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Progress in the Development of Structural Load Criteria for Extreme Waves

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ABSTRACT

Progress is reviewed for a development program intended to provide structural loading criteria for ships in extreme seaways. The results of a heavy weather damage survey and their effect on program objectives are summarized. Extreme waves from Hurricane Camille, which have been identified by half-cycle counting techniques, are compared with damaging waves observed in storms encountered by U.S. Navy ships. Synoptic conditions associated with one particular type of extreme wave are also discussed. Current capabilities for generating specific time-domain waves in test tanks are reviewed because of their importance to the development program. An example characterization of bottom-impact loadings and structural response is provided to show the potential inadequacy of "equivalent static loadings" and "peak pressures" as a basis for the design of a hull structure, and to show the importance of a prior characterization of impact loadings as a prerequisite to development of load and response prediction methods.

INTRODUCTION

An initial study of extreme hull-girder loadings (1) outlined a loads criteria development program which was composed of the following major tasks:

I. Acquire and Analyze Service Experience

The results of this task are intended to direct research efforts into areas of proven need and to furnish damage information which could be potentially helpful in other task areas.

II. Identify and Describe Extreme Wave Environments

The principal objective of this task is the identification and description of wave conditions under which major casualties are most frequently observed.

III. Create Extreme Wave Conditions Under Test-Tank Conditions

Extreme wave conditions are not only infrequently encountered, but also are potentially hazardous and, therefore, are an unlikely source of full-scale wave load measurements. Simulation of extreme wave conditions in test tanks is, thus, of considerable practical importance. This task is intended to investigate the means by which the extreme wave environments identified in Task II could be re-created under test-tank conditions.

IV. Propose New Hull Loading Conditions

Upon successful completion of Tasks II and III, it is anticipated that model tests will become a primary source of information regarding potentially critical loading conditions. As stated in the initial study (1):

> "Based upon these tests it is intended that the operating and wave conditions likely to produce critical longitudinal shear and bending loads be identified well enough to postulate limit load criteria for a) impulsive bottom loading conditions, and b) impulsive weather deck loading conditions."

V. Develop Load Prediction Methods

The major thrust of this task is the development of load prediction methods applicable to the critical circumstances of loading identified in Task IV.

VI. Develop Structural Criteria and Related Strength Prediction Methods

The major objective of this Task (previously identified as: Develop Structural Response and Strength Prediction Methods) is to establish criteria for acceptable, or unacceptable structural behavior under extreme loadings and to identify required methods of strength analysis. These methods are expected to involve acceptable elastic and/or plastic deformations and ultimate strength prediction methods.

VII. Perform Design Application Studies of Proposed Criteria

This task is intended to illustrate the application in design of proposed criteria and to assure that it is understandable and viable in the view of persons now engaged in the design of ship structure. Because the criteria which are evolved here may represent substantial departures from conventional practice, this task is of particular importance.

VIII. Recommend Specification Load Criteria

This task is the culmination of the work performed under Task VII from a ship procurement point of view.

IX. Investigate Ship Structural Monitoring Provisions

It is implicit that the load criteria developments of this program be of a rational nature[1] and, therefore, amenable to subsequent improvement, correction, or extension based on service-load monitoring information. This task is intended to initiate a feedback of certain service-load data.

Upon completion of the initial study, work on the first six tasks was undertaken with primary emphasis on Tasks I and II. The following is a summary of progress to date in each of the first six task areas together with a brief overview of program trends. No work has been performed to date on Tasks VII, VIII, and IX.

TASK I: ACQUIRE AND ANALYZE SERVICE EXPERIENCE

Two investigations have been completed under Task I. The first one reviewed catastrophic hull girder failures of American flag ships operating in American waters[2] and

[1]Rational in the sense that they are sufficiently realistic with regard to seaway loading conditions that in-service measurements which exceed those associated with proposed criteria necessarily suggest that the criteria be revised; rational also in the sense that the resulting design loads are compared directly to the available strength of the structure.

[2]Coast Guard and, more recently, National Transportation Safety Board reports are available for such cases.

found that all of the casualities occurred in seaways which were not fully developed for the winds at hand but which were steep and/or confused. In general, hull slamming or pounding was reported by the survivors prior to the casualty. From this investigation, it was concluded that slam type loadings must be considered in rationally formulated hull-girder load criteria.

The second investigation has involved a broad survey of U.S. Navy ship heavyweather damage. In this case, no hull-girder casualties were experienced. The major conclusions drawn from this study are as follows:

(a) Wave impingement on superstructures, appendages, deck mounted equipment, and structures topside is, collectively, the most common source of heavy-weather damage (35 percent of all cases) as well as an expensive type of damage to repair.

(b) Failure of antennae and other equipment aloft is the most common single type of heavy-weather damage.

(c) Structural load criteria and load prediction developments must address wave impact loading, especially those associated with certain classes of ships which tend to have structure or equipment in locations susceptible to wave impact damage.

Thus, while critical hull-girder loadings continue to be of fundamental concern, wave impact loadings are more frequently encountered during heavy-weather operation. As concluded from the initial investigation of hull-girder failures, impulsive loadings are of major concern here as well.

A third investigation is currently underway which deals with certain Navy ship heavy-weather damage incidents for which relatively detailed information is available. Only two cases have been reviewed up to this time, but, as will be noted in the discussion of Task II progress, they have been found to contain important information relative to the identification and classification of extreme waves. Because the incidents in question are part of the general data base covered by the second investigation, no changes in the general heavy-weather damage trends is anticipated from this third investigation. Important development initiatives have, nevertheless, been established as a result of these ad hoc studies as will be discussed relative to Task IV progress.

TASK II: IDENTIFY AND DESCRIBE EXTREME WAVE ENVIRONMENTS

What is an extreme wave? The answer to this question is clearly influenced by the characterstics of the particular vessel or marine structure under consideration. A wave 25 m high and 300 m long is of concern to an aircraft carrier but is of limited concern to a small vessel. On the other hand, a steep breaking wave 8 m high and 100 m long is of considerable concern to the small vessel, but of much less concern to the aircraft carrier. In view of the damage survey results, it is clear that steep, breaking waves are one type of wave for which time-domain characteristics are of considerable importance. Beyond this, the well publicized ship damage experienced off the southest coast of Africa (2) illustrates that waves of unusual proportions in an existing seaway are also important. These waves have been termed "episodic" in this investigation because they stand apart from all other waves in a particular time interval. They can be defined by the half-cycle count procedure discussed here. As illustrated by Hurricane Camille wave data, episodic waves are by no means confined to the southeast coast of Africa. Because they can be encountered at ship speeds higher than would be the case if their presence were known, they are potentially dangerous and, thus, represent a second class of waves for which extreme values are also sought. A third class of waves, namely a group or succession of waves, is also of potential importance (3) because of its cumulative effect on ship motion and load response. This class will be referred to here as a critical wave train (CWT). In this instance, more than for any other wave type, the motion-response period and damping of an individual ship or structure are major factors in determining its effect on structural loadings. The phrase "extreme wave" has a less than clear meaning in this case, and no general criteria have been established for identifying such wave groups at this time.

The approach taken in Task II to identify extreme wave environments has been mostly evolutionary. What has been learned to date, and the manner in which it has been learned, was unforeseen at the inception of this task. A key development has been the application of the half-cycle method of random data analysis to time series wave data as described in reference (4). This particular method evolved from a procedure established to facilitate the computerized accumulation of broad-band fatigue load data.

Figure 1 illustrates the basic procedure for half-cycle counting of time-series data and for entering individual counts into the data matrix, or HACYM. The signal is first banded into uniform Data Intervals[1] on either side of the Reference Data level. Each data interval is given a Data Interval Designator (+J through −J) for identification purposes. Whenever a data peak (maximum or minimum) occurs, it is identified with a particular data interval designator. In Figure 1, the half-cycle (1) has a first peak of −B and a second peak of +E, and as a result, it is entered into the HACYM Data Bin corresponding to a first peak −B and a second peak +E. In Figure 1 the half-cycle identifiers (1) through (6) have been entered for purposes of illustrating the procedure. Normally the Data Bins would contain a number which corresponds to the number of times the data sample in question had half-cycle excursions corresponding to that particular Data Bin. This procedure is repeated for other half-cycle excursions, such as (2) through (6), until all the data have been processed.

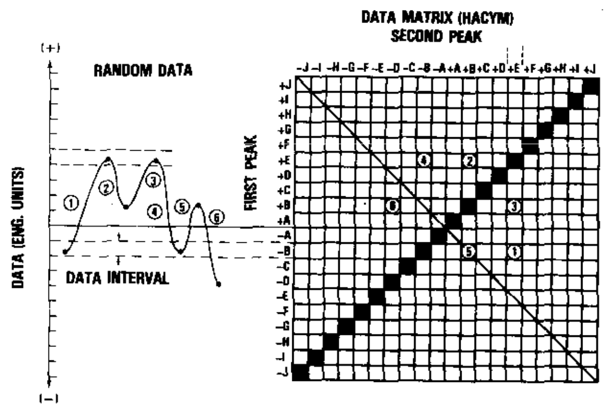

Figure 1 - Half-Cycle Counting of Random Data

As shown in Figure 2 the location of an individual half-cycle count with respect to the diagonal axes of the matrix is a direct measure of the amplitude and mean value of the data excursion in question.

