SSC-181

Results from Full-Scale Measurements of Midship Bending Stresses on Two Dry-Cargo Ships - Report #2

by

D.J. FRITCH

F.C. BAILEY

and

J.W. WHEATON

SHIP STRUCTURE COMMITTEE

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

BUREAU OF SHIPS, DEPT. OF NAVY
MILITARY SEA TRANSPORTATION SERVICE, DEPT. OF NAVY
UNITED STATES COAST GUARD, TREASURY DEPT.
MARITIME ADMINISTRATION, DEPT. OF COMMERCE
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON, D. C. 20226

March 1967

Dear Sir:

The Ship Structure Committee is currently sponsoring a project at Lessells and Associates, Inc. (now Teledyne Materials Research Co.) that is measuring the vertical bending moments on ocean-going ships.

Herewith is a copy of the fourth progress report, SSC-181, Results from Full-Scale Measurements of Midship Bending Stresses on Two Dry-Cargo Ships - Report #2 by D. J. Fritch, F. C. Bailey and J. W. Wheaton.

The project is being conducted under the advisory guidance of the Ship Hull Research Committee of the National Academy of Sciences-National Research Council.

Please address any comments concerning this report to the Secretary, Ship Structure Committee.

Sincerely yours,

John B. Oren

John B. Oren
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC - 181

Fifth Progress Report
of

Project SR-153
"Ship Response Statistics"

to the

Ship Structure Committee

RESULTS FROM FULL-SCALE MEASUREMENTS OF MIDSHIP BENDING STRESSES ON TWO DRY-CARGO SHIPS - REPORT # 2

by

D. J. Fritch, F. C. Bailey and J. W. Wheaton

Teledyne Materials Research Company
(formerly Lessells and Associates, Inc.)
Waltham, Massachusetts, 02154

under

Department of the Navy
Naval Ship Systems Command
Contract NObs - 88349

U. S. Coast Guard Headquarters
Washington, D. C.
March 1967

ABSTRACT

Tabulated stress data from unattended instrumentation systems are presented for two ships covering a total of 6, 528 hours of being at sea. One ship has her machinery amidship, while the other has hers aft.

The data indicate that the trend of maximum peak-to-peak stress vs. sea state for the two ships is similar. The maximum peak-to-peak stress recorded in this data is approximately 6900 psi for a sea state 11.

CONTENTS

INTRODUCTION 1

PRESENTATION OF DATA 1

DISCUSSION OF DATA 3

CONCLUSIONS 6

ACKNOWLEDGEMENTS 13

REFERENCES 14

APPENDIX 15

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.

Rear Admiral John B. Oren, USCG - Chairman
Chief, Office of Engineering
U. S. Coast Guard Headquarters

Captain W. M. Nicholson, USN
Assistant Chief of Bureau of Design
Shipbuilding and Fleet Maintenance
Naval Ship Engineering Center

Mr. D. B. Bannerman, Jr.
Vice President - Technical
American Bureau of Shipping

Captain P. E. Shetenhelm, USN
Maintenance and Repair Officer
Military Sea Transportation Service
Department of the Navy

Mr. E. Scott Dillon
Chief, Division of Ship Design
Maritime Administration

SHIP STRUCTURE SUBCOMMITTEE

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

NAVAL SHIP ENGINEERING CENTER

Captain S. R. Heller, USN - Chairman
Mr. John Vasta - Contract Administrator
Mr. George Sorkin - Member
Mr. T. J. Griffin - Alternate
Mr. Ivo Fioriti - Alternate

MARITIME ADMINISTRATION

Mr. R. W. Black - Member
Mr. Anatole Maillar - Member
Mr. R. Falls - Alternate
Mr. W. G. Frederick - Alternate

AMERICAN BUREAU OF SHIPPING

Mr. G. F. Casey - Member
Mr. F. J. Crum - Member

OFFICE OF NAVAL RESEARCH

Mr. J. M. Crowley - Member
Dr. G. R. Irwin - Alternate
Dr. Wm. G. Rauch - Alternate

MILITARY SEA TRANSPORTATION SERVICE

LCDR Donald B. Bosley, USN - Member
Mr. R. R. Askren - Member

U. S. COAST GUARD

CDR Claude R. Thompson, USCG - Member
LCDR R. Nielsen, Jr. USCG - Member
Mr. J. B. Robertson, Jr. - Member
LCDR J. F. Lobkovich, USCG - Alternate
LCDR James L. Howard, USCG - Alternate

DAVID TAYLOR MODEL BASIN

Mr. A. B. Stavovy - Alternate

LIAISON REPRESENTATIVES

NATIONAL ACADEMY OF SCIENCES-NATIONAL RESEARCH COUNCIL

Mr. A. R. Lytle - Director, Ship Hull Research Committee
Mr. R. W. Rumke - Executive Secretary, SHRC

AMERICAN IRON AND STEEL INSTITUTE

Mr. J. R. LeCron

BRITISH NAVY STAFF

Mr. A. C. Law
Construction CDR T. R. Rumens, RCNC

WELDING RESEARCH COUNCIL

Mr. K. K. Koopman, Director
Mr. Charles Larson, Asst. Director

RESULTS FROM FULL-SCALE MEASUREMENTS OF MIDSHIP BENDING STRESSES ON TWO DRY-CARGO SHIPS - REPORT #2

I. INTRODUCTION

This report summarizes the activities undertaken by Lessells and Associates, Inc. under Ship Structure Committee Project SR-153 during a two-year period to investigate certain aspects of the structural response of two dry-cargo ships to wave loads. This work continued earlier studies sponsored by the Ship Structure Committee; the investigations are continuing, and currently include acquisition of data from a third ship operating from California to the Far East.

The investigations under Project SR-153 are providing long-term statistical data from which extreme values of vertical longitudinal bending moment may be predicted. Ultimately, through correlation with model tests at the Davidson Laboratory of Stevens Institute of Technology, and analysis by Webb Institute of Naval Architecture, these data will contribute to the design of more efficient ships.

Data acquired by the Investigators through January 1964 were analyzed and presented in graphical form in Ship Structure Committee Report SSC-164.[1]* The data represented about 12,000 hours at sea for the SS HOOSIER STATE and the SS WOLVERINE STATE, both C4-S-B5 machinery-aft dry-cargo ships. The design and installation of the stress-measuring and recording system, and preliminary presentation of some data have been reported in Ship Structure Committee reports SSC-150[2],-153[3], and -159[4]. The present report includes tabulated data from eleven additional voyages of the SS WOLVERINE STATE and five voyages of the SS MORMACSCAN, a Type 1624 machinery-amidships dry-cargo ship. These data represent a total of 6,528 hours at sea for the two ships.

II. PRESENTATION OF DATA

The data plotted in Figures 1 through 12 were acquired by the following procedures:

1. The magnetic tape system records the signals generated by the stress transducers for at least one-half hour out of every four hours at sea. At the beginning of each four-hour interval a calibration signal (obtained by shunting one arm of the bridge with a known resistance) is superimposed. When the tape is played back in the Investigators' Laboratory, the Sierra Probability Analyzer is triggered by each calibration signal, and provides a histogram and statistical data representing the first twenty minutes of each record interval (see Figure 15, Reference 1.) At the playback speed of 60 inches per second, a half-hour of ship data requires 9 seconds to be analyzed by the machine.

*See References

TABLE I

SHIP SPECIFICATIONS

	SS WOLVERINE STATE	SS MORMACSCAN
Type:	C4-S-B5 Machinery-Aft Dry Cargo Vessel	1624 Machinery Amidships Dry Cargo Vessel
Builder:	Sun Shipbuilding and Drydock Company Chester, Pennsylvania	Same
Date:	September 1945	October 1960
Hull Number:	359	622
Length Overall:	520' - 0"	483' - 3"
Length Btwn Perp.:	496' - 0"	458' - 0"
Beam, Molded:	71' - 6"	68' - 0"
Depth, Molded:	54' - 0"	41' - 6"
Load Draft, Molded, Design	30' - 0"	28' - 6"
Load Draft, Keel	32' - 9 7/8"	31' - 5"
Gross Tonnage:	10,747 L.T.	9,315 L.T.
Net Tonnage:	6, 657 L.T.	5,609 L.T.
Midship Section Modulus:	45,631 in^2 ft (to top of upper deck)	30,464 in^2 ft (to top of upper deck)
Light Ship Weight:	6,746 L.T.	5,882 L.T.
Dead Weight at Load Draft	15,348 L.T.	12,483 L.T.
Propeller, Normal Operating RPM:	80	93
Shaft Horsepower, Normal	9,000	11,000
Shaft Horsepower, Maximum	9,900	12,100

2. The officer on watch maintains a logbook. Every four hours an entry is made and given a sequential Index number. At the time of the logbook entry, the Elapsed Time Meter reading is noted, from which the Index number may be matched to the appropriate Interval calibration signal. Report SSC-153 (Reference 3) contains reproduction of typical logbook pages.

