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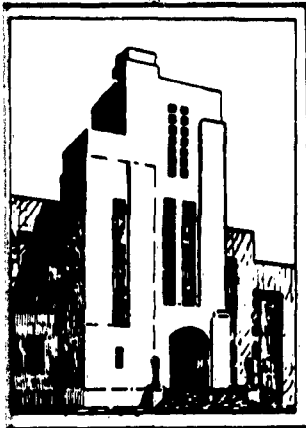


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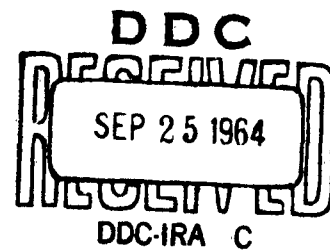
STATISTICAL PRESENTATION OF MOTIONS AND HULL BENDING  
MOMENTS OF ESSEX-CLASS AIRCRAFT CARRIERS

by

Norman H. Jasper, Dr. Eng., Roman L. Brooks, CDR, USN,  
and John T. Birmingham

AERO DYNAMICS

STRUCTURAL  
MECHANICS



APPLIED  
MATHEMATICS

STRUCTURAL MECHANICS LABORATORY  
RESEARCH AND DEVELOPMENT REPORT  
Revised Edition

June 1960

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## ABSTRACT

The motions and longitudinal hull bending moments which ships of the ESSEX Class may be expected to experience over a wide range of operating conditions are presented in statistical form. The data are based on extensive measurements made on USS VALLEY FORGE (CVS 45) and USS ESSEX (CVA 9).

From the test results, data are derived for this type of ship for use in design and operating problems involving bending moments and ship motions. Formulas are given for use in estimating probable extreme values of moments and motions.

## INTRODUCTION

The David Taylor Model Basin is conducting a long-range investigation of the strains in ships at sea<sup>1</sup> for the purpose of evaluating and improving methods for the design of ship girders and structural components. Instruments have been developed and installed on various types of ships to collect information on the wave loads, stresses, and motions which ships experience in service. For more complete background and discussion of this program see References 2 and 3.

Motions and stresses measured on three essentially similar aircraft carriers are analyzed in this report.\* USS ESSEX (CVA 9) and USS ORISKANY (CVA 34) are conversions of the basic ESSEX Class (World War II variety); USS VALLEY FORGE (CVS 45) is an unconverted carrier of this same class. The salient characteristics of the conversion that affect hull form and weight distribution—those factors that have primary effect on bending moments—are the addition of blisters throughout the midportion of the ship and a modest (10-percent) increase in full-load displacement. Data were obtained on VALLEY FORGE\*\* in the Atlantic Ocean from September 1955 to April 1957, on ESSEX during a passage around Cape Horn in July 1957,<sup>4</sup> and on ORISKANY during a rough passage around Cape Horn in June 1952.

Oscillographic recordings were made of variations of roll and pitch angle, heave accelerations (at the center of gravity of the ship), and hull strains as the ship responded to wave-induced loads. From these the following information is specified for ESSEX-Class carriers:

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<sup>1</sup>References are listed on page 34.

\*No strains were measured on ORISKANY.

\*\*These data were obtained during joint operations with USS C.S. SPERRY (DD 697); the SPERRY tests will be reported at a later date.



- a. Average, mean square, and expected maximum values of hull stresses\* and motions for various operating conditions (sea state, speed, and heading).
- b. The predicted extreme values of longitudinal bending moment and motions expected during the operating life of the ship.
- c. The frequency distributions of stresses and ship motions.

## TEST INSTALLATION AND TEST RESULTS

Most of the data utilized in this report were measured on VALLEY FORGE. However, the most severe hull stresses and motions experienced by ESSEX and ORISKANY are used whenever they are larger than those observed on VALLEY FORGE.

Hull stresses were measured by SR-4 strain gages installed at the main deck and keel amidship on VALLEY FORGE. The roll and pitch angles were measured by a stable element, and the heave acceleration was measured by a Schaevitz accelerometer located near the center of gravity. The locations of the gages are shown in Figure 1. The measurements were recorded on a TMB automatic statistical recorder. The five channels of this instrument were utilized as follows: Channel 1 recorded the heave acceleration; Channels 2 and 3 recorded the longitudinal strain from gages located on the keel and main deck, respectively; and Channels 4 and 5 recorded the pitch and roll angles, respectively. Typical oscillograms are shown in Appendix A. In order to observe the relative magnitude of the stresses induced by transverse and longitudinal bending, strains on the port and starboard side of the main deck were recorded on a Sanborn oscillograph.

All the data on VALLEY FORGE were obtained in the course of the normal assigned operations. Measurements were made whenever operating conditions were encountered for which data had not been obtained previously.

Wave heights and wave directions for the VALLEY FORGE tests were determined by two methods. Estimates made by trained observers from the ship's aerology unit were averaged, and stereophotographs of the sea surface taken by cameras mounted on the island structure were analyzed by the U.S. Hydrographic Office. Comparison of data from these two sources indicates that the observers made reliable estimates of characteristic wave heights.<sup>5\*\*</sup> During the ESSEX tests wave heights were measured with the wave height recorder developed by M.J. Tucker in Britain.

The sea conditions assumed in the calculations are those for the North Atlantic Ocean inasmuch as they probably represent the more severe continuous operating conditions that a

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\*All stresses given in this report were computed from measured strains. The hull bending moments are deduced from the strain measurements and the calculated section modulus applicable to the strain-gage location.

\*\*The characteristic wave height is the average of the highest waves observed in each of a number of groups of waves.

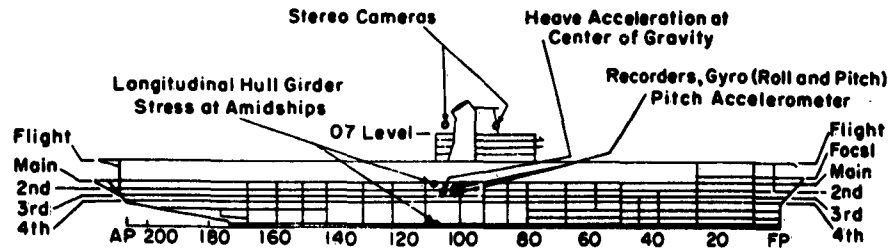


Figure 1a - Inboard Profile

The characteristics of the ship are: Length between perpendiculars, 820 ft;  
Beam, 92 ft; Draft, 29 ft; Displacement (full load), 41,500 tons.

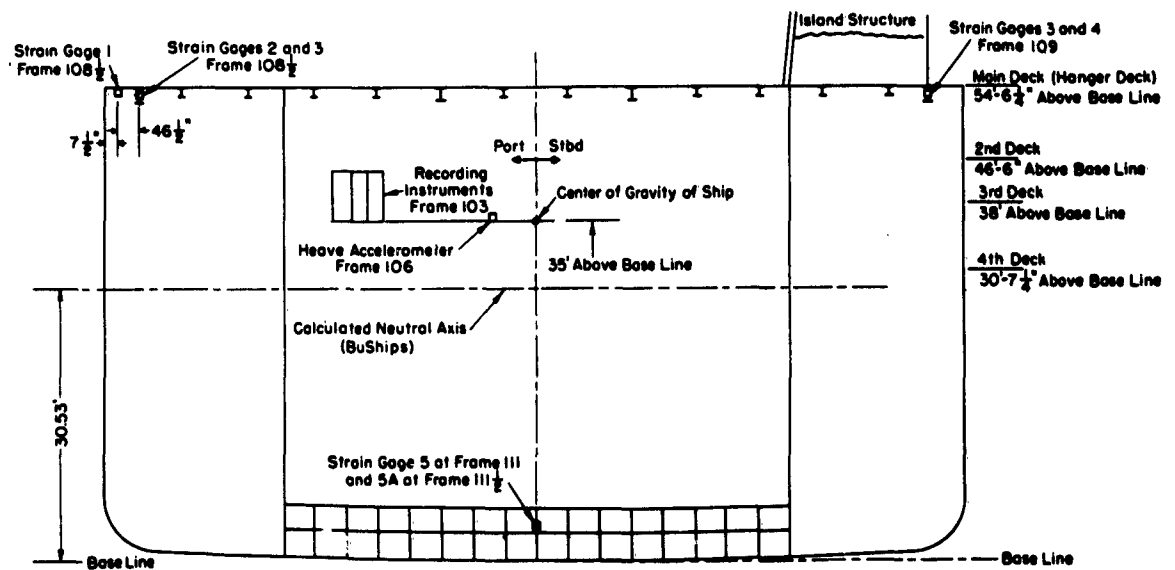


Figure 1b - Section Near Midship Looking Forward

The midship section moment of inertia is  $3.96 \times 10^6 \text{ ft}^2\text{-in}^2$  according to BuShips (Code 442) calculations dated 2 Oct 56. This value applies to the unconverted CVS45 hull.

Strain gages 2, 4 measure strain in the port and starboard outboard longitudinals at the neutral axis of the plate-stiffener combination. These gages are located 23.85 ft above the neutral axis.

Strain gage 1 measures the longitudinal stress in the deck plate (dyadic stress gage). This gage is located 23.97 ft above the neutral axis.

Strain gages 3, port and starboard, are arranged to read strains due to longitudinal hull bending. These gages are located 23.76 ft above the neutral axis.

Strain gage 5 measures the longitudinal strain at the approximate location of the neutral axis of the keel-inner bottom structure.

Figure 1 - Location of Instruments on USS VALLEY FORGE (CVS 45)

ship will experience. The probable speeds and headings at which these ships would be expected to operate under wartime conditions and the fraction of time the ships would spend at each of the various conditions were estimated by the commanding officers of a number of ships of the ESSEX Class. This information is given in Table 2 of Reference 6.

All recorded strain and motion data were classified according to appropriate ranges of ship speed, wave height, and ship's course relative to the wave direction.\* Statistical methods were used to determine the ship's response in terms of mean square values and maximum measured values for a wide variety of operating conditions; see Table 1.

The relative magnitudes of the hull stresses induced by longitudinal and transverse bending are given in Appendix B. Stresses measured on the deck plating and on the adjacent longitudinal stiffener at the outboard edge of the main deck are compared in Appendix C. Local bending stresses were small in this area.

## STATISTICAL BACKGROUND

Wave heights, ship motions, and hull bending moments experienced under a given set of conditions can be described in terms of their distribution functions. It has been shown<sup>7</sup> that the applicable distribution functions are approximated by the Rayleigh distribution for a given set of steady operating conditions (sea state, ship speed, and heading) and by log-normal distributions if the operating conditions are allowed to vary over a wide range, such as would occur over a typical year.

The Rayleigh distribution of a variable  $x$  is defined by the single parameter  $E$ , the mean square value of  $x$ ; i.e.,  $E = \overline{x^2}$ . The log-normal distribution of  $x$  is defined by two parameters: the mean value of  $\log x$  and the variance of  $\log x$ . The statistical methods utilized here are discussed in References 7 and 8.

For illustrative purposes, consider one of the variables; for example, pitch angle. All pitch angles (peak to peak) are considered to be members of a statistical "population." The distribution indicates the relative probability  $p(x)$  of encountering a pitch angle of the magnitude  $x$ . Figure 2 illustrates this distribution function. The area under the curve of Figure 2a up to a value  $x_i$  is the fraction  $P$  of all members of the population which have values less than  $x_i$ . Therefore the probability of exceeding the value  $x_i$  is  $100(1 - P)$  percent. For the Rayleigh distribution  $P(x) = 1 - e^{-x^2/E}$ .

Both the Rayleigh (Figure 2) and log-normal distributions (Figures 3 through 6) can be represented by straight lines when plotted on special graph paper. Inasmuch as the Rayleigh distribution is applicable to a given combination of sea, speed, and heading, it will be called the "short-term" distribution whereas the log-normal distribution will be designated the "long-term" distribution.

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\*It was often difficult to define the sea and the direction of the ship relative to the sea. The description given is the best that could be made.

TABLE 1

Basic Statistical Data for ESSEX-Class Carriers

All data are for VALLEY FORGE except where noted otherwise.

Wave and Speed Classification		Record Number	Stereo Photo Number	Ship Speed knots	Estimates of Characteristic Wave Height, ft					Wind and Wave Data					F <sub>v</sub> Value of
Wave Height ft	Ship Speed knots				Sea		Number of Visual Estimators †	Swell		Heading of Sea Relative to Ship deg	Heading of Swell Relative to Ship deg	E <sub>ff</sub> , ft <sup>2</sup> Mean Square Wave Height		Wind Velocity for 8 Hours Preceding Test knots	
					Average of Visual Estimates	From TMB Analysis of Stereo-Photo		Average of Visual Estimates	From TMB Analysis of Stereo-Photo			From Stereo Data	From Wind Data		
0-4	20-25	30	H-060	24		3.6	2	2.7	3.7	335-345	325-335	4.6	9.2	8-18	0.00
4-6	10-15	25	G-113	10		5.7	4	5.9	5.1	015-025	355-25	10.4	20.0	12-30	0.00
4-6	10-15	67	C-418	12			3	6.0		355	355-345	12.5	24.0	14-21	0.00
4-6	15-20	19	E-071	20		6.5	6	6.0	5.9	040-060	000	9.3	18.0	10-31	0.00
4-6	20-25	18	E-064	25		6.9	3	6.1	6.9	009-013	316-319	15.8	16.0	9-20	0.00
6-8	5-10	34	H-201	10		6.5	6	6.9	6.3	015	005-015	11.9	32.0	16-33	0.00
6-8	10-15	62		12			1	7.0		330-340	332-340			8-26	0.00
6-8	10-15	61		14			1	7.0						8-26	0.00
6-8	10-15	1	C-452	15		6.6	3	8.0	8.6	010-020		17.2	32.0	17-30	0.00
6-8	10-15	2	C-466	15		8.1	3	7.7	8.2	355		17.7	24.0	24-30	0.00
6-8	15-20	16	E-062	20		7.2	3	6.1	7.1	020	350-000	11.8	16.0	11-30	0.00
6-8	20-25	69a	I-014	25		6.4	3	7.5	7.9	338-358	318-358	22.0	30.0	14-20	0.00
8-15	5-10	41	J-040	8	12.0	17.9	3	12.1		340-000	350-000	58.8	48.0	30-40	0.00
8-15	5-10	43		8			3	10.0		340-350	342-350			23-33	0.00
8-15	5-10	46		8			3	9.0		355-357	346-354			23-33	0.00
8-15	5-10	53		10			4	10.0		358-004†	353-001†			22-28	0.00
8-15	5-10	38	J-003	8	10.5	7.3	4	9.9	9.3	007	020	21.5	24.0	22-53	0.00
8-15	5-10	39	J-003	8	10.5	7.3	4	9.9	9.3	001	019	21.5	24.0	36-54	0.00
8-15	5-10	69		8	12.0					359					0.0
8-15	10-15	4	C-495	12		5.8	6	9.0	7.0	339-342	349-356	10.7	28.0	16-19	0.00
8-15	20-25	51		25			3	10.0		358-359	349-356			22-28	0.00
> 15	5-10	72		10	14.0					014					0.00
> 15	5-10	77*		10	20					005					0.0
0-4	10-15	24	G-049	12		5.0	5	3.7	5.0	062	068	9.1	8.0	12-17	0.0
0-4	20-25	30	H-060	24		3.6	2	2.7	3.7	335-345	325-335	4.6	9.2	8-18	0.0
0-4	20-25	31	H-100	25		3.5	3	2.8	4.5		035-040	5.2	9.2	8-18	0.0
4-6	15-20	19	E-071	20		6.5	6	6.0	5.9	040-060	000	9.3	18.0	10-31	0.0
4-6	20-25	18	E-064	25		6.9	3	6.1	6.9	009-013	316-319	15.8	16.0	9-20	0.0
6-8	5-10	60		10			1	7.0		334-341	333-340			8-24	0.0
6-8	10-15	22	F-362	10		9.2	4	5.6	6.3	304	333	15.9	20.0	15-32	0.0
6-8	10-15	23	F-365	12	7.7	8.2	1		11.0	040	050-070	15.3	20.0	15-32	0.0
6-8	10-15	9	D-085	14		4.2	5	6.2	5.4	†	033-043†	6.1	10.4	2-29	0.0
6-8	10-15	10	D-122	15		6.2	7	8.0	6.5		040-050	9.9	12.0	3-10	0.0
6-8	20-25	16	E-062	20		7.2	3	6.1	7.1	020	350-000	11.8	16.0	11-30	0.0
8-15	5-10	40	J-035	8	12.5	16.5	3	12.7	12.2	317	334	29.4	40.0	24-54	0.0
8-15	5-10	47		8			4	9.0		321-322	311-318			23-29	0.0
8-15	5-10	45		8			2	9.0		349-355	347-354			23-33	0.0
8-15	10-15	70		10				16.0		025					0.0
8-15	15-20	5	C-500	18		6.3	3	8.8	8.8	†	330†	14.3	32.0	18-19	0.0
> 15	5-10	73		10	14			15.0		260					0.0
> 15	5-10	78*		10	20					300					0.0
> 15	5-10	79A**		8	24										0.0
> 15	5-10	79**		8	24										0.0

See.