One of the important characteristics of the HACYM, as applied to wave data, is that the sums of half-cycle counts in the Rows and Amplitude (right hand) Diagonals provide certain familiar wave height statistics. In the case of the row sums to the right of the Null (darkened) Diagonal, the histogram of wave height maxima for up-going excursions is formed while the row sums to the left of the Null Diagonal provide the corresponding histogram of peaks for the down-going excursions. The histograms of half-cycle counts formed from the Amplitude Diagonals provide the more frequently reported maxima of wave heights as measured from trough to crest and vice versa in which mean water level is disregarded. Thus, the HACYM has the property of providing the histograms of wave height maxima most frequently reported

[1]Capitalized terms are defined in reference (4).

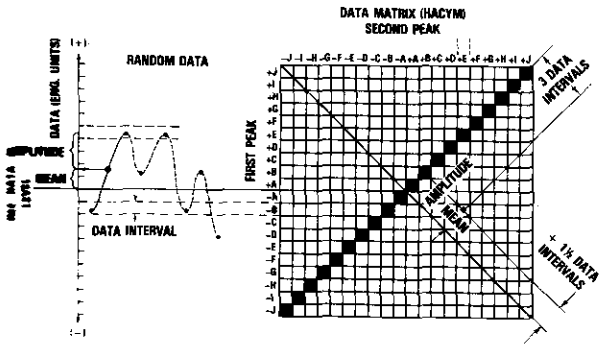

Figure 2 - Characterization of Half-Cycle Data Excursions Within the Half-Cycle Matrix

in the statistical analysis of time-series wave data. A more extensive discussion of the half-cycle counting method and related data analysis options is presented in reference (4).

An early application of the half-cycle count method to strain gage data from the hydrofoil ship PCH-1 MOD 1 revealed several interesting statistical properties of time series data when presented in HACYM format; see Figure 3. The majority of half-cycle counts presented a coherent pattern with respect to the diagonals of the HACYM (see Figure 2) and, as a result, when the severe, nonlinear loading events associated with broaching and cresting in State 5 seas occurred (see cross hatched bins), they stood apart from the majority of data excursions.[1]

Because of this property it was recently decided to process wave data measured during Hurricane Camille in HACYM format in order to identify any unusual waves which occurred at an oil production platform in 103.6 m (340 ft) of water. The initial results, as reported in reference (4), illustrate the occurrence of an episodic wave during the 1130-1200 hr time interval as well as a second one of somewhat different proportions in the following half-hour interval; see Figure 4. The episodic wave measured at 1155 hr was the largest wave measured during the storm and occurred at a time when the average wind velocity was approximately 34 knots. The time series for this wave is shown in Figure 5a. As the storm progressed both wind velocity and gustiness increased. At the same time the HACYM analysis showed that the largest waves in the seaway became elevated, that is, the excursions in wave height from trough to crest and vice versa were centered well above mean water level which is shown in the HACYM by the off-diagonal displacement of the data excursions in Figure 6. The time series for the largest wave in the interval 1500-1530 hr is shown in Figure 5b from which it can be seen that the wave is not only elevated, but also is very steep on its forward face. The extent which one can generalize from these findings is not known because it is an analysis of only one storm. Nevertheless, it can be said that during this particular storm, episodic waves occurred during an interval of less than 1 hr and perhaps of equal importance, that increasingly strong and gusty winds produced a seaway in which the largest waves were elevated and steep on their forward face.

In general, during the more intense portion of the storm, the half-cycle analysis revealed that the distinctive character

[1]Subsequent development of the half-cycle counting method has shown that when time-series random data have been normalized as a percentage of the root-mean-square value for each data analysis interval, extreme values of the process can be characterized as to: (a) self-limiting tendencies (i.e., as to whether or not a maximum ratio of x(t) to $\sigma(t)$ appears to exist, (b) certain aspects of non-linear behavior, and (c) whether or not episodic (i.e., out-lying) events have occurred. Such characterizations have been made to date for selected wave height, wind velocity, and structural strain data.

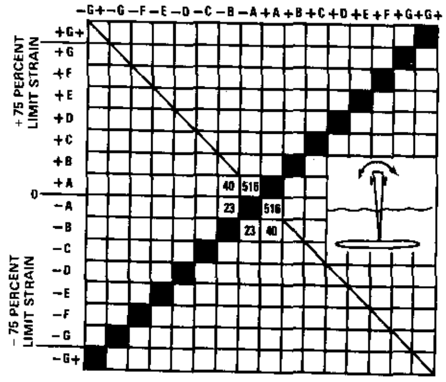

Figure 3a - State 2 Seas

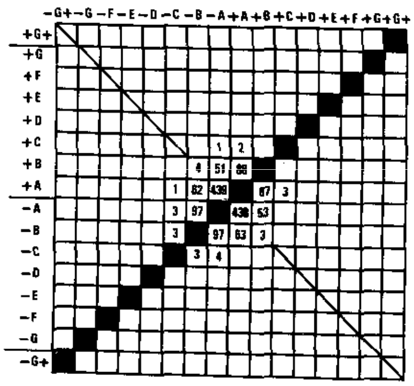

Figure 3b - State 3 Seas

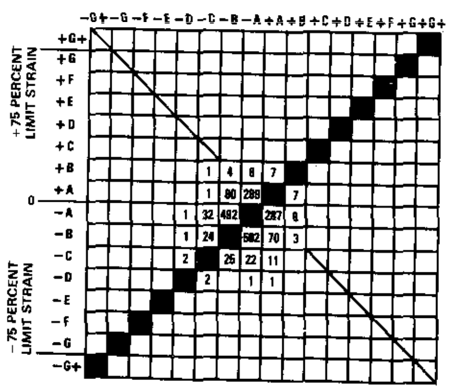

Figure 3c - State 4 Seas

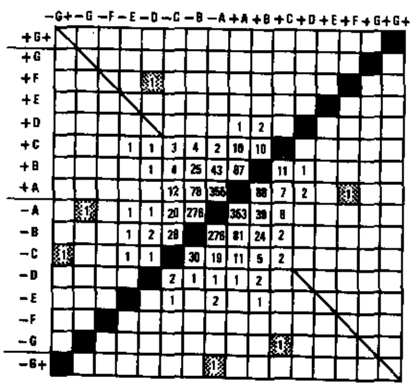

Figure 3d - State 5 Seas

Figure 3 - Half-cycle Analysis of PCH-1 MOD 1 Forward Strut Lateral Bending Strains