3. The oscillographic output from the Probability Analyzer is transcribed manually in terms of a scale of counts from the digital registers. These counts are representative, respectively, of the greatest peak-to-peak stress, the total number of peak-to-peak stress vibrations analyzed, and the mean square value of the data sample for each interval recorded.

4. Two punched cards are prepared for each interval of data. The first contains all of the logbook data and the second contains the values from the Probability Analyzer.

5. Input cards and program cards are then processed by an IBM 7094 digital computer. The computer calculates "HED" (the difference between wave direction "WVD" and ship course "COU") and the values of maximum peak-to-peak stress in kpsi, mean square stress in kpsi^2, and root-mean-square stress in kpsi.

6. The computer output for each voyage consists of a tabulation by Interval number, and also, optionally, a set of output punched cards. The data from one pass of the magnetic tape aboard ship has been given a double-letter code for identification. This coding appears on the print-out and on each output card.

Part of the data reported here was obtained from the starboard and port sides of the SS WOLVERINE STATE separately. These data have been reported as recorded (Figures 3 and 4). They have also been shown in Figure 5 recombined electrically to simulate the "average" port and starboard data obtained by connecting both transducers together into one bridge circuit.

It should be emphasized that all of these data are in raw form, directly as measured aboard ship. See Section III and the Appendix for information concerning adjustments to the data determined by a loading calibration of the SS WOLVERINE STATE.

III. DISCUSSION OF DATA

A. General

When considering the absolute values of the stress data, it must be kept in mind that these data are presented as peak-to-peak stress variations, and not as single positive or negative amplitudes about an average level. Absolute average values are difficult to determine, and are variable with loading and thermal conditions. Statistical procedures for analyzing peak-to-peak values of random variables, moreover, are well established.

Each data point in Figures 1 through 7 is based on a twenty-minute portion of a thirty-minute sample record (interval), and is assumed to be representative of four hours of operation of the ship in the seaway. In heavy-weather situations where the tape recorder operates longer than one-half hour out of every four, only the twenty-minute portion following the calibration signal (every four hours) is analyzed, under current procedures. Coastwise and in-port data have been eliminated.

There is considerable scatter of the data points in the "dot-plots" of Figures 1 through 7. This scatter might be explained on the basis of the statistical nature of the data, since the ship operates at various headings relative to the sea, and at various speeds within a given sea state. Because the reported sea state information is based on visual observations, some spread in these values as a result of individual interpretation is also likely. Operation of the Tucker Wave Meter should provide information leading to a significant reduction of scatter from this latter source.

A possible explanation for the higher than expected stress values which are observed to occur at Sea States 1 and 2, Figure 2, is the presence of swell. The logbooks of the SS MORMACSCAN were analyzed in this connection, and a distribution of swell height vs. sea state was prepared (Figure 11). If an average H/L of 1/100 is assumed, it can be seen from this figure that swell heights sufficient to cause significant bending stresses do occur even at quite low sea states. There are few reports of swell height at sea states higher than 6, however. The greater height of the wind-generated waves probably masks the swell at the higher sea states.

B. Discussion of Figures

Figure 1 shows the distribution of rms stress vs. sea state for five voyages of the SS WOLVERINE STATE during which both starboard and port transducers were connected together in a single bridge circuit, and recorded on a single channel of the tape. Data acquired in this manner is called "average" data in this report. The data are quite similar in appearance to previous data of this kind (Figure 2, Reference 1). The arithmetical average of the points is indicated by the "X" associated with each sea state.

Figure 2 is the comparable distribution for the SS MORMACSCAN. Three of the five voyages were to South America.

The average points (X) of Figures 1,2, and Figure 2, Reference 1, have been plotted in Figure 8 for direct comparison. At the higher reported sea states, the average rms stress measured on the SS MORMACSCAN is generally higher than comparable values from the SS WOLVERINE STATE.

Figures 3, 4, and 5 show, respectively, the Starboard, Port, and Combined Starboard and Port data for those voyages of the SS WOLVERINE STATE during which two stress channels were operated. When the individual starboard and port signals are added electrically ("combined") at half-amplitude to simulate the "average", or single-channel signal from the two transducers in one bridge circuit aboard ship, the result is a new signal. This new signal is the instantaneous average of the signals from both sides.

Figure 9 is a plot of the average points ("X") of Figures 3,4, and 5. The curves indicate that the port-side values of rms stress on the SS WOLVERINE STATE are consistently higher than those observed on the starboard side. Separate analyses have shown this difference to be independent of operating parameters such as heading or speed. The difference is apparently the result of differing amounts of unfairness (bow) in the 0.91-inch thick sheer strake plating on which the transducers are mounted.

The question of plating unfairness was investigated during the loading calibration which was conducted on August 1, 1965. The results of this calibration, and conclusions regarding the effect of plating unfairness on the data are discussed in the Appendix to this report.

The averages of the rms points obtained when electrically combining the port and starboard signals are shown by the crosses in Figure 9. The curve connecting these points does not follow its expected line halfway between the port and starboard curves. At present, there is no explanation available for this discrepancy. Even though there may have been substantial horizontal bending (adding or subtracting from the vertical) present in each of the rms points in Figures 3 and 4, one would expect the influence of horizontal bending to be averaged out by the time an average point is computed for each sea state.

Studies of the influence of horizontal bending moment would have to be undertaken on an interval-by-interval basis. In addition, these studies would require a satisfactory calibration of the vessel-transducer combination to provide confirmation of the factors to be applied to port, starboard and averaged data. The extent of the unfairness is such as to have a pronounced effect on stress on either surface of the plate (as compared to nominal, or heart-of-plate stress), but would have negligible influence on effective section modulus or on the linearity of the transducer.

Figures 6 and 7 show the the distribution of maximum peak-to-peak stress vs. sea state for the two ships. The two points above 9 kpsi in Figure 6 have been verified by checking the "quick-look" oscillograph of the data, and also the Probability Analyzer results. The average points for each sea state have been plotted in Figure 10, with the average points from Figure 5, Reference 1 (previous SS WOLVERINE STATE results) included for comparison.

Figure 10 indicates that the trend of maximum peak-to-peak stress vs. sea state for the two ships is similar, and quite close correspondence of actual averages for several sea states is apparent. It would be expected, however, that the dissimilarities between the two types of ships, and the relative unfairness of the plates on the SS WOLVERINE STATE (as compared with the SS MORMACSCAN) might cause greater divergence of the curves. In fact, matching the trend noted previously with reference to the rms stress averages, the average maximum peak-to-peak stresses recorded on the SS MORMACSCAN are generally higher than those from the SS WOLVERINE STATE, especially at the higher sea states.

The number of stress variations which occur during the twenty-minute data samples ranges, in general, from about 200 to 500. The twenty-minute sample equals one-twelfth of the four-hour period it represents. Thus, although the sample may be representative of effective conditions in terms of $\sqrt{E}$, there is a probability of only one in twelve (8%) that the greatest single peak-to-peak stress variation which occurs during the four hours will appear in the data sample. On this basis, it is possible that actual maximum peak-to-peak stress variation may run as much as 20% higher than that appearing in the analyzed data. This increased value is predicted from Longuet-Higgins' approximate formula*

$$X_m = \sqrt{E}\sqrt{\log_e N},$$

where X_m is the most probable value of the maximum amplitude of stress variation in a total of N variations. The rms stress variation ($\sqrt{E}$) is assumed to remain constant and the number of stress variations is increased by a factor of twelve.

Figure 11 (discussed briefly on Page 7) indicates the distribution of swell heights vs. sea state for three South American voyages of the SS MORMACSCAN. This analysis was undertaken to show the possible cause of the relatively high stresses encountered at relatively low sea states which appear in Figure 2.

Despite the questions concerning the relationships between the port, starboard, and combined data (Figure 9), it is only natural to consider the comparison between the "average" data of Figure 8 ("X") and the"combined" ("+") data of Figure 9 for the SS WOLVERINE STATE. Since the averaging process is the same whether conducted during data acquisition, or later in the laboratory, it would be expected that the curves of the averages of the rms points within each sea state would lie fairly close together. When it was found that a significant difference existed between them, the circumstances were examined closely. If the season of the data acquisition is noted from Figures 1 and 5, it will be seen that the voyages producing two-channel data (later "combined") occurred at quite different times of the year. The "average" voyages predominantly in the summer (July to December), and the "combined" voyages are predominantly in the winter (December to April). It may be hypothesized that during the winter there is a tendency for the sea states to be reported lower than they really are. If the overall effect during the winter for some presently unrecognized reason is for stresses to be equivalent to those at the next higher sea state during the summer, the curves match very closely as shown in Figure 12.