Wind and Wave Data				Response of Ship to Se														
				Heave							Strain, Main Deck Amidships							
Heading of Swell Relative to Ship deg	E <sup>††</sup> , ft <sup>2</sup> Mean Square Wave Height		Wind Velocity for 8 Hours Preceding Test knots	F, Value of Mean Square, $\sigma^2$	N <sub>h</sub> , Variations per Hour	Predicted Maximum Value in One Hour, $\sigma$	Number of Variations in Sample	Maximum Measured Variation in Sample, $\sigma$	Maximum Predicted Variation in Sample, $\sigma$	R = Predicted Max / Measured Max	F, Value of Mean Square Kips Squared	N <sub>s</sub> , Variations per Hour	Predicted Maximum Value in One Hour kips	Number of Variations in Sample	Maximum Measured Variation in Sample, kips	Maximum Predicted Variation in Sample, kips	R = Predicted Max / Measured Max	F, Value of Mean Square Degrees Squared
	From Stereo Data	From Wind Data																
Head Seas																		
325-335	4.6	9.2	8-18	0.00037††	480	0.057	80	0.040			0.026††	360	0.42	60	0.40			0.0038††
355-25	10.4	20.0	12-30	0.00023††	530	0.0116	315	0.015			0.0265††	720	0.425	420	0.40			0.00032††
355-345	12.5	24.0	14-21	0.00090††	480	0.075	112	0.065			0.73	420	2.10	98	2.00	1.83	0.92	0.22††
000	9.3	18.0	10-31	0.003	474	0.140	245	0.15	0.13	0.87	0.69	463	2.06	239	2.03	1.94	0.96	0.16††
316-319	15.8	16.0	9-20	0.0073	600	0.210	279	0.210	0.20	0.95	4.38	696	5.31	325	4.70	5.04	1.07	0.39††
005-015	11.9	32.0	16-33	0.000041††	480	0.016	240	0.015			0.060	602	0.62	301	0.54	0.58	1.08	0.0078††
332-340			8-26	0.00070	564	0.042	113	0.066	0.058	0.87	0.57	566	1.90	113	2.00	1.65	0.83	0.102
			8-26	0.00060	565	0.062	254	0.063	0.058	0.92	0.48	600	1.75	260	1.65	1.63	0.98	0.118
	17.2	32.0	17-30	0.00099	529	0.079	141	0.070	0.07	1.00	0.53	491	1.81	131	1.85	1.61	0.87	0.166††
	17.7	24.0	24-30	0.0012††	515	0.086	206	0.080			0.67	515	2.05	206	2.30	1.89	0.82	0.15††
350-000	11.8	16.0	11-30	0.0020††	510	0.110	170	0.10			2.31††	750	3.91	250	3.65			0.035††
318-358	22.0	30.0	14-20	0.0000305††	600	0.044	190	0.040			0.101††	780	0.82	250	0.75			0.019††
350-000	58.8	48.0	30-40	0.0061	404	0.200	404	0.21	0.19	0.90	3.72	444	4.76	444	4.50	4.76	1.05	1.46
342-350			23-33	0.0019††	406	0.110	210	0.10			2.05	445	3.62	230	3.68	3.34	0.91	0.80
346-354			23-33	0.0013	479	0.089	319	0.086	0.087	1.01	1.10	483	2.61	322	2.75	2.51	0.92	0.31
353-001†			22-28	0.0014	488	0.093	323	0.099	0.09	0.91	1.33	488	2.90	326	2.65	2.78	1.05	0.26
020	21.5	24.0	22-53	0.0041	418	0.248	349	0.180	0.16	0.89	10.87	389	8.03	324	7.50	7.90	1.05	2.04
019	21.5	24.0	36-54	0.0061	416	0.200	381	0.200	0.22	1.10	16.55	362	9.88	332	9.80	9.80	1.00	4.74
				0.011	408	0.258	204	0.30	0.24	0.81								
349-356	10.7	28.0	16-19	0.0019	413	0.107	344	0.090	0.106	1.18	0.60	290	1.71	249	1.87	1.82	0.97	0.50
349-356			22-28	0.00388††	600	0.157	289	0.146			4.98††	650	5.68	315	5.35			0.48††
				0.0075	400	0.212	200	0.24	0.20	0.83	28.18	360	12.92	180	12.20	12.10	0.99	9.72
				0.0138	338	0.254	169	0.22	0.27	1.23								8.132
Quarter Head Seas																		
068	9.1	8.0	12-17	0.00052††	510	0.057	340	0.055			0.22	612	1.19	306	1.15	1.13	0.98	0.046††
325-335	4.6	9.2	8-18	0.00037††	480	0.057	80	0.040			0.0152††	360	0.295	60	0.25			0.0038††
035-040	5.2	9.2	8-18	0.00023††	384	0.015	83	0.010			0.0514††	500	0.560	109	0.49			0.0069††
000	9.3	18.0	10-31	0.0033	474	0.140	245	0.15	0.13	0.87	0.69	463	2.06	239	2.03	1.94	0.96	0.160
316-319	15.8	16.0	9-20	0.0073	600	0.210	279	0.210	0.20	0.95	4.38	696	5.31	325	4.70	5.04	1.07	0.390††
333-340			8-24	0.0012	499	0.086	208	0.089	0.08	0.90	0.65	475	2.01	198	2.05	1.85	0.90	0.173
333	15.9	20.0	15-32	0.0020††	495	0.110	403	0.110			1.17	495	2.66	403	3.25	2.66	0.82	0.230††
050-070	15.3	20.0	15-32	0.0015	497	0.097	331	0.086	0.093	1.08	1.21	746	2.68	373	2.65	2.76	1.01	0.031††
033-043†	6.1	10.4	2-29	0.0037	368	0.140	276	0.140	0.14	1.00	1.31	388	2.80	291	3.35	2.74	0.82	0.610
040-050	9.9	12.0	3-10	0.0047††	483	0.170	387	0.170			1.62	484	3.17	387	3.51	3.11	0.89	0.380
350-000	11.8	16.0	11-30	0.0020††	510	0.110	170	0.10			2.31††	750	3.91	250	3.65			0.035††
334	29.4	40.0	24-54	0.0066	384	0.200	404	0.180	0.20	1.11	5.58	396	5.77	415	5.39	5.80	1.07	1.610
311-318			23-29	0.0079††	457	0.210	61	0.180			1.250††	465	2.78	62	2.26			1.470††
347-354			23-33	0.0035	465	0.150	203	0.130	0.14	1.08	1.680	460	3.20	199	3.20	2.99	0.93	0.690
											14.75	358	9.45	178	9.00	8.80	0.98	
330†	14.3	32.0	18-19	0.0031	514	0.140	137	0.140	0.12	0.86	0.60	262	1.60	70	2.10	1.60	0.76	0.270
				0.00695	428	0.187	214	0.209	0.19	0.92	9.586	390	7.60	195	6.60	7.10	1.07	4.022
				0.0083††	360	0.22	39	0.21										7.620
																		12.8
																		12.8

2

Response of Ship to Sea

Strain, Main Deck Amidships					Pitch							Roll							
Predicted Maximum Value in One Hour kips	Number of Variations in Sample	Maximum Measured Variation in Sample, kips	Maximum Predicted Variation in Sample, kips	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	$F$ , Value of Mean Square Degrees Squared	$N_A$ , Variations per Hour	Predicted Maximum Value in One Hour, deg	Number of Variations in Sample	Maximum Measured Variation in Sample, deg	Maximum Predicted Variation in Sample, deg	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	$E$ , Value of Mean Square Degrees Squared	$N_A$ , Variations per Hour	Predicted Maximum Value in One Hour, deg	Number of Variations in Sample	Maximum Measured Variation in Sample, deg	Maximum Predicted Variation in Sample, deg	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	
0.42	60	0.40			0.0038††	360	0.150	60	0.125			0.340	227	1.35	34	1.40	1.09	0.78	
0.425	420	0.40			0.00032††	240	0.042	140	0.040			0.0855††	240	0.68	140	0.65			
2.10	98	2.00	1.83	0.92	0.22††	420	1.10	98	1.00			0.33††	300	1.40	70	1.20			
2.06	239	2.03	1.94	0.96	0.16††	300	0.96	155	1.00			1.90	240	3.30	124	3.3	3.00	0.92	
5.31	325	4.70	5.04	1.07	0.39††	696	1.57	325	1.50			1.390††	194	2.70	90	2.50			
0.62	301	0.54	0.58	1.08	0.0078††	360	0.215	180	0.20			0.280	228	1.15	114	1.40	1.15	0.82	
1.90	113	2.00	1.65	0.83	0.102	521	0.80	104	0.63	0.69	1.10	0.22	521	1.17	104	1.50	1.02	0.67	
1.75	260	1.65	1.63	0.98	0.118	508	0.86	229	0.75	0.80	1.07	0.49	402	1.71	174	1.90	1.60	0.84	
1.81	131	1.85	1.61	0.87	0.166††	491	1.00	131	0.90			0.25	341	1.21	91	0.90	1.06	1.18	
2.05	206	2.30	1.89	0.82	0.15††	515	0.98	206	0.90			0.35	339	1.46	136	1.60	1.31	0.82	
3.91	250	3.65			0.035††	480	0.43	160	0.42			0.94††	210	2.24	70	2.00			
0.82	250	0.75			0.019††	600	0.35	190	0.25			0.326††	388	1.30	123	1.25			
4.76	444	4.50	4.76	1.05	1.46	388	2.95	388	3.10	2.90	0.94	1.83	321	3.25	321	4.60	3.20	0.70	
3.62	230	3.68	3.34	0.91	0.80	428	2.20	221	2.05	2.08	1.02	0.51	406	1.75	221	1.70	1.70	1.00	
2.61	322	2.75	2.51	0.92	0.31	439	1.26	293	1.40	1.32	0.94	0.34	444	1.40	296	2.50	1.40	0.57	
2.90	326	2.65	2.78	1.05	0.26	450	1.26	300	1.20	1.20	1.00	0.31	426	1.37	284	1.40	1.30	0.93	
8.03	324	7.50	7.90	1.05	2.04	380	3.50	317	3.25	3.40	1.04	1.29	373	2.76	312	4.00	2.70	0.68	
9.88	332	9.80	9.80	1.00	4.74	351	5.26	322	5.65	5.23	0.93	1.90	333	3.32	305	4.10	3.30	0.81	
1.71	249	1.87	1.82	0.97	0.50	290	1.71	241	1.87	1.65	0.88	5.80	225	5.60	196	5.80	5.52	0.96	
5.68	315	5.35			0.48††	493	1.72	238	1.62			0.74††	210	1.99	102	1.85			
12.92	180	12.20	12.10	0.99	9.72	326	7.50	163	6.90	7.04	1.01	3.18	354	4.30	177	6.00	4.06	0.68	
					8.132	328	6.90	164	5.40	6.40	1.20	18.52††	260	10.0	28	9.5			
1.19	306	1.15	1.13	0.98	0.046††	275	0.509	240	0.50			0.630	243	1.86	162	2.60	1.80	0.70	
0.295	60	0.25			0.0038††	360	0.150	60	0.125			0.340	227	1.35	34	1.40	1.09	0.78	
0.560	109	0.49			0.0069††	308	0.190	67	0.17			0.410	180	1.45	45	1.30	1.25	0.96	
2.06	239	2.03	1.94	0.96	0.160	300	0.960	155	1.00			1.90	240	3.30	124	3.30	3.02	0.92	
5.31	325	4.70	5.04	1.07	0.390††	696	1.580	325	1.50			1.390††	194	2.70	90	2.50			
2.01	198	2.05	1.85	0.90	0.173	475	1.350	198	0.95	0.96	1.01	0.460	398	1.65	166	1.30	1.50	1.15	
2.66	403	3.25	2.66	0.82	0.230††	495	1.200	403	1.20			0.350	234	1.38	191	1.40	1.35	0.97	
2.68	373	2.65	2.76	1.01	0.031††	495	0.430	373	0.42			0.400	404	1.55	202	1.40	1.40	1.00	
2.80	291	3.35	2.74	0.82	0.610	335	1.88	244	2.08	1.83	0.88	0.760	303	2.08	227	2.30	2.03	0.88	
3.17	387	3.51	3.11	0.89	0.380	280	1.45	223	1.60	1.43	0.90	0.710	309	1.98	191	2.00	1.93	0.97	
3.91	250	3.65			0.035††	480	0.43	160	0.42			0.940	210	2.24	70	2.00			
5.77	415	5.39	5.80	1.07	1.618	418	3.12	370	3.50	3.09	0.89	3.920	295	4.70	310	4.60	4.70	1.04	
2.78	62	2.26			1.470††	450	2.98	60	2.45			0.550††	450	1.83	60	1.50			
3.20	199	3.20	2.99	0.93	0.690	440	2.05	190	2.25	1.92	0.85	0.400	465	1.57	200	1.70	1.50	0.88	
9.45	178	9.00	8.80	0.98															
1.60	70	2.10	1.60	0.76	0.270	372	1.25	99	1.40	1.12	0.80	2.500††	185	3.60	37	3.00			
7.60	199	6.60	7.10	1.07	4.022	370	4.86	185	5.30	4.59	0.87	1.780	314	3.18	157	3.80	3.00	0.79	
					7.628	314	6.60	157	6.00	6.20	1.03	61.00	244	18.8	122	19.0	17.30	0.90	
					12.8				9.50										
					12.8	296	8.5	148	7.50	8.00	1.07								

3

TABLE 1 (continued)