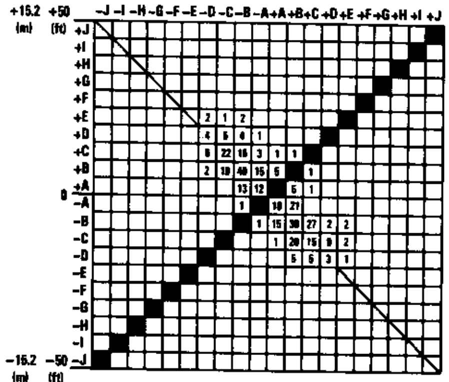

Figure 4a -
1030-1100 Hours

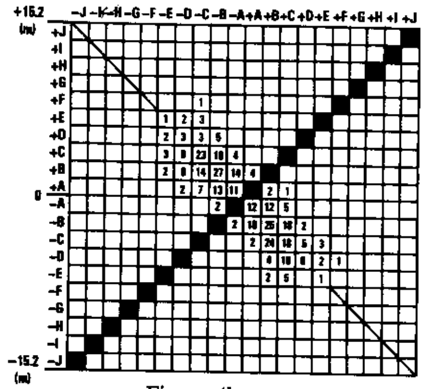

Figure 4b -
1100-1130 Hours

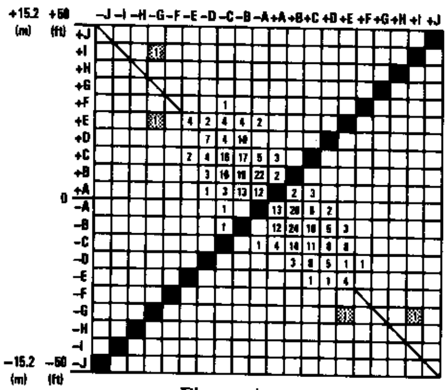

Figure 4c -
1130-1200 Hours

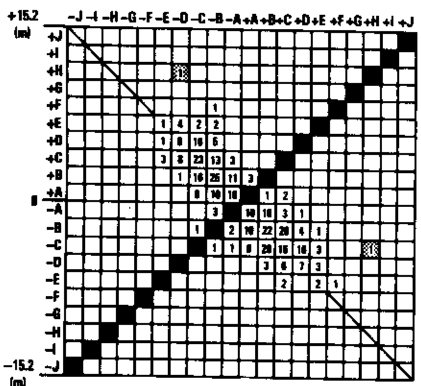

Figure 4d -
1200-1230 Hours

Figure 4 - Half-Cycle Analysis of Hurricane Camille Wave Data: 1030-1230 Hours

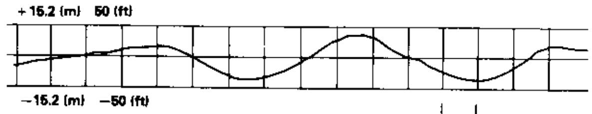

Figure 5a - Episodic Wave at 1155 Hours

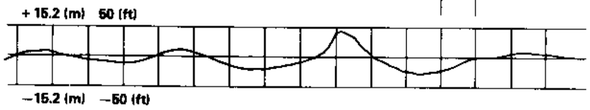

Figure 5b - Steep, Elevated Wave at 1522 Hours

Figure 5 - Extreme Waves from Hurricane Camille

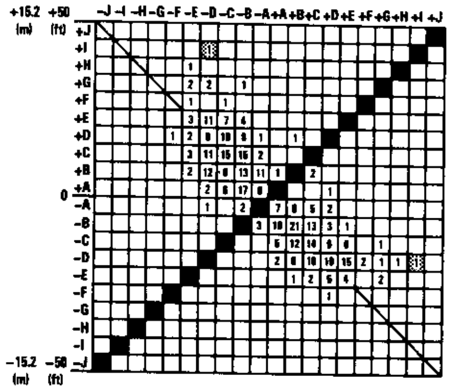

Figure 6a -
1430-1500 Hours

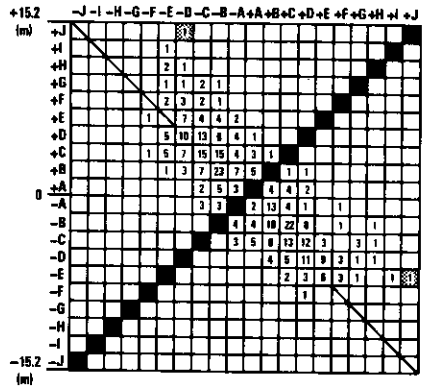

Figure 6b -
1500-1530 Hours

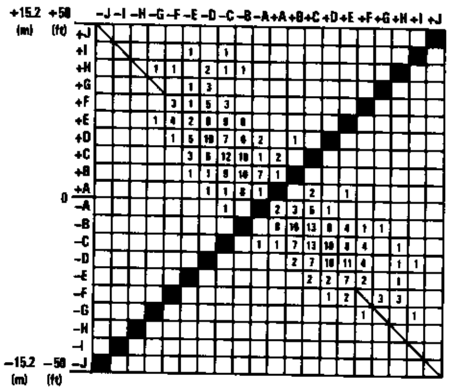

Figure 6c -
1530-1600 Hours

Figure 6 - Half-Cycle Analysis of Hurricane Camille Wave Data: 1430-1600 Hours

of the waves as analyzed by half-hour intervals was primarily associated with the largest waves in the seaway—an observation which, from a structural loading point of view, may be of considerable importance. Because frequency domain (i.e., spectral) analyses of wave data fail to detect such events due to the energy averaging nature of the analysis, and because wave elevation also is not apparent, it is believed that much can be learned about the largest and typically most dangerous waves in a storm driven seaway using half-cycle analysis techniques.

Two Navy investigations into storm encounters have provided testimony which is particularly interesting in view of the time series character of the extreme waves of Figure 5. In the one case the captain of an aircraft carrier testified:

". . . It was later that afternoon, I don't remember the exact time, that I watched my anemometer up there very closely. I recorded 74 knots on the bridge in mid-afternoon for maybe a 15-second period, and I also recorded 64 knots for over two minutes. At around four something that afternoon, I think the damage that the ship suffered occurred because of three, possibly four, waves [Note: actually over a period of about one day]. I looked out ahead, I'd estimate a mile to a mile and a half, and I saw what appeared to me to be a significant wave coming, and I mentioned to somebody that this was just like the 'Poseidon Adventure,' and the thing rolled in and I watched it all the way in, and it was right at flight deck level where the rest of them had been 25 to 30, maybe a little over 30 feet, this baby was up around 55 to 60 feet with a fairly good sized wave in front of it unfortunately. . . .But when this wave hit us, the first one hit us, lifted the nose up, she started to plow in and it was coming down as this one hit us. And it just jarred the whole ship."

The wave observed by the captain had a ratio of wave height (H) to significant wave height (Hs) of approximately 2 to 1 (60 ft/30 ft). That shown in Figure 5a is slightly more extreme with a ratio of approximately 2.3 to 1. An important point here is that the Camille wave also had "a fairly good sized wave in front of it." This could be coincidental except that the only other time-series data for an episodic wave located to date, which is shown in Figure 7, also has a marked time-domain similarity to the wave from Hurricane Camille with a large wave again in front of the episodic wave. The latter wave, which is reported in reference (5), was measured during a storm off the Irish coast and is of lesser period and height due to the less violent nature of the storm. The origin and frequency of such waves is not known, but it appears from the limited data in hand that they represent an important class of time-domain waves for consideration in structural loading criteria.

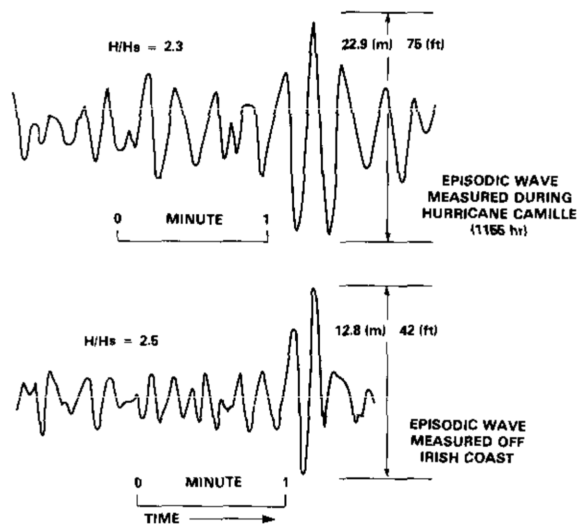

Figure 7 - Comparative Time Series for Two Episodic Waves

A second investigation of storm damage provided the following testimony from the staff watch officer:

"Just before stepping on the bridge (near midnight) I noted that the wind was sustained between 50-55 knots, with gusts as high as 69 knots. The seas were coming off the port bow. When I looked out of the window I noticed a large wave. Because of the height of the wave I felt the ship must be on a downward slope and would surely rise on the next wave. Suddenly I realized that the ship was riding the crest of the wave and that I was still looking up at the onrushing wall of water. I turned my head toward Lt.__________, who was standing by the radar, to inform him of the high wave. As I turned my head the window I was standing by exploded as did several others." See Figure 8.

Figure 8 - Bridge Damage Following Encounter with Large Elevated Wave

If one examines the time series data for the large elevated wave shown in Figure 5b, it can be seen that there was only a small wave in front of it and that it would also tend to loom up as an "onrushing wall of water." In this instance, the coincidence extends beyond a similarity in time domain characterization. As noted above, the larger waves in Camille became steep and elevated as the wind strength and gustiness became more extreme. The wind conditions involved in this ship damage incident were also found to be very strong and gusty.

An important insight into the apparent correlation of wave steepness with wind strength and gustiness is provided by the work of Glenn D. Hamilton, of NOAA's National Data Buoy Office. As reported in reference (6) four of NOAA's large ocean data buoys (approximately 10 m in diameter) had capsized and an investigation was conducted to determine if a pattern existed in terms of the local synoptic conditions prevailing at the time. He concluded as follows:

"The weather conditions associated with the four buoy capsizings were found to be remarkably similar. In general, strong winds south of deep low-pressure systems, occurred for a long enough time interval that peak wave energy was found in relatively long periods. Cold troughs with intense convective cells and thunderstorms, evident in surface analyses and satellite images, passed the buoys near the times of the capsizings.

It is postulated that extremely strong gusty winds from the squalls, superimposed on an already strong ambient wind field, created high short-period waves. With large amounts of energy in long-period waves present, the additional impetus of high-frequency energy resulted in increased height by superposition and breaking of the crests of the longer waves which precipitated the buoy capsizings. Buoy behavior in other severe weather situations was examined, and it appeared that the combination of conditions present in the capsizing cases was not encountered."

While the synoptic conditions are merely similar to those of

Camille in the vicinity of the storm center, they are almost identical to those prevailing at the time of the Navy ship damage incident referred to previously. The incident occurred immediately south of a low-pressure center and just prior to frontal passage in the presence of severe convective (thunderstorm) activity.

Hamilton's research also demonstrates the potential value of correlating extreme response and damage incidents with local synoptic conditions prevalent at the time. Because NOAA's National Climatic Center furnishes, at nominal cost, northern hemisphere surface weather charts for 6-hr intervals for a number of past years, this type of correlation is now an important aspect of Task I activities.

These findings also identify another important research initiative, namely, the acquisition and analysis in HACYM format of time series wave height data for synoptic conditions such as those identified by Hamilton. This data search has only recently begun. The NOAA data buoy capsizings themselves illustrate the somewhat ironic nature of the problem anticipated in this search. Due in part to a current pre-occupation with wave height spectra as a seaway characterization, the data buoys which capsized furnished only spectral information regarding the seaways.

Based on results to date in this program, it has been concluded that an intensive effort should be made to identify critical waves in time-series data obtained from synoptic conditions which service experience has shown to be potentially dangerous. In particular, at least two types of time-domain waves have already been identified as being of critical interest, namely the episodic wave of Figure 5a and the steep, elevated wave of Figure 5b.