IV. CONCLUSIONS

The unattended data acquisition systems continued to function with reasonable reliability during this period. Of the fifteen voyages of the SS WOLVERINE STATE which occurred since the last presentation of data, eleven produced usable data. Nine out of the first eleven instrumented voyages of the SS MORMACSCAN produced usable data. Five of these voyages are reported here. On a voyage basis, total system reliability was 77%.

*See Section III.B of Reference (3)

During the course of the reduction of these data, stress signals which exceeded the normal calibration setting of the Sierra Probability Analyzer were encountered. Magnetic tape channels containing these signals were re-analyzed at a higher "Q", or maximum equivalent stress level calibration of the 16th counter of the Probability Analyzer. These new runs matched the previous runs at the lower stress levels, and produced usable information in high-stress, high-sea-state situations.

A computer program for translating Probability Analyzer output counts into real stress values, and tabulating the logbook and stress data information in convenient form was written and used to prepare the data presented in the Appendix. This program was modified recently to provide, in addition, a set of punched cards containing all input data and results of computations.

Discovery of the difference in average level between the stresses measured on the starboard and on the port side of the SS WOLVERINE STATE has led to an investigation of the possible causes, and to calculation of correction factors which can be applied to the data from each side. Experiments have been made to determine appropriate factors to be applied to "average" or "combined" data. See Appendix.

The magnetic data tapes, and data log books and computer-processed data summaries are presently being stored at the Investigators' facility, and are available to other workers in the field. Inquiries relative to these items may be directed to the Investigators, or to the Secretary, Ship Structure Committee.

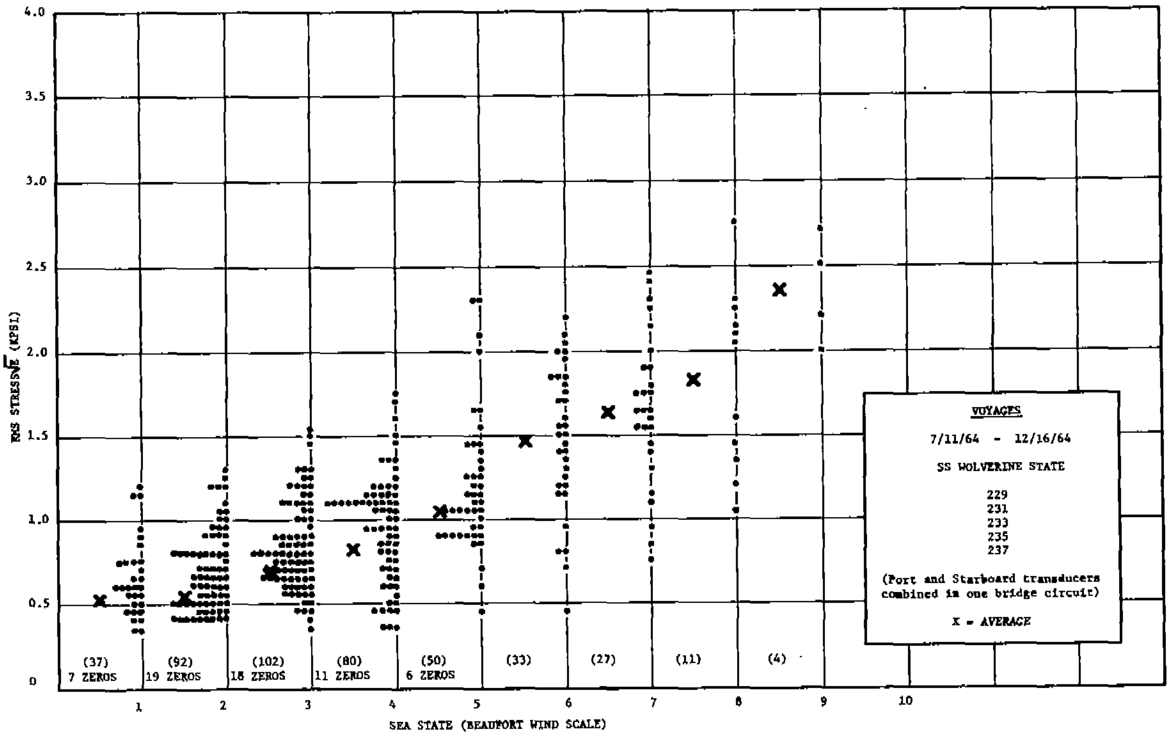


Fig. 1. RMS Stress vs. Sea State, SS Wolverine State.

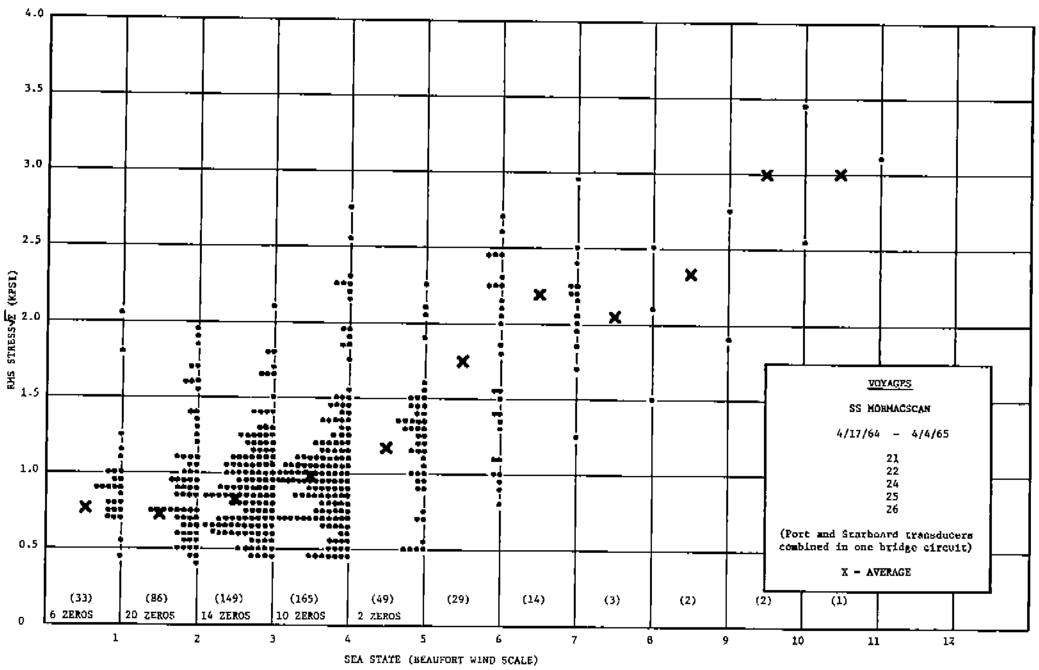


Fig. 2. RMS Stress vs. Sea State, SS Mormacscan.

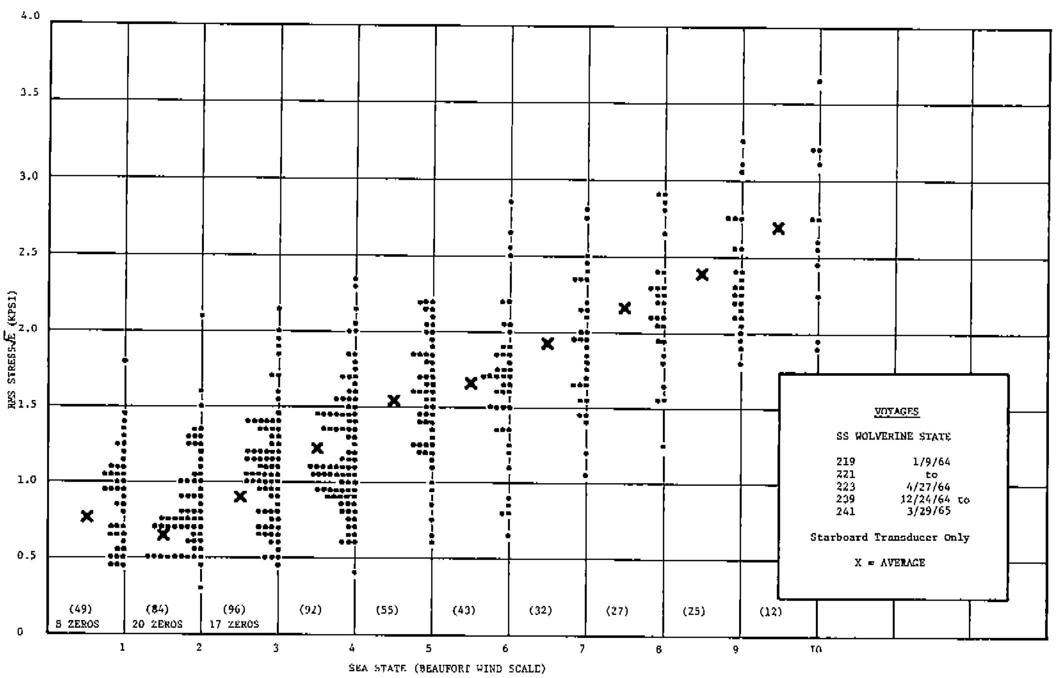


Fig. 3. RMS Stress vs. Sea State, SS Wolverine State (Starboard Transducer Only).