Wave and Speed Classification		Record Number	Stereo Photo Number	Ship Speed knots	Estimates of Characteristic Wave Height, ft					Wind and Wave Data					F <sub>1</sub> Value of
Wave Height ft	Ship Speed knots				Sea		Number of Visual Estimators ††	Swell		Heading of Sea Relative to Ship deg	Heading of Swell Relative to Ship deg	E <sup>††</sup> , ft <sup>2</sup> Mean Square Wave Height		Wind Velocity for 8 Hours Preceding Test knots	
					Average of Visual Estimates	From TMB Analysis of Stereo-Photo		Average of Visual Estimates	From TMB Analysis of Stereo-Photo			From Stereo Data	From Wind Data		
0-4	10-15	14	E-021	12		5.6	7	3.7	4.5		075-095	5.3	5.2	9-20	0.0004
0-4	15-20	29	H-087	20		2.9	1	2.7	3.7		080-100	3.5	9.2	8-18	0.0001
0-4	20-25	28	H-078	25		3.8	4	2.7		100-110	080-100	3.0	9.2	8-18	0.0000
0-4	20-25	32	H-100	25		3.5	3	2.8	4.5	265	255-265	5.2	9.2	2-13	0.0003
4-6	10-15	11	D-148	15		8.5	6	5.5	5.5	080-100	070	19.6	18.0	3-14	0.0038
4-6	15-20	20	E-074	20		7.3	3	5.9	6.5	160-180	080-098	11.3	18.0	6-30	0.0017
4-6	20-25	37	I-073	25		4.3	2	4.3	6.0	220-200	090-120	10.3	10.4	14-22	0.0026
6-8	10-15	27	G-150	12		4.2	2	6.5	7.1	082-085†	065-068†	8.1	18.4	15-21	0.0037
6-8	15-20	13	D-199	16		6.5	3	6.9	6.3		072-083	8.9	16.0	15-26	0.0031
6-8	15-20	3	C-470	20		9.1	3	7.8	7.5		095	8.9	24.0	20-28	0.0050
6-8	20-25	17	E-064	25		6.9	3	6.1	6.9	225	225-235	15.8	16.0	6-30	0.0067
8-15	5-10	52		10			5	10.0			090			22-27	0.0033
8-15	5-10	74		10	9			11.0			110				0.0022
8-15	15-20	5	C-500	18		6.3	3	8.8	8.0		330	14.3	32.0	18-19	0.0031
0-4	10-15	15	E-034	15		5.0	7	2.3		115-125	135	8.9	5.2	8-12	0.0001
4-6	5-10	7	D-017	10		2.8	3	4.5	4.5		210	5.1	9.2	8-20	†
4-6	10-15	21	F-344	12	4.8	5.8	4		5.1	†	220-230†	11.6	13.6	19-31	0.0004
4-6	10-15	63		12			1	6.0		153-158	152-158			8-26	0.0001
4-6	15-20	8	D-017	18		2.8	3	4.4	4.5		040-044	5.1	9.2	10-31	0.0004
4-6	15-20	6	D-017	18		2.8	3	4.5	4.4		206-226	5.1	9.2	9-17	0.0001
6-8	5-10	35	I-014	10		6.4	3	7.5	7.9	213-273	223-233	22.0	30.0	19-30	0.0006
6-8	10-15	26	G-127	15		5.5	6	6.6	6.7	109-119	119	19.8	16.8	10-31	0.0011
6-8	15-20	68	C-500	17		6.3	3	8.8	8.0		244	14.3	32.0	12-19	0.0004
6-8	20-25	17	E-064	25		6.9	3	6.1	6.9	255	225-235	15.8	16.0	6-30	0.0061
6-8	20-25	36	I-052	25		3.8	5	7.1	6.0	225	205-255	9.7	18.4	22-35	†
8-15	15-20	71		16	12					220					
8-15	15-20	75		16	11			11.0		210					0.0021
8-15	20-25	50		25			3	9.0		225	214-222			22-29	0.0001
0-4	20-25	33	H-155	25		6.0	6	3.6	5.3	160-170	180-190	12.0	9.2	16-20	0.0001
4-6	10-15	12	D-159	12		7.1	5	5.0	6.7	160	160	13.6	9.2	3-21	0.0006
4-6	10-15	63		12			1	6.0		153-158	152-158			8-26	0.0001
6-8	0-5	56		5			2	8.0			177			29-32	0.0001
6-8	10-15	57		15			4	8.0		167†	157-177†			29-32	0.0001
6-8	15-20	59		20			1	8.0		167	157-177			8-24	†
8-15	5-10	55		10			2	9.0		167	157-177			8-24	0.0001
8-15	10-15	42		12			4	10.0		175-185	185-195			28-31	0.0006
8-15	10-15	76		15	13			13.0		190					0.0016
8-15	15-20	48		20			4	9.0		180-182	170-178			23-29	0.0004
8-15	20-25	49		25			4	9.0		186	176-186			23-26	0.0004

\*Records were obtained on ORISKANY.

†These sea conditions were well defined and nearly unidirectional.

†Values were negative

\*\*Records were obtained on ESSEX.

††E is based on maximum measured value.

††For the method of

Wind and Wave Data					Response of Ship to													
Heading of Swell Relative to Ship deg	Mean Square Wave Height $E_{\text{M}}^{\dagger\dagger}$ , ft <sup>2</sup>		Wind Velocity for 8 Hours Preceding Test knots	Heave							Strain, Main Deck Amidships							
	From Stereo Data	From Wind Data		$E_s$ Value of Mean Square, g <sup>2</sup>	$N_A$ Variations per Hour	Predicted Maximum Value in One Hour, g	Number of Variations in Sample	Maximum Measured Variation in Sample, g	Maximum Predicted Variation in Sample, g	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	$E_s$ Value of Mean Square Kips Squared	$N_A$ Variations per Hour	Predicted Maximum Value in One Hour kips	Number of Variations in Sample	Maximum Measured Variation in Sample, kips	Maximum Predicted Variation in Sample, kips	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	$E_s$ Value of Mean Square
Beam Seas																		
075-095	5.3	5.2	9-20	0.0004††	444	0.051	370	0.50			0.330	444	1.41	370	1.47	1.40	0.95	0.034
080-100	3.5	9.2	8-18	0.00016††	600	0.032	250	0.030			0.072††	600	0.68	250	0.63			†
080-100	3.0	9.2	8-18	0.000057††	610	0.019	225	0.018			0.0376††	446	0.48	164	0.438			0.005†
255-265	5.2	9.2	2-13	0.00038††	540	0.049	595	0.05			0.130††	390	0.88	430	0.88			0.060
070	19.6	18.0	3-14	0.0038††	420	0.150	350	0.15			0.660	434	4.00	373	2.30	1.92	0.86	0.180
080-098	11.3	18.0	6-30	0.0017	524	0.130	253	0.130	0.098	0.75	1.270††	134	2.50	65	2.30			0.005†
090-120	10.3	10.4	14-22	0.0026††	540	0.128	225	0.120			0.590	591	1.94	246	1.81	1.81	1.00	0.190
065-068†	8.1	18.4	15-21	0.003†	447	0.109	373	0.150	0.13	0.87	0.490	437	1.76	364	1.75	1.70	0.97	0.040
072-083	8.9	16.0	15-26	0.003††	450	0.138	375	0.140			0.900	497	2.36	415	2.70	2.33	0.86	0.096
095	8.9	24.0	20-28	0.0050	422	0.170	218	0.170	0.17	1.00	0.300	368	1.36	190	1.35	1.26	0.94	0.450
225-235	15.8	16.0	6-30	0.0067	484	0.210	242	0.190	0.19	1.00	2.630	524	4.20	262	4.50	3.83	0.85	0.340
090			22-27	0.0003††	436	0.240	73	0.200			1.160††	472	2.68	79	2.25			0.830
110				0.0022	398	0.115	199	0.127	0.11	0.87	2.788	320	4.03	160	4.05	3.77	0.93	0.872
330	14.3	32.0	18-19	0.0031	514	0.140	137	0.140	0.12	0.86	0.60	262	1.60	70	2.10	1.60	0.76	0.270
Quarter Following Seas																		
135	8.9	5.2	8-12	0.00052††	420	0.056	350	0.055			0.170	400	1.01	332	1.22	1.00	0.82	0.043†
210	5.1	9.2	8-20	†							0.160	203	0.92	88	0.95	0.86	0.91	0.0068
220-230†	11.6	13.6	19-31	0.00061††	480	0.061	240	0.060			0.630	374	1.93	187	1.80	1.80	1.00	0.117†
152-158			8-26	0.00012††	450	0.027	240	0.026			0.442††	300	1.57	160	1.47			0.140†
040-044	5.1	9.2	10-31	0.00063††	450	0.062	316	0.060			0.340††	135	1.30	94	1.27			0.0515
206-226	5.1	9.2	9-17	0.00017††	360	0.032	180	0.030			0.220	144	1.03	72	1.35	0.97	0.72	†
223-233	22.0	39.0	19-30	0.000042††	485	0.016	216	0.015			0.150	395	0.92	178	1.07	0.89	0.83	0.040
119	19.8	16.8	10-31	0.00150	468	0.096	234	0.11	0.091	0.83	0.530	406	1.78	203	2.10	1.68	0.80	0.110†
244	14.3	32.0	12-19	0.00040††	390	0.049	150	0.045			2.120††	208	3.36	80	3.05			0.390†
225-235	15.8	16.0	6-30	0.0067	484	0.210	242	0.190	0.19	1.00	2.630	524	4.20	262	4.50	3.83	0.85	0.340
205-255	9.7	18.4	22-35	†							0.100	240	0.74	140	0.95	0.70	0.74	†
				0.00254	422	0.136	211	0.165	0.12	0.73	6.498	268	6.05	134	6.40	5.64	0.83	10.08
214-222			22-29	0.00076	510	0.043	220	0.069	0.064	0.93	1.470	251	2.85	109	3.50	2.60	0.75	0.260
Following Seas																		
180-190	12.0	9.2	16-20	0.000144††	420	0.029	189	0.028			0.043††	420	0.51	189	0.475			0.0188
160	13.6	9.2	3-21	0.000039††	420	0.0155	350	0.015			0.550	248	1.74	206	2.11	1.72	0.81	0.017†
152-158			8-26	0.00012††	450	0.027	240	0.026			0.442††	300	1.57	160	1.47			0.140†
177			29-32	0.00012	480	0.028	240	0.030	0.026	0.87	0.590	368	1.87	184	1.78	1.75	0.98	0.170
157-177†			29-32	0.00022††	480	0.037	240	0.038			0.380	360	1.50	180	1.50	1.40	0.94	0.070
157-177			8-24	†							0.270††	240	1.22	40	1.00			0.054†
157-177			8-24	0.00014††	420	0.029	153	0.026			0.430††	300	1.57	110	1.43			0.136†
185-195			28-31	0.00009††	480	0.023	256	0.022			1.290††	319	2.71	170	2.78	2.58	0.92	0.130
				0.00162	400	0.138	200	0.138	0.092	0.67	11.347	224	7.85	112	7.65	7.30	0.95	4.52
170-178			23-29	0.00047††	430	0.053	100	0.046			0.930††	180	2.20	33	1.80			0.190†
176-186			23-26	0.00040	530	0.047	256	0.050	0.047	0.94	1.050††	312	2.46	156	2.30			0.111

and nearly unidirectional.

†Values were negligible.

††For the method of computing  $R$  see TMB Report 1091 (Reference 5).

†In cases where conditions did not permit visual estimates, estimates of wave height were made by extrapolation from earlier and later visual estimates.

2



Response of Ship to Sea

Time per Hour	Strain, Main Deck Amidships					Pitch						Roll							
	Predicted Maximum Value in One Hour kips	Number of Variations in Sample	Maximum Measured Variation in Sample, kips	Maximum Predicted Variation in Sample, kips	Predicted Max $R = \frac{\text{Measured Max}}{\text{Predicted Max}}$	$\Sigma$ , Value of Mean Square Degrees Squared	$V_n$ , Variations per Hour	Predicted Maximum Value in One Hour, deg	Number of Variations in Sample	Maximum Measured Variation in Sample, deg	Maximum Predicted Variation in Sample, deg	Predicted Max $R = \frac{\text{Measured Max}}{\text{Predicted Max}}$	$E$ , Value of Mean Square Degrees Squared	$N_n$ , Variations per Hour	Predicted Maximum Value in One Hour, deg	Number of Variations in Sample	Maximum Measured Variation in Sample, deg	Maximum Predicted Variation in Sample, deg	Predicted Max $R = \frac{\text{Measured Max}}{\text{Predicted Max}}$
144	1.41	370	1.47	1.40	0.95	0.034††	420	0.45	350	0.60		0.470	314	1.64	262	1.70	1.62	0.96	
500	0.68	250	0.63			†						0.480	233	1.60	97	1.65	1.48	0.90	
146	0.48	164	0.438			0.0055††	333	0.179	121	0.162		0.970	204	2.28	85	2.50	2.02	0.81	
190	0.88	430	0.88			0.060††	480	0.610	530	0.630		1.000	152	2.25	186	2.40	2.30	0.96	
134	4.00	373	2.30	1.92	0.86	0.180	223	0.99	186	1.10	0.97	1.000	179	2.28	149	1.90	2.20	1.16	
134	2.50	65	2.30			0.0056††	228	0.175	110	0.162		2.320	241	3.56	116	4.10	3.30	0.81	
191	1.94	246	1.81	1.81	1.00	0.190††	540	1.10	225	1.00		1.750	264	3.10	110	3.10	2.86	0.92	
137	1.76	364	1.75	1.70	0.97	0.040	385	0.49	321	1.15	1.52	0.210	392	1.12	327	1.40	1.11	0.79	
197	2.36	415	2.70	2.33	0.86	0.096††	420	0.78	350	0.75		0.750	225	2.20	188	1.75	1.99	1.14	
168	1.36	190	1.35	1.26	0.94	0.450††	309	1.60	159	1.50		3.600	246	4.45	127	4.20	4.18	0.99	
124	4.20	262	4.50	3.83	0.85	0.340††	524	1.45	262	1.37		2.130	216	3.40	108	3.20	3.16	0.99	
172	2.68	79	2.25			0.830††	426	2.24	71	1.88		0.950††	426	2.40	71	2.35			
120	4.03	160	4.05	3.77	0.93	0.872	336	2.25	168	2.40	2.12	1.773	370	3.22	135	3.40	2.95	0.87	
162	1.60	70	2.10	1.60	0.76	0.270	372	1.25	99	1.40	1.12	2.500††	185	3.60	37	3.00			
100	1.01	332	1.22	1.00	0.82	0.043††	400	0.50	332	0.50		0.500	183	1.60	154	1.50	1.59	1.06	
103	0.92	88	0.95	0.86	0.91	0.0068††	203	0.195	88	0.175		0.900	202	2.18	87	2.10	2.00	0.95	
174	1.93	187	1.80	1.80	1.00	0.117††	374	0.83	187	0.78		1.400	250	2.78	125	2.60	2.60	1.00	
100	1.57	160	1.47			0.140††	240	0.87	128	0.82		10.100††	240	7.40	128	7.00			
135	1.30	94	1.27			0.0515††	186	0.518	130	0.50		3.710	186	4.43	130	4.60	4.20	0.92	
144	1.03	72	1.35	0.97	0.72	†						2.740	168	3.75	84	4.20	3.48	0.83	
195	0.92	178	1.07	0.89	0.83	0.040	320	0.49	144	0.45	0.45	2.900	278	4.13	125	4.35	3.75	0.86	
106	1.78	203	2.10	1.68	0.80	0.110††	406	0.81	203	0.75		3.370	244	4.30	122	5.00	4.03	0.81	
208	3.36	80	3.05			0.390††	208	1.43	80	1.30		15.290	217	9.0	105	9.80	8.40	0.86	
124	4.20	262	4.50	3.83	0.85	0.340††	524	1.45	262	1.37		2.130	216	3.40	108	3.20	3.16	0.99	
140	0.74	140	0.95	0.70	0.74	†						0.740	161	1.94	94	2.00	1.85	0.92	
168	6.05	134	6.40	5.64	0.82	10.08	334	7.70	167	8.00	7.70	0.90							
151	2.85	109	3.50	2.60	0.75	2.724	276	3.92	138	3.70	3.68	0.99	61.00	204	18.2	102	19.0	16.80	0.88
						0.260	365	1.16	158	1.25	1.15	0.92	4.800	212	5.06	92	5.00	4.70	0.94
120	0.51	189	0.475			0.0188††	415	0.33	187	0.31		0.77††	193	2.05	87	1.85			
148	1.74	206	2.11	1.72	0.81	0.017††	248	0.31	206	0.25		2.90	196	3.95	162	3.80	3.80	1.00	
100	1.57	160	1.47			0.140††	240	0.87	128	0.82		10.100††	240	7.40	128	7.00			
168	1.87	184	1.78	1.75	0.98	0.170	383	1.01	192	1.00	0.94	0.590	358	1.86	179	2.00	1.75	0.88	
160	1.50	180	1.50	1.40	0.94	0.070	336	0.63	168	0.63	0.61	11.16	226	7.80	113	7.50	7.30	0.98	
140	1.22	40	1.00			0.054††	424	0.57	106	0.50		3.80	195	4.35	48	6.10	3.85	0.64	
100	1.57	110	1.43			0.136††	300	0.88	110	0.80		2.950††	330	4.13	102	3.70			
119	2.71	170	2.78	2.58	0.92	0.130	448	0.88	239	0.88	0.85	14.140	286	8.85	153	9.90	8.50	0.86	
124	7.85	112	7.65	7.30	0.95	4.52	218	4.93	109	5.10	4.62	54.77	202	16.80	101	19.0	15.90	0.84	
180	2.20	33	1.80			0.190††	300	1.03	55	0.88		10.300††	180	7.30	33	6.00			
112	2.46	156	2.30			0.111	348	0.81	174	0.75	0.76	8.10	176	6.50	88	7.50	6.03	0.81	

Conditions did not permit visual estimates, estimates of wave extrapolation from earlier and later visual estimates.

