, J.J., and Kime, J.W. "Comparison of Slamming Damage of a Ship's Structural Model With Recently Developed Theories." David Taylor Model Basin Tech. Note SML-760-61, July 1963.

Leibowitz, R.C. "A Method for Predicting Slamming Forces and Response of a Ship Hull." David Taylor Model Basin Report 1691, September 1963.

Davis, A.V. "Whipping Response of a Victory Ship." David Taylor Model Basin Report in preparation.

Clough, R.W., and Maclean, W.M. "Dynamic Response of an Idealized Hull Girder to Slam Type Loadings." University of California, Inst. of Engr. Res., Report No. NA-63-6, July 1963.

Nibbering, J.J.W. "Fatigue of Ship Structures." Netherlands' Research Center T.N.O. for Shipbuilding and Navigation, Report No. 55S (S 1/68).

SNAME. "Some Effects of Hull Form on Ship Performance in a Seaway." Technical and Research Symposium, N.Y., October 10, 1967.

LIST OF SYMBOLS

SYMBOLS		DEFINITION
b	=	width of the plate
c	=	sound velocity
C	=	constant of proportionality between pressure and velocity at impact
H	=	distance from the apex of the wedge to the end of the wetted surface
ℓ	=	half breadth plate dimension
L	=	distance from ship's c.g. to a point on the bow
M	=	body mass
n	=	normal vector to surface S
p	=	pressure
q	=	fluid velocity
r	=	radius of the immersed body at the water line
S	=	describes arbitrary surface
$S_z(\omega)$	=	heave spectrum of ship
$S_\theta(\omega)$	=	pitch spectrum of ship
t	=	time
T	=	kinetic energy
$T_{z\eta}$	=	response amplitude operators for heave
$T_{\theta\eta}$	=	response amplitude operators for pitching
V	=	rigid body velocity
w	=	vertical air gap height
$Z(t)$	=	vertical displacement response of the ship at c.g.
f_s	=	frequency of slamming
p_*	=	pressure corresponding to the critical velocity v_o
α	=	phase angle
β	=	wedge angle
γ	=	correlation coefficients

LIST OF SYMBOLS

SYMBOLS		DEFINITION
Δt	=	time interval
η	=	wave height
θ	=	pitch angle at ship's c.g.
μ	=	mass density
ρ	=	relative displacement between wave height and ship; see equation (11)
$\dot{\rho}$	=	relative velocity between the ship's keel and the wave
σ_ρ	=	standard deviation of the relative displacement, ρ
σ_ρ^2	=	variance of the relative displacement, ρ
ϕ	=	velocity potential
ω	=	frequency

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Teledyne Materials Research	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

SLAMMING OF SHIPS: A CRITICAL REVIEW OF THE CURRENT STATE OF KNOWLEDGE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Henry, J. R. and Bailey, F. C.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
1970	38	47

8a. CONTRACT OR GRANT NO. NObs 94252 N00024-67-C-5312 b. PROJECT NO. N00024-69-C-5231 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) SR-172 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) SSC-208

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Ship Systems Command

13. ABSTRACT This critical review of the current status of the knowledge of bottom slamming phenomena was undertaken to assure that maximum value will be gleaned from recorded data obtained on the *SS Wolverine State*. The review covers experimental laboratory and ship data and their correlation with available theory; and structural implications and possible design improvements. Although there are certain areas in the theory which require expansion, the most pressing need is for additional full-scale experimental data to provide confirmation of existing analytical techniques.

DD FORM 1 JAN 64 1473

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
SHIPS SLAMMING REVIEW						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

UNCLASSIFIED
Security Classification

SHIP RESEARCH COMMITTEE
Maritime Transportation Research Board
National Academy of Sciences-National Research Council

The Ship Research Committee has technical cognizance of the Ship Structure Committee's Research Program. This entails recommending research objectives, preparing project prospectuses, evaluating proposals, providing liaison and technical guidance, reviewing project reports, and stimulating productive avenues of research.

PROF. R. A. YAGLE, Chairman
Professor of Naval Architecture
University of Michigan

DR. H. N. ABRAMSON
Director, Dept. of Mechanical Sciences
Southwest Research Institute

MR. W. H. BUCKLEY
Chief, Structural Criteria and Loads
Bell Aerosystems, Co.

DR. D. P. CLAUSING
Senior Scientist
U. S. Steel Corporation

MR. A. E. COX
Senior Program Manager
Newport News Shipbuilding & Dry Dock Co.