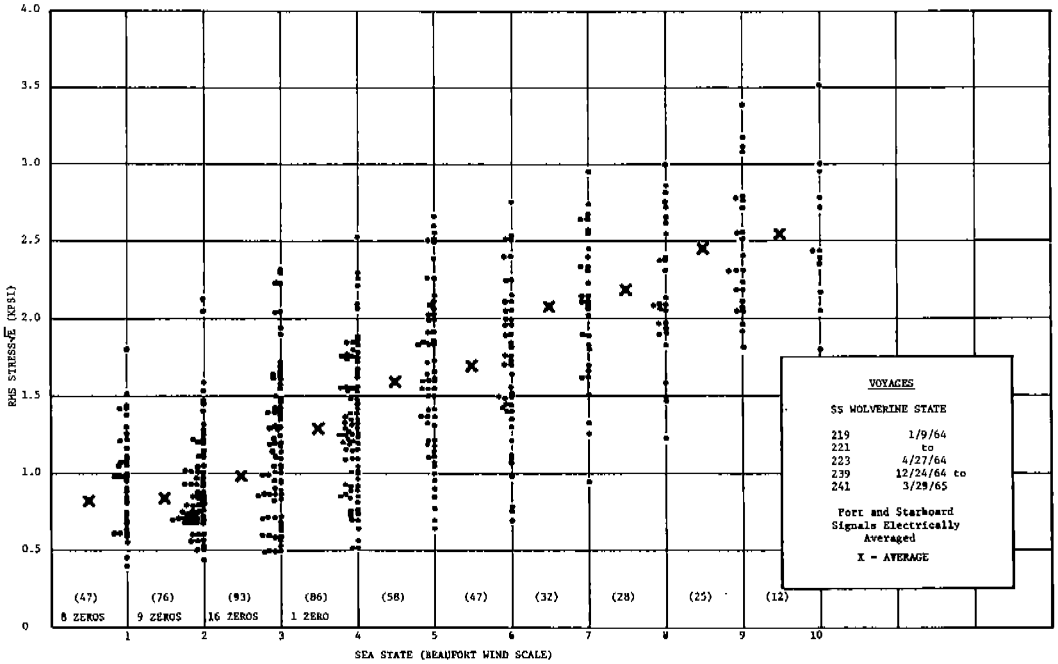


Fig. 4. RMS Stress vs. Sea State, SS Wolverine State (Port Transducer Only).

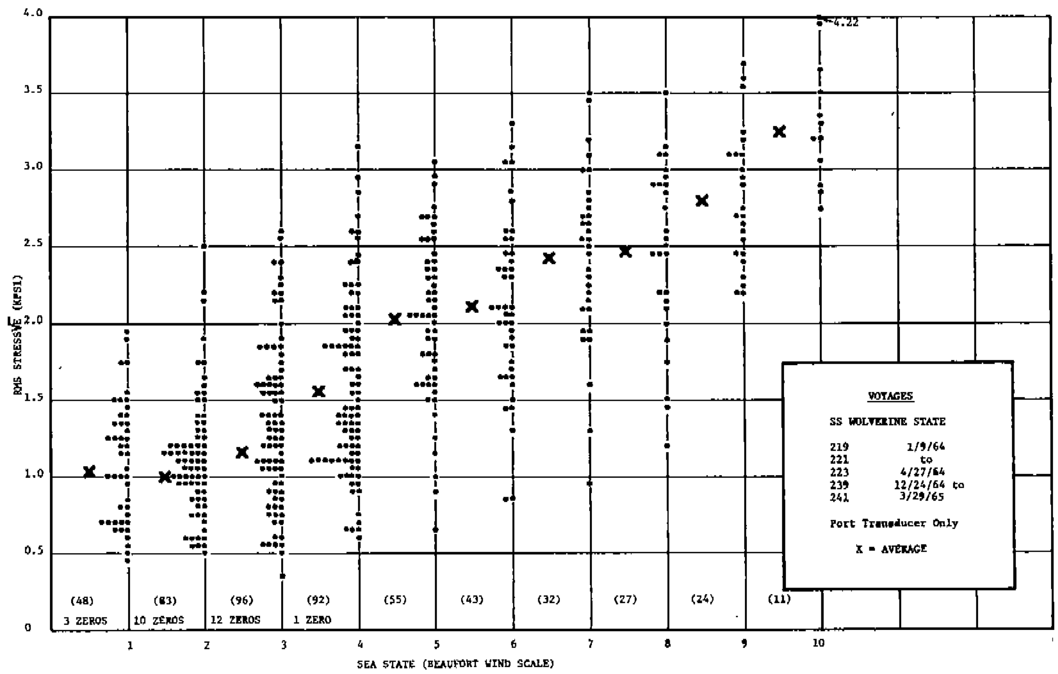


Fig. 5. RMS Stress vs. Sea State, SS Wolverine State (Port and Starboard Transducers Electrically Averaged).

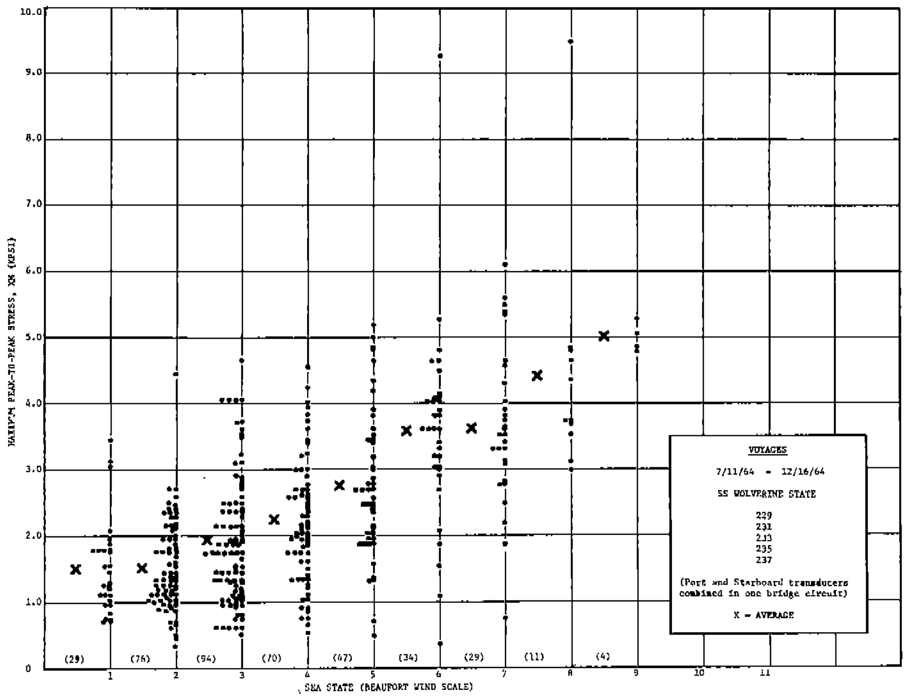


Fig. 6. Maximum Peak-to-Peak Stress vs. Sea State SS Wolverine State.

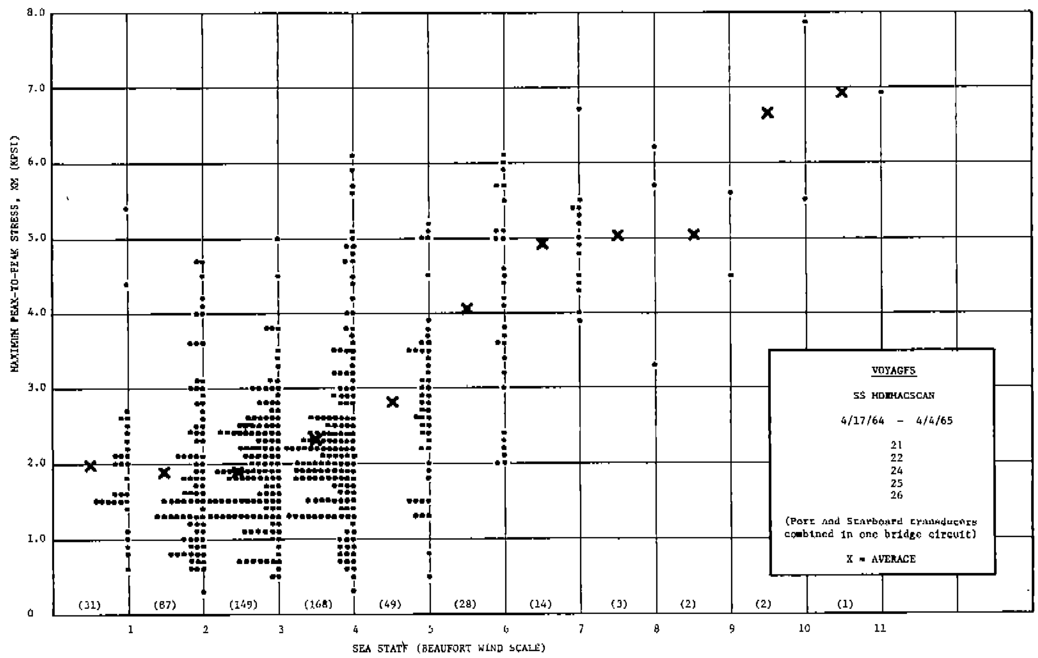


Fig. 7. Maximum Peak-to-Peak Stress vs. Sea State SS Mormacscan.