2 3

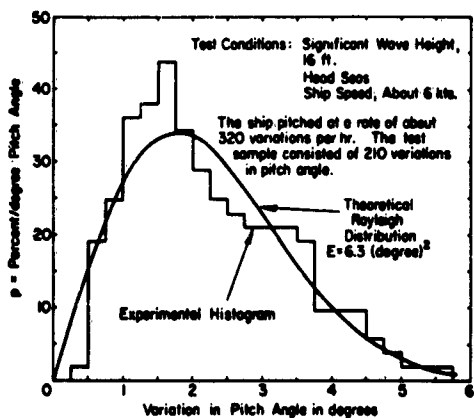


Figure 2a - Distribution of Variation in Pitch Angle

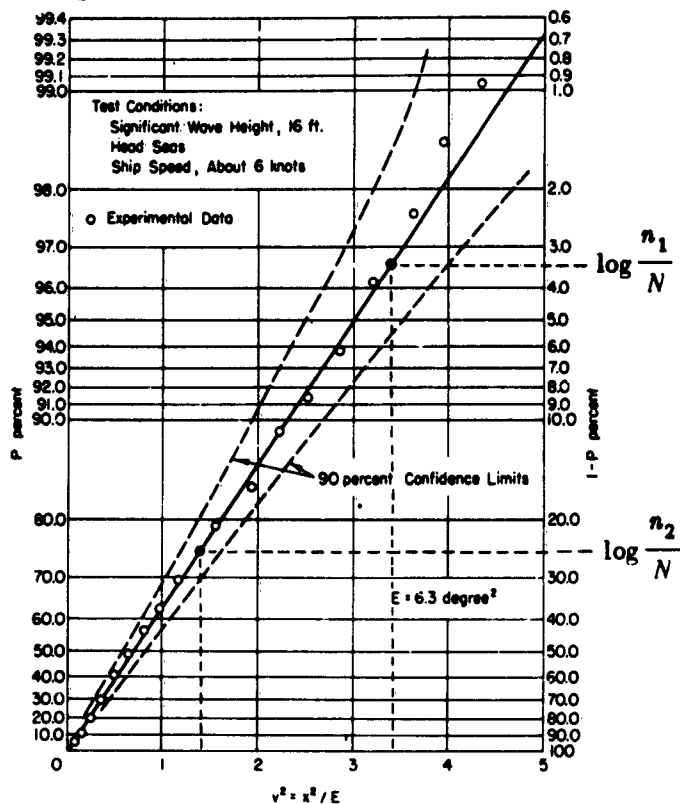


Figure 2b - Cumulative Distribution of Variation in Pitch Angle  
 Figure 2 - Sample of Rayleigh (Short-Term) Distributions

Note: To determine  $E$  from a set of experimental data we need to

know two points on the line  $\left(\frac{n_1}{N}, v_1^2\right)$  and  $\left(\frac{n_2}{N}, v_2^2\right)$

where  $n_i$  denotes the number of variations exceeding  $x_i$ , and  $N$  is the total number of variations in the set of data.

From the equation of the slope of the line we obtain:

$$E = \frac{x_1^2 - x_2^2}{\log_e n_2 - \log_e n_1}$$

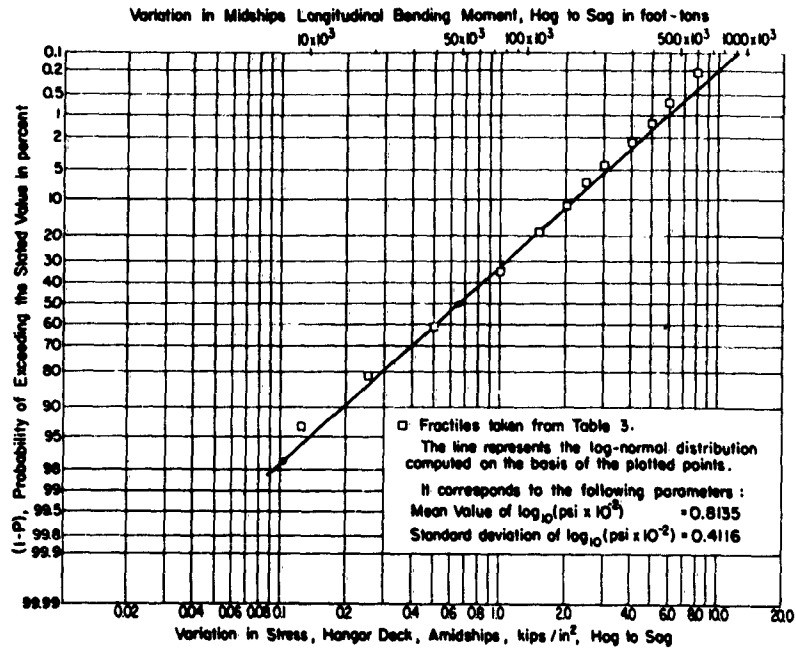


Figure 3 - Long-Term Cumulative Distribution of Longitudinal Stress and Bending Moment Amidship, for Wartime Service in North Atlantic Ocean

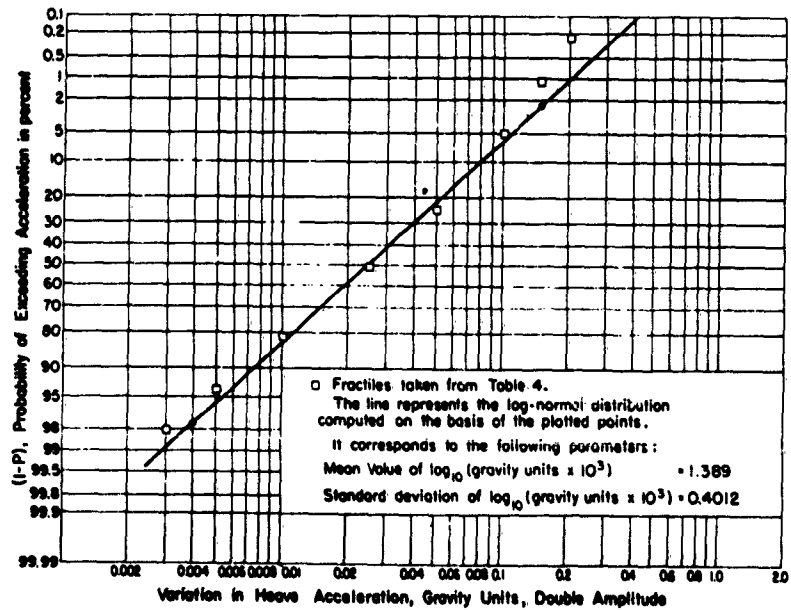


Figure 4 - Long-Term Distribution of Heave Acceleration for Wartime Service in North Atlantic Ocean

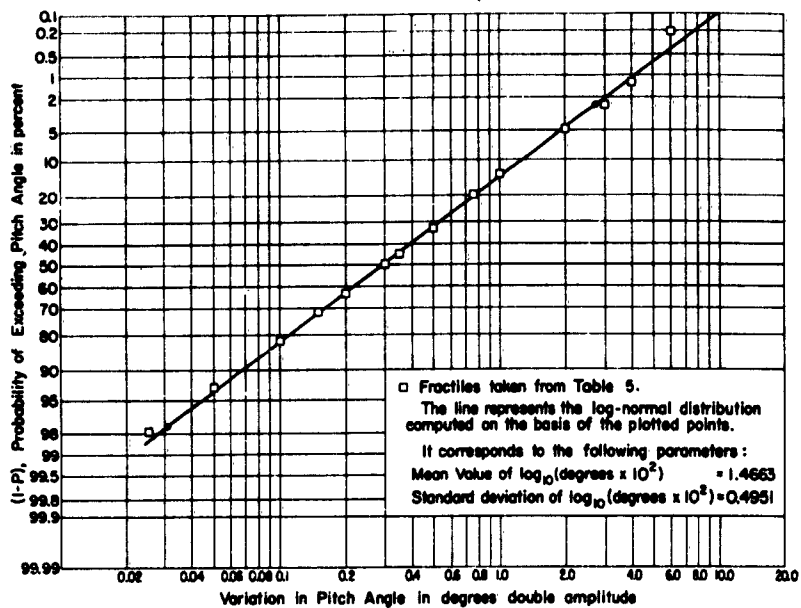


Figure 5 – Long-Term Cumulative Distribution of Pitch Angle for Wartime Service in North Atlantic Ocean

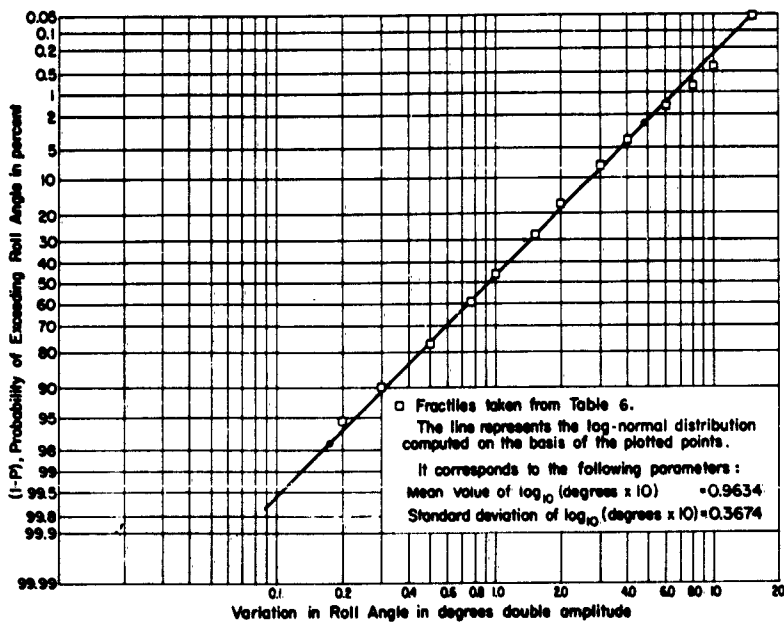


Figure 6 – Long-Term Cumulative Distribution of Roll Angle for Wartime Service in North Atlantic Ocean

The distribution patterns give the probability of exceeding any given magnitude of motion or bending moment and can be utilized as a load spectrum in designing for endurance strength. For any set of operating conditions, characteristic and extreme values can be predicted from a knowledge of the corresponding value of  $E$ . Useful statistical estimates are made as follows:<sup>9</sup>

- a. The most frequent magnitude of variations\* is  $0.707 \sqrt{E}$ .
- b. The average magnitude of the variations is  $0.866 \sqrt{E}$ .
- c. The most probable extreme value  $x_m$  experienced in a sample of  $N$  variations is  $x_m = k\sqrt{E}$ . For large values of  $N$ ,  $k$  is approximately equal to  $\sqrt{\log_e N}$ .

For design purposes we may make a statistical estimate of the extreme value of the various variables as follows:

Let the value of  $E$  corresponding to the most severe condition be  $E_m$ . If the ship is expected to experience  $N$  variations during the time it is exposed to this operating condition, then

$$x_{m_1}^2 = E_m (y + \log_e N)$$

where  $N$  is assumed large.

The value of  $y$  is a function of the risk\*\*  $f$  (selected by the designer). Table 2 of Reference 10 gives  $y$  as a function of  $f$ . For example, if we take one chance in a thousand,  $f = 0.001$  and  $y = 7.0$ . For  $f < 0.1$ ,  $y = \log_e (1/f)$ .

The value  $x_{m_1}$  is then that magnitude of the variable which, on the average, is exceeded only by the fraction  $f$  of many similar ships operating under the most severe service conditions.

## DISTRIBUTION PATTERNS OF SHIP MOTIONS AND LONGITUDINAL HULL BENDING MOMENTS

The motions and stresses (bending moments) given in this section are those associated with the rigid body motions of the ship (heaving, rolling, and pitching) and do not include vibratory motions and stresses induced by slamming.

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\*The motion, stress, and bending moment will be given in terms of their variation, which is defined as the magnitude of the change from a maximum value to the succeeding minimum value.

\*\* $f$  is the fraction of all samples of size  $N$ , belonging to a distribution specified by  $p(x)$ , which will have at least one value of  $x > x_{m_1}$ .

## SHORT-TERM DISTRIBUTION

The Rayleigh distribution corresponding to a particular set of operating conditions (sea state, speed, and course) is defined by the corresponding mean square value  $E$ . All Rayleigh distributions become identical if the probability  $P$  is plotted against  $v^2 = x^2/E$  instead of against  $x$  directly. With this artifice it is necessary to know only the value of  $E$  corresponding to a particular sea condition, ship speed, and heading in order to obtain the probability of exceeding any value of  $x$  from a single graph (Figure 2b) which is equally applicable to wave heights, ship motions, and hull stresses. The previous section gives formulas which may be used to estimate characteristic and expected extreme values.

## LONG-TERM DISTRIBUTION

The short-term distributions, each of which is characterized by a value  $E$ , will now be used as building blocks to construct the long-term frequency distribution patterns of the ship responses to the sea applicable to *wartime service in the North Atlantic Ocean*. Distribution patterns for other "missions" or operating areas can be readily computed from data given in this report. Each of the short-term distributions will be weighted in accordance with the relative fraction of time in which carriers of this class will operate in a given sea state  $f_2$ , at a given heading to the waves  $f_3$ , and at a given ship speed  $f_1$ .