TASK III: CREATE EXTREME WAVES UNDER TEST TANK-CONDITIONS

Work in this task area has been confined to determining wavemaking capabilities for specified time-domain waves, i.e., waves specified in terms of wave height vs. time. The present emphasis on generating specific time-domain waves represents a departure from the current practice of evaluating ship model responses statistically based on data obtained from a seaway modeled in the frequency domain. The rationale for this departure is as follows:

(a) Extreme loadings can be the result of nonlinear environmental behavior, or the result of a nonlinear response to the environment, or both. It is frequently assumed that linear superposition of frequency-domain ship motion or load responses applies to extreme loading cases which have been forecast by statistical methods. Unfortunately, this potentially unconservative assumption is difficult to verify in practice, and it has been considered prudent to avoid it altogether if possible in this program.

(b) The study of model-scale ship or other marine structure responses to extreme waves should be conducted in the time domain so that structural loadings and responses can be evaluated as to the particular seaway characteristics which result in critical loadings as well as in regard to the particular structural components which are in jeopardy (i.e, hull girder, bridge structure, cargo hatches, equipment installed on deck, etc.). It is assumed in this rationale that nonlinear loading effects can be most easily identified and studied as a result of time-domain testing.

(c) Half-cycle analysis of random data provides a method by which extreme events can be identified when, as in the case of wave data, the majority of events follow well-defined statistical trends. This, of course, requires that time-series data be available for environmental conditions which are capable of producing extreme waves. It also requires, having identified critical events, that the environmental or operating conditions causing them be identifiable. These assumptions are obviously bound to the successful completion of Task II.

This rationale leads to the current objective of Task III which is the recreation, at model-scale, of potentially critical time-domain waves so as to permit a rational investigation of the structural loadings which they are capable of producing.

In the case of ships, the results of the Task I casualty studies are intended to identify those ship types and individual structural components of primary interest from a casualty point of view so that they can be investigated in addition to those, such as the hull girder, which are already of obvious interest.

The investigations conducted to date under this task have been solely to determine if a capability exists for creating specified domain waves at a designated time and location in a test tank. The hydraulic laboratory of the National Research Council of Canada, reference (7), has demonstrated that creating an extreme wave at a specified time and location in a test tank is feasible using a computer-controlled wavemaker. The state-of-the-art for generating a wave of specified time-domain character at the designated location is not as advanced, however. Progress in this area is encouraging nevertheless, and the laboratory has re-created several of the extreme waves from the Hurricane Camille time-series data.

The question of what types of time-series waves we wish to generate is believed to be answered, in part, by current Task II results. The episodic wave of Figure 5a and the steep elevated wave of Figure 5b are certain candidates. Beyond this, little can be said at this time except to note that a key development is the acquisition and processing in HACYM format of time-series wave data from critical synoptic situations. It is well to reiterate that the initial thrust here is in the direction of identifying, with some precision, the effects which such waves have on ships and other marine structures. This knowledge is itself a vital element in the process of specifying what might be termed "design waves" for individual ships and marine structures.

TASK IV: PROPOSE NEW HULL LOADING CONDITIONS

This task, as originally conceived in reference (1), placed primary emphasis on model testing to reveal the interrelationship of ship and seaway characteristics which could result in critical hull-girder loadings. This approach is still considered to be the most appropriate for improving our understanding of seaway-induced loadings. However, since reference (1) was written, the program scope has broadened to include wave impact loadings because of the findings of Task I.

With respect to hull-girder loadings, reference 1 noted a predominance of steep, wind-driven seaways in the hull-girder casualty information available for American flag ships operating in American waters. Application of half-cycle counting methods to Hurricane Camille wave data has subsequently revealed a tendency for large, steep and elevated waves to occur as local storm winds become strong and gusty. Further insight into the critical nature of this type of seaway is provided by data gathered from the SL-7 containership S.S. SEA-LAND McLEAN during a severe Atlantic storm. These measurements were obtained as part of a major data gathering program for this class of ship under the sponsorship of the Ship Structure Committee, see references (8), (9), and (10). The hull-girder midship bending strains presented in Figure 9 represent the highest values ever recorded by Teledyne Engineering Services, Inc. in the course of a variety of hull-girder strain measuring programs conducted by them under Ship Structure Committee and American Bureau of Shipping sponsorship. Because the stresses of Figure 9 could have approached material yield strength locally (depending upon the magnitude of the still-water-bending stresses), they are regarded here as potentially dangerous and, thus, of considerable interest with respect to the seaway conditions which caused them. An analysis of the associated data is, therefore now in progress.

The results of the survey of U.S. Navy ship heavy-weather damage, discussed under Task I, have emphasized the practical importance of dealing effectively with wave-impact loadings. Here also steep wind-driven seaways are of considerable importance. The effect of this type of seaway on ship structure loadings is potentially diverse, i.e., both hull-girder and local structural loadings are apt to be of importance. In the latter case, loadings on local structures such as

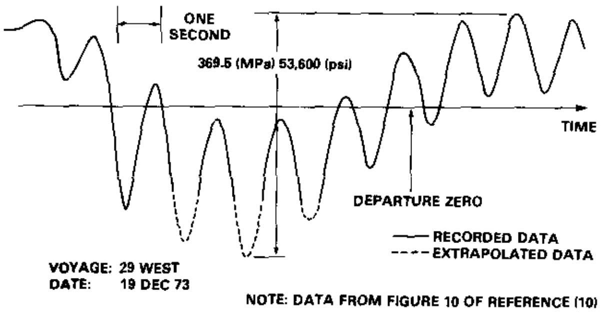

Figure 9 - Extreme Hull Girder Bending Stress Measured on S.S. SEALAND-McLEAN

hatches, superstructure, windows, and deck mounted equipment or weapons are all of potential concern. Because this tends to represent a somewhat overwhelming array of potential loading problems, the results of on-going damage surveys and individual in-depth heavy-weather damage studies are being used to focus attention on ship types and structural components of known concern so that model testing objectives can be established in a logical manner.

It is well to note here that the Task IV goal of identifying critical loading conditions could conceivably be accomplished without recourse to model testing. In the case of the SL-7, for example, at least one seaway loading condition of critical interest is considered self-evident from the full-scale measurements discussed previously. For most ship designs, however, these unique full-scale data do not exist and other means are required. At this point one might consider emphasizing either computer simulations or model tests to identify critical loading conditions. The latter course of development has been chosen here because of the nonlinear loading and response behavior anticipated as well as because local loadings on superstructure, cargo hatches, etc., are required (as well as hull girder shear and bending loads) in view of the findings of the damage survey. Only a scale model can readily furnish information relative to all of these concerns. At the same time, it is recognized that no satisfactory basis exists for scaling wave impact loadings from a model to a full-scale ship. As a minimum, however, model tests in critical time domain waves can identify loading problems associated with a particular ship configuration as well as suggest changes which would help to circumvent individual problems. The choice between scale modeling and computer modeling is, thus, believed to favor the former at this time. In the long run, however, computer modeling is expected to be more economical and less time consuming than scale modeling so that its development and validation remains an important initiative not withstanding the emphasis currently placed on model testing.

TASK V: DEVELOP LOAD PREDICTION METHODS

The recognition of wave impact loadings as a significant damage source clearly calls for emphasis on the development of load prediction methods appropriate to this type of loading. Window failures in particular have suggested the importance of replacing "equivalent static load" criteria with more realistic dynamic load criteria so that the response of structures containing glass, when subject to the loadings associated with extreme waves, can be properly evaluated. The extreme hull girder bending strains measured on the high-speed containership S.S. SEA-LAND McLEAN (10) reveal whipping stresses on the same order as the coincident wave-induced bending stresses. In view of this, the development of bow-flare load prediction methods is clearly essential for overall hull girder shear and bending moment determinations. Based on at-sea measurements of hull-girder bending strains on the dry cargo ship S.S. WOLVERINE STATE (11), a similar statement can be made relative to bottom slamming loads in dealing with extreme stresses for this class of ship. In order to exploit anticipated progress in defining critical time-domain waves, it is also clear that deterministic impact load prediction methods will be required.

The limited research performed to date in this Task has been directed toward load characterization as indicated in Figure 10 because load prediction methods must necessarily account for the dominant physical characteristics of the process. Because of the availability of a relatively complete set of test data for certain flatbottomed and 10-deg deadrise models which are representative of full-scale construction (12), (13), (14), characterization of bottom slamming loads was undertaken first. Equally important initiatives for bow-flare slamming and wave-impact load characterizations (including sloshing loads) also exist.

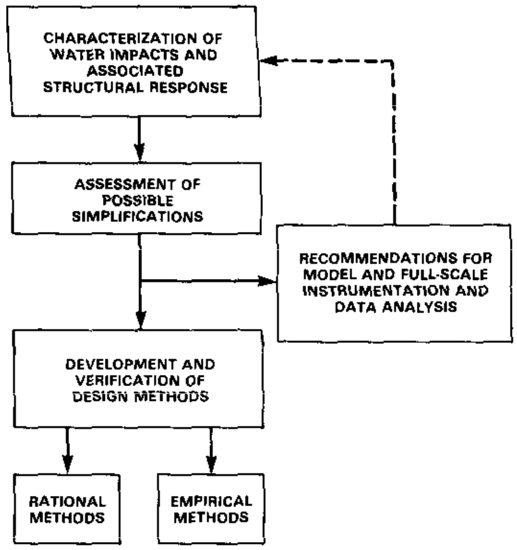

Figure 10 - Sub-Tasks for Development of Load and Response Prediction Methods for Water Impacts

The model tests upon which bottom-slamming characterization has been undertaken were somewhat unique in that the models which were tested were 1/4-scale representations of the bottom structure of a U.S. Coast Guard ship, see Figures 11 and 12. The instrumentation suite, while quite limited in certain important respects, nevertheless provided relatively extensive hull-bottom pressure measurements, as well as a limited number of component strain, deflection, and velocity measurements. In the case of the 10-deg deadrise models, extensive permanent set measurements were made and the models were generally tested until severe hull-bottom distortions were experienced. On a less positive note, the high-frequency pressure gages on the models were not flush mounted, but instead were attached to the outside of the bottom surface where they appear to have been subject to pressures associated with transverse flow across the bottom of the models. These pressures appear to have been generally low, however, and primarily associated with the 10-deg deadrise model. Because the tests were performed near an exposed bay, the water surface was subject to small waves as shown in Figure 13. This condition is regarded here as advantageous from an impact characterization point of view because full-scale impacts normally occur on water surfaces which are highly irregular. While the test conditions were not truly representative of rough-water operation, they at least permit a partial assessment of the influence of a realistic sea surface.

