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(SL-7-5)

SL-7 INSTRUMENTATION PROGRAM BACKGROUND AND RESEARCH PLAN

SHIP STRUCTURE COMMITTEE

1976

SHIP STRUCTURE COMMITTEE

AN INTERAGENCY ADVISORY
COMMITTEE DEDICATED TO IMPROVING
THE STRUCTURE OF SHIPS

ADDRESS CORRESPONDENCE TO:

Secretary
Ship Structure Committee
U.S. Coast Guard Headquarters
Washington, D.C. 20590

SR-217
16 JAN 1976

This report is one of a group of Ship Structure Committee Reports which describes the SL-7 Instrumentation Program. This program, a jointly funded undertaking of Sea-Land Service, Inc., the American Bureau of Shipping and the Ship Structure Committee, represents an excellent example of cooperation between private industry, regulatory authority and government. The goal of the program is to advance understanding of the performance of ships' hull structures and the effectiveness of the analytical and experimental methods used in their design. While the experiments and analyses of the program are keyed to the SL-7 Containership and a considerable body of data will be developed relating specifically to that ship, the conclusions of the program will be completely general, and thus applicable to any surface ship structure.

The program includes measurement of hull stresses, accelerations and environmental and operating data on the S.S. Sea-Land McLean, development and installation of a microwave radar wavemeter for measuring the seaway encountered by the vessel, a wave tank model study and a theoretical hydrodynamic analysis which relate to the wave induced loads, a structural model study and a finite element structural analysis which relate to the structural response, and installation of long term stress recorders on each of the eight vessels of the class. In addition, work is underway to develop the initial correlations of the results of the several program elements.

Results of each of the program elements will be published as Ship Structure Committee Reports and each of the reports relating to this program will be identified by an SL- designation along with the usual SSC- number. A list of all of the SL- reports published to date is included on the back cover of this report.

This report contains a discussion of the several program elements and possible correlations of their results.

W. M. Benkert
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

FINAL REPORT

on

Project SR-217, "SL-7 Data Analysis and Correlation"

SL-7 INSTRUMENTATION PROGRAM

BACKGROUND AND RESEARCH PLAN

by

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under

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U. S. Coast Guard Headquarters
Washington, D.C.
1976

ABSTRACT

The SL-7 Instrumentation Program is one of the most comprehensive coordinated surface ship load and response analysis programs ever undertaken. The program includes measurement of hull stresses, accelerations and environmental and operating data on the S.S. SEA-LAND McLEAN, development and installation of a microwave radar wavemeter for measuring the seaway encountered by the vessel, a wave tank model study and a theoretical hydrodynamic analysis which relate to the wave-induced loads, a structural model study and a finite element structural analysis which relates to the structural response, and installation of long term stress recorders on each of the eight vessels of the class. This report presents an overview of the program. The experimental background upon which the program was based and the major features and expected outputs of each of the program elements are discussed, and some preliminary conclusions drawn from the research results are presented. A detailed description of the possible data correlations and their consequences is included. The long-range goal of the program is to advance understanding of the performance of ships' hull structures and the effectiveness of the analytical and experimental methods used in their design. A research plan to achieve this is outlined.

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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.

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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.

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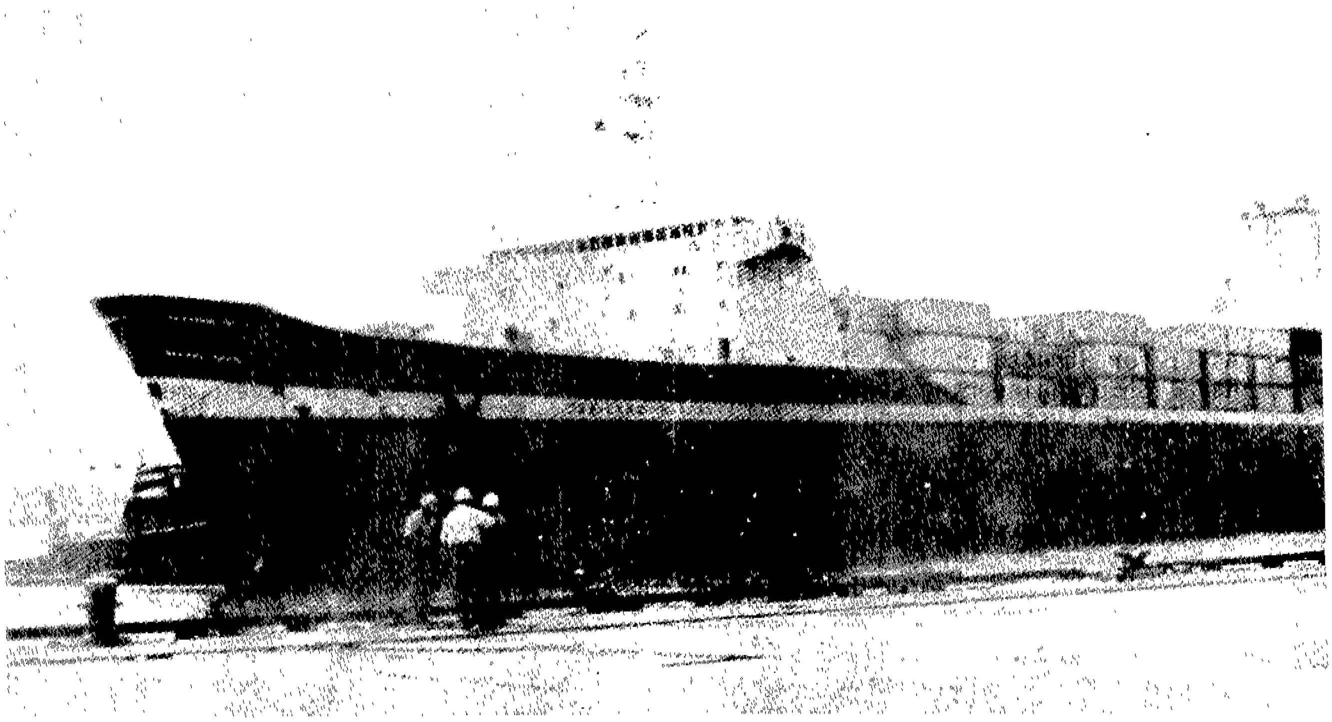


S.S. SEA-LAND McLEAN

CHARACTERISTICS OF S.S. SEA-LAND McLEAN

Name:	SEA-LAND McLEAN
Builder:	Rotterdam Dry Dock (HULL 330)
Class:	SL-7 Containership
Length, overall	946' 1-1/2"
Length, between perpendiculars	880' 6"
Beam, molded	105' 6"
Depth to main deck, forward	64' 0"
Depth to main deck, aft	68' 6"
Draft, design	30' 0"
Draft, scantling	34' 0"
Dead weight - long tons	27, 315
Displacement (34' 0" draft) - long tons	50,315
Machinery	Two separate cross-compound steam turbines driving two propeller shafts
Shaft horsepower-maximum continuous, both shafts	120,000
Propeller RPM	135
Speed, maximum, knots	33
Center of gravity - full load	399.32' forward of aft perpendicular 42.65' above base line

Container Capacity

	8' x 8.5' x 35'	8' x 8.5' x 40'	Total
Below deck	554	140	694
Above deck	342	60	402
TOTAL	896	200	1,096

INTRODUCTION

The SL-7 Research Program is the most comprehensive coordinated surface ship load and response analysis research program ever undertaken. The program is a jointly funded, multi-element research program, sponsored by the Ship Structure Committee, the American Bureau of Shipping, and Sea-Land Service Inc. which includes theoretical analysis, model tests, and full-scale measurements of seaway loads. Although the analytical and experimental work was performed for the SL-7 containership, the techniques are completely general and thus may be applied to similar conventional ship types.

As originally conceived, the program included five elements:

1. Reduction and analysis of the data obtained from the instruments installed on board the SL-7 vessel S.S. SEA-LAND McLEAN, by Teledyne Materials Research, Waltham, Mass.; SR-211, "SL-7 Data Collection Program".

2. Structural model tests of the SL-7 by the University of California, Berkeley, California; ABS sponsored.

3. Finite element analysis (DAISY) of the SL-7 and structural model by the American Bureau of Shipping.

4. Bending and shear load model tests by Stevens Institute of Technology, Hoboken, N. J.; SR-204, "SL-7 Torsional Model Study".

5. Theoretical hydrodynamic analysis (SCORES) by Oceanics, Inc., Plainview, N. Y.; SR-205, "SL-7 Load and Computer Response".

Although these five initial projects were designed so that the experimental data were of some form and content, the results of each were reported separately. It was therefore necessary to integrate and correlate the research results and test data to maximize the usefulness of the total program. This work was undertaken by the Naval Ship Engineering Center and consisted of a review of the nature and characteristics of the results of the other elements of the SL-7 research program, definition of the interactions of these outputs (e.g., correlations) and identification of groups of data and specific quantities for detailed correlations:

6. SL-7 Data analysis and correlation by the Naval Ship Engineering Center, Hyattsville, Maryland; SR-217, "SL-7 Data Analysis and Correlation".

This report includes a description of the overall program, outlines some of the details of the planning for the program not reported elsewhere, describes some of the possible correlations and comparisons of the program results and, finally, presents a summary research plan for the analysis of the program results and the integration of them into the long-range goals of the Ship Structure Committee.

The SL-7 Research Program has deep roots in the Ship Structure Committee's research history. It was preceded by an extensive series of model tests, computer analyses, and full-scale data collection projects. In fact, most of the full scale vessel instrumentation technology in use today, both in this program and elsewhere, was developed under the sponsorship of the Ship Structure Committee. In planning for this project, it was necessary to review the reports of all of the preceding related projects to identify those factors to be considered and to provide a basis for selection of the various methods of approach. One of the results of this review was the preparation of a brief history of these preceding projects, which is included in this report. Many of these prior projects had a profound impact on the SL-7 Research program and, where possible, this impact has been identified and discussed, particularly where these prior projects have influenced the formulation of the method of data acquisition in the SL-7 Research Program.

The second section of this report contains a description of the projects which make up the program, including the wave data reduction and correlation project; SR-221, "Correlation and Verification of Wavemeter Data from SL-7". While this project was not one of those originally considered in the development of the SL-7 Research Program, it quickly became apparent that this was an obvious, if not vital, aspect of the overall effort. In fact, it is the measurement of wave data rather than simple visual observation of it which sets the SL-7 Instrumentation Program apart from other similar work.

The third section of the report consists of a discussion of the preliminary correlations and comparisons of the results of the various projects. A brief discussion of some of the possible errors in the data is also included.

Section four presents an outline of the long-range research plan by which it should be possible to utilize the data from the SL-7 Instrumentation Program to make significant progress toward achieving several long-range goals of the Ship Structure Committee. This plan contemplates numerous years before all of the data collection is completed, and relies heavily on research outside of the SL-7 Instrumentation Program as well.

Finally, this report contains three appendices which discuss details on the rational behind and of difficulties and inaccuracies involved in strain-gage instrumentation of a large ship, such as the SL-7 containership.

While this report is complete in itself, it must be emphasized that it is only one of a series of Ship Structure Committee reports concerning the SL-7 Research Program. The discussions in this report of the separate projects in the program are necessarily brief and reference should be made to the individual reports of the projects before any conclusions as to their validity or method of performance are reached. Furthermore, the suggestions for follow-on research projects included in this report are based on preliminary experimental data. It is altogether possible that detailed analyses will point toward research in a distinctly different direction. However, working with the information available to date, this report represents a summary of the thinking behind and the long-range purposes of the SL-7 Instrumentation Program.

I. BACKGROUND

The Ship Structure Committee has sponsored a considerable amount of research involving model tests, theoretical analyses and full-scale instrumentation. One of the steps in the development of the SL-7 Instrumentation Program was a thorough review of the reports of this earlier research. This section contains the results of this review and a description of how this prior work influenced the SL-7 Instrumentation Program.

A. Hydrodynamic Model Data

The determination of wave-induced structural loads from experimentation on ship models is a relatively new procedure. Lewis [1] at Webb first presented an early analysis in 1954. These initial experiments involved measurement of just midship bending moments in only head and following seas. Subsequently, the experimental procedures were expanded to cover a greater range of parameters. Numata [2] at Davidson Laboratory, conducted tests of a model of a T-2 tanker running oblique to the waves in order to obtain vertical and lateral bending moments and torsional moments. Numata's work was quickly followed in 1960 by an extensive series of tests on Series 60 models by Vossers, et al., [3] at the Netherlands Ship Model Basis (NSMB). Additional tests were conducted for determination of wave-induced loads at points along the hull other than at midships. However, few results from these experiments are available, and some experimental problems still exist. An intensive test series of a model of a Series 60 hull, with block co-efficient of .80 was reported by Wahab [4] in 1967. These experiments were conducted over a wide range of regular wave lengths and heading angles. Measurements included vertical, lateral, and torsional bending moments, and vertical and lateral shears, all at midships.

Recently, the Ship Structure Committee has supported experimental work at Davidson Laboratory [5, 6, 7, 8, 9, 10, 11]. The majority of this Ship Structure Committee research involved measurement of model midship bending moments in regular and irregular waves and was related to full-scale measurement projects. The initial phase of this group of projects was conducted by Dalzell [5], and covered investigations of trends of midship bending moment in a model of a MARINER class vessel as a function of extreme wave steepness. These experiments included a variation in freeboard, two weight distributions, two speeds, i.e. drifting and 20 knots prototype, for head and following regular seas of steepness as great as 1/9. In addition to bending moments, trends of pitch and heave amplitudes with wave steepness, in head or following seas, were examined. Comparisons of the data from these experiments with previous independent data showed reasonably close agreement at low wave heights in 1.0 L waves at both speeds [12], but greater differences arose at the other wave lengths. Other model tests [13, 14], with a higher block coefficient model, generally showed higher moments, particularly in 1.0 L waves. This is to be expected, according to Dalzell [13], who demonstrated that wave bending moment increases as the block coefficient increases.

Subsequent work by Dalzell [6] involved the running of model tests, similar to those previously run [5], for a tanker (106,000 DW tons) and a destroyer. Wave length ratios were varied from .5 L to 1.75 L, speeds varied from drifting to full forward, into head or with following seas. Comparison of data obtained, with other work [12, 13, 15] is satisfactory, and earlier results [16] agree with this work. This implies that midship bending moments are roughly proportional to wave steepness over a very large range of steepness with no apparent upper physical limit. The tanker model results were compared with similar ship-form data [12, 13, 15] and good agreement was shown.

The earlier work [5, 6, 7] was limited to midship bending moments, although it was known that maximum moments could occur elsewhere. The succeeding phase of the studies conducted by Maniar [8] at Stevens examined the longitudinal distribution of bending moments in a model of a MARINER-class cargo ship in regular waves of extreme steepness. The model selected was that of the original MARINER with the same cargo amidships loading that had been tested previously. Experiments were run in essentially the same waves as the previous experiments [5, 6, 7], but with a variation in wavelength to ship length ratios from .75 to 1.75, and the wavelength to ship length ratios from .05 to .11, for forward, zero, and drift speed in head seas, and with forward speed in following seas. Dalzell's work [5, 6, 7] was done on the same ship with the same weight and configuration, except for a minor difference in the midship deckhouse. Comparison of Dalzell's work with Maniar's at midships shows that the sagging moments Dalzell measured were consistently lower than those of Maniar by about 10 percent, while Dalzell's hogging moment results were generally higher than Maniar's by about 30 percent in head seas and 12 percent in following seas. In all cases a visual comparion of slope variations of corresponding curves show good agreement between the two sets of results. Additionally, bending moment results in head seas compare very well with the David Taylor Model Basin data [17].

