No. 251
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For Presentation to
The Society of Naval Architects
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G.L. & G.R. Section
October 7, 1982

THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

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Department of Naval Architecture
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College of Engineering
The University of Michigan
Ann Arbor, Michigan 48109

ABSTRACT

Calculation of hull deflections in way of machinery spaces of two Great Lakes bulk carriers is presented. Methods of modeling and analysis by the finite element method is discussed, and some results are shown. Calculated results are compared to measured results. Calculation of shaft bearing influence coefficients with hull flexibility included is discussed. An application in which a proposed alteration to an existing ship was analyzed is covered.

ACKNOWLEDGEMENTS

The work discussed here was done under the University Research Program of the Maritime Administration, U S Department of Transportation, contract MA79SAC0099. A grant from the Bethlehem Steel Corporation was applied in part to this work.

Essential information was contributed by shipbuilders, designers, ship operators, and manufacturers of machinery. Bay Shipbuilding, R A Stearn, and the Falk Corporation were especially noteworthy in this group.

We appreciate the help of all of these contributors.

INTRODUCTION

A wise engineer (he was educated in naval architecture and marine engineering at the Massachusetts Institute of Technology) once proclaimed that the deflection of a ship's hull was of no consequence to its propulsion machinery, this because machinery that stretched over any great span (e.g. the propulsion shaft) was always much more flexible than the hull. But he said that in 1950, and the wise persons of today will chorus "no more, no more," this because hulls have become larger (therefore more flexible), while machinery has become more powerful (therefore less flexible) and often drives through shorter (again less flexible) shafting.

Propulsion transmission components, especially pinions of reduction gear sets, fail more often than we think they should in spite of well-made gears and carefully aligned shafting. The deflections imposed by flexible hulls on stiff machinery, upsetting to the shafting alignment and hence to bearing load distributions, may be the underlying cause. (For parallel reading, see, for example, [1],[2].) The cure may lie in restoring the flexibility of the machinery, and/or restoring the stiffness of hulls. Whatever the cure, the first step in illuminating the problem, and in showing the way to possible stiffness enhancing measures for the hull, lies in analysis of hull deflections under the several loads (e.g. propeller thrust and torque, hydrostatic pressure) that bear upon it.

A promising method of analyzing deflections of ship hulls is the finite element method, a method in which structures of complicated shape are replaced by an equivalent structure of small elements -- beams, plates, membranes, trusses, and several others -- that collectively behave as does the actual structure. The art of the analyst lies in the judicious selection of elements to represent actuality. The labor of the analyst lies in establishing the coordinates of the nodes that connect elements, of establishing data necessary to each element, and then in typing the resulting mountain of information into a computer input file. (A professor at Michigan, pressed into the minimum-wage drudgery of the typing, complained that he did enough work to have built the ship being modeled.) The labor of the computer -- a labor well beyond human capability for a multi-element problem -- lies mainly in solving the resulting array of equations.

For ship hull analysis at the University of Michigan we use a local version (called MSAP) of the SAP IV program [3], accompanied by a preprocessor (data input) program

[4], and a graphics display program [5]. We have used these tools to analyze the in-service deflections of two recent (built in late 1970s) Great Lakes bulk carriers (identified as Ship A and Ship B in this paper). When compared to deflection measurement on the prototype ships, the finite element modeling is seen to have produced results reasonably close to reality. The results can therefor be used to predict the hull-imposed movements of machinery bearings.

Once the computer models are made (i.e. the data has been organized by the preporocessor program) it can be preserved for analysis of similar ships during their design stage, or for analysis of proposed structural alterations in the prototypes. One instance of the latter use is outlined here.

Most of the material in this paper, plus some additional details, is also included in a report to the Maritime Administration [6].

THE SHIPS

Two ships delivered by Bay Shipbuilding (Sturgeon Bay, Wisconsin) in the late 1970s are the subjects of the analysis described here. Both are self-unloading bulk carriers of geared diesel propulsion. They have names, of course, but we identify them as Ship A and Ship B. Table 1 lists a few characteristics of each, and Figures 1 and 2 picture them.