The characterization of bottom impact loadings has been undertaken on the basis of: (a) rigid-bottom impacts on smooth water, (b) flexible-bottom impacts on substantially smooth water, and (c) flexible-bottom impacts on a disturbed water surface. Because the test data being examined are necessarily limited, the characterization illustrates certain

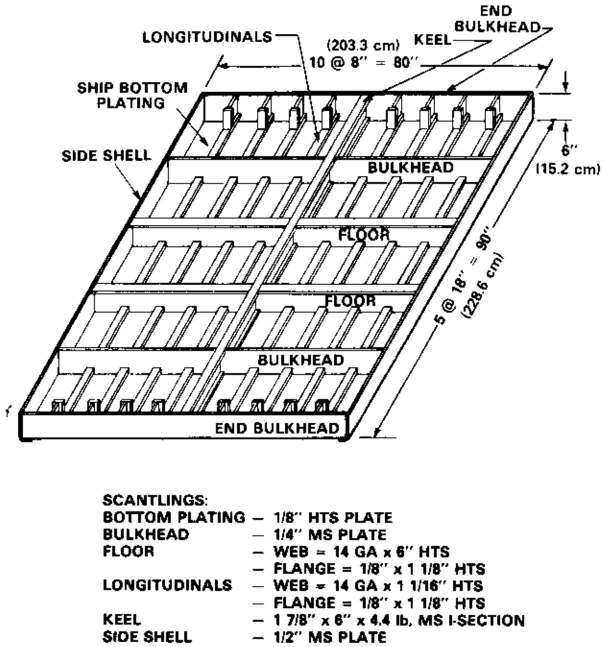

Figure 11 - One-Quarter-Scale Model Representing a Flat Bottom Portion of a Ship Bottom

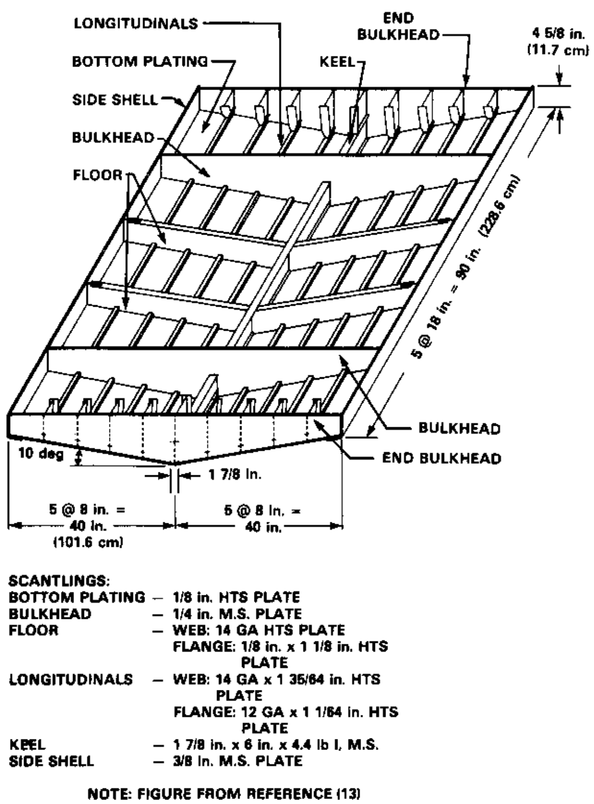

Figure 12 - One-Quarter-Scale Model Representing a 10-Degree Portion Deadrise Portion of Ship Bottom

dominant characteristics of bottom slamming and do not represent a full characterization of the impact process.

RIGID-BOTTOM IMPACTS

The model tests reported by Chuang (15), have been reexamined using the "velocity mapping" approach described next in order to characterize the temporal and spatial aspects of calm-water impacts for the 3, 6, 10, and 15 deg deadrise models employed in these tests. The basic model geometry is shown in Figure 14 together with representative pressure pulses measured during the drop tests. The instant of maximum pressure at each of the pressure gages has been identified and the relationship between gage location and time for

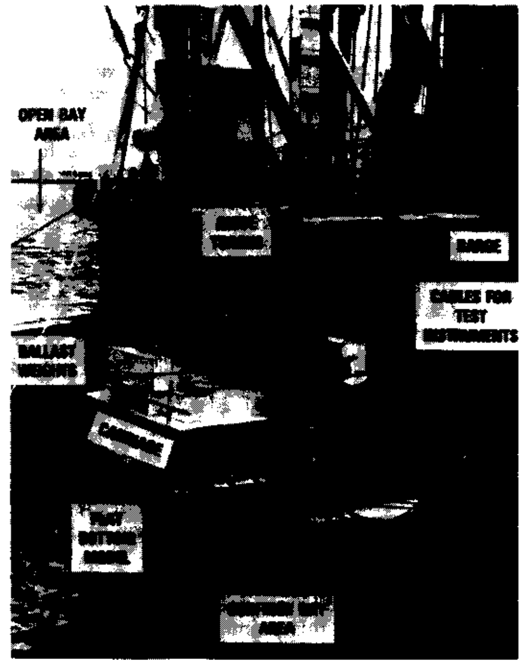

Figure 13 - Facility for 1/4-Scale Model Drop Tests

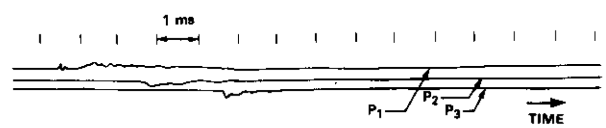

Figure 14a - 3-Degree Deadrise Model

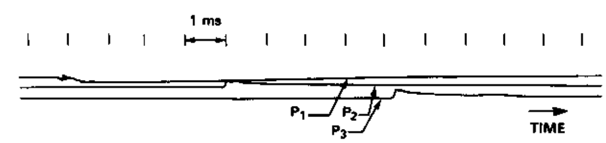

Figure 14b - 6-Degree Deadrise Model

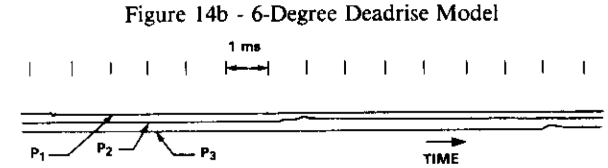

Figure 14c - 10-Degree Deadrise Model

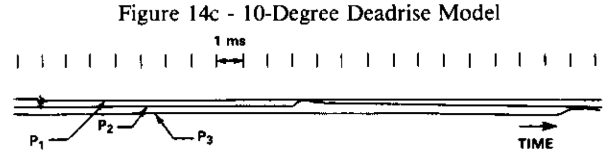

Figure 14d - 15-Degree Deadrise Model

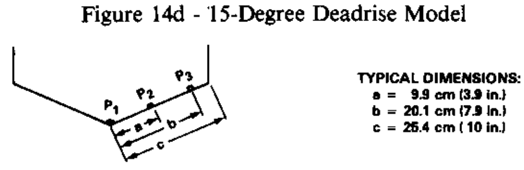

Figure 14 - Pressure versus Time Traces from Rigid Bottom Model Drop Tests

the peak pulse to reach it are plotted in Figure 15. The local slope of each curve defines the velocity with which the pressure peak passed over the respective gage. This then permits individual pressure versus time traces to be interpreted as pressure versus distance. For discussion purposes, the width of a pressure pulse has been arbitrarily defined as shown in Figure 16. The width of the various pulses in time and in space have been tabulated in Figure 16 from which it can be seen that, for deadrise angles of 6, 10, and 15 deg, the pressure pulse was approximately 1.1 cm (0.4 in.) in width and traveled at a speed approximately 1.5 times the model velocity at impact divided by the sine of the deadrise angle. At a deadrise angle of 3 deg the pulse widened to approximately 2 cm (0.8 in.). The peak pressure loading is clearly of such speed and limited size that it cannot logically be treated as a static loading. Moreover, the statement of peak pressure without futher specification of its size, shape, and speed of propagation is inadequate for purposes of evaluating structural response.