Maniar and Numata continued their experiments with the MARINER-type cargo ship [9], augmenting their earlier work [8] with high, irregular, long-crested waves, equivalent to a sea state 7, and obtained time history records of wave bending moments and wave elevations. The bending moment response amplitude was obtained and plotted versus frequency of wave encounter, giving a Response Amplitude Operator (R.A.O.) plot. These data were then analyzed to test the premise that a ship-wave system is linear. The hypothesis has been stated by Lewis as follows: "The response of a ship to an irregular sea can be represented by a linear summation of its response to the components of the sea" [9]. Maniar's tests of each loading condition in regular waves [8, 9] showed bending moments which are reasonably linear with wave height. The superposition principle was applied to these data, and this showed resonable agreement between the results from regular and irregular waves. Only in the forward quarter of the ship was there consistent, significant difference. Maniar suggested that this was due to significant forefoot emergence and slamming detected in the regular-wave tests [5, 6]. It is possible that slamming augmented the bending moment in a non-linear manner, particularly at the forward quarter. Ochi [18], also using data from a MARINER hull model, has shown the superposition technique to be valid in rough seas if ship motion response functions are obtained from tests in regular waves of moderate height.

Reasonable agreement in irregular-regular wave comparisons, as was shown by Maniar [9], leads to the alternate procedure of using a response operator from tests in regular waves to predict the energy spectrum of bending moment response of either a ship model in a known wave spectrum or a ship in a real seaway.

Chiocco and Numata [10] obtained wave bending moment results to be used by Webb Institute in the model-ship correlation program. A 1/96 scale self-propelled model of the cargo ship WOLVERINE STATE (C4-S-BJ) was built and tested in a procedure similar to that used for the MARINER [5] a tanker [6], and a destroyer [7]. The object of Chiocco and Numata's investigations was to obtain wave bending moment response data from model tests and to reduce these data to a form usable by Webb Institute in their prediction and correlation project. The vertical and lateral bending moment data were presented in the dimensionless form of moment-amplitude/wave-amplitude ratio as a function of ship speed, and wave length/ship length ratio. Model tests were run with a full-scale ship speed range of 8 to 17 knots at seven headings relative to regular waves. Wave lengths were varied between .3 and 1.8 times the model LBP and wave height not exceeding one-fiftieth of the length. The bending moments measured were due solely to wave-induced loads and were measured with respect to a still water datum. Data trends in the study were in general agreement with analytical calculations made by Fukuda [19] for a ship of similar proportions and fullness.

Supplementing these tests on the WOLVERING STATE [10], Numata and Yonkers tested a 1/96 scale model of the MARINER-class cargo ship CALIFORNIA BEAR [11]. The object of this investigation was to acquire lateral and vertical wave bending moment data from model tests and similarly, to reduce them to a form usable by Webb Institute in their prediction and correlation project. This model was run with a full scale ship speed range of 10 to 22 knots at seven headings relative to regular waves. Wave lengths were varied between .2 and 2.0 times the model LBP, and again wave heights were one-fiftieth of the length. Unlike the prior studies, in this project time histories of vertical and lateral bending moments were reduced to obtain the average range of moments during the test interval of model travel. In addition, the phase relationship between the two moments was determined. The model data were presented in plots of the ratio of vertical and lateral bending moment-amplitude/wave-amplitude versus ship speed, for various wave lengths. Tests were conducted for two loading conditions, representative of actual westbound and eastbound trans-Pacific voyages. In this study as well, the data trends were in general agreement with analytical predictions for a ship of similar fineness by Fukuda [19].

Conclusions Based on Hydrodynamic Model Data

A survey of these previous model test studies [5, 6, 7, 8, 9, 10, 11] leads to the following general conclusions:

1. No clear upper limit on the bending moments is indicated for the range of ship types and headings tested.

2. Wave bending moments are essentially proportional to wave heights.

3. Maximum bending moment occurs within 12.5% of amidships. Therefore the practice of concentration on midships bending moments both in design studies and full-scale measurements appears to be justified.

4. Analysis of wave bending moment trends shows that maximum vertical moments tend to occur in head seas while maximum lateral moments occur in either bow or quartering seas, with both maxima occuring at the same wave length to ship length ratio.

5. The past studies, by demonstrating a linear relationship between bending moments and wave heights over a considerable range of wave severity, have strengthened the case for determining design moments on the basis of superposition using statistical analysis of sea spectra.

Basis for SL-7 Hydrodynamic Data Collection

The studies outlined above set the tone for the hydrodynamic modeling of the SL-7 containership. Initially it was believed that the torsional loads would be the most critical loads that this open hatch structure would experience; however, in the interests of completeness it was decided that modeling would include the full range of parametric data collection. When the full scale ship instrumentation data were obtained much later in the program, it was found that the ship was actually much more torsionally stiff than had been at first thought.

Most of the previous tests had measured bending moments at midships, because early work had concluded that this was where maximum lateral and vertical bending moments occurred. However, in the model tests of the SL-7, bending and shear data were obtained both amidship and at the forward quarterpoint. In fact, the most notable difference between the SL-7 hydrodynamic modeling and previous studies is that so much more information was obtained on the SL-7 model. Measurements were made of vertical, lateral and torsional bending moments and vertical and lateral shear at the two "sections" (i.e., amidships and forward quarter) and of roll, pitch, heave and rudder angle, for seven headings, two displacements, three relatively high speeds, (i.e., 24 and 32 knots full-scale speed) and a number of wavelengths in regular seas of moderate wave amplitude.

B. Hydrodynamic Computer Models

While model experiments offer a means to evaluate the performance of a hull form over a range of conditions in which it would be impractical, if not out-and-out unsafe, to test the full-scale ship, such experiments are time consuming, and by no means inexpensive. The wide availability of large, high-speed, electronic computers has opened a possibility of mathematical modelling of ship hull response and considerable effort has been made in this area [20, 21, 22, 23, 24, 25]. The Ship Structure Committee has sponsored one such effort at Oceanics, Inc. to develop a computerized simulation of ship structural response in waves. As might be imagined, such a mathematical scheme is quite general, being adapted to consider any regular hull form in a reasonable sea state, at any relative heading and forward speed. Moreover, either regular or irregular wave inputs can be considered and the short-crestedness of an actual seaway can be included.

The varying vertical and lateral bending moments due to waves are obtained using a linearized model based on strip theory, with each ship hull cross-section assumed to be of Lewis-form for the purpose of calculating hydrodynamic forces. The effect of roll motion and its influence in the lateral plane is included, with the model sufficiently general to also allow computation of resulting torsional moments.

On the basis of limited hand calculation comparisons, it was expected that the computer program [21, 22] would produce results that showed good agreement, with model data [10]. The versatility of the computer allowed many parametric changes, so that comparison with available model data could be accomodated easily. Kaplan, in [21, 23], sought verification of the capability of this digital computer technique for conventional hull form ships. In order to evaluate the analytical methods presented for the calculation of wave-induced moments, the results of such calculations were compared with Steven's experimental results [5, 6, 7, 8, 9, 10, 11]. The comparisons between Kaplan's calculation of vertical and lateral bending moments and the experimental results for the WOLVERINE STATE [10] indicated very good agreement, according to Kaplan. This held for both loading conditions, both speeds, and over the range of wave angles and wavelengths. In head and following seas, lateral motions and loads should be zero, and this is what the calculation indicated, but the experimental results for lateral bending moments showed non-zero results, indicative of the possible error, or range of discrepancy, to be expected combining calculations with experimental results. These loads were believed to arise in the model tests due to its free-running, but rudder controlled, condition. That is, the model may have undergone small lateral or yaw motions, with rudder corrections to maintain course, which led to the measured lateral bending moments.

The comparison for the Series 60, block .80 hull by Wahab [4] of vertical and lateral bending moments indicates excellent agreement. Similar results were also shown for this hull by Faltinsen [24] based on a new strip theory of Salvesen [25]. The agreement for torsional moments was only fair, and indicated excessive response at roll resonance conditions. The agreement of the shear forces was quite good, in general, with the exception of some deviation in lateral shear at 110° wave angle. A wide range of ship speed was covered in the Series 60, block .70 hull form [3] and T-2 tanker model data [2]. In general, Kaplan said the agreement was fairly satisfactory, considering the factors involved in the experimental comparison.

Experimental data points for midship vertical bending moments induced by waves on the 1/136 scale model of the aircraft carrier USS ESSEX [26] show considerable scatter. In spite of this scatter, Kaplan said the computer results appeared to show generally good agreement with the experimental data, with the least agreement for the zero speed case. Power spectra comparisons with the ESSEX have shown reasonable agreement with theoretical predictions using computer results. A comparison of the bending-moment output characteristics obtained from the hybrid-computer simulation, with the ESSEX experimental model data in [26], for two cases, showed quite good agreement for the sea state 7 condition, but poor agreement for the sea state 9 case. This lack of conformity for sea state 9 could be anticipated in view of the extreme wave heights and the bottom impact and bow-flare slamming possibility. Lack of comparison for this particular environmental condition would not necessarily be important since the ship would not be expected to proceed at such a high speed in a sea of such severe waves.

Since the ESSEX model test data have been shown to be in agreement with full-scale data [27], Kaplan inferred that this method of computer simulation provided a useful prediction of the structural response of the USS ESSEX in a seaway. Therefore, a reasonable means existed to obtain spectra, and resulting R.M.S. values, for both vertical and lateral wave-induced bending moments in oblique seas, for a ship moving at a prescribed forward speed and heading.

Influence on the SL-7 Correlation

The test data used by Kaplan for comparison were the result of model tests in regular waves in oblique headings. These tests were conducted by using a free-running self-propelled model. A model such as this must have an operating rudder which maintains the model on the prescribed wave-to-course angle. The computer calculations do not include any rudder force and moment effects. This points out a difference between experimental conditions and the computer calculations. The point is that the calculations are being compared with experiments which include additional unaccounted force and moment effects which are not necessarily realistic with regard to full-scale behavior. Obviously, these forces and moments have some effect upon the motion responses of the model and therefore upon the measured loadings. The extent and nature of these effects are unknown, although the only important ones will be those forces at the frequency of encounter in the regular wave tests. However, in the reports of the experimental work [2, 3, 4], little or no significance has been given to these forces. The details of the rudder and control system were not described, rudder motion was not given, and even leeway and yaw angles were not always reported. The effects of leeway, yaw, and rudder forces may turn out to be small in many cases, but they must still be recognized as an unknown element in the comparison. Each of these effects must be considered in the SL-7 correlation.

What Was Done for the SL-7 Program

Based on the satisfactory results obtained from the computer program, a project was begun to exercise the computer program for the model of the SL-7 containership.

C. Full-Scale Instrumentation

The third portion of this research program was the collection of full-scale data by Teledyne Materials Research, a Division of Teledyne, Inc. [28, 29, 30, 31, 32]. This included the recording, reduction, and preliminary analysis of midship bending stresses from many ship-years of operation, for numerous ships. These instrumented ships were dry cargo carriers, two of which had a similar C4 hull. Included were the HOOSIER STATE, WOLVERINE STATE, MORMACSCAN, CALIFORNIA BEAR, and lastly the containership BOSTON.

The averaged output of electrical resistance stress gages mounted amidships on the port and starboard deck edge of these ships was automatically recorded for thirty minutes each four hours, and continuously whenever stresses exceeded a preset level. The recorded signal resulted from a combination of bending moments produced by still water loading, waves, slamming, and diurnal temperature variation. During reduction of the data, the signals were filtered to remove all but the signals representing the stress in the fore and aft direction induced at the gage location by the vertical component of the wave-induced longitudinal bending moment, i.e., the stresses resulting from hogging and sagging.

For each particular ship, there was considerable scatter of the data points, each of which represents a thirty minute sample of four hours of ship operations for a given Beaufort wind state. This scatter may be attributed to variables neglected in the date analysis, i.e., the ship operating at various headings relative to the sea, and at various speeds within a given sea state. Because the reported Beaufort wind state information was based on visual observations, some spread in these values as a result of individual interpretation is also likely. There is one added complication. The majority of the previous work had presented bending moment and wave data as bending moment amplitude to wave amplitude ratio versus wavelength to ship length ratio. Inherent in this procedure is a strong reliance on the "correctness" of both the wave height and wavelength data. This presents no difficulty in tank tests or computer modeling, but it leads to very complex problems when an attempt is made to correlate these data with full-scale results. Normally full-scale wave information is based on a visually observed or estimated wave height and really relies on the mariner's judgment. Sometimes, wave height is reported on a basis of a measured wind speed. Unfortunately, neither the visual estimates nor the implied height based on a measured wind speed yield reliable or consistent information. Thus, any attempted correlation between model and full scale data must be tempered by an awareness of the poor data upon which the comparisons are based. A wave height measuring device is a necessity if there is to be any real correlation. Operation of the Tucker wave height meter and the radar wave height meter on the SL-7 should provide information leading to a significant reduction of scatter from this latter source.

It must be noted that the data in all of the "Teledyne" reports were presented as peak-to-trough stress variations, and not as single positive or negative amplitude about an average level. The number of stress variations counted during the analysis range, in general, from about 200 to 500 per record interval. But on a probabilistic basis it is possible that actual maximum peak-to-trough stress variations may run as much as 20 percent higher than those appearing in the 20 minute sample record. Absolute average values are difficult to determine, and are variable with loading and thermal conditions. Statistical procedures for analyzing peak-to-trough values of random variables, moreover, are well established.

Graphs of R.M.S. stress and maximum peak-to-trough stress versus Beaufort wind state were plotted for each ship. Additionally, graphs indicating the distribution of the time spent by each ship in various sea states during data acquisition, and data on time spent at various ship speeds, were included for statistical completeness.

The WOLVERINE STATE instrumentation [30] was unique in that during the last part of the program the stress gages mounted on the port and starboard sides were not combined into a single signal but rather left as two separate signals. This allowed a determination of the effect of unfairness upon individual gages. Dot-plots were made showing the same data for combined, port, and starboard readings. The uncorrected averages were corrected for unfairness and compared with the combined average. Additionally, a Tucker wave height meter installed aboard the WOLVERINE STATE for three voyages allowed plotting of R.M.S. average wave height (Tucker) and maximum peak-to-trough wave height (Tucker), versus Beaufort sea state. For comparison purposes, dot-plots of estimated wave heights, from visual data logbooks, versus Beaufort sea states were shown. Additionally, dot-plots of R.M.S. average stress versus R.M.S. average wave height (Tucker), and maximum peak-to-trough stress versus maximum peak-to-trough wave height (Tucker), were given for three voyages.

The BOSTON instrumentation [31, 32], included a more complete collection of data than the previous work. Maximum peak-to-trough vertical and horizontal bending stress, and hull torsional shear stress were plotted versus Beaufort wind state. Starboard box beam stresses versus Beaufort wind state were included for comparison with vertical bending data. Vertical and horizontal accelerometers were installed in bow, midship, and stern locations. The devices were located at approximately the same positions as those on the S.S. WOLVERINE STATE to permit comparison with data acquired from that vessel. Maximum peak-to-trough vertical and horizontal accelerations at the stern, midships, and bow were graphed versus Beaufort wind state. Augmenting these devices, were two transducers located at amidships which provided pitch and roll angle data. This was likewise plotted versus Beaufort wind state. A successful wave buoy launching was accomplished, providing wave data while the sea was dropping from wind force 8 to 6.