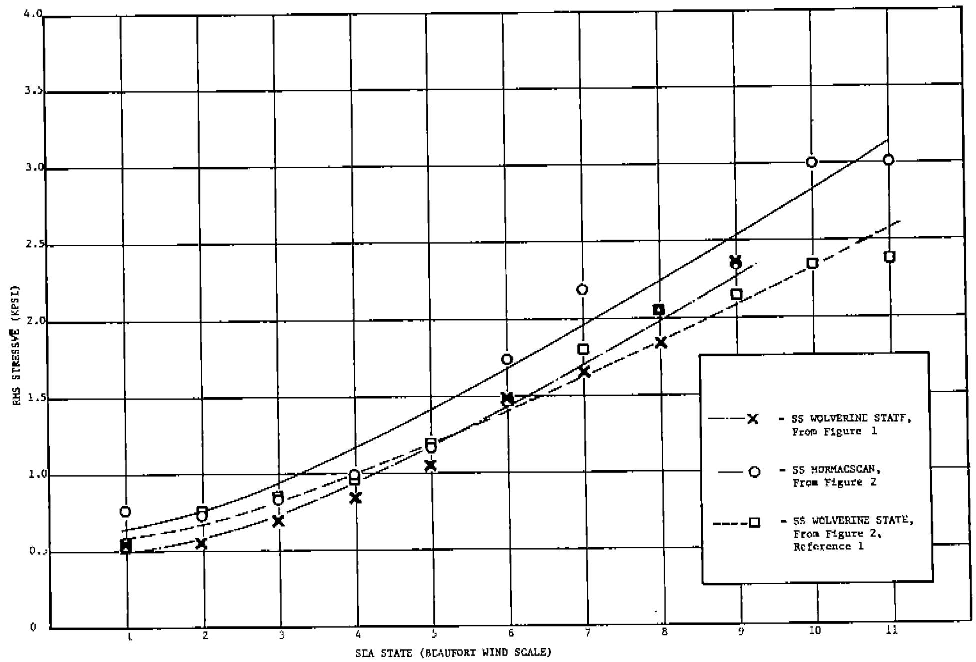


Fig. 8. Average RMS Stress vs. Sea State, Figure 1, Figure 2, and Figure 2, Reference 1.

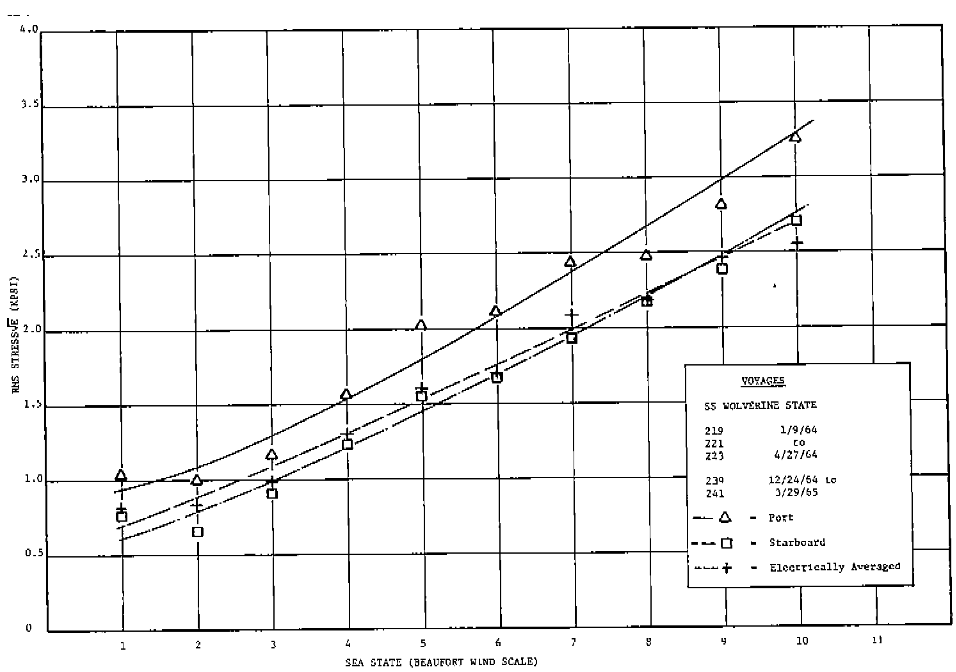


Fig. 9. Average RMS Stress vs. Sea State, SS Wolverine State Starboard, Port, and Combined.

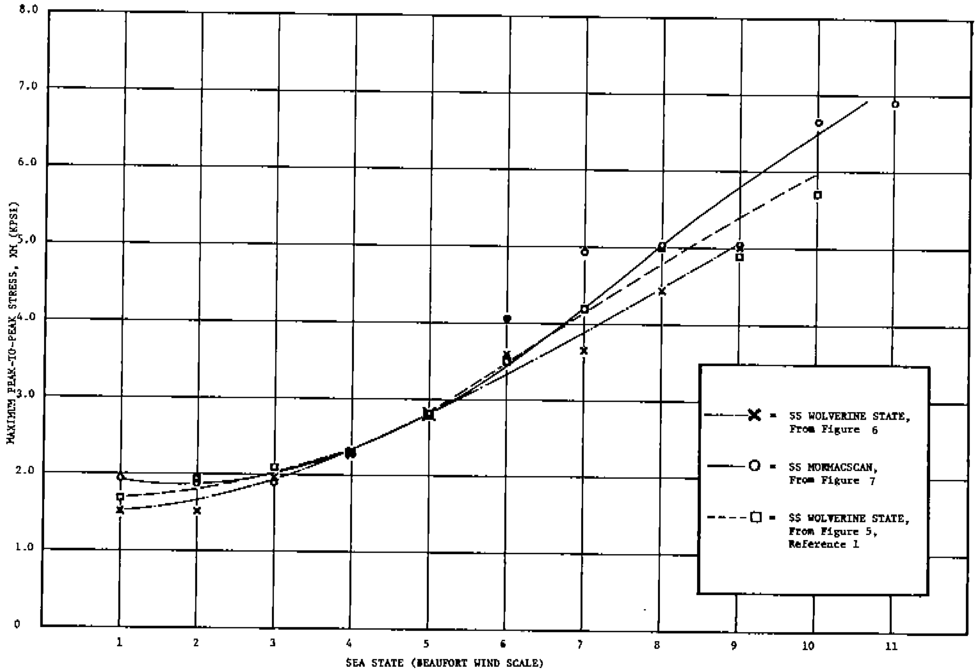


Fig. 10. Average Maximum Peak-to-Peak Stress vs. Sea State, Figures 6, 7, and Figure 5, Reference 1.

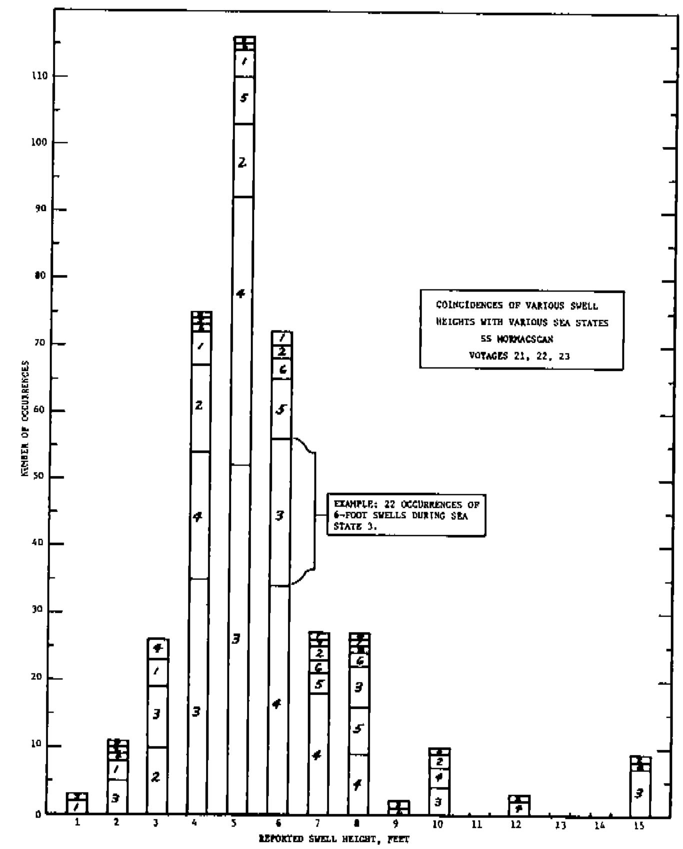


Fig. 11. Coincidences of Various Swell Heights with Various Sea States, SS Mormacscan, Voyages 21, 22, 23.