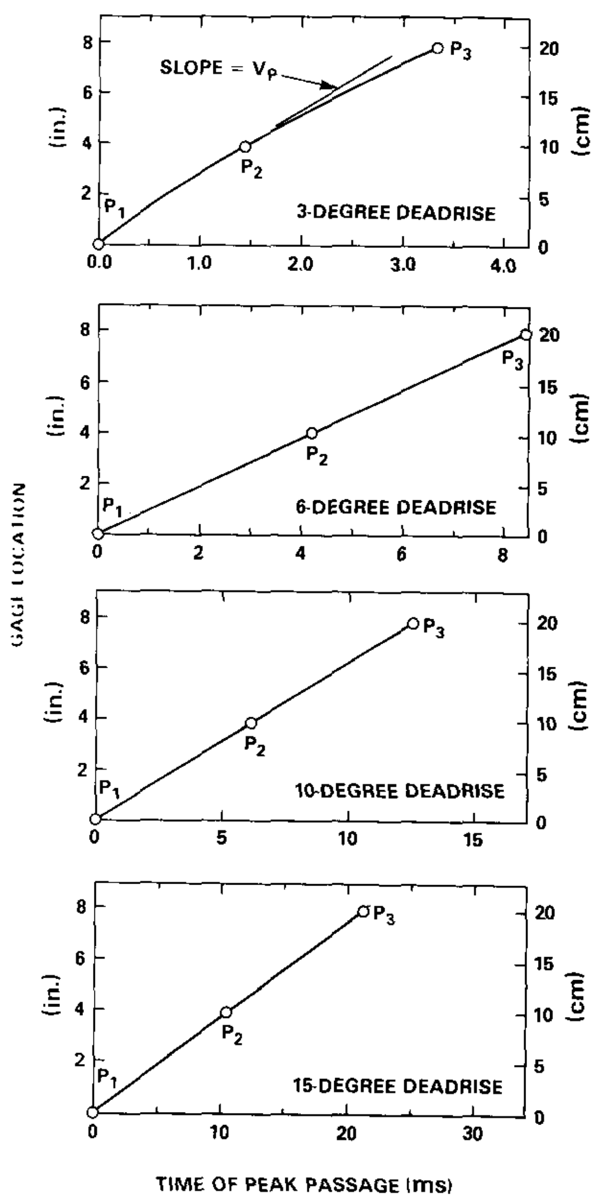

Figure 15 - Determination of Velocity of Peak Pressure Pulse from Rigid Model Drop Tests

LOCATION	V_P (cm/ms)	V_T (cm/ms)	V_P/V_T	PULSE WIDTH (ms)	(cm)	(in.)
3-DEGREES DEADRISE						
P_2	5.84	3.30	1.77	0.39	2.29	0.90
P_3	4.83	3.30	1.46	0.39	1.88	0.74
6-DEGREES DEADRISE						
P_2	2.39	1.65	1.45	0.47	1.12	0.44
P_3	2.39	1.65	1.45	0.39	0.94	0.37
10-DEGREES DEADRISE						
P_2	1.60	0.99	1.62	0.69	1.09	0.43
P_3	1.60	0.99	1.62	0.69	1.09	0.43
15-DEGREES DEADRISE						
P_2	0.97	0.66	1.46	1.30	1.24	0.49
P_3	0.97	0.66	1.46	–	–	–

V_P = VELOCITY OF PEAK PRESSURE PULSE.
V_T = IMPACT VELOCITY OF MODEL/SINE OF DEADRISE ANGLE.

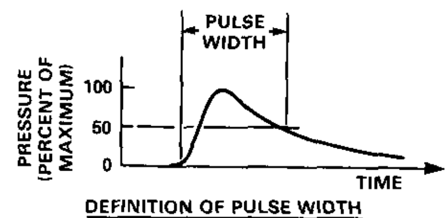

Figure 16 - Widths of Pressure Pulses from Rigid Model Drop Tests

For very low deadrise angles, the entrapment of air and local depression of the water surface enter as major characterizations, see Chuang (16). The pressure loading under these circumstances broadens rapidly in time and space which presents a substantially different loading model than that observed at higher deadrise angles. For low deadrise impacts on calm water, it should be noted that velocity mapping is no longer possible, or, in fact, necessary.

The question of scaling the width of a pressure pulse associated with the higher deadrise angle impacts is a matter of some interest. Because of the progressive nature of the impact, the width of the pressure pulse would appear to be independent of model size. The pulse, in a sense, simply runs out of bottom surface sooner on a model than on the full-scale structure. As noted below, the effects of structural deformation and the irregular contour of an actual seaway also play major roles in determining transient pressure patterns and further discussion will be deferred.

FLEXIBLE-BOTTOM IMPACTS

The subjects of flexible-bottom and irregular water surface effects will be discussed separately using the test data of references (12), (13), and (14).[1] It is unavoidable, however,

[1]The data from these reports which are shown in Figures 17, 18, 19, 22, 23, and 24 exceeds the minimum needed to illustrate the major points of this discussion. A liberal approach has been taken because these reports have not been available for general distribution for an extended period of time. The number of drop tests and material conditions associated with the tests, on the other hand, far exceeds those discussed here.

that both effects exist concurrently in all of the model drop tests. Because water surface irregularities least effect the 10-deg deadrise model, the associated test results are more suitable for characterizing the effects of elasticity alone. On the other hand, the zero-degree deadrise model test results are most effected by surface irregularities so that they have been considered to be more suitable for characterizing the effects of water surface roughness.

The results of drop tests of the 10-deg deadrise model from heights of 6 (1.83 m), 8 (2.44 m), and 25 ft (7.62 m) which are presented here in Figures 17, 18, and 19 are taken directly from Figures 8, 9, and 10 of reference (13). First, considering the bottom pressures of Figure 17 from the 6-ft drop test, it is evident that the various pressure versus time pulses are highly irregular compared to those measured on the rigid-bottom model of reference 15. Moreover, the characteristic pressure pulse for impact at high dead-rise angles first appears at PE-7 which is 16 in. from the keel of the model. In the case of the 8-ft drop test (Figure 18), the same is true except that PE-6 has a more clearly defined pulse than in the 6-ft drop. The pressure traces from the 25-ft drop of Figure 19, in which major structural distortions occurred, show even less tendency to result in the characteristically smooth pressure versus time pulses representative of rigid bottom impacts on calm water. The following table presents a comparison of the peak pressures measured in these three drops with those predicted by Figure 12 of reference 15 for a rigid-bottom model having the same 10-deg deadrise:

Drop (ft)	Pressure Gage	Peak Pressure (psi)	Rigid Bottom Peak Pressure (psi)	Pressure Ratio	(Flexible / Rigid)
6	PE-7	200	162	1.23	
8	PE-7	270	216	1.25	
25	PE-10	475	676	0.70	

For the 6- and 8-ft drops in which very little permanent deformation of the bottom structure was noted, local-peak pressures were approximately 25% higher than those predicted from the rigid-model tests, while in the 25-ft drop, which produced approximately 3 in. of permanent deformation at the center of the keel, the peak pressure was reduced to 70% of the rigid-model peak pressure. As shown in Figure 20, the apparent widths of the pressure pulses were 3.0- and 1.4-in. for the 6- and 8-ft drop, respectively, which is somewhat larger than the value of 0.4-in. for the rigid model. The pressure pulse at PE-7 for the 25-ft drop can be seen to be lower in magnitude (16% of the rigid-model value) and of longer duration than the previous pressure pulses. The inward permanent deformation at PE-7 was approximately 3 in. following this drop. It will be noted in Figures 17 and 18 that, for drops in which the model deflections were essentially elastic, the pressure pulse at PE-7, which was situated on a longitudinal stiffener, had a more abrupt initial pulse than the pressure measured at PE-6 which was located at the center of an adjacent plating panel. Of particular interest is a comparison of the time-varying pressure at PE-4 to the corresponding strain response of the transverse strain gage ST-4 on the plating panel at the same location. As shown in Figure 21, there is a correlation between panel deformations and panel pressures. The apparent modal frequency of 170 Hz can also be seen to appear in the pressure traces for PE-1, PE-2, and PE-3 and in the midpanel deflection gages MD-1 and MD-3.

It is thus clear, as noted earlier by Chuang (17), for example, that the deflection characteristics of the bottom structure can have a major influence on the pressures and stresses experienced during a bottom-impact loading.