The fractions of time  $f_1$  that the ship will make the given speeds for the specified range of characteristic wave heights, including all headings relative to the predominant wave direction, are:

Speed knots	Characteristic Wave Height, feet				
	0-4	4-6	4-8	8-15	> 15
5-10	0.051	0.053	0.079	0.188	0.503
10-15	0.288	0.369	0.425	0.537	0.368
15-20	0.353	0.376	0.346	0.201	0.099
20-25	0.175	0.139	0.119	0.052	0.035
25-30	0.112	0.057	0.026	0.021	0
> 30	0.021	0.006	0.005	0	0

The fractions of time  $f_2$  that specified ranges of characteristic wave heights will be experienced in the North Atlantic Ocean are:

Characteristic Wave Heights, feet				
0-4	4-6	6-8	8-15	> 15
0.24	0.22	0.17	0.27	0.10

**TABLE 2**  
**Product of Weighting Factors ( $f_1 f_2 f_3$ ) Applicable to Different**  
**Sets of Operating Conditions**

Ship Speed		Relative Direction of Sea deg	Characteristic Wave Height, ft				
Knots	Class		0-4	4-6	6-8	8-15	> 15
5-10	1	0	0.00153	0.00146	0.00168	0.01270	0.01258
		± 45	0.00306	0.00292	0.00336	0.01270	0.01258
		± 90	0.00306	0.00292	0.00336	0.00635	0.00629
		± 135	0.00306	0.00292	0.00336	0.01270	0.01258
		180	0.00153	0.00146	0.00168	0.00635	0.00629
10-15	2	0	0.00864	0.01015	0.00904	0.03626	0.00920
		± 45	0.01728	0.02030	0.01808	0.03626	0.00920
		± 90	0.01728	0.02030	0.01808	0.01813	0.00460
		± 135	0.01728	0.02030	0.01808	0.03626	0.00920
		180	0.00864	0.01015	0.00904	0.01813	0.00460
15-20	3	0	0.01059	0.01034	0.00735	0.01358	0.0025
		± 45	0.02118	0.02068	0.01470	0.01358	0.0025
		± 90	0.02118	0.02068	0.01470	0.00679	0.0012
		± 135	0.02118	0.02068	0.01470	0.01358	0.0025
		180	0.01059	0.01034	0.00735	0.00679	0.0012
20-25	4	0	0.00525	0.00383	0.00253	0.00350	0.00088
		± 45	0.01050	0.00766	0.00506	0.00350	0.00088
		± 90	0.01050	0.00766	0.00506	0.00175	0.00044
		± 135	0.01050	0.00766	0.00506	0.00350	0.00088
		180	0.00525	0.00383	0.00253	0.00175	0.00044
25-30	5	0	0.00336	0.00156	0.00055	0.00142	
		± 45	0.00672	0.00312	0.00110	0.00142	
		± 90	0.00672	0.00312	0.00110	0.00071	
		± 135	0.00672	0.00312	0.00110	0.00142	
		180	0.00336	0.00156	0.00055	0.00071	
> 30	6	0	0.00063	0.00016	0.00011		
		± 45	0.00126	0.00032	0.00022		
		± 90	0.00126	0.00032	0.00022		
		± 135	0.00126	0.00032	0.00022		
		180	0.00063	0.00016	0.00011		

TABLE 3

Derivation of Predicted Distribution for Variations in Stress for Wartime Duty in the Atlantic Ocean

Wave Height Class H	Characteristic Wave Height, ft Visual		Relative Heading between Waves and Ship deg	Ship Speed Class* Class*	Weighting Factor $\Sigma f_1 f_2 f_3 f_4 \dots$	Number of Variations per Hour N	Average Number of Variations per Hour Contributed by Each Operating Condition $f_1 f_2 f_3 f_4 \dots V = n$	Probability of Exceeding Given Magnitude of Variation (1 - P) (Magnitude in kpsi)												σ <sub>mean</sub> Square Variation			
	Sea	Swift						0.125	0.250	0.500	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	8.0		10.0		
0-4		2.7	±45	4 (1, 2, 3, 5, 6) 2 (1)	0.0200	300	10.800	0.555	0.090	0.321	0.011								0.0260				
								0.932	0.753	0.271											0.270		
								0.736	0.293	0.086												0.0514	
								0.954	0.426	0.148	0.046											0.330	
								0.405	0.420	0.031												0.0720	
								0.680	0.198	0.046												0.0376	
								0.887	0.619	0.146												0.130	
								0.513	0.693	0.230												0.170	
								0.636	0.235													0.0430	
								0.559	0.099													0.0285	
								0.979	0.916								0.254	0.046					0.730
								0.978	0.916								0.234	0.039					0.696
								0.957	0.906								0.944	0.796	0.026				4.38
0.976	0.916								0.696	0.599	0.076				0.690								
20.326	463								0.944	0.796	0.026				4.38								
10.077	696								0.682	0.219	0.026				0.660								
2.771	134								0.968	0.952	0.023				1.27								
0.1110	591								0.974	0.900	0.043				0.900								
0.0292	203								0.907	0.677	0.218				0.160								
0.10115	374								0.976	0.904	0.073				0.630								
0.10115	300								0.965	0.868	0.104				0.442								
0.11989	125								0.955	0.834	0.096				0.340								
0.11989	144								0.932	0.752	0.321				0.220								
0.13175	248								0.972	0.884	0.635				0.550								
0.13175	300								0.965	0.868	0.568				0.442								
4-6		5.9	0	2 (1)	0.0058	720	4.176	0.371	0.353	0.616								0.0000					
								0.9226	0.896	0.645	0.174	0.019								0.570			
								0.9226	0.878	0.595	0.125										0.490		
								0.9226	0.911	0.624	0.150	0.014										0.530	
								0.9226	0.911	0.688	0.225	0.035										0.670	
								0.9226	0.973	0.897	0.648	0.378	0.067									2.31	
								0.9226	0.973	0.897	0.648	0.378	0.067									0.101	
								0.9226	0.973	0.897	0.648	0.378	0.067									0.550	
								0.9226	0.973	0.897	0.648	0.378	0.067									1.17	
								0.9226	0.973	0.897	0.648	0.378	0.067									1.21	
								0.9226	0.973	0.897	0.648	0.378	0.067									1.62	
								0.9226	0.973	0.897	0.648	0.378	0.067									2.31	
								0.9226	0.973	0.897	0.648	0.378	0.067									0.490	
0.9226	0.973	0.897	0.648	0.378	0.067									0.900									
0.9226	0.973	0.897	0.648	0.378	0.067									0.300									
0.9226	0.973	0.897	0.648	0.378	0.067									2.63									
0.9226	0.973	0.897	0.648	0.378	0.067									0.150									
0.9226	0.973	0.897	0.648	0.378	0.067									0.530									
0.9226	0.973	0.897	0.648	0.378	0.067									2.12									
0.9226	0.973	0.897	0.648	0.378	0.067									2.63									
0.9226	0.973	0.897	0.648	0.378	0.067									0.100									
0.9226	0.973	0.897	0.648	0.378	0.067									0.300									
0.9226	0.973	0.897	0.648	0.378	0.067									2.70									
8-15		12.1	0	1	0.0212	444	0.941	0.999	0.983	0.935	0.764	0.512	0.342	0.186	0.098	0.014	0.001	3.72					
								0.999	0.970	0.865	0.614	0.296	0.142	0.048	0.013					2.05			
								0.999	0.970	0.865	0.614	0.296	0.142	0.048	0.013						1.10		
								0.999	0.970	0.865	0.614	0.296	0.142	0.048	0.013						1.33		





TABLE 4

Derivation of Predicted Distribution for Variations in Heave Acceleration for Wartime Duty in the Atlantic Ocean

Wave Height Class H	Characteristic Wave Height, H Visual		Relative Heading between Waves and Ship deg	Ship Speed Class*	Weighting Factor $\Sigma f_i f_j f_k f_l$	Number of Variations per Hour N	Average Number of Variations per hour Contributed by each Operating Condition $f_i f_j f_k f_l N = n$	Probability of Exceeding given magnitude of Variation (1 - P) (Magnitude in units of gravity)										Mean Square Variation	
	Sea	Swell						0.003	0.005	0.01	0.025	0.05	0.1	0.15	0.2	0.25			
0-4			0	4 (1, 2, 3, 5, 6)	0.0300	480	14.400	0.976	0.932	0.760	0.184	0.001						0.000370	
							10.373	0.983	0.950	0.826	0.300	0.008						0.000520	
							9.5104	0.976	0.932	0.760	0.184	0.001						0.000370	
							7.614	0.962	0.890	0.647	0.066	0.002						0.000230	
							9.031	0.978	0.938	0.779	0.210	0.002						0.000400	
							12.708	0.945	0.853	0.535	0.020	0.002						0.000160	
							5.636	0.854	0.645	0.174	0.001	0.001						0.0000570	
							4.990	0.977	0.935	0.770	0.190	0.001						0.000380	
							25.200	0.983	0.950	0.826	0.300	0.008						0.000520	
							12.600	0.940	0.838	0.500	0.013	0.006						0.000144	
							3.074	0.688	0.352	0.015	0.015	0.001						0.0000230	
							2.784	0.999	0.970	0.890	0.500	0.064						0.000900	
							4.901	0.999	0.999	0.970	0.835	0.460	0.049					0.00330	
							3.336	0.999	0.999	0.999	0.986	0.710	0.252	0.047		0.004			0.00730
							20.761	0.999	0.999	0.999	0.970	0.485	0.049	0.001					0.00330
6.660	0.999	0.999	0.999	0.986	0.518	0.252	0.047					0.00330							
9.710	0.999	0.999	0.974	0.854	0.520	0.074	0.003					0.00380							
10.836	0.999	0.986	0.943	0.693	0.230	0.003	0.003					0.00170							
5.994	0.999	0.999	0.962	0.786	0.382	0.021						0.00260							
5.549	0.985	0.960	0.849	0.353	0.017	0.001						0.000610							
2.784	0.999	0.970	0.816	0.435	0.085	0.005						0.000120							
4.50	0.985	0.961	0.854	0.372	0.019	0.019						0.000630							
7.150	0.985	0.961	0.854	0.372	0.019	0.019						0.000170							
5.720	0.949	0.866	0.555	0.025	0.005	0.005						0.000390							
2.784	0.977	0.935	0.770	0.190	0.001	0.001						0.000170							
6.188	0.928	0.816	0.468	0.068	0.008	0.008						0.000410							
0.806	0.978	0.942	0.888	0.542	0.088	0.088						0.000410							
1.275	0.967	0.975	0.866	0.410	0.028	0.028						0.000700							
2.277	0.965	0.959	0.853	0.351	0.016	0.016						0.000600							
1.196	0.999	0.975	0.904	0.532	0.080	0.080						0.000990							
1.164	0.999	0.980	0.920	0.594	0.124	0.124						0.00120							
3.748	0.999	0.987	0.951	0.732	0.286	0.286	0.006					0.00200							
1.914	0.975	0.989	0.987	0.987	0.987	0.987	0.006					0.000305							
6.00	0.999	0.980	0.960	0.320	0.054	0.054	0.007					0.00120							
3.247	0.999	0.987	0.951	0.732	0.288	0.288	0.007					0.00200							
3.260	0.999	0.984	0.936	0.660	0.190	0.190	0.007					0.00150							
2.414	0.999	0.999	0.973	0.848	0.510	0.510	0.067	0.002				0.00370							
3.168	0.999	0.999	0.979	0.875	0.587	0.587	0.115	0.008				0.00470							
3.260	0.999	0.984	0.936	0.659	0.188	0.188	0.001					0.00150							
3.253	0.999	0.987	0.951	0.731	0.288	0.288	0.007					0.00200							
9.584	0.999	0.999	0.999	0.814	0.434	0.434	0.040					0.00310							
3.307	0.999	0.999	0.969	0.817	0.443	0.443	0.040					0.00300							
3.102	0.999	0.999	0.984	0.885	0.606	0.606	0.136					0.00500							
3.068	0.999	0.999	0.985	0.911	0.688	0.688	0.224					0.00670							
1.630	0.979	0.956	0.892	0.556	0.379	0.379	0.088					0.000470							
8.460	0.999	0.984	0.936	0.659	0.188	0.188	0.001					0.00150							



TABLE 5

Derivation of Predicted Distribution for Variations in Pitch Angle for Wartime Duty in the Atlantic Ocean

Wave Height Class R	Characteristic Wave Height, R Visual		Relative Heading between Waves and Ship deg	Ship Speed Class*	Designing Factor $\geq f_1 f_2 f_3 f_4$	Number of Variations per Hour	Average Number of Variations per Hour Contributed by each Operating Condition $f_1 f_2 f_3 f_4 V - n$	Probability of Exceeding given Magnitude of Variation (1 - P) (Magnitude in degrees)											Mean Square Variation		
	Sea	Swift						0.025	0.05	0.100	0.150	0.200	0.300	0.350	0.500	0.750	1.00	2.00		3.00	4.00
0-4		2.7	0	4 (1, 2, 3, 5, 6)	0.300	360	10,800	0.048	0.518	0.074	0.614	0.420	0.142	0.70						0.00380	
		3.7	±45	2 (1)	0.02034	275	5,594	0.067	0.947	0.005										0.0460	
		2.7	±45	4 (3, 5, 6)	0.01983	360	7,139	0.048	0.518	0.074										0.00380	
		2.8	±45	4 (3, 5, 6)	0.01983	360	6,108	0.014	0.686	0.234	0.039									0.00690	
		3.7	±90	2 (1)	0.02034	420	8,543	0.067	0.929	0.746	0.309	0.072								0.0340	
		2.8	±90	4 (3, 5, 6)	0.01983	480	9,818	0.089	0.959	0.847	0.516	0.222	0.130	0.016						0.0600	
		2.7	±135	4 (3, 5, 6)	0.01983	333	6,603	0.094	0.634	0.162	0.016									0.00550	
		2.3	±135	2 (1, 3, 4, 5, 6)	0.02000	480	24,000	0.063	0.844	0.792	0.332	0.124	0.0600							0.0430	
		3.6	±180	3 (1, 2, 4, 5, 6)	0.03000	415	12,495	0.065	0.870	0.574	0.206	0.108								0.0180	
	4-6		6.0	0	2 (1)	0.00500	240	1,392	0.049	0.969	0.056	0.906	0.634	0.664	0.573	0.320	0.078	0.015			0.000370
			6.0	0	2 (1)	0.00500	420	2,436	0.099	0.985	0.330	0.859	0.775	0.570	0.464	0.210	0.030	0.002			0.220
			6.0	0	3	0.01034	360	3,102	0.099	0.985	0.330	0.859	0.775	0.570	0.464	0.210	0.030	0.002			0.160
			6.1	0	4 (5, 6)	0.00555	696	3,853	0.099	0.999	0.975	0.944	0.908	0.794	0.730	0.526	0.236	0.077			0.390
			6.0	±45	3 (1, 2)	0.01000	300	13,140	0.099	0.985	0.339	0.871	0.779	0.570	0.464	0.210	0.030	0.002			0.160
			6.1	±45	4 (5, 6)	0.01110	696	7,726	0.099	0.999	0.975	0.944	0.903	0.794	0.730	0.526	0.236	0.077			0.390
			5.5	±90	3	0.02000	228	5,156	0.099	0.985	0.347	0.885	0.806	0.696	0.506	0.250	0.044	0.004			0.100
		5.9	±90	3	0.02000	228	4,715	0.099	0.985	0.347	0.885	0.806	0.696	0.506	0.250	0.044	0.004			0.00560	
		4.3	±90	4 (5, 6)	0.0130	540	5,994	0.099	0.967	0.640	0.688	0.620	0.624	0.524	0.268	0.064	0.006			0.190	
		4.5	±135	1	0.00792	203	0,933	0.013	0.692	0.230	0.370	0.918	0.825	0.700	0.464	0.350	0.118	0.008		0.00680	
		4.4	±135	2	0.01010	374	3,777	0.099	0.970	0.910	0.825	0.700	0.464	0.350	0.118	0.008				0.117	
		4.4	±135	2	0.01010	240	2,424	0.099	0.983	0.931	0.854	0.750	0.526	0.418	0.168					0.140	
		5.0	±180	2 (1, 3, 4, 5, 6)	0.01375	240	3,438	0.064	0.865	0.356	0.826	0.694								0.0515	
		6.0	±180	2 (1, 3, 4, 5, 6)	0.01375	240	3,800	0.099	0.982	0.931	0.854	0.750	0.526	0.418	0.168	0.018				0.0170	
		6.9	0	1	0.01168	360	0,685	0.023	0.726	0.278	0.278	0.676	0.414	0.360	0.86					0.00790	
6-8			7.0	0	2	0.00726	521	1,177	0.099	0.976	0.907	0.884	0.676	0.614	0.360	0.86					0.102
		7.0	0	2	0.00726	500	1,140	0.099	0.970	0.910	0.826	0.712	0.466	0.354	0.120	0.009				0.118	
		8.0	0	2	0.00726	491	1,118	0.099	0.985	0.940	0.870	0.780	0.572	0.463	0.212	0.030	0.002			0.161	
		7.7	0	2	0.00726	515	1,164	0.099	0.984	0.936	0.860	0.766	0.555	0.442	0.188	0.024				0.190	
		6.1	0	3	0.00735	480	3,828	0.092	0.931	0.750	0.526	0.318	0.077							0.0350	
		7.5	0	4 (5, 6)	0.00319	600	1,914	0.068	0.878	0.580	0.306	0.112								0.0190	
		7.0	±45	1	0.00336	475	1,596	0.099	0.985	0.944	0.878	0.794	0.594	0.492	0.236	0.039	0.003			0.173	
		6.6	±45	2 (3)	0.00656	495	3,247	0.099	0.989	0.958	0.905	0.840	0.676	0.586	0.348	0.0	0.013			0.230	
		6.2	±45	2 (3)	0.00656	335	2,196	0.099	0.999	0.974	0.484	0.274	0.260							0.0310	
		8.0	±45	2 (3)	0.00656	280	1,837	0.099	0.999	0.980	0.957	0.925	0.839	0.786	0.612	0.332	0.160			0.510	
		7.7	±45	2 (3)	0.00656	495	3,247	0.099	0.989	0.958	0.905	0.840	0.676	0.586	0.348	0.0	0.013			0.360	
		6.1	±45	4 (5, 6)	0.00336	370	1,075	0.099	0.999	0.971	0.936	0.889	0.768	0.607	0.480	0.192	0.056			0.0400	
		6.6	±135	2	0.01000	466	7,340	0.099	0.999	0.981	0.959	0.927	0.844	0.794	0.624	0.346	0.150			0.110	
		8.0	±135	3	0.01070	288	3,058	0.099	0.999	0.975	0.944	0.872	0.794	0.730	0.526	0.236	0.077			0.390	
		6.1	±135	4 (5, 6)	0.00336	524	3,463	0.099	0.999	0.971	0.936	0.889	0.768	0.608	0.480	0.192	0.056			0.0600	
		8.0	±180	2 (1)	0.01072	336	3,001	0.099	0.985	0.866	0.725	0.564	0.276	0.174	0.028					0.0700	
	8.0	±180	3 (4, 5, 6)	0.01064	424	4,468	0.099	0.955	0.831	0.668	0.476	0.190	0.104	0.030					0.054		
8-15		12.1	0	1	0.00212	308	0,822	0.099	0.999	0.999	0.975	0.940	0.920	0.844	0.680	0.504	0.084			1.46	
		16.0	0	1	0.00212	428	0,967	0.099	0.999	0.999	0.972	0.951	0.883	0.858	0.732	0.605	0.286	0.007		0.000	
		9.0	0	1	0.00712	470	0,931	0.099	0.999	0.999	0.972	0.951	0.883	0.858	0.732	0.605	0.286	0.007		0.000	
		9.0	0	1	0.00712	470	0,931	0.099	0.999	0.999	0.972	0.951	0.883	0.858	0.732	0.605	0.286	0.007		0.000	