Full-Scale Instrumentation Results

A comparison of the average values of all data points within each wind state indicates good agreement between the two sister ships, HOOSIER STATE and WOLVERINE STATE [28]. This was especially evident in wind states 3 to 7, where most data were available. Close agreement was expected since the ships were of the same type and operating on the same route.

The average R.M.S. stress measured on the MORMACSCAN [29] was generally higher than comparable values from the WOLVERINE STATE. The maximum peak-to-trough stresses versus Beaufort No. plots show similar trends. The actual averages for several Beaufort Nos. show quite close correspondence between the two. It would be expected, however, that the dissimilarities between the two types of ships (the MORMACSCAN is a machinery amidship type, while the WOLVERINE STATE has machinery aft), might cause greater divergence of the curves. In fact, the average maximum peak-to-trough stresses recorded on the MORMACSCAN are generally higher than those from the WOLVERING STATE, especially at the higher wind states. The data for the MORMACSCAN [30] was graphed for both its North and South Atlantic runs. WOLVERINE STATE data were presented for three categories, winter North Atlantic, summer North Atlantic, and Pacific. This seasonal division was found necessary in the North Atlantic data because of the greater likelihood of encountering large swells at relatively low Beaufort wind state during the winter season. The seasonal variation is not as severe in the Pacific.

Although the Tucker wave height meter data for the WOLVERINE STATE do not agree with the estimated wave heights, the accuracy of the estimate was probably not good. Several different people were involved in making these estimates, and their ability to judge wave heights correctly is, of course, unknown. Not surprisingly, the measured bending stress and wave height correspondence is also poor, probably also because of the difficulties of obtaining accurate and consistent wave height data.

Comparison of BOSTON data [32, 33] with WOLVERINE STATE data [28, 29, 30] has shown some disparity. Comparisons of the BOSTON's bow vertical acceleration data with that collected on the WOLVERINE STATE show quite good agreement. A decrease in g level at the higher sea states in the BOSTON values was most likely due to the Sea-Land policy of immediate "slow-down" if strong head seas were encountered. The purpose of this policy was to minimize the possibility of on-deck container and cargo damage which would result from taking water over the bow. Comparison of the R.M.S. wave height computed from data power spec-tral density with the logbook data gave acceptable agreement.

Full-scale strain measurements on ships in service have been made in several other countries [33, 34]. Actual stress records have been found to be very irregular, both within a single record, and from one record to another, both because of the fluctuations of the waves encountered and because of variations in the instrumentation techniques.

Analysis and Interpretation of Full-Scale Data

A thorough analysis and comparison of stress data from full-scale measurements on the two C-4-type cargo vessels, the S.S. WOLVERINE STATE, and S.S. HOOSIER STATE, and additionally the MORMACSCAN and the CALIFORNIA BEAR was performed by Lewis [35, 36]. Bar graphs of stress probability density versus stress were presented showing an apparent agreement with an ideal Rayleigh distribution curve. These bending stresses were plotted versus the calculated probability of exceeding that stress, and also the number of stress reversals. This was done for each of the ships, including separate plots for the more important seasonal runs, and varied ocean routes. In a similar manner the bending moment coefficient was plotted versus the probability of exceeding that bending moment, and versus the number of moment reversals, for some routes and ships.

The analysis at Webb Institute for the HOOSIER STATE, and its sister ship the WOLVERINE STATE, showed excellent stress agreement for all but the highest wind states, once certain calibration corrections were included. Lewis also presented the R.M.S. stress and bending stress versus the probability of exceeding those values for each wind group, as used by Band [37]. These results showed that the expected bending moment for a typical cargo ship in 20 years of North Atlantic service was more likely to be caused by Beaufort 8 to 9 storms than by Beaufort 10 to 12, since the latter occur so rarely. This removed the urgency from the search for the elusive "worst possible storm". Plots of extreme stress versus the probability of exceeding that stress, tended to converge to the curve obtained from R.M.S. data. Hence, in the practical range of full-scale stress measurements covering about one ship-year to 100 ship-years, there seemed to be good agreement between the results obtained by the two methods and the actual histogram results.

Bending moment trends for the various ships on various routes show a large amount of scatter, some of which must be due to the differences in weather encountered by the ships. Based on North Atlantic weather, bending moment trends show much less scatter; however, considerable differences remain that were not readily accounted for. Although the ships were not very different in size, the largest, the CALIFORNIA BEAR, had somewhat smaller bending moment coefficients than the WOLVERINE STATE. On the other hand, the smallest ship, the MORMACSCAN had the lowest bending moments. The data for the MORMACSCAN, and to a lesser extent, the CALIFORNIA BEAR, are not extensive, and it may be that these data result in an inadequate statistical sample for these ships.

Based on his analysis and interpretation of full-scale data, Lewis reached the following conclusions:

1. Classifying ship stress data in respect to wind force provides a basis for analysis of long-term trends that take into account the different weather conditions encountered by different ships in service.

2. Data obtained from several different ships on the same, and on different trade routes, can be compared on the basis of non-dimensional wave bending moment coefficients in the same "standard" weather distributions, extrapolated to long periods of time.

3. Analytical methods were proven to yield long-term distributions of stress that agree very well with histogram data over the limited period covered by the data; the methods that could be extrapolated to longer periods of time also have shown good agreement within the range of interest.

Direction of Full-Scale Testing Previous to SL-7 Work

The data collection aboard the five ships, HOOSIER STATE, WOLVERINE STATE, MORMACSCAN, CALIFORNIA BEAR, and BOSTON accomplished several objectives. Considerable confidence has been built up in the means of data acquisition, and the type of data collected.

Data collection was begun on the WOLVERINE STATE on a modest scale, with only vertical bending moment data being collected at midships. As the large-scale program progressed, the small-scale hydrodynamic modeling suggested measuring lateral and torsional bending moments, and ship motions data, which were added to the large scale program.

Prior to the SL-7 program, the most important failing of full-scale data collection was the method of "measuring" the seaway. Most full-scale data were presented based upon the Beaufort wind state at the particular interval of stress measurement. These Beaufort wind states are recorded based upon visual sightings of the effect of the wind on the waves. The inherent shortcomings as far as repeatability and consistency are concerned are obvious. In the first place, there is no way to measure and account for the variations from observer to observer although they are known to exist. Secondly, there is no assurance that the sea surface has responded to the wind existing and there is no means of allowing for rapid changes of wind state during the measurement period. Any valid wave measurement system must remove all personal judgment and opinion from the data acquisition and measure the seaway at the time the other measurements are being taken.

The full-scale data were plotted against Beaufort wind state, but unfortunately, the small scale hydrodynamic modeling of Stevens and Oceanics was based upon sea states, using a normalization of data to wave height and wave length. Comparison of the full-scale data with this modeling must be based on ocean wave data. This may be accomplished by a statistical analysis and comparison of Beaufort wind state and sea states. From this, an accurate appraisal of what wave height and wave length are representative (on the statistical average) of a particular sea or wind state must be made. This has essentially been accomplished by Band [37] and Lewis [36]. Values suggested by these authors must be tempered by the knowledge that they are still statisitcal, and by no means may they be interpreted as the actual or instantaneous data. These values are still based on the sailor's visual estimate of sea state or at best anemometer readings. Alternatively, comparisons and correlations may be based directly upon sailors' visual sightings of the wave height and length, rather than using the statistical process, which is itself based on the same visual sightings. Neither way is satisfactory for correlation purposes, but in the absence of more accurate wave data, they must be used.

SL-7 Instrumentation Differences

The SL-7 containership instrumentation program differs from previous S.S.C. full-scale measurement programs in three important ways:

1. Extreme stress measurement
2. Wave height meters (Tucker and radar)
3. Torsional stress measurement (open-hatch ship).

1. Each of the eight SL-7 ships has been instrumented with unattended extreme stress scratch gages which record bending stresses on sensitized graph paper. Data collected will allow for interpolation of long term maximum stresses. This was undertaken because of encouraging stress extrapolations completed by Lewis [35]. Since there are eight essentially identical SL-7 ships, and they operate nearly continuously, a great number of ship-years of operation may be collected in a short span of time.

2. The SL-7, S.S. SEA-LAND McLEAN has been equipped with both a Tucker wave height meter, and the radar wave height meter. Using both of these for comparison and cross-check purposes, it should be possible to have an accurate wave height measurement simultaneously with the stress and ship motion data collection. In addition, it will be possible to compare the relative accuracy of these two devices. Measured seaway data will make the correlation with model data possible, and furthermore will improve the accuracy of the statistical procedures.

3. Torsional stress measurements were made on the BOSTON [32], but the SL-7 differs in two important ways from these earlier experiments. The SL-7 is approximately twice as long, which should mean higher torsional moments. The SL-7 is almost entirely an open hatch ship, with effective deck area only at the bow, stern, and in the way of machinery.

D. Significant Correlations

WOLVERINE STATE and CALIFORNIA BEAR - Lewis

The comparison of full-scale data under real sea conditions with simulated model results requires either elaborate instrumentation for full-scale trials or, alternatively, a lengthy procedure of statistical data collection and reduction. Lewis [39] made comparisons on a statistical basis, although some limited direct comparisons were made in cases in which wave records were obtained.

A statistical approach was necessary because a ship in service encounters many different sea conditions in any one voyage, and many more in a year of operation. To predict a maximum bending moment that the ship must withstand it is necessary to know the long-term distribution of bending moments. To obtain this it is necessary to determine the ship response to many different sea conditions. By superimposing responses the average or typical spectrum representing sea conditons of different levels of severity is obtained. The response of a ship to an irregular sea is described by its response spectrum, which can be predicted by a technique presented by St. Denis and Pierson [40]. This method has been confirmed experimentally [41], and has proven to be very versatile. It involves the assumption that a ship's response to a seaway can be obtained by the linear superposition of its responses to all of the wave components. Using model test results in regular waves, together with the appropriate sea spectrum, leads to a response spectrum that provides a complete statistical description in statistical terms of the ship's response to that particular sea. Thus the bending moment response can be determined by calculations for any number of representative sea conditons.

For purposes of prediction from model results, it has been found more satisfactory to use wave height, rather than wind speed as a basis for classifying sea spectra, although full-scale results were usually referred to wind [28, 29, 30, 31, 32]. It has been shown that a normal distribution of R.M.S. bending moment is still applicable, but the standard deviation will be less than when wind is used as a basis [42]. Several relationships between wave height and wind speed are commonly given for open ocean conditions and care must be taken to distinguish those representing ideal fully developed seas from those describing average conditions.

Experimentally determined Response Amplitude Operators (R.A.O.'s) for the WOLVERINE STATE and the CALIFORNIA BEAR at seven different headings of 0°, 30°, 60°, 90°, 120°, 150° and 180° were obtained from model tests in regular waves at the Stevens Davidson Laboratory [10, 11]. The R.A.O.'s for both ships, taken at numerous frequencies, along with wave spectrum data, were used to calculate the mean response and its standard deviation at different levels of wave height. The prediction of wave-induced bending moments on ships operating in realistic short-crested irregular seas was then accomplished by the principle of superposition, in which R.A.O.'s from model test results, and the short-crested sea spectra were combined. The products of points on a wave spectrum component curve and the corresponding R.A.O. curve at the same heading angle gave points on the bending moment response spectrum component curve.

The statistically predicted trends of bending moment are not directly comparable with full-scale data because of the wave height measurement problem. One way to facilitate comparison is to convert these trends predicted on the basis of significant wave height to data based on Beaufort number. But because this wind-wave curve assumes a fully developed sea, a large standard deviation of both wave height and bending moment is found when classifying on a wind scale basis [43].

The predicted values of R.M.S. bending moment and standard deviation for both ships were plotted versus wind speed for the various drafts and routes. The considerable difference between full-scale results for east- and westbound voyages was roughly predicted from model tests on the basis of differences in draft. Model predictions tended to overestimate bending moments somewhat at lower wind speeds both east- and westbound, but especially westbound. Furthermore, the upward trend of the predictions was much less steep than full-scale. However, in the range of 30-45 knot wind speed the magnitudes were satisfactory. The magnitude of the predicted standard deviations was quite good westbound, but somewhat high eastbound at higher wind speeds. However, when mean draft was used as a basis of comparison, the agreement between model prediction and full-scale results was much better. The less satisfactory results for east- and westbound separately could be due to the reduction in the statistical sample size of the full-scale data as a result of the separation of data.

The final step taken by Lewis was to make a weighted integration of bending moment curves for individual weather groups on the basis of the frequency of occurrence of the different weather conditions. These long-term predictions for both ships over both routes, resulted in a definite overestimation in comparison with full-scale.

Lewis made the following basic conclusions based on these correlation studies:

1. When the modified statistical technique was applied to the WOLVERINE STATE and CALIFORNIA BEAR data it was found to overestimate the long term trends of bending moments, whereas the more traditional procedures, i.e. observed wave spectra [44], agree very closely with full-scale trends.

2. When east- and westbound voyages of the CALIFORNIA BEAR were compared separately, the differences were accounted for on the basis of draft differences, but long-term bending moment trends were further overestimated, perhaps because of an inadequate sample size of full-scale data.

3. In general, it was evident that success in using the statistical prediction procedure was dependent on the quality of sea data available. However, more complete and accurate ocean wind and wave data were needed, including wave records from which spectra can be determined, particularly for other important trade routes besides the North Atlantic. But, as pointed out by Lewis, a purely statistical treatment of the ship wave bending moment problem cannot yield a satisfactory general design

tool. Statistics are helpful in designing ships similar to those for which stress data were collected, but cannot provide direct guidance in designing different ships.

4. It is believed that the application of the statistical procedure for predicting long-term bending moment trends to two different ships in two different oceans has demonstrated a rational basis for the quantitative determination of wave bending moment requirements for possible new designs of the future.

E. Effect of Previous Work on the SL-7 Program

Many previous studies have led to the development of the SL-7 Instrumentation Program. From these past studies much information has been culled, and areas for future work defined. The following is a synopsis of the influence of these studies on the SL-7 program.

What Has Been Learned

1. An analysis method and accompanying computer program is available which can consider both regular and irregular waves, to give good prediction of stresses, moments, and ship motions.

2. A correlation between data based on Beaufort wind state, and data based upon wave data (wave height and wave length), will necessarily have to make major assumptions and idealizations. The correlation can be no better than the judgment used in the making of these assumptions and has thus far proven unacceptable.

3. Statistics are helpful in designing ships similar to those for which extensive stress data have been collected, but cannot provide direct guidance in designing different ships.

Critique of SL-7 Overall Background

In brief form, the following opinions were formed from the historical search of SSC sponsored projects:

1. Hydrodynamic modeling has had a well-checked and consistent history. Most data is consistent with itself, and with that of other researchers. More importantly, it is reproducible. While experimental difficulties were found with a few of the many variations of parameters, these were fortunately in parameters of little significance, and therefore the effect was largely inconsequential. It is felt that the hydrodynamic modeling has shown and will continue to show high reliability.

2. Computer analytical modeling has received little published comparison with previous work, probably due to its newness and continuing development. In-depth hand calculation results have shown good comparison, but full-scale correlations, and to a lesser degree those based on hydrodynamic modeling, remain unproven to any extent. On the plus side the computer provides complete reproducibility and great ease

of parametric changes, features which have obvious application toward actual use of the method in ship design.

3. Full scale data collected under the SSC program has been gathered almost exclusively by one contractor, thus the data format are intimately consistent both within the individual project and usually with earlier work. Comparisons with outside sources, especially the extensive work being done by foreign concerns, have not been performed.