IMPACTS ON DISTURBED WATER

The results of drop tests of the flat-bottom model of Figure 11, which are presented here in Figures 22, 23, and 24, have been assembled using data from several of the figures

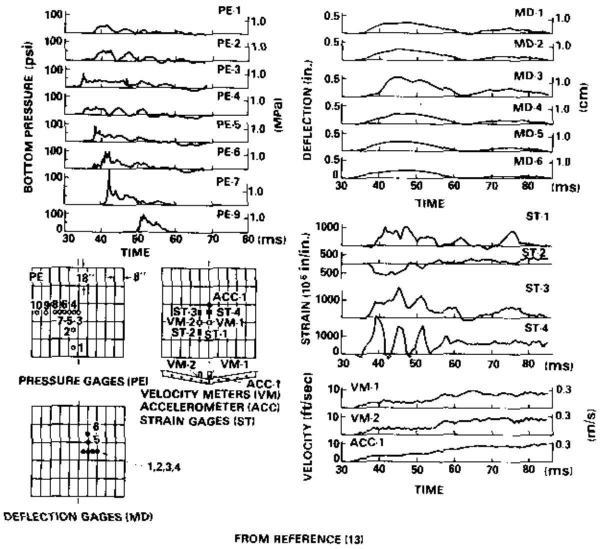

Figure 17 - Test Results for 6-Foot Drop Test of 10-Degree Deadrise Model

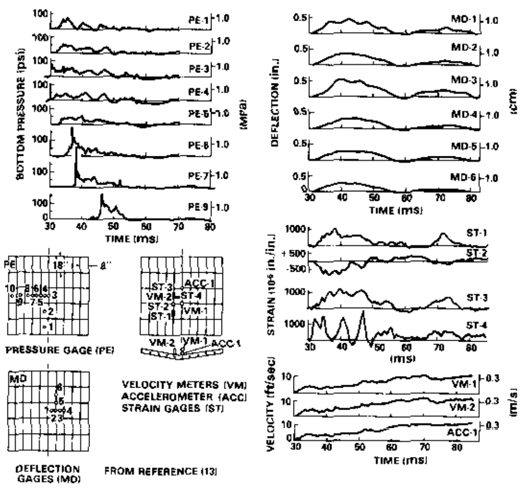

Figure 18 - Test Results for 8-Foot Drop Test of 10-Degree Deadrise Model

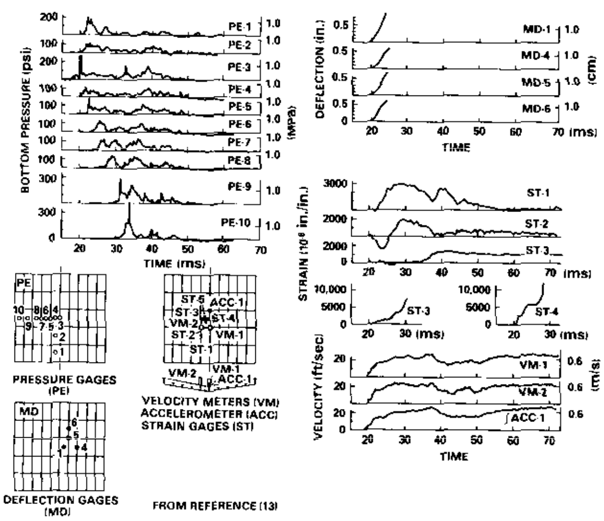

Figure 19 - Test Results for 25-Foot Drop Test of 10-Degree Deadrise Model

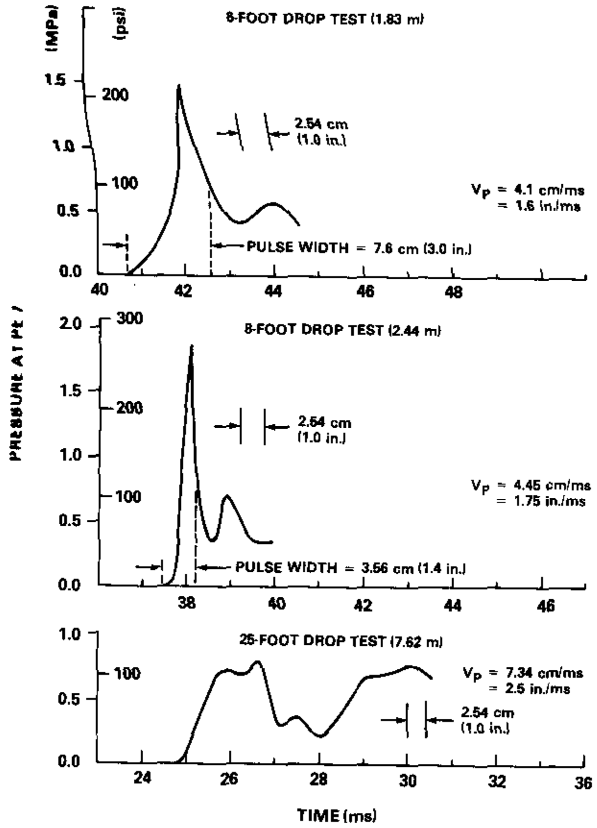

Figure 20 - Width of Pressure Pulses from Flexible Model Drop Tests

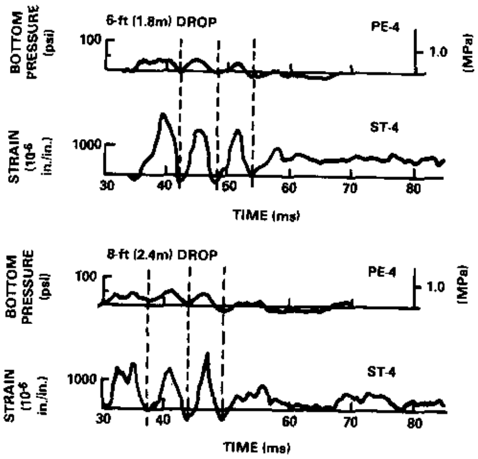

Figure 21 - Correlation of Panel Modal Response with External Pressure for 10-Degree Deadwise Model

presented in reference (12). The drop test heights in this test series were 2 (0.61), 4 (1.22), and 6 ft (1.83 m). No testing beyond 6 ft was performed because the bottom of the model had been dished-in approximately 0.8 in. so that it was no longer considered representative of flat-bottom hull construction.

The bottom pressure data, presented in Figure 22 for a 2-ft drop, reveal that impact occurred first near PE-17 and last (among locations where pressure was measured) at PE-10. The time lag between pressure peaks at these locations was approximately 13 milliseconds which corresponds to a vertical-motion increment of the model of about 3.5 in. This permits a rough estimate of the local slope of the water of about 3.5 in. in a distance of 72 in. between gages, or approximately 2.8 deg, which is a relatively modest slope considering what might be encountered in an actual seaway.

The pressure data of Figures 23 and 24 reveal that the model impacts were essentially flush during the 4-ft and 6-ft drops. It is, thus, of interest to compare the pressure, structural strain, and deflection characteristics from the 2-ft drop with the other two. During the 2-ft drop, the pressure measured at PE-4 and the corresponding midpanel strain measured by ST-4 show a strong modal response which is more characteristic of the 10-deg deadrise model data than that of the corresponding data of Figures 23 and 24 for the flush-impact drops. Of more interest perhaps is the fact that the extrapolated peak strain at ST-4 is greater for the 2-ft drop than either the 4- or 6-ft drops. Given that the peak pressure at PE-4 was approximately as great in the 2-ft drop as the other two and that a rapid rise to this pressure occurred, it is not surprising that a large dynamic panel strain occurred compared to the 4- and 6-ft drops where almost no dynamic response resulted. Comparing the peak strain at ST-4 due to a flush impact from a 6-ft drop height as shown in Figure 24, to that of Figure 17 for the 10-deg deadrise model when dropped from the same height, reveals that the latter produced a higher peak panel strain, namely 2200 versus 1300 10^{-6} in./in. This finding is essentially consistent with the result of the 2-ft drop of the flat-bottomed model onto disturbed water producing a higher panel strain than a 6-ft drop of the same model onto a undisturbed water surface.

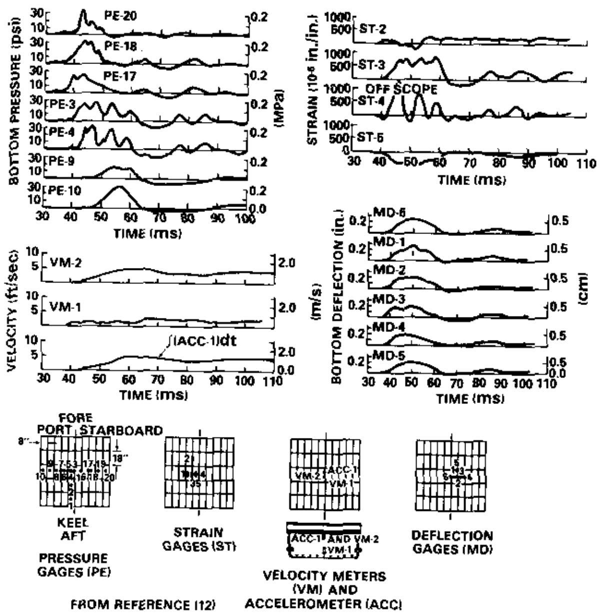

Figure 22 - Test Results for 2-Foot Drop Test of Flat Bottomed Model

The vertical-velocity traces of Figures 22, 23, and 24 for VM-2, which was rigidly mounted on the flat-bottomed model, indicate that the initial acceleration of the model in each case was as follows:

Model	Initial Deceleration (VM-2) (g's)	Drop Height (ft)
Flat Bottom	9.3 (VM-2)	2
Flat Bottom	19.4 (VM-2)	4
Flat Bottom	31.1 (VM-2)	6
10-Degree Deadrise	13.2 (VM-1)	6

The initial deceleration of the flat-bottom model appears to be approximately proportional to the drop height and, judging by the results of the 2-ft drop, was apparently not much affected by the slightly disturbed water surface in-