4-4	2.8	±.65	6,108	0.696	0.224	0.639	0.222	0.138	0.016	0.815	0.078	0.003170
	4(2, 5, 6)		2,436	0.956	0.399	0.664	0.573	0.328				0.0270
	2(1)		2,136	0.895	0.399	0.570	0.464	0.218	0.838	0.002	0.002	0.160
	2(1)		2,136	0.965	0.464	0.570	0.464	0.218	0.838	0.002	0.002	0.160
	3		3,972	0.959	0.779	0.794	0.738	0.526	0.396	0.077	0.077	0.396
	4(5, 6)		3,663	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	3(1, 2)		13,140	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	4(5, 6)		7,776	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	2(1)		5,156	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	3		4,715	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
4-8	5.9	±.38	2,408	0.895	0.600	0.808	0.820	0.624	0.768	0.054	0.005	0.00640
	6		1,932	0.959	0.587	0.949	0.825	0.710	0.464	0.358	0.118	0.117
	6		2,136	0.959	0.587	0.949	0.825	0.710	0.464	0.358	0.118	0.117
	6		2,136	0.959	0.587	0.949	0.825	0.710	0.464	0.358	0.118	0.117
	2		3,777	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	3(4, 5, 6)		2,424	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	2(1, 3, 4, 5, 6)		5,907	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	2(1, 3, 4, 5, 6)		3,418	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	2(1, 3, 4, 5, 6)		3,388	0.999	0.975	0.944	0.878	0.664	0.218	0.838	0.002	0.160
	1		0.085	0.923	0.726	0.778	0.894	0.676	0.414	0.300	0.06	0.00760
6-4	7.8	±.45	521	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	8		508	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	8		508	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	8		508	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	2		1,148	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	2		1,148	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	2		1,148	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	2		1,148	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	2		1,148	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
	2		1,148	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.06	0.00760
<15	12.1	±.180	388	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	13.0	±.180	428	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
	9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46
9.0	±.180	438	0.999	0.999	0.999	0.999	0.975	0.940	0.844	0.680	1.46	

\*The numbers in parentheses in column 4 represent ship speeds for which no data are available and for which the experimental data corresponding to the indicated speed class is assumed to apply for the purposes of the table.

\*\*The factors  $f_1, f_2, f_3$  are defined on pages 11 and 17. The factor  $f_4$  is a weighting factor used when several similar sets of test data are utilized. For example, if 4 sets of similar test data were available and were utilized in the table, then  $f_4 = 0.25$ .

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TABLE 6

Derivation of Predicted Distribution for Variations in Roll Angle for Wartime Duty in the Atlantic Ocean

Wave Height Class	Characteristic Wave Height, ft		Relative Heading between Waves and Ship deg	Ship Speed Class*	Weighting Factor $\sum_{i=1}^6 f_i$	Number of Variations per Hour $N$	Average Number of Variations per Hour Contributed by Each Operating Condition $f_1, f_2, f_3, f_4, N = n$	Probability of Exceeding Given Magnitude of Variation (1 - P) (Magnitude in degrees)										Yearly Exceedance Variation										
	Sea	Swell						2.00	3.00	4.00	6.00	8.00	10.0	15.0														
0-4		2.7	0	4 (1, 2, 3, 5, 6)	0.0300	227	6.810	0.480	0.192	0.057											0.240							
								0.835	0.673	0.410	0.204	0.072													0.630			
								0.935	0.867	0.673	0.480	0.192	0.057														0.340	
								0.908	0.806	0.594	0.254	0.048																0.410
								0.919	0.826	0.588	0.302	0.118																0.470
								0.920	0.829	0.594	0.310	0.124																0.490
								0.900	0.811	0.773	0.580	0.356																1.000
								0.961	0.914	0.790	0.570	0.380	0.101															0.970
								0.923	0.835	0.688	0.324	0.136	0.011															0.500
								0.949	0.890	0.722	0.482	0.272	0.058															0.170
4-6		6.8	0	2 (1)	0.0658	240	1.392	0.626	0.374	0.090											0.0655							
								0.886	0.716	0.468	0.182	0.050													0.230			
								0.979	0.954	0.877	0.744	0.590	0.200														1.900	
								0.972	0.937	0.836	0.666	0.488	0.200	0.057														1.330
								0.979	0.954	0.877	0.744	0.590	0.200	0.057														1.900
								0.972	0.937	0.836	0.666	0.488	0.200	0.057														1.330
								0.961	0.914	0.786	0.570	0.355	0.106	0.018														1.000
								0.963	0.962	0.898	0.784	0.650	0.380	0.168	0.021													2.320
								0.970	0.950	0.867	0.726	0.566	0.276	0.181	0.095													1.750
								0.957	0.904	0.758	0.536	0.330	0.084	0.012														0.900
4.8		6.8	2.135	2	0.0101	250	2.525	0.972	0.638	0.207	0.040	0.008									1.400							
								0.999	0.999	0.975	0.946	0.905	0.840	0.764	0.544	0.340	0.088	0.013	0.002							10.100		
								0.989	0.976	0.935	0.860	0.764	0.694	0.694	0.440	0.232	0.038	0.005									3.710	
								0.965	0.963	0.913	0.814	0.814	0.694	0.440	0.232	0.038	0.005											2.740
								0.966	0.969	0.918	0.824	0.708	0.608	0.460	0.250	0.045	0.004											2.900
								0.999	0.999	0.975	0.946	0.905	0.840	0.764	0.544	0.340	0.088	0.013	0.002									10.100
								0.967	0.975	0.934	0.828	0.726	0.628	0.528	0.328	0.128	0.011	0.010										0.280
								0.834	0.664	0.322	0.078	0.011																0.220
								0.922	0.834	0.660	0.318	0.130	0.010															0.490
								0.854	0.698	0.370	0.106	0.018																0.290
6-8		7.7	2.135	2	0.00226	341	0.771	0.894	0.774	0.490	0.200	0.058									0.350							
								0.955	0.909	0.766	0.550	0.344	0.091													0.140		
								0.885	0.758	0.464	0.164	0.047															0.325	
								0.917	0.824	0.580	0.294	0.114																0.460
								0.894	0.774	0.490	0.200	0.064																0.350
								0.905	0.800	0.535	0.244	0.084																0.760
								0.949	0.889	0.770	0.478	0.268	0.054															0.400
								0.945	0.881	0.794	0.454	0.244	0.044															0.710
								0.905	0.800	0.535	0.244	0.084																0.100
								0.958	0.832	0.766	0.550	0.346	0.091	0.014														
7.7		6.1	2 (1)	0.06336	396	1.337	0.854	0.654	0.262	0.078	0.011											0.210						
							0.948	0.887	0.716	0.472	0.262	0.050														0.750		
							0.948	0.887	0.716	0.472	0.262	0.050															3.600	
							0.981	0.959	0.888	0.785	0.626	0.358	0.151	0.015													2.130	
							0.981	0.959	0.888	0.785	0.626	0.358	0.151	0.015													2.900	
							0.986	0.970	0.918	0.828	0.708	0.604	0.395	0.200	0.060	0.008	0.000										3.370	
							0.986	0.970	0.918	0.828	0.708	0.604	0.395	0.200	0.060	0.008	0.000										15.300	
							0.999	0.999	0.984	0.964	0.936	0.884	0.808	0.758	0.555	0.350	0.151	0.015									0.740	
							0.948	0.886	0.712	0.468	0.258	0.048	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	11.200	
							0.999	0.999	0.948	0.951	0.914	0.818	0.698	0.446	0.233	0.040	0.015										3.600	
8-15		12.1	0	1	0.00212	321	0.681	0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007					1.830							
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007										0.510		
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340
								0.978	0.952	0.872	0.736	0.578	0.412	0.252	0.112	0.007												0.340



The fractions of time  $f_3$  that the ship will make a given heading\* to the sea for all operating speeds and for all characteristic wave heights not exceeding 8 ft are:

Head Seas	Quarter Head Seas	Beam Seas	Quarter Following Seas	Following Seas
0.125	0.25	0.25	0.25	0.125

For characteristic heights greater than 8 ft, the values in the table are modified such that  $f_3$  is taken 0.125 for beam seas and 0.25 for head seas.

The weighting factors  $f_1$  and  $f_3$  are based on estimates made by the commanding officers of a number of ships of the ESSEX Class, as reported in Table 2 of Reference 6. The factors  $f_2$  have been taken from the frequency distribution of wave heights shown in Figure 18 of Reference 7 and are applicable to Ocean Station C in the North Atlantic Ocean. The products of the weighting factors used in the calculations are given in Table 2.

The distribution patterns are calculated in Tables 3 through 6, where the probabilities  $(1 - P)$  of exceeding given values of the variable are tabulated. The last line in each table is obtained by summing up all environmental conditions and thus gives the derived values of  $(1 - P)$  for the long-term distributions. The latter values are plotted on the cumulative probability charts in Figures 3 through 6.

The straight lines shown on these charts have been computed directly from the percentages represented by the plotted points, on the assumption that the long-term distribution is of the log-normal type. The rather good fit of the computed line to the plotted points indicates that this assumption is reasonable.

The wave-induced hull girder stresses have been converted to bending moment amidships by making use of the midship section modulus which is applicable to the gage location. On VALLEY FORGE the strain gage was located 54.8 ft above the baseline and 28.76 ft above the calculated location of the neutral axis. The section modulus applicable to this strain-gage location is 167,000 ft-in.<sup>2</sup>

## DESIGN AND OPERATIONAL CONDITIONS FOR WARTIME SERVICE

It has been pointed out that the distribution patterns give the probability of exceeding any given magnitude of motion or stress and that the distribution pattern can also be used as a load spectrum for calculations of endurance strength. In this section, design and operational

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\*In this report the heading  $\phi$  of the ship relative to the wave direction is defined as follows: For head seas,  $\phi = 0$  deg; for quarter head seas,  $\phi = \pm 45$  deg; for beam seas,  $\phi = \pm 90$  deg; for quarter following seas,  $\phi = \pm 135$  deg; for following seas,  $\phi = 180$  deg.



conditions for wartime service will be determined on the basis of the following assumptions:

1. The vessel will generally be operating in the North Atlantic Ocean. The observations of sea conditions at Weather Station C (52 deg N 37 deg W), see Figure 13 of Reference 7, are considered typical of conditions in the North Atlantic and are assumed to represent the conditions the ships will encounter in service.
2. Operating speed patterns, corresponding to various sea conditions, are assumed to follow those reported in the last section.
3. All headings of the ship relative to the predominant wave direction are assumed equally probable, except that seas coming approximately off the beam are considered unlikely for combinations of high speeds and rough seas, as previously indicated.

### LONG-TERM DISTRIBUTIONS

Figures 3 through 6 give the probability of exceeding and of not exceeding given values, if all the motions and stresses are considered to which the ship is subjected over a period of years. For example, only 3 percent of all variations in roll angle would, on the average, exceed a value of 4.5 deg port to starboard; see Figure 6. These distributions may be considered valid up to variations corresponding to a value of  $(1 - P)$  equal to 1 percent.

### PREDICTION OF EXTREME VALUES

In order to estimate the largest values of motions and bending moments for design purposes, the extreme value formula discussed on page 10 may be used:

$$x_{m_1}^2 = E_m (y + \log_e N)$$

It will be assumed that the worst combination of operating conditions is that which gives the largest value of  $E$ ,  $E_m$ . The value of  $N$  may be estimated as follows: Assume that the ship will be subject to the worst operating conditions for a period, here taken as 4 hours, and will experience  $V$  variations during that time, and that this situation will be repeated  $n$  times during the service life of the ship. Therefore  $N = nV$ .

As an example of the prediction of an extreme, consider the maximum variation of longitudinal bending moment, excluding the effects of slamming. From Table 7

$$E_m = 0.156 \times 10^{12} \text{ (ft-ton)}^2, V = 1440$$

If we take  $f = 0.001$ , then Reference 10 gives  $y = 7.0$ . Therefore, with  $n = 20$ ,

$$\begin{aligned} x_{m_1} &= [0.156 \times 10^{12} (7.0 + 10.27)]^{1/2} \\ &= 1,640,000 \text{ ft-tons hog to sag} \end{aligned}$$

TABLE 7

Maximum Values of Ship Motions and Longitudinal Bending Moments for ESSEX-Class Carriers

All values given refer to peak-to-peak variation.

Quantity	Ship	Location of Test Area	Conditions for Which Extreme Value is Predicted (2)			Mean Square Value of the Variation, $E_m$ - also Equals Four Times the Area under Power Spectrum	Number of Variations Expected per 4-hr Period	Number of Variations Expected during Operating Life of Ship Corresponding to $E_m$	Estimated Most Probable Maximum Value in One Storm (4-hr Operation)	Maximum Expected Value* during Operating Life of Ship ( $\sigma = 0.001$ )	Largest Variation Measured (3)	Maximum Variation for Design Purpose
			Wave Height ft (1)	Direction of Seas Relative to Ship's Course	Ship Speed (from R.P.M.s) knots							
Roll Angle	ORISKANY	Cape Horn	> 15	Quarter Head	10	61.0 deg <sup>2</sup>	980	19,500	32 deg	19 deg	32 deg	
Pitch Angle	ESSEX	Cape Horn	24	Quarter Head	8	12.8 deg <sup>2</sup>	1180	23,700	14.9 deg	9.5 deg	15 deg	
Heave Acceleration	ORISKANY	Cape Horn	20	Head	10	0.014 g <sup>2</sup>	1350	27,000	0.49 gravity units	0.3 g (USS VALLEY FORGE)	0.5 gravity units	
Longitudinal (4) Bending Stress	VALLEY FORGE	North Atlantic	> 18	Head	10	28.2 (kpsi) <sup>2</sup>	1440	28,800	22.3 kpsi	12.2 kpsi	22 kpsi	
Longitudinal (4) Bending Moment	VALLEY FORGE	North Atlantic	> 18	Head	10	$0.156 \times 10^{12} \text{ ton}^2 \text{ ft}^2$	1440	28,800	1,640,000 ft-tons	910,000 ft-tons	1,600,000 ft-tons	
Longitudinal (5) Bending Moment Due to Whipping (5)	ESSEX	Cape Horn	20	Quarter Head	17	-	52 cycles per minute when whipping occurs	-	-	1,230,000 ft-tons	1,850,000 ft-tons	

(1) This is the average height of the larger, well-defined waves, as determined by visual observations.