4. Statistical correlations must necessarily make numerous statistical and wave data assumptions. Any analysis based on "observed" wave data must be viewed with caution. Of course this statistical correlation basis was chosen by necessity, but hopefully can be avoided in the future by the use of wave height measuring devices.

What Areas Need More Research

1. A fundamental area of need, based on previous work, was a means of measuring actual wave height. It was for this reason that a Tucker wave height meter, and a radar wave height meter were installed on the SL-7 containership, S.S. SEA-LAND McLEAN.

2. Computer analysis of shipboard loads and wave data has had insufficient time to be fully developed and does not include response to all significant wave loadings. Further development is necessary.

3. The computer analysis and full-scale data collection have not been compared sufficiently with outside data sources.

II. THE ELEMENTS OF THE SL-7 INSTRUMENTATION PROGRAM

A. SL-7 Ship Instrumentation - Teledyne Materials Research Co.; SR-211, "SL-7 Data Collection Program".

The objective of this effort was to obtain full-scale calibration and measurement of seaway loads response. This task included the design and installation of an instrumentation system, the calibration and operation of this system, and reduction and analyses of the data. Data collection began in September 1972 and continued through the winter of 1972-1973 and winter of 1973-1974.

The primary measurements made on the vessel were as follows:

a. Midship wave-induced vertical bending stress
b. Torsional shear stresses
c. Principal stresses at hatch corners
d. Vessel pitch and roll
e. Gross hull accelerations
f. Accelerations of forward and aft deckhouses
g. Longitudinal stresses at the four extreme "corners" and at the neutral axis of the midship section.

The above data were supplemented by log book entries of environmental and operational conditions. For additional details of instrumentation see TMR Report E-1345(b) and E-1559(f), SSC 238, and Appendix A.

The stresses measured on the vessel are not absolute levels of stress in the structure, but rather only the dynamic increment of stress. The absolute value of stress is made up of a combination of residual and fabrication stresses, "still water" stresses resulting from cargo and/or ballast loading, "thermal" stresses resulting from temperature differences side-to-side, deck-to-bottom, and various other unknown stresses. All of the stresses except those which result from the action of the seaway change very slowly, and thus it is possible to examine only those wave-induced stresses without regard for the other effects.

These wave-induced stresses show great irregularity and variability, and have been evaluated statistically in other programs [45, 46, 47]. Appendix B contains a further discussion of the total stress experienced by a ship hull, and the problems of evaluating those portions resulting from a particular cause.

The results of the wave-induced stress measurements will be compared with model and computer analytical data. The ultimate aim is to secure sufficient confidence in the calculation procedure, so that model testing and full-scale data collection may be eliminated.

B. Structural Scale Model - University of California

The objective of this effort was to measure stresses and deflections of a small-scale structural model for various component loadings. The model loading is one of separate and combined torsion and bending.

The model of the SL-7 containership is of welded steel construction, with geometric scaling of 1:50. Thicknesses of the plating are distorted to a ratio of 3:50 because it was not possible to weld the thinner material satisfactorily. Because the scaled plating thickness was not available in all cases, it was not possible to retain this scale ratio for all of the structural components.

The experimental investigation was concerned with the primary response of the ship. Therefore only those structural components which were expected to contribute to the primary strength of the ship's hull were included in the model configuration. These components were:

a. longitudinally continuous plating of side shell, inner and outer bottom, and decks
b. longitudinal girders in way of the double bottom,
c. longitudinal stringers,
d. longitudinal torsion boxes,
e. watertight and non-watertight transverse bulkheads with vertical stiffeners and horizontal stringers,
f. transverse boxes at the bulkheads.

Generally, several of the girders and stiffeners were taken together and were represented by one component with a cross-section equivalent to the sum of their individual cross-sections. The areas of small plate stiffeners were included in the area of the plates.

The model was placed in a loading frame and loaded by means of weights and pulleys. The model was equipped with strain gage rosettes, single gages, and dial gages to measure strain and displacements.

The following torsional, vertical, and lateral bending moments were combined, scaled, and applied to the model:

A. Longitudinal Bending
   1. Large Bending Moment
   2. ± 1/2 Large Bending Moment
B. Torsion
   1. ± Large Torque
   2. ∓ 1/2 Large Torque
C. Lateral Loading
   1. ± Large Bending Moment
D. ± Large Midship Shear
E. Large Combined Loads
   1. Vertical Bending and Torsion
   2. Lateral Bending and Torsion
F. Distributed Loading (Wave Form)
   1. Vertical, Horizontal Bending and Torsion
G. Deckside Tests (various levels of loading)

It was found necessary to use the loadings "Large Hog, 1/2 Large Sag, etc.", due to experimental difficulties resulting primarily from the very high stiffness of the model. This was expected to create no real problem as the distribution of the resulting stresses, not their absolute values, was of primary importance.

The model stresses and deflections will be scaled and compared with those calculated by the DAISY Structural Analysis Program, and the full-scale SL-7 instrumentation data.

C. Finite Element Structural Analysis Program (DAISY) - American Bureau of Shipping

The purpose of this project was to apply the DAISY program to analyze the Sea Land SL-7 containership. The program is general with regard to program type, computer size, and configuration.

A promising approach taken within the DAISY program, is that of reduced element substructure. The reduced element substructure model is particularly advantageous because not only is the need for local analysis eliminated, but the substructure model is incorporated in the computation of the overall displacements, rendering them more accurate. The analysis of an entire containership on an oblique sea wave using the finite element method (DAISY) with the reduced element substructure technique represents a step forward in analytical structural analysis of complex ship structures. Only an idealized quasi-static treatment of the loading representing expected maximum values can be made at this time, until more realistic representations of loading are developed. The results of the calculations show response of the hull girder and resultant stress distributions. Although the magnitudes of the calculated stress values were dependent on the applied loads, which were to a certain degree idealized ones, these stress magnitudes served to define regions where actual high stresses could be expected. For additional details of the program and the results obtained, see ABS Report "Structural Analysis of SL-7 Containership Under Combined Loading of Vertical, Lateral and Torsional Moments Using Finite Element Techniques", November 1972, and SSC 243.

D. Bending and Shear Load Model Tests - Hydrodynamic Model; Stevens Institute of Technology; SR-204, "SL-7 Torsional Model Study"

The objective of this effort was to conduct an experimental model investigation of wave-induced vertical, horizontal and torsional bending in the hull girder. The data obtained from these ship model studies will be used in later correlations between theory, model tests and full-scale experiments.

Vertical, lateral and torsional wave bending moments, and vertical shears were measured at two sections of a 1/140-scale model of the SL-7 containership. The model was self-propelled, with prototype ship speeds of 24 and 32 knots at seven headings to regular waves of lengths between .25 and 2.0 times the length between perpendiculars.

Ship motions were measured, and two ship conditions, light and full load were covered. The results are presented in charts of load or motions amplitude/wave amplitude versus wave length, and phase lag versus wave length, with heading, ship speed, and loading conditions as parameters.

The principal accomplishment of this study was to obtain the three components of wave-induced bending moments, and the two components of wave shear forces at two sections of a high speed containership. The results of this model study provide only an indirect correlation with full scale due to the practical limitations of being able to model only "regular" waves, rather than a general irregular wave spectrum. The aim was to establish R.A.O.'s for the regular waves for prediction of irregular sea cases. For additional details of the model study, and the results obtained, see Stevens Institute of Technology Report DL-71-1613, and SSC 239.

E. Theoretical Hydrodynamic Analysis (SCORES) - Oceanics, Inc., SR-205, "SL-7 Load and Computer Response"

The objective of this effort was to apply the SCORES computer program to the SL-7 containership. Both vertical and lateral motions and loads were considered for the ship underway at several speed-heading combinations in regular waves, and in irregular seas. Strip theory was used and each ship hull cross-section was assumed to be of Lewis-form shape for the purpose of calculating hydrodynamic added mass and damping forces in vertical, lateral and rolling oscillation modes. The coupled equations of motion are linear, and the superposition principle was used for statistical response calculation in regular seas. All three primary ship hull loadings, i.e., vertical bending, lateral bending, and torsional moments were determined, as well as shear forces, at predetermined points along the length. Additional details of the computer analysis, may be found in SSC 229 and 230, and the results of this analysis are presented in Oceanics report 73-96, and SSC 246.

F. Waveheight Data Reduction and Comparison - Stevens Institute of Technology; SR-221, "Correlation and Verification of Wavemeter Data from the SL-7"

Under this project, seaway measurements made with the Tucker wave height meter will be compared with those made with the radar wave height meter. These comparisons will be complex because the ship motion must first be removed from the wave profile signal, as measured by the radar wave height meter, and then the reduced signal must be processed to determine the "recorded" sea conditions. In order to obtain an accurate representation of the ocean surface, the motion of the wave height meter antenna due to ship motions must be determined and removed from the radar range data. To achieve this, the ship has been instrumented with accelerometers, and roll and pitch pendulums (see Appendix A) by which the ship motions are measured and recorded. The accuracy of the radar wave height meter will be compared to that of a Tucker wave height meter that has been installed aboard the McLEAN. Sea spectra will be determined by performing a wave form analysis on the corrected measured ocean surface profile. The log book wave data entries will be compared with the derived seaway data, to determine the relative accuracy of the log book data. Correlation between the log book and the measured heights will be investigated.

III. PROGRAM ELEMENT INTERACTION

The projects of the SL-7 Instrumentation Program are interrelated in two primary respects, correlation and prediction. The hydrodynamic and structural models are to be used primarily for correlation with the theoretical computer programs that will be used to predict hydrodynamic loads and stresses on the SL-7. The model and analytical data, in turn, will be correlated with the full-scale measurements. Figure 1 shows a schematic of the various data comparisons which can be made.

A. Hydrodynamic Model and SCORES Comparison

As previously mentioned, vertical, lateral, and torsional wave bending moments and vertical and lateral shears were measured at two sections of the 1/140 hydrodynamic model. The model test conditions were used as input conditions to the regular wave case of the SCORES program calculations. The calculated response amplitude operators (R.A.O.) can be compared directly to those measured in the model tests. Figure 2 illustrates eight possible comparisons between the model tests and the computer calculations. Direct comparison between these results is possible, and will serve to verify the degree to which the SCORES program applies to a ship of the SL-7 hull form and speed.

B. DAISY Verification

Verification of the DAISY program as applied to open hatch container vessels of the SL-7 Class will be accomplished using structural model test data. A single point comparison of calibration test results, where the ship, the model, and theoretical analysis would all have known (equivalent) loadings is also contemplated. This would be the only comparison where such load correspondence would be available, and as such represents one of the most important elements of the entire SL-7 program. Figure 3 shows the comparison planned for the calibration loading case.

The comparison of the ship measurements with the computer calculation for the calibration loading case is important since it is the only one where the exact loads on the ship structure will be known with any real accuracy. The information obtained during the calibration experiment, i.e., the location of the neutral axis for vertical bending and response of gages to a known applied load, is required for the reduction and interpretation of at-sea measurements. Thus, the stresses shown in Figure 3 (indicated by 3A), must be compared in detail.

A second comparison may be made between stresses calculated from the DAISY program for the calibration loading with stresses obtained from the model. It may be possible that by proper superposition of the model load conditions, the actual calibration experiment loads may be approximated with acceptable accuracy to estimate the response of the model to the calibration experiment loadings.

The third comparison of the calibration loadings is between

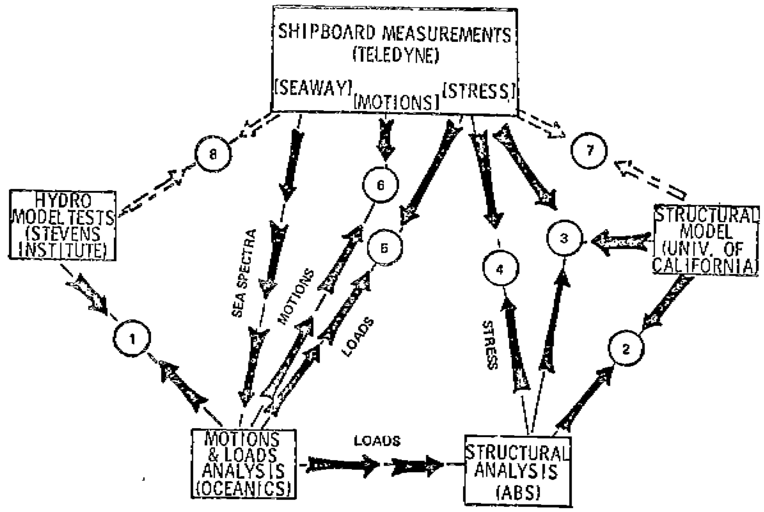


FIGURE 1 SL-7 DATA COMPARISON

SR 206

SR 204

	ROLL	PITCH	HEAVE		LATERAL SHEAR	VERTICAL SHEAR	LATERAL BENDING MOMENT	VERTICAL BENDING MOMENT	TORSIONAL BENDING MOMENT		
TORSIONAL BENDING MOMENT ⊕ & FR 258									1		
VERTICAL BENDING MOMENT ⊕ & FR 258								1			
LATERAL BENDING MOMENT ⊕ & FR 258							1				
VERTICAL SHEAR ⊕ & 258						1					
LATERAL SHEAR ⊕ & 258					1						
ROLL	1*										
PITCH		1									
HEAVE			1								

NOTE: COMPARISONS ARE TO BE MADE FOR SAME CONDITIONS (HEADING, SPEED, DISPLACEMENT & WAVELENGTH)

*NUMBER REFERS TO NUMBER 1 OF FIGURE 1.

FIGURE 2 HYDRODYNAMIC MODEL TEST/COMPUTER CALCULATION CORRELATION

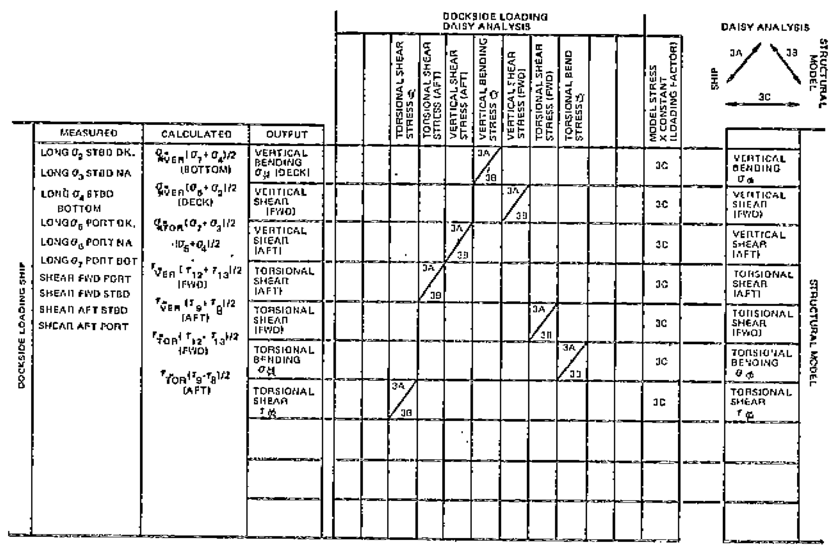


FIGURE 3 DOCKSIDE CALIBRATION

the stresses measured on the ship and those on the structural model. This comparison will indicate how accurately the model represents the actual ship structure, and thus determine whether additional calibration type information may be obtained from the model in future tests. If there is sufficient agreement between the results for the structural model and the actual ship structure, then it may be possible to obtain additional "calibration" type data from additional model testing.