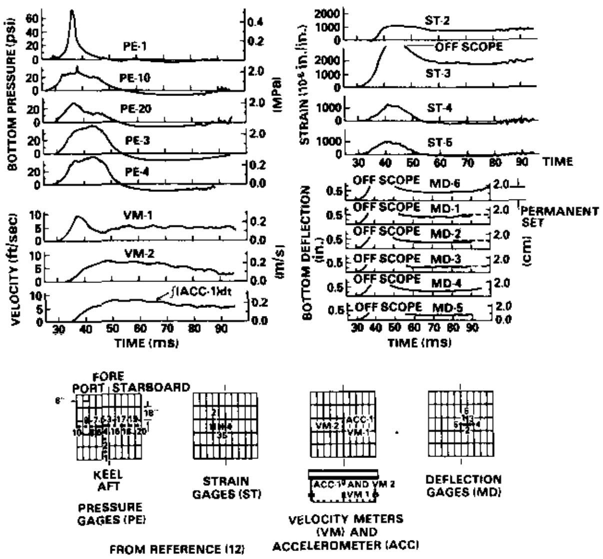

Figure 23 - Test Results for 4-Foot Drop Test of Flat-Bottomed Model

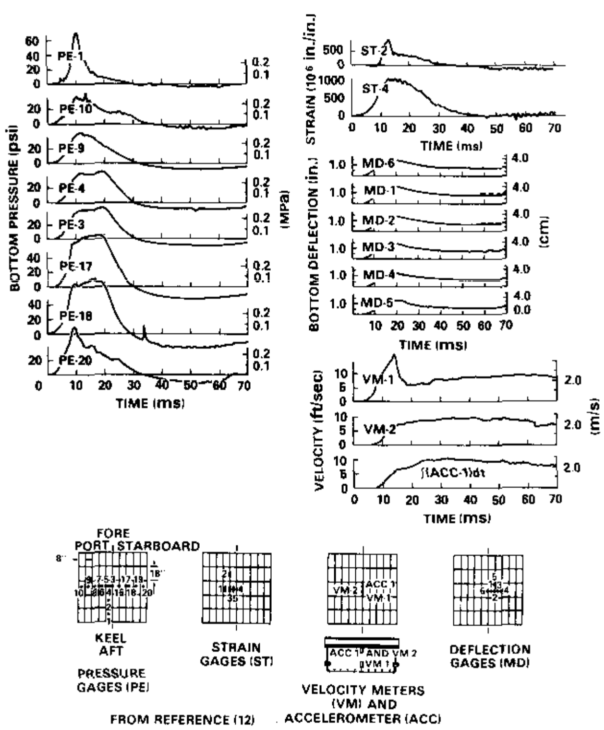

Figure 24 - Test Results for 6-Foot Drop Test of Flat-Bottomed Model

volved. The initial acceleration for the 6-ft drop of the 10-deg deadrise model is also given here to illustrate the alleviation of initial acceleration by hull-bottom deadrise. In this case, the velocity meter was mounted on the flexible bottom of the model so that the rigid body deceleration is likely to be significantly less than the value indicated by VM-1 (e.g., compare VM-1 to VM-2 in Figure 24).

It can be seen from the foregoing discussion that 10 deg of deadrise produces substantially lower overall bottom loadings but higher local plating pressures and stresses than a flat-bottomed model of the same size when dropped from the same height. This trend is further confirmed by other strain and deflection data. The deflection gages MD-1 through MD-6 of Figure 24 show that permanent deformation of the transverse members of the flat-bottomed model occurred during the 6-ft drop. The strain gage ST-4 in this figure indicates, however, that no significant permanent deformation occurred in the plating panel which was strain gaged. The corresponding data of Figure 17 for the 6-ft drop of the 10-deg deadrise model show that the reverse was true of that model because ST-4 shows a significant permanent strain whereas the deflection gages show no appreciable set in the transverse members.

Based on the foregoing characterizations it is believed reasonable to conclude that the peak pressures associated with rigid-bottom impacts at moderate deadrise angles tend to apply over very limited areas (measured in the direction of the advancing spray root) and, therefore, are apt to have limited meaning from a structural response point of view without further characterization. Flexibility in hullbottom structure appears generally to diminish peak pressures and to cause them to act over a larger area of the local structure. In addition, dynamic response of hull-bottom plating can substantially alter the pressures seen by the plating. Relative to the influence of an actual seaway surface on impact pressures, it is seen that a flat-bottomed structure impacting on an irregular water surface can produce plating stresses characteristic of a hull-bottom with deadrise impacting on a smooth water surface; see also reference (18). Finally, it is believed reasonable to conclude that a complete characterization of water impacts and structural response is an essential first step in the process of developing load prediction methods.

Returning to Figure 10, the second major subtask in Task V is the assessment of possible simplifications in the process of transitioning from impact characterization to the development of structural response prediction methods. In view of the complexity evident in the characterization of flexible-bottom impact loadings and associated structural response, it is believed that the development of viable methods for estimating design loadings is critically dependent upon the identification of justifiable simplifications or restriction in methodology. No work has been undertaken to date on this subtask because characterization of slamming and wave-impact loadings has itself only recently been initiated. Among the obvious approaches in this area are:

(a) Treating plating, supporting members, and hull-girder loadings separately as regards design methods.

(b) Defining applied loadings on an impulsive basis (i.e., integral of Fdt) rather than in a force versus time context.

(c) Identifying and addressing "worst cases" primarily.

(d) Using damage patterns and service experience to direct methods of development toward most needed areas and to help preclude unrealistic assumptions or approximations.

Successful completion of the subtask of Figure 10, designated Development and Verification of Design Methods, is believed to be heavily dependent upon how well the previous subtasks have been accomplished. Major efforts in this area will be deferred until the subtasks have been substantially completed.

An auxillary subtask of Figure 10 is Recommendations for Model and Full-Scale Instrumentation and Data Analyses. Instrumentation and associated data analysis methods employed in bottom-slamming and wave-impact experiments must be related to the results of the first two subtasks of Figure 10. This relationship exists because, on the one hand, meaningful impact characterizations are critically dependent upon the availability of test data which permit meaningful characterizations, while on the other hand, appropriate instrumentation requires that a comprehensive characterization of the impact process has been completed so that appropriate instrumentation and data analysis procedures will be employed. The brief characterization of bottom-slamming presented here suggests that an extensive, high-frequency response instrumentation suite is apt to be required when testing nonrigid structural models. Certainly, structural members typically subject to damage, such as frames and hull plating, should be well strain gaged in addition to shell plating. In regard to data analysis methods, it is recommended that velocity mapping be employed whenever possible to provide adequate spatial and velocity characterization of transient pressure peaks.

The subtask of Figure 10 entitled Development and Verification of Design Methods is anticipated to have two paths of development, namely Empirical Methods, which attempt to deal with the complexity revealed by characterization studies in an essentially empirical manner, and Rational Methods which deal with the problem essentially from first principles. The former may be a practical necessity in view of the inherent complexity of the latter.

TASK VI: DEVELOP STRUCTURAL CRITERIA AND RELATED STRENGTH PREDICTION METHODS

Structural design to withstand loadings associated with extreme waves introduces the need for criteria defining acceptable structural behavior under extreme design loads. Hull and superstructure plating when subject to "once in a lifetime" loadings should be permitted to experience substantial permanent deformation where watertight integrity has been preserved and where the costs of plating repairs are unlikely to be recurring because of the "once in a lifetime" nature of the wave loading. Failure of members which could result in substantial loss of watertight integrity or which could result in gross structural failures obviously should not be permitted. Again structural deformations as such are not prima facie evidence of structural failure under such conditions. There is a clear need for strength prediction methods under "ultimate" loading conditions as well as for criteria defining acceptable structural behavior. Fortunately, some important ground work has been layed in these areas but more development is believed required. See for example, the report of Committee 11.2 in reference (19). The primary objective of this task in any event is to establish criteria defining acceptable or unacceptable structural behavior under extreme loadings and to clearly identify any new structural analysis method requirements associated with them. The success of the overall loads development program discussed here is thus dependent upon developments in the realm of strength prediction methods which are beyond the scope of the immediate program.

AN OVERVIEW

The broad approach to load criteria development undertaken here could become self defeating because the limited resources in hand for the overall program could easily be inadequate for significant progress to be made in any one task area. Up to the present time, however, this has not been the case for several reasons. First of all, progress in Tasks I and II (especially the latter) has been encouraging due to the use of half-cycle data analysis techniques to identify extreme waves and also because the respective task findings have complimented one another. Progress in regard to Task III which has now been directed toward time-domain wave generation is benefiting from research in tank wave generation in the civil engineering community. While there has been only limited program activity to date relative to Tasks IV, V, and VI, it now appears that the results of earlier model tests and full-scale measurements will be helpful in these task areas and that significant progress is possible initially for relatively modest investments of time and money.

Ultimately, progress in most of these task areas will require more substantial investments in manpower and funding. Because of this, it is the authors' hope that the loads criteria development program reviewed here will not only prove to be a workable plan of development, but also will stimulate interest and further research activity by other investigators. In particular, two tasks are suggested as candidates for coordinated research.

(a) The first is time-series wave generation in both linear and seakeeping test tanks. The mechanical and operating control characteristics of wave making equipment capable of producing specified time-domain waves at a specified time and location in a test tank for model response characterization needs to be investigated. This capability, which is vital in determining the effect of extreme waves on ships and other marine structures, is also important in capsizing studies.

(b) The second is the establishment of recommended instrumentation and data analysis methods for use in model and full-scale testing involving slam and wave impact loadings. The temporal and spatial characteristics of such loadings must be better defined than has been done typically in the past if response prediction methods are to be properly developed. The interaction between structural response and applied loadings must be considered as well as the fact that most water impact loadings of practical interest occur on rough water surfaces. In view of the relatively high incidence of ship heavy weather damage due to wave impacts, instrumentation and data analysis methods are essential for such loadings as well as those associated with hull bottom and bow flare slamming.

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