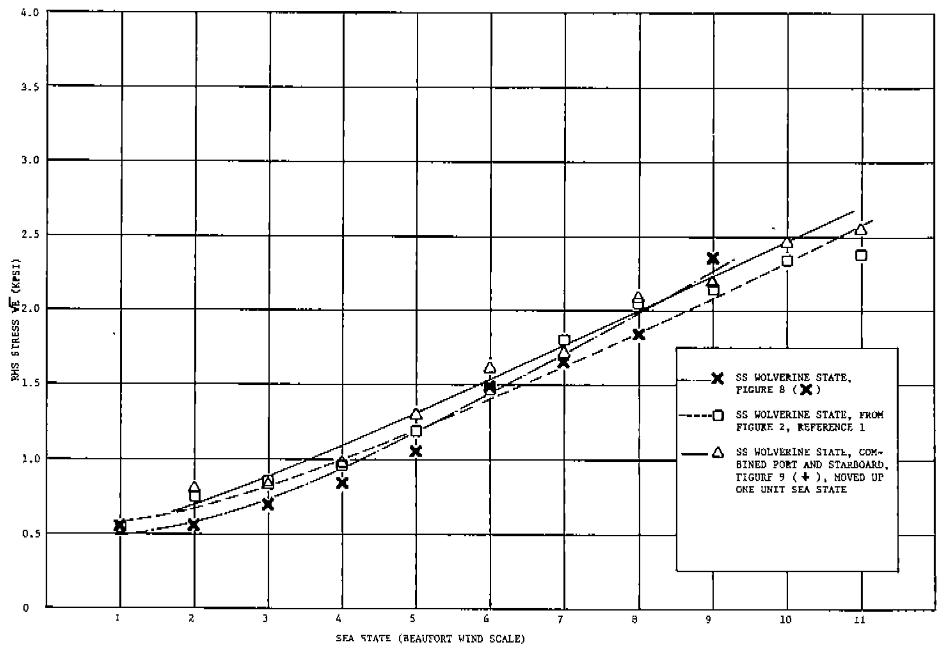


Fig. 12. Average RMS Stress vs. Sea State, SS Wolverine State, From Figure 8, Figure 9 (Modified), and Figure 2, Reference 1.

V. ACKNOWLEDGEMENTS

This project is sponsored by the Ship Structure Committee with guidance from the Ship Hull Research Committee of the National Academy of Sciences, National Research Council. The research program is supervised and coordinated with other related SSC projects through the Ship Hull Response Panel chairmaned by Mr. T.M. Buermann.

The excellent cooperation of States Marine Lines has continued to contribute very substantially to the progress of this investigation. Mr. John Ritter, Naval Architect, and the officers and men of the SS WOLVERINE STATE deserve an especial vote of thanks.

For the past two years data acquisition equipment has been operating aboard the SS MORMACSCAN, providing data on the response of a different type of vessel. The cooperation of Moore-McCormack Lines and the officers and men of the SS MORMACSCAN is sincerely appreciated.

VI. REFERENCES

1. Fritch, D.J., Bailey, F.C., and Wise, N.S. Results From Full-Scale Measurements of Midship Bending Stresses on Two C4-S-B5 Dry-Cargo Ships Operating in North Atlantic Service, Ship Structure Committee Report SSC-164, September 1964.

2. Fritch, D.J. and Bailey, F.C. An Unmanned System for Recording Stresses and Acceleration on Ships at Sea, Ship Structure Committee Report SSC-150, June 1963.

3. Fritch, D.J., Bailey, F.C., and Wise, N.S. Preliminary Analysis of Bending Moment Data from Ships at Sea, Ship Structure Committee Report SSC-153, December 1963.

4. Bailey, F.C., Fritch, D.J., and Wise, N.S. Acquisition and Analysis of Acceleration Data, Ship Structure Committee Report SSC-159, February 1964.

APPENDIX

Preliminary Calibration of Stress Gages Aboard SS WOLVERINE STATE and Evaluation of the Effects of Sideshell Plating Unfairness

I. INTRODUCTION

On August 1 and 2, 1965, a loading calibration was conducted on the SS WOLVERINE STATE for the purpose of:

A. Comparing the stress due to vertical longitudinal bending moment as measured at the midship stress transducers with that calculated for an applied bending moment load.

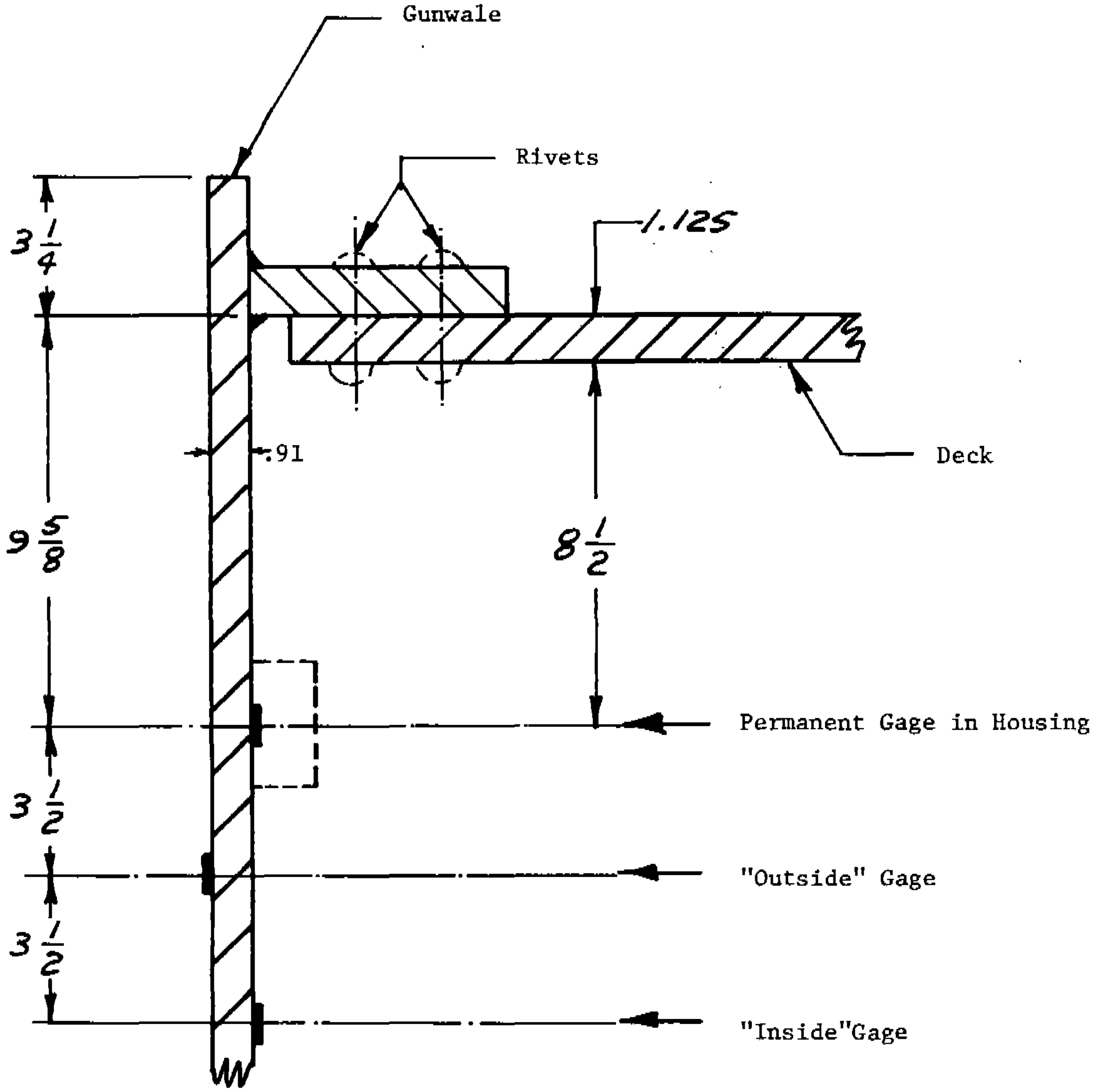
B. Evaluating the effects of sideshell plating unfairness (bowing) at the port and starboard stress transducer locations in an attempt to explain observed differences in the relative outputs of the transducers.