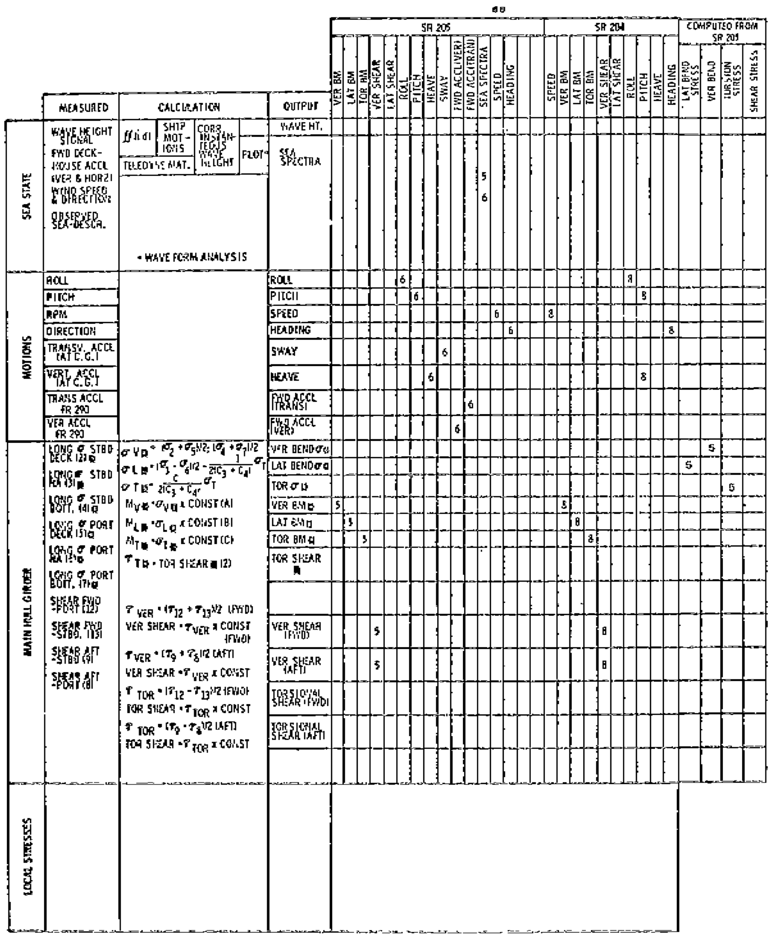
C. Ship Motion Verification

Once the ship's motion is "removed" from the radar wave height meter data, it will map the targeted portion of the ocean's surface; parallel to the ship course, and thus measure wave heights. In order to establish a base for comparison between theoretical predictions from SCORES and actual ship measurement data, the spectrum of the sea in which the ship operates must be developed; this will be accomplished by performing a wave form analysis on the reduced ocean surface trace. These spectral wave heights and frequencies will be compared with standard sea spectra representations. Significant wave heights obtained from the processed signal will be compared with logbook entries. This will be a check of "reasonableness" as well as a comparison with previously observed seaways. It should be noted that the directional properties of the seaway and its spectrum cannot be determined.

The next step will be to compare ship motions to model data and to calculations. These comparisons are shown by the numbers 8 and 6 respectively in Figure 4. As indicated, for a given speed and heading, roll, pitch, heave and sway model tests and calculations may be compared directly. Roll comparisons are not expected to be due to the nonlinearity due to viscous damping. Comparison can also be made of midship bending moment (stress) for head sea cases. The transverse and vertical accelerations at frame 290 may also be compared since they are to be both calculated and measured.

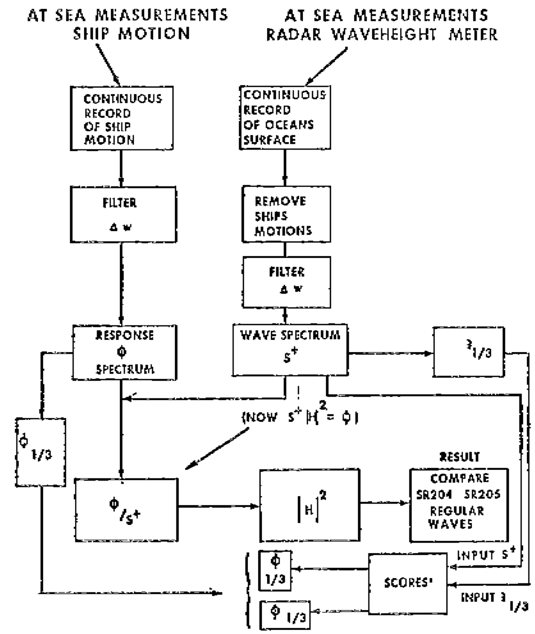
The significant wave height determined from signal processing can be used as an input to the SCORES program. Thus the ship motions will be calculated from the Pierson-Moskowitz Spectrum with the measured significant wave height as an input. A second approach would be to use the sea spectrum obtained from signal processing of wave height meter data as an input to the SCORES Program. The values calculated from the SCORES Program (e.g. roll, pitch, yaw, accelerations) may be compared directly with processed ship data. Significant values (average of 1/3 highest), R.M.S. values or average one-tenth greatest motion values may be used for direct comparison. The ship versus calculation comparison may be presented as plots of significant motion's versus significant wave heights.

Figure 5 indicates a method of comparing ship motion measurements with Steven's model test results. As indicated in this figure, the continuous record of wave heights and ship motion must be filtered to obtain a sea spectrum and motion spectrum. For a given motion, the response amplitude operator may be obtained. This is indicated below by the well known R.A.O. and spectrum relationship:



** NUMBERS REFER TO NUMBERS OF FIGURE 1

FIGURE 4 FULL SCALE/MODEL TEST/COMPUTER CALCULATION CORRELATION



* INPUT TO SCORES REQUIRES HEADING INPUT

FIGURE 5

$$S^+|H|^2 = \phi$$

where; ϕ = motion spectrum (roll, pitch, yaw, heave or acceleration)

S^+ = measured sea spectrum

Thus,

$$|H|^2 = \phi/S^+$$

By using this technique the R.A.O.'s of ship motions may be compared directly with R.A.O.'s measured for regular waves in model tests for similar headings. Since these relationships are based on long-crested seas, results must be considered approximate for real short-creasted seas.

D. Seaway Loads Verification

The SCORES program calculates the wave-induced bending moments (vertical, lateral and torsional) on a ship in an irregular sea. The instrumentation on board the ship, on the other hand, measures and records the combined stress at a given location. In order to obtain a base for comparison between theory and measurement, the combined stress signal measured on the ship must be reduced to its component stress, i.e., lateral, vertical and torsional bending stress. Appendix C contains the development of the equations for reducing the measured stresses to the individual components. In addition, the loads calculated for the ship by SCORES must be converted to stress values or alternatively the measured values must be expressed in terms of induced moments and shear loads. Since the results of most of the previous at-sea measurements have been reported in terms of measured stresses, it would seem logical that this procedure be followed in this program. The instrumented ship has been calibrated [48] so that the response to a given load is known, and thus a basis for converting loads predicted by SCORES into actual stress levels has been established.

The measured main hull girder stresses may be compared with the calculated values at three principal locations along the ship's hull, i.e., the forward quarter point, amidships and the aft quarter point.

During a normal 24 hour day of ship operation, data are recorded on each of two recorders for approximately 12 hours. It is apparent, with the ship operating an average of 11 days per voyage, and a total of approximately 24 voyages, that a considerable body of data will be developed. Thus, it is imperative that this data be sampled judiciously for initial comparisons. One obvious sampling technique would be to select the data with the aid of the ship's log. By scanning the log, different data periods could be selected which represent a range of sea state variations. Data for these periods could be processed and a tape containing the component bending stress data prepared. Next, a "quick-look" record could be made to identify areas of interest and from selected areas on the processed tapes information such as:

a. Significant stress (average 1/3 highest)
b. R.M.S. stress
c. Average stress
d. Average stress (average of the 1/10 highest)

could be obtained. These values could be plotted against corresponding values of wave height for a record of the same time frame as previously discussed.

It is recognized that the four values of wave height and stress mentioned above are related statistically with each being a function of the mean squared amplitude:

$$A_{RMS} = A^2 \quad (1)$$

$$A_{AVG} = 1.25\ A_{RMS} \quad (2)$$

$$A_{1/3} = 2.0\ A_{RMS} \quad (3)$$

$$A_{1/10} = 2.55\ A_{RMS} \quad (4)$$

It is also recognized that the data measured in the "real world" will probably not correspond to these simplified relations.

E. Stress Verification

One comparison having an important implication for future ship design work, if successful, would be that of comparing measured stresses on the ship at sea with those stresses predicted using the SCORES and DAISY computer programs. Circle number 4 in Figure 1 illustrates this comparison. The DAISY program requires input information for a particular instant of time, involving hydrodynamic loading (or at least wave profile) and amplitudes of motion (or acceleration). A processed radar wave height meter record, along with simultaneous acceleration record, would provide a basis for these inputs. The wave record should be carefully selected for a case of head seas that are relatively long-crested and regular. For each of several suitable instants of time in this record, an approximate wave profile along the length of the ship could be derived. On the basis of this profile, and the corresponding measured accelerations, the DAISY program would then calculate local stresses for comparison with the stresses measured on the ship.

This proposed comparison represents a formidable task, and there are many possible sources of error. The input to the SCORES program depends upon the accuracy of measured data which has been processed twice, once to remove the ship's motion and once to determine the sea spectrum.

As an alternative approach, the relatively regular portion of the wave record selected would be assumed to be part of a regular sinusoidal wave train. This would be used as input to the SCORES program to calculate motions and accelerations for comparison with ship measurements, and the instantaneous distribution of bending moment and shear along the length of the ship would provide a second input to DAISY.

Several significant comparisons could be made between the DAISY calculations and the stresses measured at various locations, including the hatch corners and the hatch corner-deckhouse intersections. Determining the accuracy by which these stresses can be predicted would be very important to future ship design.

F. Structural Model/Ship Verification

The opportunity to compare measured ship stresses with those inferred from model tests will be available from the data generated by the ship calibration experiment. Close comparison of these data will indicate to what extent the simplified model simulates the stress behavior of the actual ship. Greater insight should be gained as to the degree that particular details should be modeled. The comparison of local stress at hatch corners and hatch corner-deckhouse intersections will be particularly interesting, for purposes of stress distribution, if not for verifying actual stress levels. Expressing local stresses as a fraction of vertical bending stress may provide a convenient means of comparing either ship calibration loadings or ship seaway loadings with model stresses.

G. Secondary Correlations

Possible secondary correlations include:

1. Accelerometer data compared with the S.S. WOLVERINE STATE and the S.S. BOSTON, for similar crossing (accelerations at midships, forward and aft); similar comparisons may be made of the midship vertical bending moment.

2. Compare calculated, and measured "significant" wave heights with previously published results.

3. Check the "significant" wave height against the log book entries.

4. As with "significant" wave heights, compare R.M.S. values.

IV. LONG-RANGE RESEARCH PLAN

The SL-7 Instrumentation Program was undertaken to increase the level of understanding of the relationship between theoretical analyses, model tests and actual performance of a ship's hull structure. In addition, the long range purpose of the Program is to provide an important step in reaching the Ship Structure Committee goal of developing rationally based load criteria for ship hull structures.

This section presents a plan for accomplishing both of these purposes through a series of related research projects. A few of the more immediate projects have already been started or are in the planning process. The details of the follow-on projects are less clearly defined and it may be that the third or fourth project in a sequence cannot be accomplished at all because it will turn out that the preceding projects did not yield the expected information. Because of these uncertainties, there must be continuous supervision of these projects. However, this is exactly the sort of supervision which the Ship Structure Committee has been able to provide so successfully in the past, and this is not considered to be a major difficulty in completing the plan.

No attempt has been made to estimate funding levels for the various projects, but a rough estimate of the timing sequence required to complete the plan has been attempted. A flow diagram of the plan is presented in Figure 6 and condensed work statements for the individual projects follow. The numbers of the projects correspond to the numbers in the lower right hand corners of the boxes on the diagram.

1. Model Test of Calibration Experiments

Perform experiments on the steel and plastic SL-7 models using loads equivalent to those which were applied to the ship during the calibration experiment.

2. Compare Steel and Plastic Models

Perform a detailed comparison of the welded steel and rigid vinyl plastic structural models, including ease and cost of fabrication, accuracy and consistency of results and any other significant experimental factors.

3. Calculations of Calibration Experiments

Perform structural response calculations with the response program using the same loads as those applied to the ship during the calibration experiments. In addition, perform structural analysis calculations of the models using the equivalent calibration loads.

4. Compare Calculations and Model

Perform a detailed analysis of the results of the model experiments over the entire range of loads investigated and of the related structural response calculations. Compare the results and

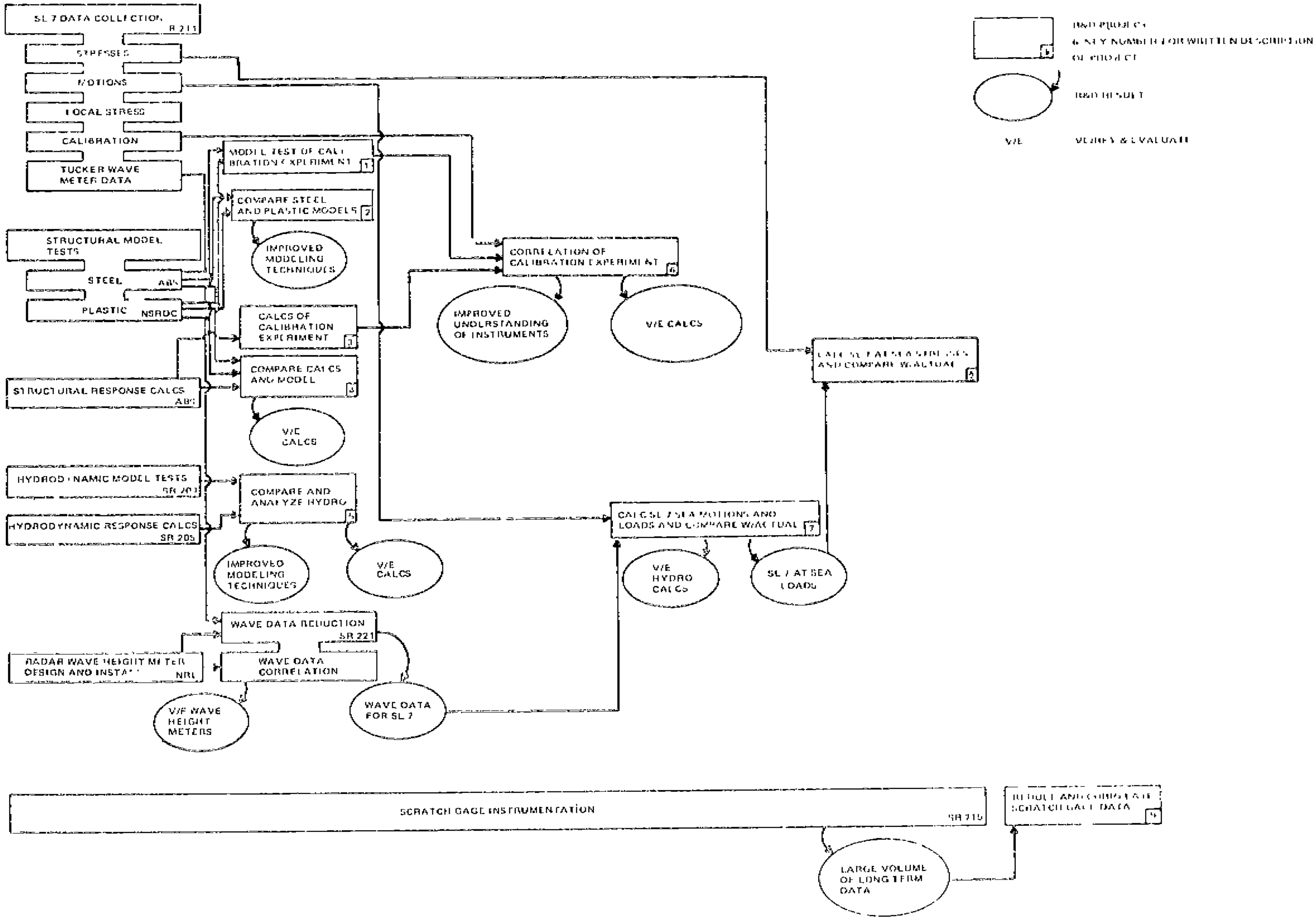


FIGURE 6 SSC SL-7 INSTRUMENTATION PROGRAM LONG RANGE RESEARCH PLAN

evaluate the errors in each. Estimate the validity of the calculation program and suggest changes to improve it.