(2) These are the conditions under which the largest values recorded at any time were obtained (peak-to-peak variation).

(3) These are the largest values recorded throughout seaworthiness tests on carriers, and cover about 2 years operation at sea.

(4) Stress, c.i. main deck, amidships. This is the ordinary wave-induced stress free of whipping stresses. The applicable section modulus = 167,000 ft-in<sup>2</sup>.

(5) This bending moment is superimposed on the ordinary bending moment. The bending moments were computed from the stress by use of the design midship section moment of inertia, as calculated by Bureau of Ships.

\*These values are estimated on the assumption that all variations are independent. This assumption is not strictly valid and results in a slight overestimate of the extreme value.

Maximum values for the other variables considered herein have been estimated similarly by taking  $f = 0.001$  and  $n = 20$ . They are listed in Table 7 together with the largest values measured at any time during the rough sea trails of ESSEX, VALLEY FORGE, and ORISKANY.

Predictions of extreme values should be used with caution because the method may break down by predicting too extreme a value. The extreme values listed in the last column of Table 7 are regarded as reasonable.

## DESIGN MIDSHIP BENDING MOMENT

The midship bending moment just calculated must be augmented by the vibratory bending moment incident to slamming and by the still-water bending moment. It is, furthermore, desirable to estimate the parts of the total variation due to hogging and sagging. The still-water bending moment will vary with the ship's loading and can readily be computed by routine methods. Therefore, only the contributions of the vibratory and the ordinary wave-induced moments will be considered.

The most severe hull stresses experienced\* by ESSEX occurred when the ship encountered a wave 26 ft high and 1028 ft in apparent length (821 ft real length) at a ship speed of 16 knots. The oscillogram, Figure 5a of Reference 4, indicates that the ordinary stress variation at the frequency of wave encounter was made up of approximately 60-percent sag and 40-percent hog relative to the still-water stress. A large, higher-frequency stress variation, corresponding to the two-noded mode of vertical whipping vibration, was superimposed on the ordinary wave stress.

The midship bending moment variations\*\* corresponding to the most severe stresses measured during the passage of a single wave 26 ft high were: 515,000 ft-tons (60-percent sag, 40-percent hog) for the ordinary wave-induced stress, and 1,230,000 ft-tons for the whipping stresses. The stress may be expected to increase roughly as the wave height.<sup>4</sup> If, for design purposes, a wave 39 ft high is assumed† rather than the 26-ft wave actually experienced, the bending moment (corresponding to the ordinary wave-induced and to the whipping stresses) would be expected to be increased by 50 percent; i.e., the moments become 773,000 ft-tons and 1,850,000 ft-tons, respectively.

The midship design bending moment may then be calculated as follows, on the assumption that a 39-ft wave will be encountered.

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\*Measured at the centerline of the hangar deck (Gage 3). The maximum stress value including ordinary wave-induced and vibratory whipping stresses was 13,500-psi sag and 10,000-psi hog.

\*\*Midship section modulus applicable to the location of Gage 3, 54.69 ft above the baseline, is 158,000 in.<sup>2</sup> ft.

†Figure 2, Reference 11, indicates that, for waves of apparent length nearly equal to the ship's length, a height of 26 ft will certainly be encountered and a height of 43 ft will be experienced rarely or never. The assumed value of 39 ft is considered a conservative, realistic compromise.

### **Method 1 (Without Use of Statistical Methods)**

$$\begin{aligned}\text{Hogging Moment} &= 0.40 (773,000) + 0.50 (1,850,000) + \text{still-water moment} \\ &= 1.23 \times 10^6 \text{ ft-tons} + \text{still-water moment}\end{aligned}$$

$$\begin{aligned}\text{Sagging Moment} &= 0.60 (773,000) + 0.50 (1,850,000) + \text{still-water moment} \\ &= 1.39 \times 10^6 \text{ ft-tons} + \text{still-water moment}\end{aligned}$$

### **Method 2 (Statistical Prediction of Ordinary Wave-Induced Bending Moment)**

Expected design extreme value of ordinary wave-induced bending moment variation is 1,600,000 ft-tons (from Table 7). The maximum variation in bending moment incident to whipping (for the 39-ft wave) is 1,850,000 ft-tons.

$$\begin{aligned}\text{Hogging Moment} &= 0.40 (1,600,000) + 0.50 (1,850,000) + \text{still-water moment} \\ &= 1.57 \times 10^6 \text{ ft-tons} + \text{still-water moment}\end{aligned}$$

$$\begin{aligned}\text{Sagging Moment} &= 0.60 (1,600,000) + 0.50 (1,850,000) + \text{still-water moment} \\ &= 1.89 \times 10^6 \text{ ft-tons} + \text{still-water moment}\end{aligned}$$

### **Method 3 (Alternative Statistical Prediction, See Appendix D)**

It should be noted that the bending moment calculations are based on the midship section modulus which is computed on the assumption that the ship structure above the hangar deck does not contribute to the section modulus. It is suggested that the bending moments computed by Method 3 be used for hull structural design. It should not be necessary to apply a safety factor to these design values. For ships geometrically similar to ESSEX, the design bending moment may be assumed to vary roughly as the fourth power of the length.

## **DISCUSSION**

The reader will readily appreciate that many operating difficulties make it impossible to obtain as complete and accurate data as desired. For example, the sea state is the most difficult variable to assess. Ship operations allowed test runs for only a few combinations of ship speed and heading for a continuous period of time when sea conditions were fairly constant. Consequently, it was necessary to take data for the missing combinations when approximately the same sea state was again encountered. These difficulties can be overcome by model testing rather than full-scale testing. Moreover, model testing can be accomplished more economically and for a wider variety of operating conditions. Furthermore, the general method of synthesis used in this report is equally applicable to model test data.

The statistical methods described in this report are sufficiently general that, together with the basic data in Table 1, they can be applied to predict motions and bending moments of ESSEX-Class carriers or geometrically similar ships for a wide variety of different missions or types of operations. For example, a high-speed, nuclear-powered carrier similar in form to ESSEX might be treated. For this ship, the weighting factors should be adjusted to allow much more time of operation at higher speeds than ESSEX.

#### ACKNOWLEDGMENTS

The cooperation received from the commanding officers and personnel of VALLEY FORGE and ESSEX was of the highest order and made it possible to obtain realistic operational data that have long been needed. Assistance in analysis of the great volume of data was given by Mr. R.J. Dominic. Installation of trial gear was greatly expedited by the expert assistance of engineers and technicians of the Instrumentation Division.

## APPENDIX A

### SAMPLE OSCILLOGRAMS

Samples of typical oscillograms, obtained by the TMB automatic statistical recorder on VALLEY FORGE, are given in Figures 7 through 10. Each oscillogram is identified by the record number which corresponds to that given in Table 1; Table 1 also gives the pertinent environmental and operating conditions. On these oscillograms Channel 1 measured heave acceleration at the ship's center of gravity, Channel 2 (Gage 5) measured longitudinal strain in the keel, Channel 3 (Gage 3) measured longitudinal strain in the hangar deck, and Channels 4 and 5 measured pitch and roll angle, respectively. Strain-gage locations are shown in Figure 1.

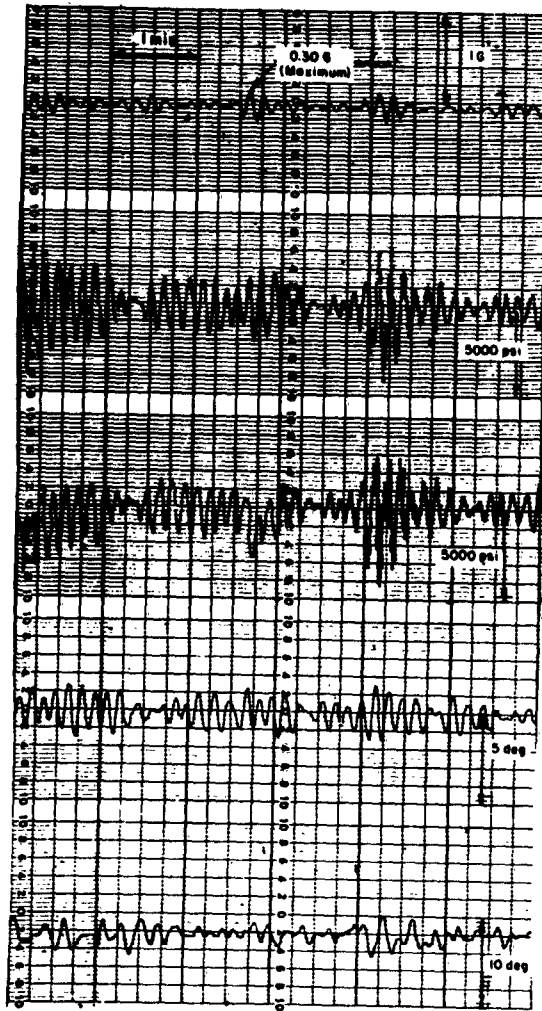


Figure 7 - Oscillogram Showing Maximum Heave Acceleration Record Number 69 on VALLEY FORGE

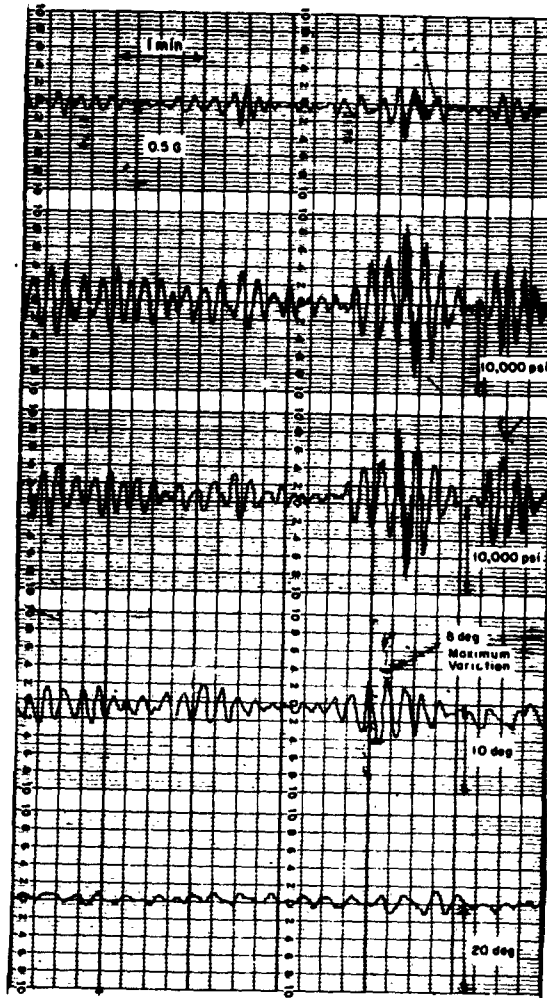


Figure 8 - Oscillogram Showing Maximum Pitch Angle Record Number 71 on VALLEY FORGE

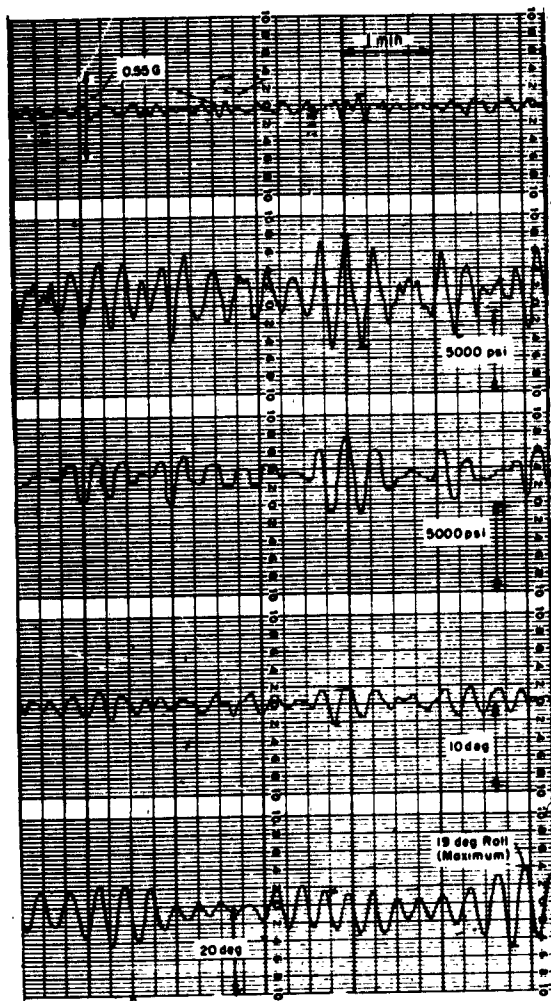


Figure 9 - Oscillogram Showing Maximum Roll Angle Record Number 75 on VALLEY FORGE

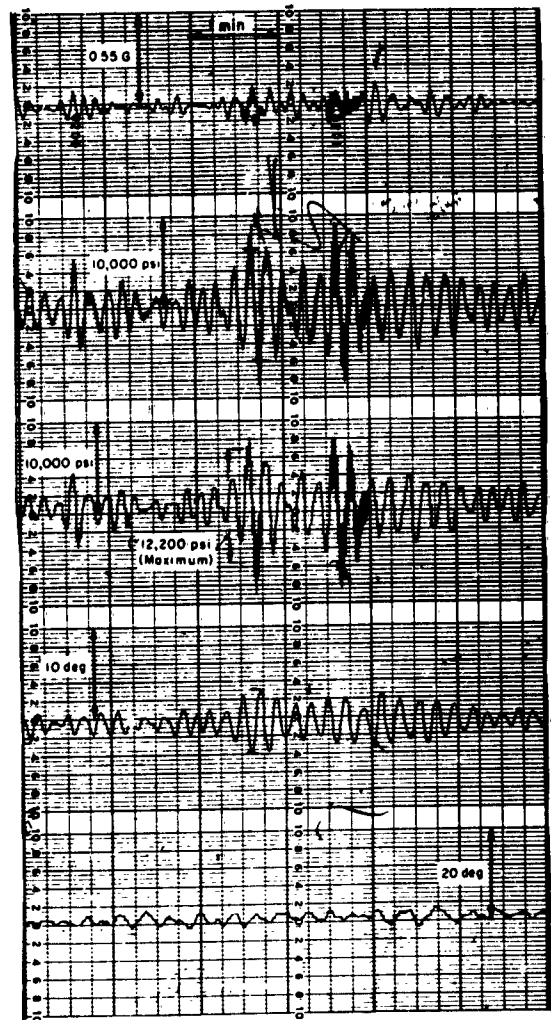


Figure 10 - Oscillogram Showing Maximum Longitudinal Stress Amidships Record Number 72 on VALLEY FORGE



## APPENDIX B

### COMPARISON OF LONGITUDINAL AND TRANSVERSE BENDING STRESSES

Longitudinal and transverse hull bending stresses (hangar deck amidships) are compared in Table 8. Stress variations obtained during the passage of a single wave are given for those occasions on which transverse bending made an appreciable contribution to the stresses. Figure 11 shows a sample record in which the strains on the port and starboard sides differ appreciably due to transverse bending.

It is apparent that for some operational conditions transverse bending moments\* are appreciable; viz., for beam seas. However, the most severe bending stresses are experienced in head seas when transverse bending is relatively small.