MR. J. F. DALZELL
Senior Research Engineer
Stevens Institute of Technology

DR. W. D. DOTY
Senior Research Consultant
U. S. Steel Corporation

MR. F. D. DUFFEY
Welding Engineer
Ingalls Shipbuilding Corporation

CDR D. FAULKNER, RCNC
Staff Constructor Officer
British Navy Staff

PROF. W. J. HALL
Professor of Civil Engineering
University of Illinois

MR. J. E. HERZ
Chief Structural Design Engineering
Sun Shipbuilding & Dry Dock Company

MR. G. E. KAMPSCHAEFER, JR.
Manager, Application Engineering
ARMCO Steel Corporation

PROF. B. R. NOTON
Prof. of Aerospace & Civil Engineering
Washington University

MR. W. W. OFFNER
Consulting Engineer

CDR R. M. WHITE, USCG
Chief, Applied Engineering Section
U. S. Coast Guard Academy

MR. R. W. RUMKE
Executive Secretary
Ship Research Committee

This project was coordinated under the guidance of the following Advisory Group I, "Ship Strain Measurement and Analysis " membership:

MR. J. F. DALZELL, Chairman, *Senior Research Engineer, Stevens Institute of Technology*

DR. H. N. ABRAMSON, *Director, Dept of Mechanical Sciences, Southwest Research Inst.*

MR. W. H. BUCKLEY, *Chief, Structural Criteria & Loads, Bell Aerosystems Company*

CDR D. FAULKNER, RCNC, *Staff Constructor Officer, British Navy Staff*

PROF. A. FREUDENTHAL, *Professor of Engineering, George Washington University*

MR. R. C. STRASSER, *Director of Research, Newport News Shipbuilding & Dry Dock Co.*

CDR R. M. WHITE, USCG, *Chief, Applied Engineering Section, U. S. Coast Guard Academy*

SHIP STRUCTURE COMMITTEE PUBLICATIONS

These documents are distributed by the Clearinghouse, Springfield, Va. 22151. These documents have been announced in the Clearinghouse journal U. S. Government Research & Development Reports *(USGRDR) under the indicated AD numbers.*

SSC-193, *Development of Mathematical Models for Describing Ship Structural Response in Waves* by P. Kaplan. January 1969. AD 682591.

SSC-194, *Feasibility Study of Model Test on Ship Hull Girder* by H. Becker. May 1969. AD 687220.

SSC-195, *Recommended Emergency Welding Procedure for Temporary Repairs of Ship Steels* by A. L. Lowenberg and P. D. Watson. May 1969. AD 668119.

SSC-196, *Analysis and Interpretation of Full-Scale Data on Midship Bending Stresses of Dry Cargo Ships* by D. Hoffman and E. V. Lewis. June 1969. AD 689657.

SSC-197, *An Investigation of the Utility of Computer Simulation to Predict Ship Structural Response in Waves* by P. Kaplan, T. P. Sargent and A. I. Raff. June 1969. AD 690229.

SSC-198, *Flame Straightening and Its Effect on Base Metal Properties* by H. E. Pattee, R. M. Evans and R. E. Monroe. August 1969. AD 691555.

SSC-199, *Study of the Factors Which Affect the Adequacy of High-Strength Low-Alloy Steel Weldments for Cargo Ship Hulls* by A. L. Lowenberg, E. B. Norris, A. G. Pickett and R. D. Wylie. August 1969. AD 692262.

SSC-200, *Index of Ship Structure Committee Reports* January 1969. AD 683360.

SSC-201, *Midship Wave Bending Moment in a Model of the Cargo Ship "Wolverine State" Running at Oblique Headings in Regular Waves* by M. J. Chiocco and E. Numata. September 1969. AD 695123.

SSC-202, *Midship Wave Bending Moments in a Model of the Cargo Ship "California Bear" Running at Oblique Headings in Regular Waves* by E. Numata and W. F. Yonkers. November 1969. AD 698847.

SSC-203, *Annual Report of the Ship Structure Committee* November 1969. AD 699240.

SSC-204, *Simulated Performance Testing for Ship Structure Components* by R. Sherman. 1970. AD 705398.

SSC-205, *Structural Design Review of Long, Cylindrical, Liquid-Filled Independent Cargo Tank Barges* by C. W. Bascom. 1970.

SSC-206, *Permissible Stresses and Their Limitations* by J. J. Nibbering. 1970.

SSC-207, *Effect of Flame and Mechanical Straightening on Material Properties of Weldments* by H. E. Pattee, R. M. Evans, and R. E. Monroe. 1970.