5. Compare and Analyze Hydrodynamic Data

Perform a detailed analysis of the results of the hydrodynamic model tests (SR-204) and calculations (SR-205), evaluate the errors in each, estimate the validity of the calculation program, suggest changes to improve both the calculation program and the experimental techniques of the model tests.

6. Calibration Experiment Correlation

Perform a detailed analysis of the calibration experiment performed on the vessel and of the equivalent analysis calculations and model tests. Evaluate the errors in each. Estimate the validity of the calculation program and suggest changes to improve it. Critique the plan and performance of the calibration experiment and suggest ways to improve experiments such as this.

7. Calculate SL-7 At-Sea Motions and Loads and Compare with Actual

Using the improved hydrodynamic response program and the data from the waves actually encountered and measured, as determined from the wave data reduction project, calculate the predicted motions and accelerations response for the vessel. Compare these predictions with the motions and accelerations actually measured on board the vessel. Evaluate the errors in the at-sea measurements and in the calculation program. Estimate the validity of the calculation program and suggest changes to improve it. Unless the validity of the calculation program is found to be unacceptable, calculate the predicted structural loads for the seaway actually encountered.

8. Calculate SL-7 At-Seas Stresses and Compare with Actual

Using the at-sea loads predicted from the calculations above and the improved structural response calculation program, calculate the stresses and compare these calculations with the stresses actually measured on board the vessel. Evaluate the errors in the at-sea measurements and in the calculation program. Estimate the validity of the program and suggest changes to improve it.

9. Reduce and Correlate Scratch Gage Data

Perform a detailed analysis of the data obtained from SR-215, Extreme Stress Data Collection, using data from SR-211, SL-7 Data Collection, and other sources as necessary. Reduce the long-term data to a form which can be used as input to previous work on statistical prediction of hull structural loads.

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APPENDIX A

Discussion of the Ship Response Instrumentation System Aboard the SL-7 Class S.S. SEA-LAND McLean

Introduction

A complex array of measuring and recording instruments has been installed on board the S.S. SEA-LAND McLEAN. The purpose of this appendix is to discuss the data which will be obtained from these instruments and the possible uses to which they will be put. Recognizing that it is the output of the system which is of interest, it is nevertheless convenient to refer to the individual measuring instruments which have been installed. Furthermore, since the measurement of a given response, for example vertical bending stress, often requires the output of two or more instruments combined in a particular way, the instruments are discussed in combinations. These combinations are called Data Acquisition Groups (DAG), and the output of the instruments in a DAG will be raw data which, when suitably processed, will yield a particular type of response information. Figure A-1 shows the position of the various measuring instruments with DAG referred to in the text indicated.

It must be stressed that the outputs of all the various instruments cannot be recorded simultaneously. Limitations of space and funds dictated that only two thirteen channel, instrument grade, precision tape recorders were available. One recorder was used to record 13 channels of general information two hours out of every four hours of ship operation. The other was set up to record 13 independent channels of data on four different modes of operation or 52 channels of information. Each recording mode operated for a one-half hour period out of every four hour recording cycle. In periods of high seaway loads, the data were recorded continuously.

The amount of data available have been further increased by the use of switching devices, such as the Girder Selection Box (GSB), Rosette Selection Box (RSB), and a Selector Switch. Use of these switching devices allowed a greater amount of data to be monitored and evaluated for future recording. The various switching devices will be described in the write-ups for the various DAG.

DAG I - Ship Motion Data
(4, 5, 6, 7, 8, 9, 10A, 11A)*

The ship's motion was measured by four bidirectional accelerometers and roll and pitch pendulums. One of the accelerometers and roll and pitch pendulums were located at Frame 178, 52 feet forward of the design draft LCF and 33 1/2 feet forward of the ship's center of gravity. This accelerometer was used to obtain the ship's heave and sway acceleration. It is recognized that approximately 10% of the ship's pitch motion and approximately 7% of the ship's yaw motion was included in the measured heave and sway accelerations respectively, because of the location of

*Numbers in parenthesis refer to recording channels, [49].

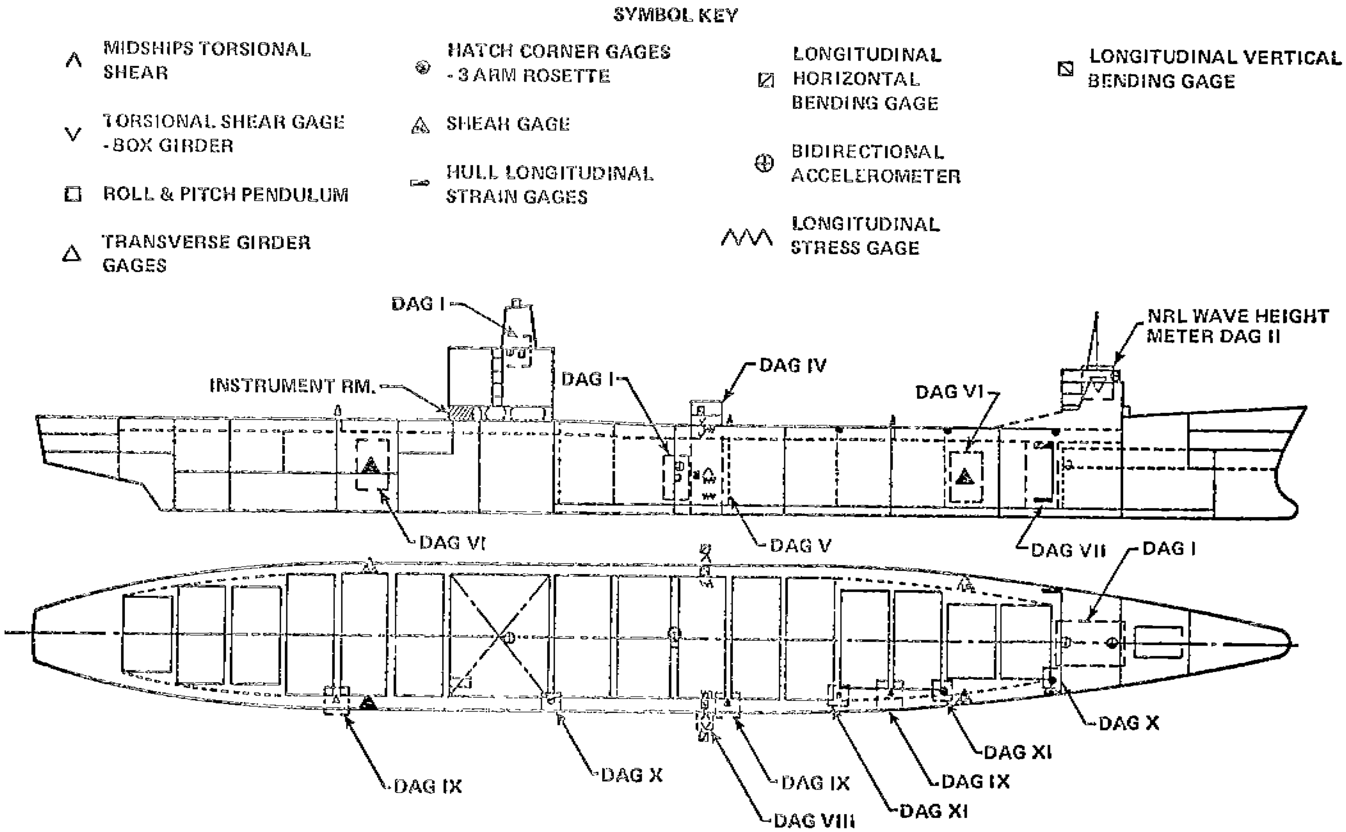


FIGURE A-1 -- INSTRUMENTS ON BOARD S.S. SEA LAND McLEAN SHOWING DAG LOCATIONS the accelerometer. Accelerations from this gage were recorded every two hours out of four, as were the roll and pitch pendulum data.

The forward deckhouse accelerometer, located on the 04 level at Frame 310 shared recording channels with the aft deckhouse accelerometer located on the 05 level at Frame 125. The outputs of either of these accelerometers could be recorded one half hour out of each four hour period. This accelerometer, besides measuring the G forces at the forward deckhouse, provided data for reducing the relative motion data from the radar wave height meter under project SR-221.

The aft deckhouse accelerometer measured G forces in the vertical and longitudinal direction at the after deckhouse. These data relate to the acceleration loads experienced by the cargo containers but are not needed for the overall hull structural analysis.

The fourth bidirection accelerometer was located at Frame 290 - beneath the forward deckhouse. The signal from this accelerometer was recorded two hours out of each four and served two important purposes. First, it provided information on the vertical and athwartships accelerations experienced by the forward part of the vessel and; second, this acceleration data was to be combined with that of the forward deckhouse accelerometer to determine the actual acceleration at the location of radar wave height meter.

DAG II - Wave Height
(3)

The radar wave height meter provided a measurement of the distance from the 03 level of the deckhouse (Frame 302) to the surface of the ocean. The wave meter operated continuously and recorded for two hours of each four hour cycle. The accelerometer recordings described in DAG I were to be used in processing this signal to establish the actual height of waves encountered.

DAG III - Ship Operation Information
(10)

The ship's operating parameters - RPM, rudder angle and wind speed - were multiplexed and were recorded during the two hour recording cycle. The ship's course was recorded on a conventional strip chart course recorder and in the data log book. The strip chart records will be retained on the ship for a period of one year from date of recording, but they may be obtained for data analysis at the end of that period should the need arise.

DAG IV - Vertical Bending (Ref Stress)
(1, 1A, 1B, 1C, 1D)

Longitudinal dyadic stress gages were located port and starboard under the deck inside the longitudinal box girder, Frame 186 1/4. The gages were wired together to eliminate lateral and torsional bending stresses, thus the gages measured the longitudinal stress from vertical bending. This signal was recorded as a reference on all recording modes.

DAG V - Midship Section (Frame 186 1/4)
(2, 11, 2A thru 7A)

The midship section group of gages consisted of four longitudinal dyadic stress gages at the sections corners, two longitudinal dyadic stress gages on the port and starboard sideshell at the vertical axis, and a pair of shear rosettes located on the sideshell at the neutral axis - one gage per side. See Figure A-2.

Longitudinal Stress Gages
(2A, 3A, 4A, 5A, 6A, 7A)

The signals of the four corner stress gages and the one stress gage at the neutral axis on each sideshell were recorded separately. These gages measured the instantaneous combined vertical, lateral and torsional bending stress at their respective locations and were recorded one half hour out of each four hour period of ship operation.

Figure A-3a. shows a schematic representation of the midship section (Frame 186 1/4) with the longitudinal stress gage positions indicated by numbers 2 through 7. The combined instantaneous longitudinal stress at the gage locations is indicated in Figure A-3b, as σ_2 through σ_7. For example, with a clockwise torque, a hogging moment and a lateral bending moment with the load applied port side, gage 2 experiences a tensile stress due to hogging, a tensile stress due to lateral bending and an additional tensile stress due to the applied torque. The component load stress distributions for all the gages are shown in Figures A-3c, 3d and 3e. Appendix C contains an explanation of the method of determining component stresses as shown in Figure A-3c to 3e from the combined measured stresses.

Lateral Bending
(11)

In addition to the six longitudinal dyadic stress gages at Frame 186 1/4, two additional stress gages of the same type were mounted port and starboard near the neutral axis at positions 3 and 6 (Figure A-3a). These two gages were wired together so as to eliminate the vertical bending signal. Thus the signal was proportional to a combination of lateral bending stress and a component of longitudinal warping stress. This signal was recorded for the 2 hour recording period and it may be used as a lateral bending stress reference signal.

Torsional Shear
(2)

Two-arm strain-gage rosettes were mounted on the sideshell port and starboard near the neutral axis (Frame 186 1/4), in a shear configuration. The two sides were wired together to form a four-arm bridge circuit. (Figure A-4 shows the common axis of the gages.) By wiring the gages in this manner, the shear associated with vertical bending was eliminated, thus torsional and lateral bending shearing stress is measured.

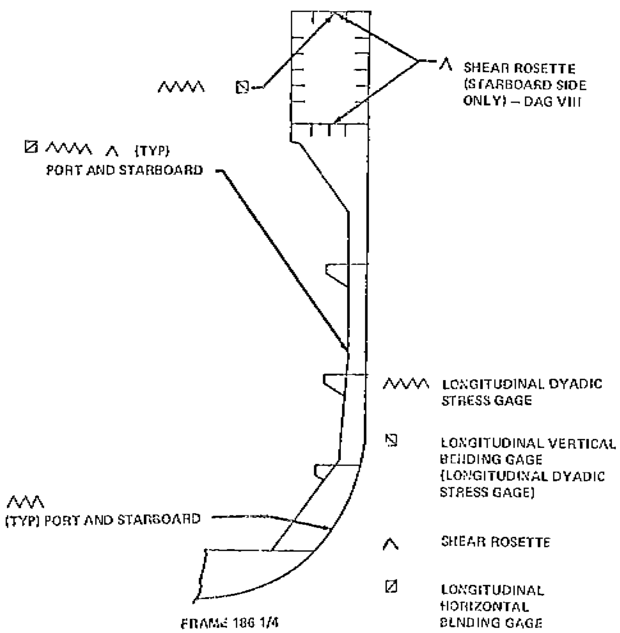


FIGURE A 2 – MIDSHIPS STRESS GAGE LOCATIONS

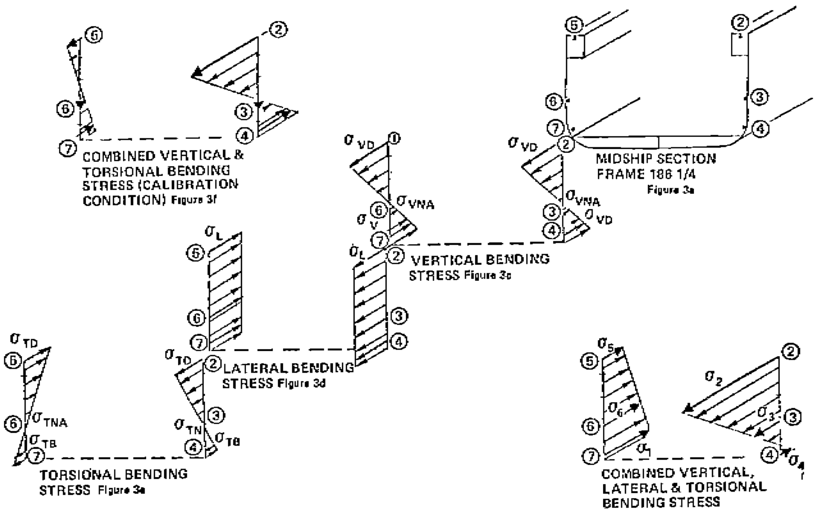
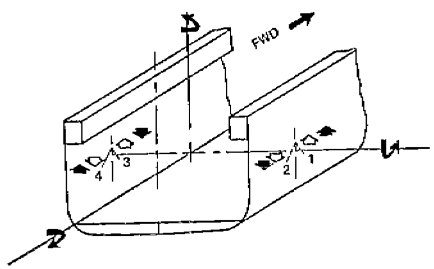


FIGURE A-3 – STRESS CONFIGURATIONS



	VERTICAL SHEAR	LATERAL BEND	TORSIONAL SHEAR
1 = STBD FWD	C	E	C
2 = STBD AFT	E	E	E
3 = PORT FWD	C	C	E
4 = PORT AFT	E	C	C

E = R_2 (INCREASE)
C = R_1 (DECREASE)

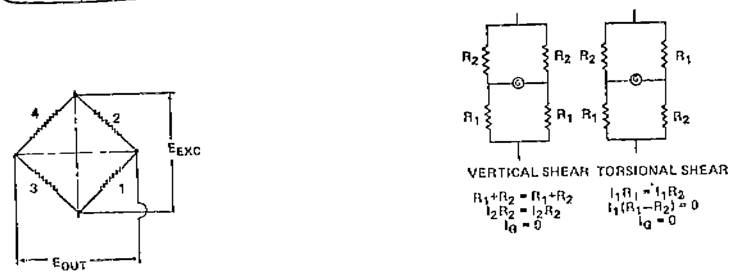


FIGURE A-4 – MIDSHIPS SHEAR GAGES

DAG VI - Quarter Point Shear
(12, 13, 8A, 9A)

Two-arm shear rosettes were located port and starboard near the forward and aft quarter points, Frames 265-266 and 87-88 respectively.