TABLE 1 Characteristics of the Two Ships

	Ship A	Ship B
LOA, feet	728.0	1000.0
Beam (molded), feet	78.0	105.0
Depth at side (molded), feet	45.0	56.0
Gross tonnage	14960	35650
Midsummer keel draft, feet	30.91	34.06
Approximate deadweight, long tons	38000	81000
Propulsion type	geared diesel single screw	geared diesel twin screw
Propulsion bhp	7000	14000
Engine/shaft rpm	900/120	890/120

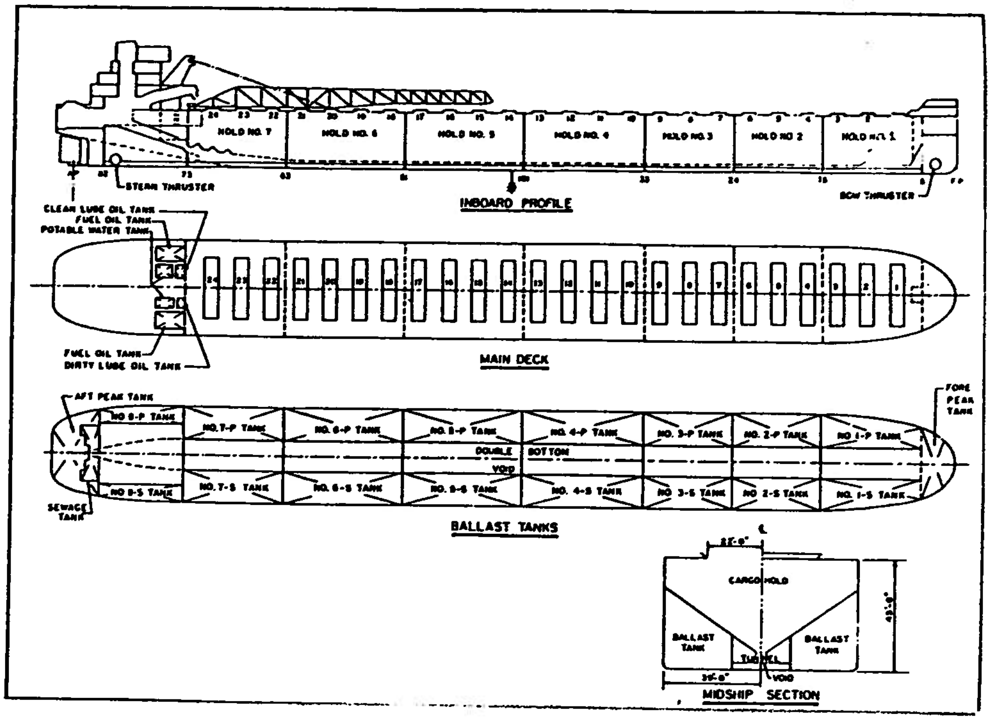

FIGURE 1 Ship A General Arrangement

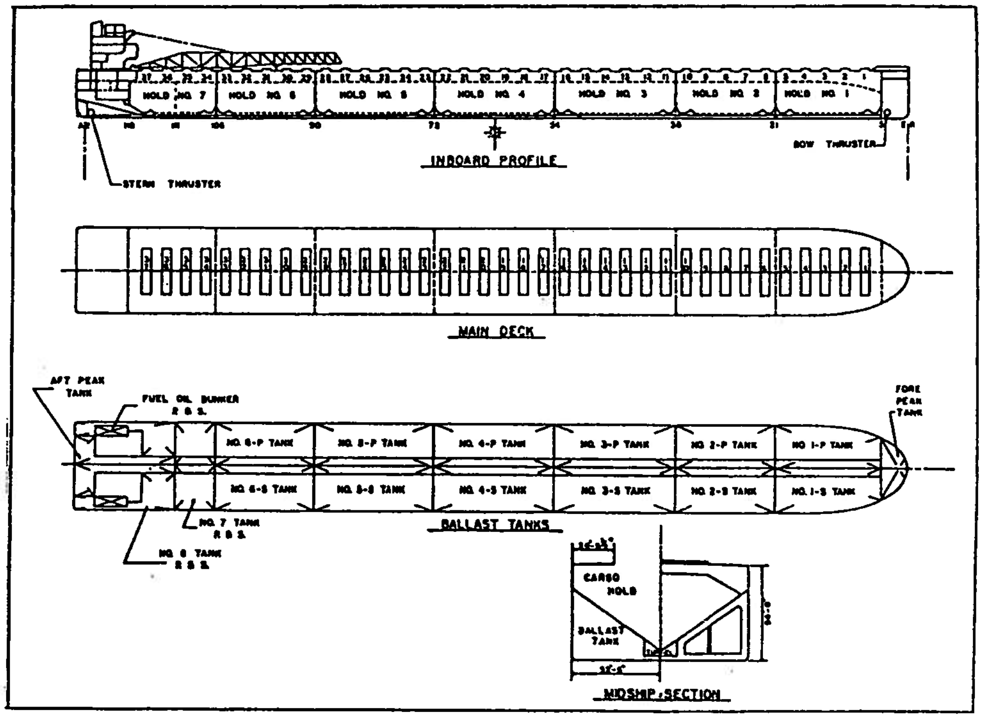

FIGURE 2 Ship B General Arrangement

THE MODELING

The Structure

Our principal interest is in the effect of hull structure deflections on the propulsion shafting and gears, and in consequence the finite element modeling is limited to hull and associated structure (e.g. machinery foundations, structural tanks) in way of the machinery spaces. The aftermost 108 feet of Ship A (frame 73 aft) and the aftermost 120 feet of ship B (frame 111 aft) are included in the respective models. Because of hull symmetry about the centerline, only port-side structure is actuallly included. Ship A has some minor differences in its port and starbord structures, a feature that its model overcomes by averaging of scantlings and locations. No house structure is included for either ship.

The models were created from construction drawings furnished by the shipbuilder.

Both ships are framed longitudinally in the machinery spaces and fitted with floors on the web frames. In way of the propulsion machinery, two equally spaced floors are placed between the web frames. For each web frame we produced a simplified scale drawing that indicates all structural data necessary for finite element modeling. Similar drawings were made for the intermediate floors. (In some areas short longitudinal bulkheads were shifted inboard or outboard a few feet to simplify the analysis.) Sketches and drawings were also made to show the modeling needed for decks, tank top, longitudinal girders, shell plating, foundations, and miscellaneous structural members.

Figure 3 is a sample of the many simplified drawings that were necessary. It depicts the bulkhead at frame 82 of Ship A.