This calibration was undertaken under circumstances which would provide a change in stress of only about 2000 PSI at the gages. A change of 5 to 10 times this would be desirable to minimize the effects of errors inherent in the measuring system, and of temperature changes in various portions of the vessel. Since it is hoped that a more satisfactory calibration can be accomplished at some time in the future, the data reported herein will be considered preliminary.

II. METHOD OF CALIBRATION

As a part of the preparations for the calibration additional (temporary) stress gages were installed on the inner and outer surfaces of the sideshell plates in way of the permanent gages. The locations of the new gages are noted in Figure A-1. The purpose of these temporary gages was to provide a direct check on the corresponding permanent gage and, by analysis of data from each side of the plate, some measure of the influence of plating unfairness. It should be noted that the two temporary gages on each side of the vessel were connected to temperature-compensating gages mounted on a block of mild steel and placed in contact with the shell plating adjacent to the inside gage on either side. The vertical separation of 3 1/2 inches between the "inside" and "outside" temporary gages is not considered significant in developing the data.

All gages were read using a Strainsert strain indicator. A Young's Modulus of 30×10^6 PSI was used to convert the incremental strain indicator readings to stress changes. In addition, the permanent gage data were recorded on magnetic tape using the shipboard recording system.



Notes:

1. All gages BLH type FAB-28-S6 stress gages with longitudinal element in longitudinal direction on plate.
2. All gages on same transverse section.
3. Pattern repeated port and starboard.
4. Section shown is midway between frames 104 and 105.
5. Dimensions in inches.

FIGURE A-1

STRAIN GAGE LOCATIONS FOR CALIBRATION OF
S.S. WOLVERINE STATE AUGUST 1 & 2, 1966

Fig. A-1. Strain Gage Locations for Calibration of SS Wolverine State August 1 & 2, 1966.

The corresponding stress values were determined by comparing the output signal during playback with standard 10,000 PSI calibration signals which also had been recorded on the tape.

The change in bending moment to effect the calibration was obtained by pumping out fresh water ballast from the fore peak tank and after peak tank, and bunkering with fuel oil in the No. 4 double bottom tanks, thus inducing a sagging bending moment amidship. Tank soundings were taken during the course of the calibration. Vessel drafts were read also, but with considerable difficulty, and the reliability of the readings was subsequently questioned.

The entire calibration procedure took place at dockside in the Delaware River, Philadelphia, Pa., between 2100 on August 1 and 0500 on August 2. The bulk of the change in bending moment was accomplished by 0210 August 2. The weather during this period was good, if not ideal, for the calibration, starting off as overcast with occasional light rain and changing gradually to cloudy with a fresh breeze toward the end of the interval. As is typical for this type of vessel, piping and pump capacities limited the speed at which fluid could be moved and dictated the rather long time which, unfortunately, was required to accomplish the change in bending moment.

Although the stress gages were read at several intervals during the calibration, bending moment computations were made for only the near-terminal condition at 0210 hours.

III. RESULTS OF CALIBRATION

The results of the ship calibration are reported in the data and computations tabulated as Table A-I. The major result is the good agreement between the final values at 0210 of the corrected tape recorded stress, 1688 $\pm$ 300 PSI (Column 12); the average vertical longitudinal bending moment stress at the transducer location as calculated from the loading data, 1800 $\pm$ 100 PSI (Column 13); and the average vertical component of the heart-of-plate stress calculated from the temporary transducer data, 1734 PSI.

The observed differences between port and starboard sea-way stress as recorded by the magnetic tape system during ocean voyages are verified by the calibration. Port/starboard ratios of the portion of the average stress due to vertical bending moment and sensed by the inside gages are shown in Column 10 of Table A-I. The average of these ratios for the three measurements is 1.19. Table A-II is a tabulation of the average values of rms seaway-induced stress on the port and starboard sides of the SS WOLVERINE STATE for sea states 3 through 10 (from Figures 3 and 4 of the body of this report). The average ratio (port/starboard) of these average values of rms seaway-induced stress is shown to be 1.24. This ratio is in good agreement with the above value of 1.19 determined by using the data from the ship calibration.

IV. DISCUSSION OF RESULTS

In discussing the calibration answers will be sought to the following four questions:

1. Can the output of the permanent transducer, using tape-recorded stress data, be satisfactorily correlated with the calculated average stress resulting from vertical bending moment.

2. Is the anomaly between port and starboard stresses observed in the tape-recorded seaway data also observed in the calibration data?

TABLE A - I

STRESS VALUES DURING CALIBRATION

1	2	3	4	5	6	7	8	9	10	11	12	13
Side	Date, Time	"Outside" σ_o, PSI	"Inside", σ_i, PSI	σ_m, PSI	$\frac{\sigma_i}{\sigma_m}$	σ_{va}, PSI	σ_{ha}, PSI	σ_{vi}, PSI	$\frac{\sigma_{vip}}{\sigma_{vis}}$	σ_T, PSI	σ_{TCorr}, PSI	σ_{Cal}, PSI
Port	8/1/65 2116	0	0	0	-		0	0		0		
	8/2/65 0000	1362	965	1168	.835		-175	1120		-		
	0150	1950	1362	1656	.825		-172	1510		-		
	0210	1790	1285	1538	.835		-196	1450		1347		
					Avg .832							
					Inv 1.20							
Stbd	8/1/65 2116	0	0	0	-		0	0		0		
	8/2/65 0000	2060	975	1518	.642		175	865		-		
	0150	2560	1440	2000	.720		172	1315		-		
	0210	2420	1440	1930	.746		196	1290		1228		
					Avg .702							
					Inv 1.43							
Avg	8/1/65 2116					0			-		0	0
	8/2/65 0000					1343			1.30		-	-
	0150					1828			1.15		-	-
	0210					1734			1.12		1688	1800
									Avg 1.19		± 300	± 100

Column

3,4) Stresses on outside and inside of sideshell plating as measured by temporary gages.

5) $\sigma_m = \frac{\sigma_o + \sigma_i}{2}$ = heart-of-plate stress

7) $\sigma_{va} = \frac{\sigma_m(\text{Port}) + \sigma_m(\text{Stbd})}{2}$ = average heart-of-plate stress due to vertical bending moment

8) $\sigma_{ha} = \sigma_m - \sigma_{va}$ = average heart-of-plate stress due to horizontal bending moment

9) $\sigma_{vi} = \sigma_{va} \frac{\sigma_i}{\sigma_m}$ = proportion of σ_{va} measured by inside gage

11) σ_T = stress measured from magnetic tape record

12) $\sigma_{TCorr} = \frac{\{1.20(1347) + 196\} + \{1.43(1228) - 196\}}{2}$

13) σ_{Cal} = Stress due to vertical bending moment as calculated by SML naval architects from drafts and loadings.

TABLE A - II

Average RMS Stress ($\sqrt{E}$) for Sea States 3 Through 10, Port and Starboard (From Figures 3 and 4)

BSS	Starboard (Fig. 3)	Port (Fig. 4)	P/S
3	0.90	1.15	1.28
4	1.25	1.55	1.24
5	1.55	2.05	1.32
6	1.65	2.10	1.27
7	1.90	2.40	1.26
8	2.15	2.45	1.14
9	2.40	2.80	1.17
10	2.65	3.25	1.22
			8/9.90
			1.24 Average

3. Is there an explanation for the anomaly?

4. What, if anything, should be done to data collected in the past to convert to a representative average midship bending moment stress, and should anything be changed for future data acquisition?

A. Derivation of Table A-I Values

The heart-of-plate stress for each side of the ship (Column 5) has been derived by averaging the measured data from the corresponding "inside" (Column 4) and "outside" (Column 3) temporary stress transducers located as shown in Figure A-1. The difference between the inside stress values as measured for each side of the ship is indicative of sideshell plating unfairness. The starboard side evidently possesses a greater unfairness than the port side.

In addition, with the type of loading applied during the calibration, one would expect the values of the heart-of-plate stress to be identical on both sides of the ship. This, however, is not the case. This inequality indicates the presence of an unexpected horizontal component in the longitudinal stress data. At this time there are no data from which to derive an explanation for the origin of this horizontal component of bending moment stress. However, since the contribution of this component would be equal and opposite on each side, the vertical and horizontal components of the heart-of-plate stress can be determined from the average sum and the average difference, respectively, of the previously calculated heart-of-stress values (Column 5). These values appear in Column 7 (average vertical) and Column 8 (average horizontal - port and starboard).

Column 6 of Table A-I shows the ratios of inside stress to heart-of-plate stress. The averages of these ratios are 0.832 (port) and 0.702 (starboard), and are measures of the relative unfairness of the two sideshell plates. They also are the factors by which the average vertical component of the heart-of-plate stress (Column 7) can be multiplied to determine the response of the corresponding inner gage to the heart-of-plate stress which results from the vertical component of the longitudinal bending moment. This value has been computed, and is shown in Column 9.