The shear gages were each wired as a single shear transducer, forming one half of a four-arm bridge. The port and starboard signals were recorded separately thus allowing the forward or aft signals from each rosette to be added or subtracted during laboratory analysis to determine vertical shear stress or torsional shear. See Figure A-5.

DAG VII - Longitudinal Warping Restraint Gages
(2D, 3D, 4D, 5D)

Four longitudinal strain gages were located on the sideshell port and starboard immediately aft of the transverse bulkhead at the forward deckhouse, Frame 290. The deck gages were located 12 inches under the longitudinal box girder and the bottom gages were located 12 inches above the innerbottom. See Figure A-6.

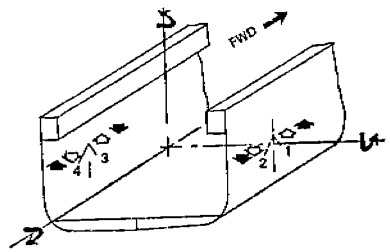
By positioning a selector switch on the Program Status Unit (PSU), the operator could select whether he would record the output of these longitudinal warping restraint gages or the signals from the four corner gages in the transverse beam at Frames 242-244. The operator noted the position of the selector switch in his data log book. The signals were recorded for one half hour out of the two-hour recording cycle. The output of these gages was a measure of the resistance to warping which existed at the transition from open hatch to closed section at the forward deckhouse.

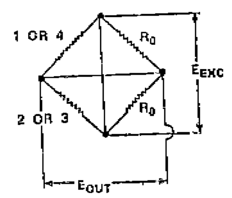
DAG VIII - Longitudinal Girder
(12A, 13A)

One two-arm shear rosette was located on the overhead surface and another on the deck surface of the starboard box girder at Frame 186 1/4. The common axis of the dyadic configuration was in the transverse direction. The signals from the overhead and deck gages were recorded independently during the one half hour recording cycle. The signals could be added during analysis to obtain the total torsional shearing stress in the longitudinal girder.

DAG IX - Transverse Beams
(2D-5D, 6D-9D, 10D-13D)

Three transverse beams were strain-gaged to investigate the "S" bending due to torsional loads experienced by the ship. Two of the transverse beams at Frames 78-80 and Frames 242-244 contained single strain gages at the corners on the starboard side at each corner (see Figure A-7). The signal from each corner gage was recorded separately





	VERTICAL SHEAR	LATERAL BEND	TORSIONAL SHEAR
1 = STBD FWD	C	E	C
2 = STBD AFT	E	E	E
3 = PORT FWD	C	C	E
4 = PORT AFT	E	C	C

ASSUME: E = INCREASED, $R = R_2$
C = DECREASED, $R = R_1$

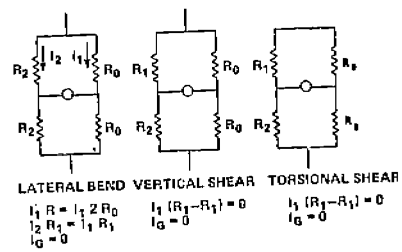


FIGURE A-5 – QUARTER POINT SHEAR GAGES

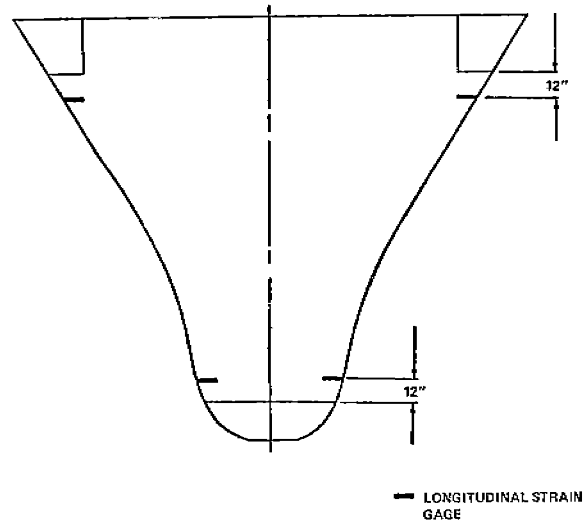
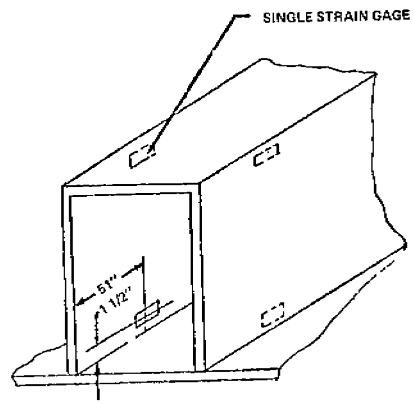


FIGURE A-6 – LONGITUDINAL STRAIN GAGES AT FRAME 290



FRAME 78-80 & FRAME 242-244

TYPICAL LOCATION -- STARBOARD SIDE ONLY

FIGURE A-7 – TRANSVERSE BEAM GAGE LOCATIONS during the half hour recording cycle. The signals from the four transverse beam gages at Frames 242-244 shared recording channels with the data of DAG VII through the Selector Switch on the PSU.

The starboard side of the transverse beam at Frames 194-196 contained 12 gages. (See Figure A-8.) Four of the gages were of the single strain gage type and were mounted on each corner. Four single strain gages were mounted at the same cross section - one at the midpoint of each cross section dimension of the beam. The third set of four gages consisted of two-element shear gages at the quarter points of the two side walls. As the gages were originally wired, only four gage signals could be recorded at any given time, with the gages that were to be recorded selected through the Girder Selection Box (GSB), with an appropriate notation in the data log book. Three combinations of four signals were available for selection: (1) the four corner gages, (2) the four mid-point gages, or (3) the four quarter-point gages on the two side walls.

DAG X - Deckhouse/Hatch Intersection
(2C-13C, 2B-13B)

Four three-arm strain gage rosettes were installed between Frames 290-291 and between Frames 143-144 to lead to determination of the stress magnitude and direction at the forward house/hatch intersection and the aft-house/hatch intersection. (See Figures A-9 and A-10.) The three elements of the strain gages - designated as A, B and C - measured the longitudinal, diagonal and transverse strains respectively.

The signals from the aft-house/hatch intersection gages were recorded during the regular half hour recording cycle. The gages at the forward-house/hatch intersection were, on the other hand, wired to a patching unit designated the Rosette Selection Box (RSB). Using the RSB, the operator could select the signals from four rosettes at the forward-house/hatch intersection or from one of two hatch transitions as described in DAG XI as input to the recorder for the half hour recording interval.

The evaluation of the transfer of longitudinal stress (from all sources: torsion, vertical, lateral, etc.) from the open hatch, box beam structure in way of the holds to a rigid closed section at the house was the primary purpose of these gages. The stress concentration which exists at the hatch corner could also be evaluated.

In addition to the four strain gage rosettes at the aft-house/hatch intersection, single gages were located around the circumference of the starboard beam/hatch intersection cutout, (see Figure A-10). These gages were originally not wired for recording purposes but existed for future consideration.

DAG XI - Hatch Corners
(2C-13C)

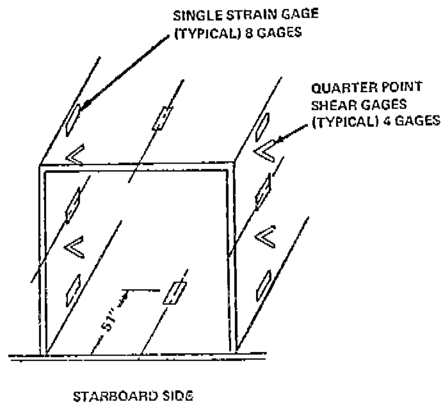


FIGURE A-8 – TRANSVERSE BEAM GAGE LOCATIONS AT FRAMES 194-195

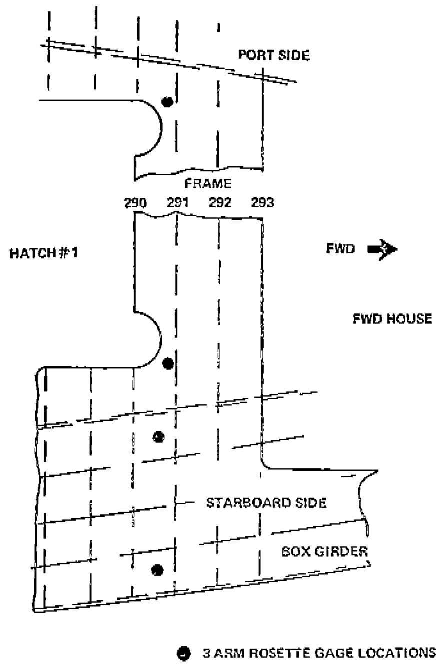


FIGURE A-9 – FWD HOUSE/HATCH ROSETTE GAGE LOCATIONS

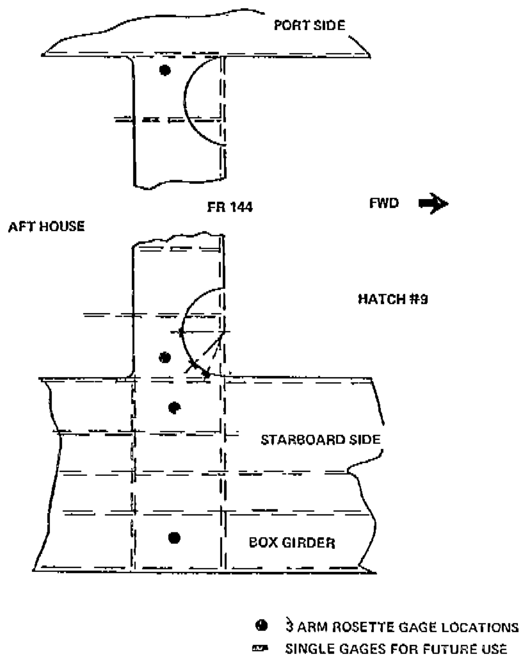


FIGURE A-10 – AFT HOUSE/HATCH ROSETTE GAGE LOCATIONS

Data Acquisition Group XI consists of 10 rosettes with 3 elements per rosette for a total of 30 separate signals. Five rosettes were located at the hatch transition at Frames 226-227 and five at the hatch transition at Frames 258-280. (See Figure A-11.) The gages were wired to the RSB previously in DAG X. By means of patching cables, the operator could select any four rosettes as input to the recorder, however, all elements, i.e., the A, B, and C arms of any one rosette had to be recorded together. The outputs of the selected rosettes were recorded for the half hour recording cycle.

The three arms of the rosettes, A, B, and C recorded the longitudinal, diagonal and transverse strains respectively. Using this information, the magnitude and direction of the principal stresses in the area of the hatch transitions could be determined. This information would be used to evaluate the stress concentration factors in these areas.

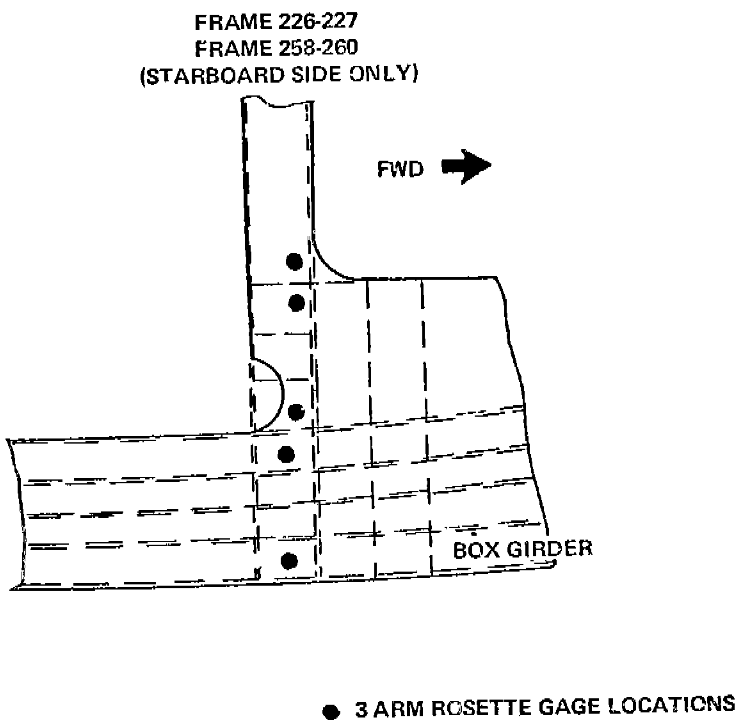


FIGURE A-11 - HATCH TRANSITION ROSETTE GAGE LOCATIONS

In addition to loads from cargo, ballast and the seaway encountered, another load variation results from diurnal changes in air temperature and in radiant heating from the sun. The effect is clearly shown in Figure B-1, taken from the SR-198 report, "Load Criteria for Ship Structure Design", SSC 240. Such thermal stresses can be explained on the basis of irregular or uneven thermal gradients, which can be considered as the "loads". In general, if a beam is subject to heating that produces a uniform thermal gradient from top to bottom, it will deflect and there will be no resulting stresses. But, if the gradient is not uniform, stresses will be induced. In the case of a floating ship, the temperature of all the steel in contact with the water will be at the nearly uniform water temperature, and there will be a very little change from day to night. But the portion of the hull above water will usually be at a different temperature, and that temperature changes continually and depends on the air temperature, the amount of sun radiation, the extent of cloudiness, the duration of sunlight, and altitude of sun at noon and even the color of the deck. There is usually a marked change in stress in the vicinity of the waterline, especially on the sunny side of the ship, but from the point of view of longitudinal strength, the temperature gradient between the weather deck and the underwater hull is most significant.