TABLE 8

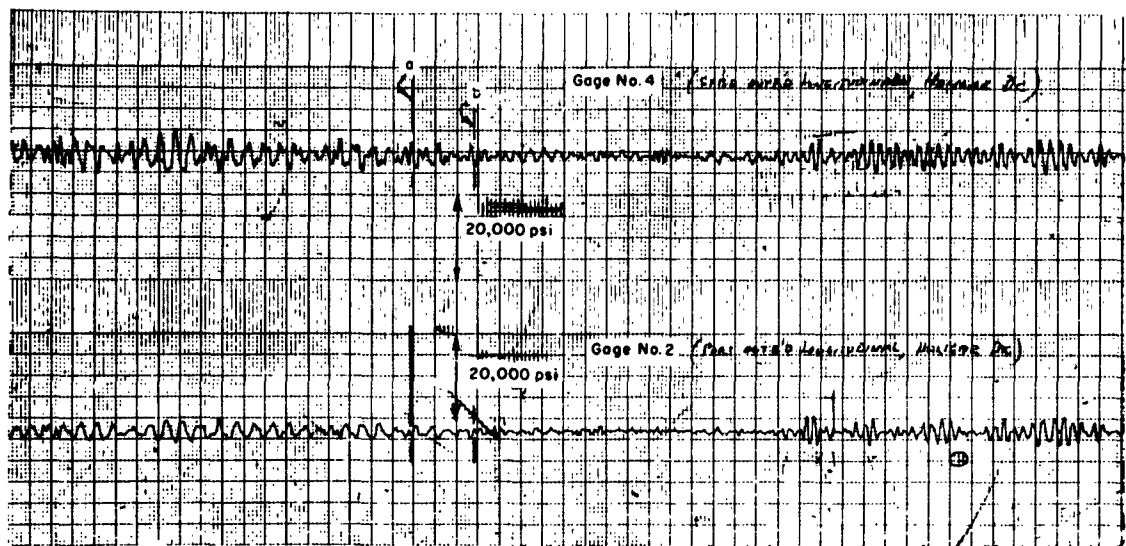
Comparison of Longitudinal and Transverse Bending Stresses for  
Occasions at which Transverse Bending Was Appreciable

Measurements were obtained on USS VALLEY FORGE.

Date	Ship Speed knots	Characteristic Wave Height ft	Relative Heading Ship to Waves	Stress, ksi				Transverse Stress Longitudinal Stress
				Gage 2	Gage 4	Longitudinal Bending	Transverse Bending	
9 Dec 55	10	10	Quarter Head	5	7.5	6.3	1.3	0.21
10 Dec 55	8	14	Quarter Head	6.7	3.1	4.9	1.8	0.37
9 Dec 55	10	-	-	4.0	6.7	5.4	1.4	0.26
9 Dec 55	10	-	-	2.5	5.7	4.1	1.6	0.39
9 Dec 55	10	-	-	3.0	8.3	5.7	2.7	0.47
1 Oct 55	10	9	Beam	1.4	2.7	2.1	0.65	0.31
1 Oct 55	10	9	Beam	1.0	4.0	2.5	1.5	0.60*
1 Oct 55	10	9	Beam	4.2	9.0	6.6	2.4	0.36
1 Oct 55	10	9	Beam	5.0	10.0	7.5	2.5	0.33
1 Oct 55	10	9	Beam	1.1	5.5	3.3	2.2	0.67**

\*See instant marked a in Figure 11.  
\*\*See instant marked b in Figure 11.

\*It should be noted that, at the midship section, the effective area moment of inertia for transverse bending is much larger than the moment of inertia for longitudinal bending.



**Figure 11 – USS VALLEY FORGE Sample Oscillogram**

Date of test, 1 Oct 1955; zone time, 13:40–14:00; ship speed, 10 knots; beam sea; characteristic wave height, 9 ft.

Original chart scale: Smallest division equals 1 mm, chart speed is 0.25 mm/second.

## APPENDIX C

### COMPARISON OF STRAINS ON STRINGER PLATE AND ON LONGITUDINAL

On VALLEY FORGE a strain-gage bridge (Gage 1) was installed on the hangar deck  $7\frac{1}{2}$  in. inboard of the shell, and a single gage (Gage 2) was installed on the longitudinal stiffener closest to Gage 1. Both gages were oriented to measure strains in the longitudinal direction. Gage 1 consisted of a series of gages connected so as to give a signal proportional to longitudinal stress.

The purpose of Gages 1 and 2 was to determine whether a strain gage mounted directly on the deck plate, close to the shell, will be free of *local* plate bending stresses. Gage 2, on the longitudinal, was free of these local stresses and was subject to longitudinal strains only.

Gage signals are compared in Figure 12 for various magnitudes of strain variations. The two stresses are proportional, but Channel 1 indicates a magnitude about 10 percent greater than Channel 2. This difference may be due in part to the contribution of transverse bending.

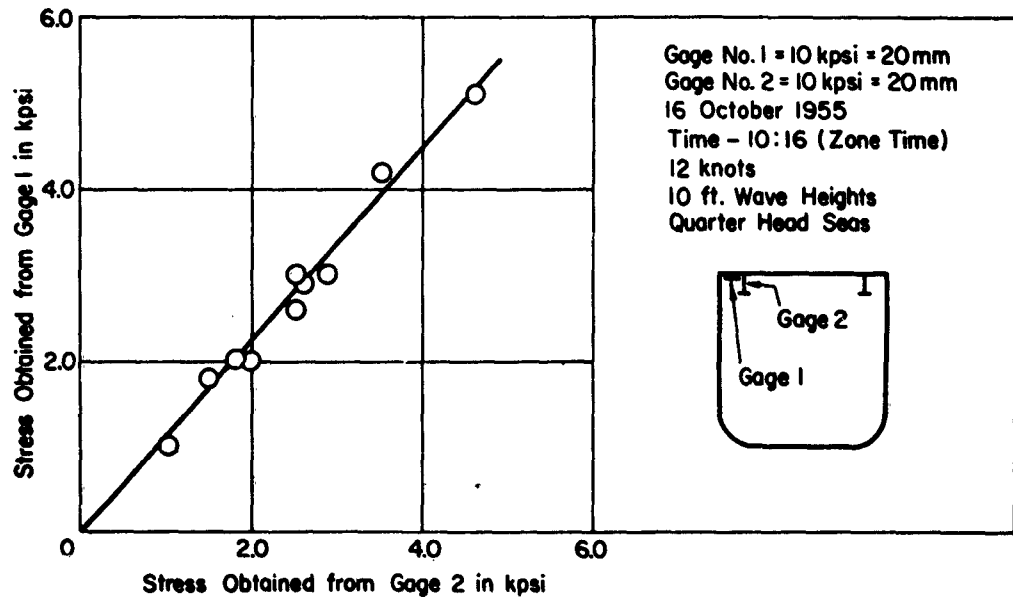


Figure 12 - Comparison of Longitudinal Stress Measured on Stringer Plate and on Longitudinal

(USS VALLEY FORGE)

## APPENDIX D\*

### ESTIMATION OF EXPECTED EXTREME BENDING MOMENT ON THE BASIS OF THE LONG TERM DISTRIBUTION OF THE CHARACTERISTIC PARAMETER $E^{1/2}$

In this report the expected extreme bending moment has been based on the assumption that the most severe operating condition (and the resultant ship response defined by the parameter  $E_s$ ) actually experienced during the periods of sea trials is the worst to be expected during the ship's life.

Another more general approach would be to estimate the expected extreme value of  $E^{1/2}$  (rms bending moment or stress) on the basis of a known distribution of this parameter. Thus far the distribution of  $E^{1/2}$  for hull girder bending moment had not been studied. Extensive studies of the corresponding parameter for ocean waves  $E_w^{1/2}$  (actually of significant wave height) were made in References 7 and 5 and this parameter was found to have a log-normal distribution. It would not be unreasonable to expect the rms value of ship response to wave action to follow the same type of distribution. Accordingly, an attempt was made to fit the log-normal distribution to the values of  $E^{1/2}$  for hull bending moment (stress). The  $E$  values were taken from Table 3 and the corresponding probabilities from column 6 of Table 3. The resulting distribution, shown in Figure 13, approximates to a log-normal distribution. A similar study was made for a destroyer; the results are also shown in Figure 13.

Let us devise a method for prediction of expected extreme bending moment on the basis of:

- a. A known long term distribution of bending moment, Figure 13.
- b. A known long term distribution of sea conditions (in terms of characteristic wave heights and wave lengths or power spectra of the waves).

For each ship we postulate\*\* an "Extreme Sea State" comprising all seas for which:

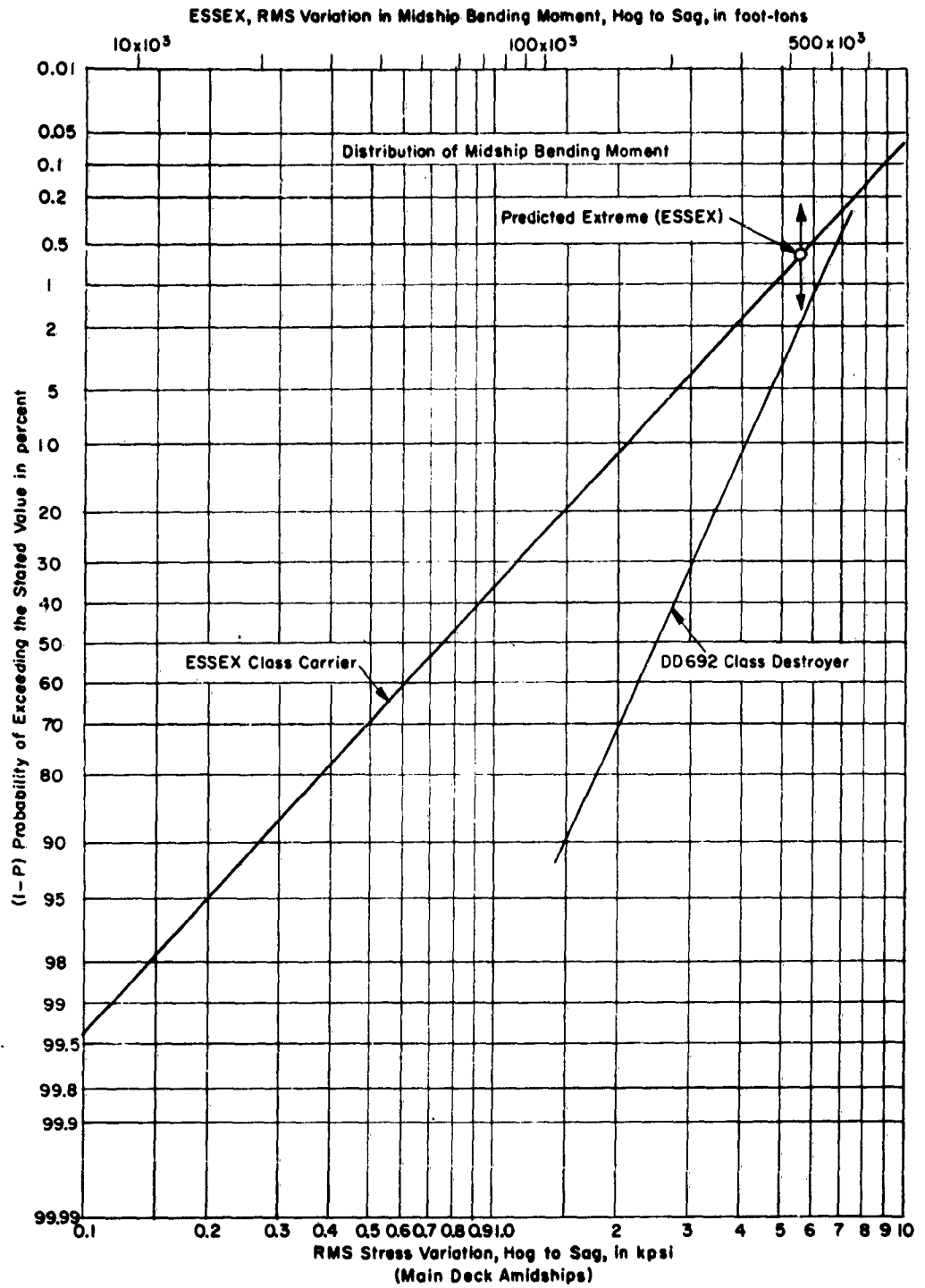
- a. The characteristic wave length †  $L_w$  is less than  $\sqrt{2} L_s$  and larger than  $\frac{1}{\sqrt{2}} L_s$ , where  $L_s$  is the LBP of the ship.
- b. The characteristic wave height  $H_w$  is equal to or greater than the most probable wave height for a wave of length equal to the length of the ship. This height may be read from Curve C, Figure 2, TMB Report C-555. For ships of length larger than 800 ft a characteristic wave height of 28 ft is correct with  $\pm 3$  ft.

The percent of time (1-P), that the ship will be exposed to the "Extreme Sea State" can be read from the statistical joint distribution of wave height and length such as prepared by Dr. Roll<sup>12</sup> corresponding to the particular values of  $L_w, H_w$ .

\*The method given here was proposed by Dr. N.H. Jasper.

\*\*A more refined definition of "Extreme Sea State" will eventually be developed in terms of power spectra of waves and ship response to waves.

†The wave length may be calculated from the wave period  $T_w$  usually reported by shipboard observers by the relationship  $L_w = 3.4 T_w^2$  ( $T$  is given in seconds and  $L_w$  in feet).



**Figure 18 – Long Term Cumulative Distribution of Longitudinal RMS Stress  
and RMS Bending Moment Amidship, for Wartime Service  
North Atlantic Ocean**

## REFERENCES

1. Bureau of Ships letter S 29-7 (442-440-330) of 21 Jun 1948 to David Taylor Model Basin.
2. Jasper, N.H., "A Statistical Approach to the Longitudinal Strength Design of Ships," *Journal American Society of Naval Engineers*, Vol. 62, No. 3 (Aug 1950).
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The RMS value  $E^{1/2}$  corresponding to (1-P) determined as described above may then be read from the long term distribution of  $E^{1/2}$ , such as shown in Figure 13. The most probable extreme value of stress (or bending moment) corresponding to an exposure of (1-P) to the "Extreme Sea State" may then be calculated in the usual manner and is illustrated in the following example.

**EXAMPLE: ESSEX CLASS CARRIER**

1. LBP 320 ft

Extreme Sea State: 580 ft <  $L_w$  < 1150 ft  
 13.2 sec <  $T_w$  < 18.4 sec  
 $H_w$  > 23 ft

Midship Section Modulus (Main Deck) =  $Z = 167,000 \text{ ft-in}^2$

2. Percent Exposure to "EXTREME SEA CONDITION," (1-P) = 0.6 percent  
 This value is obtained from Reference 12 corresponding to the "EXTREME SEA STATE."

3. RMS Bending Moment corresponding to (1-P) = 0.6 percent is  $E_m^{1/2} = (5.6 \text{ KPSI})Z = 415,000 \text{ ft-tons}$ , HOG TO SAG (from Figure 13).

4. Number of stress variations experienced during the exposure to the "EXTREME SEA STATE" =  $N$ . Assume a life of 20 years, 100 days at sea each year.

$$N = \frac{20 \times 100 \times 24 \times 3600 \times (1-P)}{T_{stress}}, \text{ where}$$

$$T_{stress} = T_{wave} = \frac{1}{2} (13.2 + 18.4) \text{ secs}$$

$$N = 86,000 \text{ variations}$$

5. The expected Extreme Bending Moment =  $E_m^{1/2} (y + \log_e N)^{1/2} = M_m$   
 Taking a 10 percent risk\* ( $f = 0.1$ ) that  $M_m$  may be exceeded  $y = 2.3$   
 $M_m = 415,000 (2.3 + 11.1)^{1/2} = 1.52 \times 10^6 \text{ ft-tons}$

The Design Bending Moment = Wave BM + Whipping BM + Still Water BM  
 HOGGING MOMENT =  $0.40 (1.52 \times 10^6) + 0.50 (1.85 \times 10^6)$   
 + Still Water BM =  $1.53 \times 10^6 \text{ ft-tons} + \text{Still Water Moment}$   
 SAGGING MOMENT =  $0.60 (1.53 \times 10^6) + 0.50 (1.85 \times 10^6)$   
 + Still Water BM =  $1.84 \times 10^6 \text{ ft-tons} + \text{Still Water Moment}$

\*For the method used here a higher risk may be taken than in the estimate made in Table 7, because we are now dealing with an extrapolated extreme operating condition.

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