The values in Column 9 can now be compared with seaway data which has been reduced to rms stress values, since it would be expected that any horizontal stress effects at sea would disappear during the process of determining the rms values. The comparison (see Table A-II for seaway data) shows that: a) port values are consistently higher than starboard values for both sources of data, and b) the average port/starboard ratio of 1.24 as determined from the seaway rms data agrees well with the average ratio 1.19 (Column 10) from the calibration data.

Column 11 of Table A-I shows the stress values for the port and starboard transducers as reduced from the tape-recorded data. To provide stress values which can be compared directly with the values which were calculated by the naval architects from the measured drafts and loading conditions, these tape-recorded data must be corrected for the effects of plating unfairness and for the presence of the horizontal stress component.

Since the permanent transducers are "inside" stress gages, the port and starboard tape-recorded data may be corrected, first, for the effects of plating unfairness by multiplying each by the corresponding reciprocal of the factor obtained from Column 6, and then by subtracting the corresponding horizontal stress value obtained from Column 8. It seems reasonable to assume that these correction factors and horizontal stress values, determined by using data from the temporary gages, should apply equally well to the permanent gages.

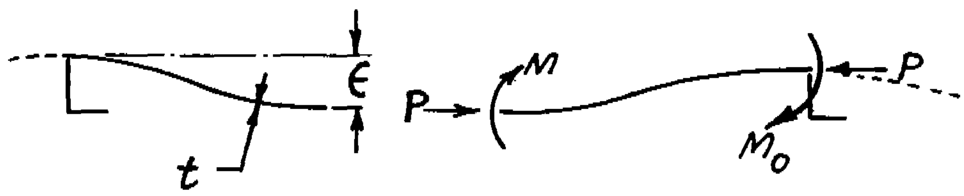
After correction, the port and starboard taped data are averaged and the result can be compared to the stress calculated from the ship calibration loading data. This correction procedure is performed below to derive the corrected average vertical component of stress at 0210 August 2 from the port and starboard stress changes indicated by the tape-recorded data.

$$\sigma_{Tcorr} = \frac{[1.20\ (1347) + 196] + [1.43\ (1228) - 196]}{2}$$

$$= 1688 \text{ PSI}$$

Considering half of the plate width between stiffeners, of unit depth:

From symmetry,



$M_o = \frac{P\varepsilon}{2}$, and the stress at the center is

$$\sigma = \sigma_{mean} \pm \frac{Mc}{I}$$

$$M = P\varepsilon - \frac{P\varepsilon}{2} = \frac{P\varepsilon}{2}$$

$$c = \frac{t}{2}$$

$$I = \frac{t^3}{12}$$

$$P = \sigma_{mean}\ t$$

Thus:

$$\sigma = \sigma_{mean} \left(1 \pm \frac{3\varepsilon}{t}\right)$$

$$\therefore \frac{\sigma_i}{\sigma_{mean}} = 1 - \frac{3\varepsilon}{t}$$

FIGURE A-2

COMPUTATION OF SURFACE STRESSES IN AN UNFAIR, EDGE-LOADED PLATE

Fig. A-2. Computation of Surface Stresses in an Unfair, Edge-loaded Plate.

B. Tolerances

Tolerances must be assigned to the stress values reported because of several possible sources of inaccuracies. Reading errors alone contribute a tolerance of $\pm$ 100 PSI in the measured stress values. In addition, gross temperature changes from point-to-point in the vessel can contribute a stress change of as much as 100 PSI per degree F. Since temperature during the calibration varied by about 2 degrees, the measured stresses could be different from bending-moment-induced stresses by 200 PSI. These two sources of error, therefore, require an overall tolerance of $\pm$ 300 PSI to be assigned to the measured data.

In the case of the calculated values derived by naval architects of States Marine Lines, the uncertainty in the draft values (measured at night under difficult conditions) is sufficient to assign a tolerance of $\pm$ 100 PSI to the calculated value of 1800 PSI.

Both the measured values and the calculated values of stress would be far more precise had the stress change been an order of magnitude larger.

C. Plating Unfairness

Information bearing on the question of plating unfairness can be obtained not only from strain measurements, but also from a theoretical analysis. Figure A-2 shows condensed calculations of the effect of unfair plating on the ratio of inside stress to heart-of-plate stress. Given the stress ratio (Column 6, Table A-I), the amount of unfairness, ε, can be derived from the last equation of Figure A-2. Using the average ratios of 0.832 and 0.702 for port and starboard plates, respectively, the amount of unfairness at the gage locations can be computed as 0.050 and 0.090 inches for a plating thickness of 0.91 inches.

Measurement of plating unfairness at the permanent gage locations is not possible. However, measurements made 54 inches below the under-surface of the deck (on the plate containing the gage) indicate an unfairness of 0.038 inches in the port plate and 0.068 in the starboard. Adjacent plates having the same unfairness at this lower position have, respectively, about 0.055 and 0.080 inch unfairness at the gage location. The coincidence of the values is sufficient evidence to uphold the validity of the hypothesis that plating unfairness is the source of the anomaly between port and starboard data.

V. SUMMARY AND RECOMMENDATIONS

A. Within the accuracy limitations imposed by the low stress levels achieved during the calibration, the permanent stress transducer gives data which can be correlated with midship bending moment stress.

B. The anomaly observed in port and starboard stress data is the result of different amounts of unfairness in the plates on which the port and starboard transducers are mounted.

C. In order to obtain heart-of-plate data, the reported port and starboard stresses should be multiplied by 1.20 and 1.43 respectively.

D. Port and starboard data which have been averaged aboard ship prior to recording can be converted to average midship bending moment stress by using a multiplier of 1.33. This average value was verified experimentally by electrically averaging individually corrected port and starboard signals in the laboratory.

E. All of the above factors must be considered tentative until a more satisfactory calibration of the vessel can be conducted.

F. An ideal calibration of the vessel-transducer system would involve stress changes of about 20,000 PSI over a fairly short (4 hours) interval of time.

G. Stress gages mounted on unfair plates are satisfactory as midship bending moment transducers as long as the factor relating apparent to actual bending moment stress can be determined, as by calibration.

GPO 919-629

NATIONAL ACADEMY OF SCIENCES-NATIONAL RESEARCH COUNCIL

DIVISION OF ENGINEERING

The Ship Hull Research Committee undertakes research service activities in the general fields of materials, design, and fabrication, as relating to improved ship hull structure, when such activities are accepted by the Academy as part of its functions. The Committee recommends research objectives and projects; provides liaison and technical guidance to such studies; reviews project reports; and stimulates productive avenues of research.

SHIP STRUCTURE COMMITTEE PUBLICATIONS

These documents are distributed by the Clearinghouse, Springfield, Va. 22151. These documents have been announced in the Technical Abstract Bulletin (TAB) of the Defense Documentation Center (DDC), Cameron Station, Alexandria, Va. 22314, under the indicated AD numbers. There is no charge for documents for registered users of the DDC services. Other users must pay the prescribed rate set by the Clearinghouse.

Index of Ship Structure Committee Publications (1946 - April 1965)

SSC-168, *Rolling History in Relation to the Toughness of Ship Plate* by B. M. Kapadia and W. A. Backofen. May 1965. AD 465025.

SSC-169, *Interpretative Report on Weld-Metal Toughness* by K. Masubuchi, R. E. Monroe and D. C. Martin. July 1965. AD 466805.

SSC-170, *Studies of Some Brittle Fracture Concepts* by R. N. Wright, W. J. Hall, S. W. Terry, W. J. Nordell and G. R. Erhard. September 1965. AD 476684.

SSC-171, *Micro- and Macrocrack Formation* by B. L. Averbach. October 1965. AD 473496.

SSC-172, *Crack Extension and Propagation Under Plane Stress* by A. R. Rosenfield, P. K. Dai and G. T. Hahn. March 1966. AD 480619.

SSC-173, *Exhaustion of Ductility Under Notch Constraint Following Uniform Prestraining* by C. Mylonas, S. Kobayashi and A. Armenakas. August 1966. AD 637143.

SSC-174, *Investigation of Residual Stresses in Steel Weldments* by K. Masubuchi and D. C. Martin. September 1966. AD 639619.

SSC-175, *Mechanical Properties of a High-Manganese, Low-Carbon Steel for Welded Heavy-Section Ship Plate* by R. D. Stout and C. R. Roper, Jr. August 1966. AD 637211.

SSC-176, *Biennial Report of the Ship Structure Committee.* June 1966. AD 641333.

SSC-177, *Guide for Interpretation of Non-Destructive Tests of Welds in Ship Hull Structures* by The Weld Flaw Evaluation Committee. September 1966. AD 639053.

SSC-178, *A Survey of Some Recent British Work on the Behaviour of Warship Structures* by J. Clarkson. November 1966. AD 644738.

SSC-179, *Residual Strains and Displacements within the Plastic Zone Ahead of a Crack* by J. Cammett, A. R. Rosenfield, and G. T. Hahn. November 1966. AD 644815.