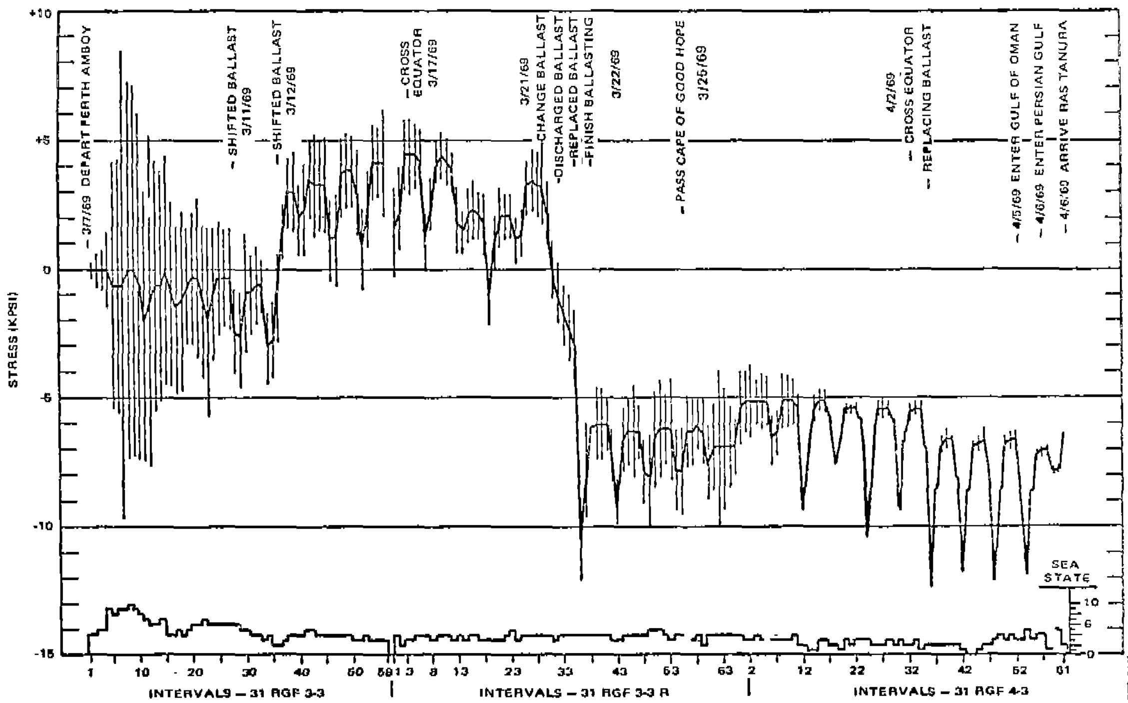


FIGURE B-1 – TYPICAL VOYAGE STRESS VARIATION

NOTES

APPENDIX C

Derivation of Midship Stresses

The combined longitudinal stresses (Figures A-3b) may be written in terms of their component loading stresses in the general form as:

(1) $\sigma_n = \sigma_{\ell n} + \sigma_{Vn} + \sigma_{Tn}$

where the subscript n (n = 2, 3, 4, 5, 6, 7) refers to the gage locations as shown in Figure C-1, and ℓ, V and T designate lateral, vertical and torsional bending stresses respectively.

For the case where a single loading of vertical, lateral or torsional bending exists, it is known that:

(2) $\sigma_{\ell 2} = \sigma_{\ell 3} = \sigma_{\ell 4} = -\sigma_{\ell 5} = -\sigma_{\ell 6} = -\sigma_{\ell 7} = \sigma_{\ell}$ (Lateral bending stress) (Figure A-3d)

(3) $\sigma_{V2} = \sigma_{V5} = \sigma_{VD}$ (Vertical bending stress at deck) (Figure A-3c)

(4) $\sigma_{V4} = \sigma_{V7} = -\sigma_{VB}$ (Vertical bending stress near bottom) (Figure A-3c)

(5) $\sigma_{T2} = -\sigma_{T5} = \sigma_{TD}$ (Torsional bending stress at deck) (Figure A-3e)

(6) $-\sigma_{T4} = \sigma_{T7} = \sigma_{TB}$ (Torsional bending stress near bottom) (F gure A-3c)

(7) $\sigma_{V3} = \sigma_{V6} = \sigma_{Vna}$ (Vertical bending stress near neutral axis) (Figure A-3c)

(8) $\sigma_{T3} = -\sigma_{T6} = \sigma_{Tna}$ (Torsional bending stress near neutral axis) (Figure A-3e)

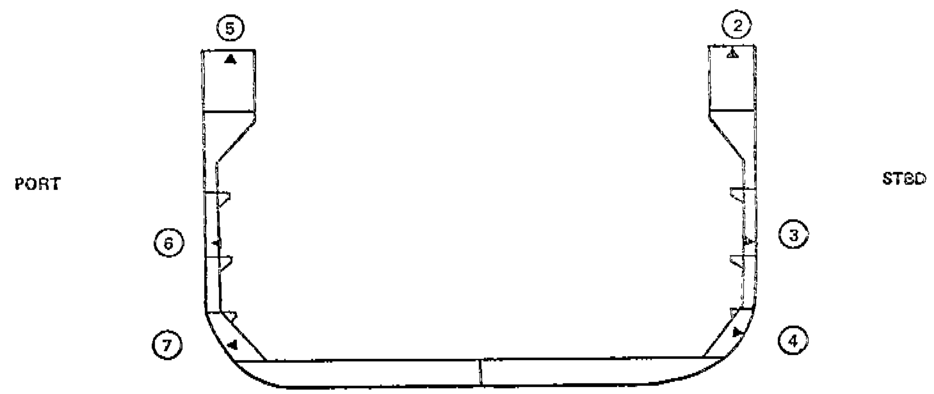


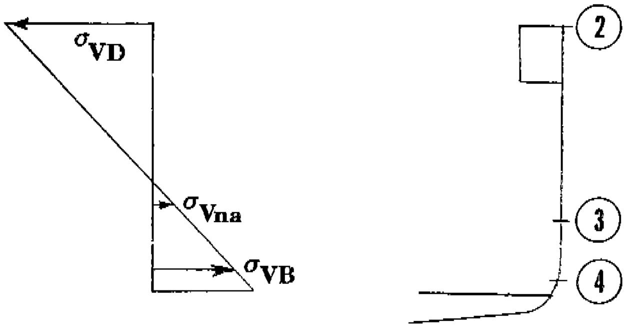
FIGURE C-1

MIDSHIP SECTION STRAIN GAGES (FR 186 1/4)

The vertical bending stress at the deck and bottom may be expressed in terms of the vertical bending stress at the "neutral axis", i.e., gage location 3 and 6, as:

$\sigma_{VD} = C_1 \sigma_{Vna}$

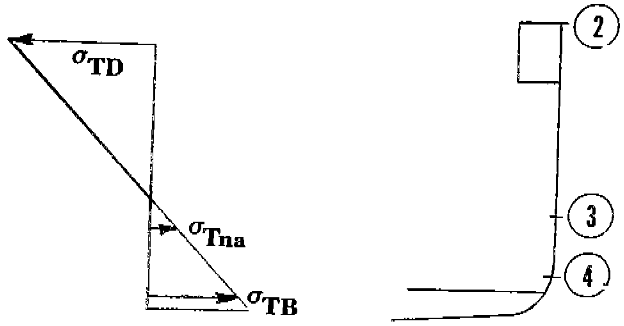
$\sigma_{VB} = C_2 \sigma_{Vna}$



Likewise, the torsional bending stress (warping stress) at the deck and bottom may be expressed in terms of the torsional bending stress at the "neutral axis" as:

$\sigma_{TD} = C_3 \sigma_{Tna}$

$\sigma_{TB} = C_4 \sigma_{Tna}$



C_1, C_2, C_3 and C_4 are constants which depend on the relationship between the location of gages 3 and 6 and the actual neutral axis for vertical and torsional bending. By writing equation (1) in its component form and making substitutions from relations (2) through (8), one obtains, for the sign conventions assumed, the following equations:

(11) $\sigma_2 = \sigma_\ell + \sigma_{VD} + \sigma_{TD}$

(12) $\sigma_3 = \sigma_\ell + \sigma_{Vna} + \sigma_{Tna}$

(13) $\sigma_4 = \sigma_\ell - \sigma_{VB} - \sigma_{TB}$

(14) $\sigma_5 = -\sigma_\ell + \sigma_{VD} - \sigma_{TD}$

(15) $\sigma_6 = -\sigma_\ell + \sigma_{Vna} - \sigma_{Tna}$

(16) $\sigma_7 = -\sigma_\ell - \sigma_{VB} + \sigma_{TB}$

By adding equations (11) and (14), one obtains the vertical bending stress near the deck.

$$\sigma_{VD} = (\sigma_2 + \sigma_5)/2 = C_1\sigma_{Vna}$$

Likewise, adding equations (13) and (16), one finds the vertical bending stress near the bottom of the section.

$$\sigma_{VB} = -(\sigma_7 + \sigma_4)/2 = C_2\sigma_{Vna}$$

and the vertical bending stress near the neutral axis is (from equations (12) and (13)).

$$\sigma_{Vna} = (\sigma_3 + \sigma_6)/2$$

Writing equations (11) and (13) in terms of σ_{Tna} one has the following equations:

$$\sigma_2 = \sigma_{VD} + C_3\sigma_{Tna} + \sigma_\ell$$

$$\sigma_4 = -\sigma_{VB} - C_4\sigma_{Tna} + \sigma_\ell$$

subtracting and substituting for σ_{VB} and σ_{VD} one obtains:

$$\sigma_{Tna} = 1/[2(C_3 + C_4)](\sigma_2 - \sigma_4 + \sigma_7 - \sigma_5)$$

the combinations of $(\sigma_2 - \sigma_4 + \sigma_7 - \sigma_5)$ appears throughout the analysis and thus been designed σ_K (Total Torsional Stress)

$$\sigma_{Tna} = 1/[2(C_3 + C_4)]\ \sigma_K$$

Using equations (9) and (10) leads to:

$$\sigma_{TB} = C_4/[2(C_3 + C_4)]\ \sigma_K$$

and

$$\sigma_{TD} = C_3/[2(C_3 + C_4)]\ \sigma_K$$

To determine the lateral bending stress, σ_ℓ, one substitutes into equation (15), σ_{Vna} and σ_{Tna}

$$\sigma_\ell = -\sigma_6 - 1/(C_3 + C_4)[(\sigma_2 - \sigma_4)/2 + (\sigma_7 - \sigma_5)/2] + (\sigma_3 + \sigma_6)/2$$

or

$$\sigma_\ell = (\sigma_3 - \sigma_6)/2 - 1/[2(C_3 + C_4)]\ \sigma_T$$

Thus, it can be seen that the component stresses can be obtained from the six longitudinal stress gages provided the constants C_3 and C_4 are known. C_3 and C_4 as well as C_1 and C_2 will be obtained from the ship's calibration experiments, as explained below.

Calibration

Consider a torsional warping stress along the side shell in which σ_{TD}, σ_{Tna} and σ_{TB} are known. See Figure C-2.

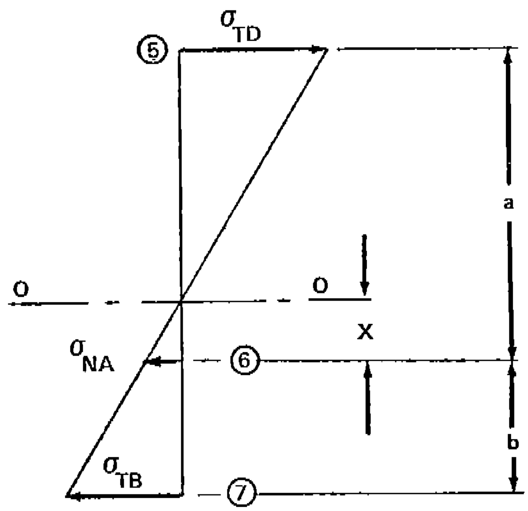


Figure C-2 - TORSIONAL BENDING STRESS

x is the distance from the axis at zero warping stress to the longitudinal gage located near the neutral axis. Let a equal the vertical distance from the gage at 6 (σ_{Tna}) to the gage at 5 (σ_{TD}) and b equal the vertical distance from the gage at 6 (σ_{Tna}) to the gage at 7 (σ_{TB}).

From Similar Triangles:

$$\sigma_{TB}/(b + x) \; [\sigma_{Tna}/x]$$

or,

$$\sigma_{TB} = \sigma_{Tna}[(b/x) + 1]$$

Likewise,

$$\sigma_{TD} = \sigma_{Tna}[(a/x) - 1]$$

Referring to equations (9) and (10)

$$C_3 = [(a/x) - 1]$$

and

$$C_4 = [(b/x) + 1]$$

The loads applied during calibration were a combination of vertical bending and torsional bending. This combined bending stress condition is shown in Figure A-3f. Since, during calibration, $\sigma_{\ell} = 0$, the stresses measured during calibration may be written in their component stresses (equations 11 - 16) as follows:

$$\sigma_2 = \sigma_{TD} + \sigma_{VD}$$

$$\sigma_3 = \sigma_{Tna} + \sigma_{Vna}$$

$$\sigma_4 = -\sigma_{TB} - \sigma_{VB}$$

$$\sigma_5 = -\sigma_{TD} + \sigma_{VD}$$

$$\sigma_6 = -\sigma_{Tna} + \sigma_{Vna}$$

$$\sigma_7 = \sigma_{TB} - \sigma_{VB}$$

or combining,

$$\sigma_{VD} = (\sigma_2 + \sigma_5)/2$$

$$\sigma_{Vna} = (\sigma \quad + \sigma_6)/2$$

$$\sigma_{VB} = -(\sigma_4 + \sigma_7)/2$$

$$\sigma_{Tna} = \sigma_3 - \sigma_{Vna} = (\sigma_3 - \sigma_6)/2$$

$$\sigma_{TD} = -\sigma_5 + \sigma_{VD} = (\sigma_2 - \sigma_5)/2$$

$$\sigma_{TB} = \sigma_7 + \sigma_{VB} = (\sigma_7 - \sigma_4)/2$$

Once σ_{Tna}, σ_{TD} and σ_{TB} are determined from the calibration, x may be determined by plotting the stresses, measurements, and fairing a straight line through the data points, and from x, C_3 and C_4 will be determined. A similar procedure is followed to determine C_1 and C_2.

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13. ABSTRACT

The SL-7 Instrumentation Program is one of the most comprehensive coordinated surface ship load and response analysis programs ever undertaken. The program includes measurement of hull stresses, accelerations and environmental and operating data on the S.S. SEA-LAND McLEAN, development and installation of a microwave radar wavemeter for measuring the seaway encountered by the vessel, a wave tank model study and a theoretical hydrodynamic analysis which relate to the wave-induced loads, a structural model study and a finite element structural analysis which relates to the structural response, and installation of long term stress recorders on each of the eight vessels of the class. This report presents an overview of the program. The experimental background upon which the program was based and the major features and expected outputs of each of the program elements are discussed, and some preliminary conclusions drawn from the research results are presented. A detailed description of the possible data correlations and their consequences is included. The long-range goal of the program is to advance understanding of the performance of ships' hull structures and the effectiveness of the analytical and experimental methods used in their design. A research plan to achieve this is outlined.

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SL-7-1, (SSC-238) - *Design and Installation of a Ship Response Instrumentation System Aboard the SL-7 Class Containership S.S. SEA-LAND McLEAN* by R. A. Fain. 1974. AD 780090.

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