Beam, truss, and membrane elements are used in modeling the structure. Deck beams and other structural members that function principally as beams are modeled by the beam element. Stanchions, certain flanges, and miscellaneous tension and compression members are modeled by the truss element. Plating is modeled by the membrane element. Plate stiffeners are not directly modeled, but are accounted for by appropriate adjustment of membrane thickness. Propulsion shafting and machinery foundations are included as part of the structure.

The Ship A model contains 1018 membrane elements, 263 beam elements, and 180 truss elements. The Ship B model contains 1417 membrane elements , 197 beam elements, 108 truss elements, and 9 contact elements. (The contact elements in Ship B are used to model the flexibility of shaft bearings.)

The Geometry

Origin of coordinates is at the intersection of the plane of the transom, the center plane, and the base plane. The x-axis is longitudinal, positive forward; the y-axis is transverse, positive to port; the z-axis is vertical, positive upward.

Nodes are located on the hull exterior at each frame. The connecting finite elements give an approximately correct section area at each frame. A series of nodes forming the intersection of hull and skeg, the tangent points at the bilges, etc, are located by fairing and by comparison with curves through similar points on the ship hulls. The interior nodes are located on major structural members.

Nodes on the center plane are fixed in y-translation, x-rotation, and z-rotation to account for the missing starboard half of the modeled hull. Nodes at the forward bulkheads are completely fixed. Nodes are numbered by frame beginning at the transom and going forward frame by frame. The Ship A model contains 669 nodes and the Ship B model contains 829.

Figure 4 is a sample of the modeling, showing the nodes and elements developed for the Ship A bulkhead shown in Figure 3.

The Loads

The deflections of the hulls, and of the models we have constructed, are caused by structural weights, by weights of liquids in tanks, by weight of cargo (the Ship B model includes part of a cargo hold), by propeller thrust and torque, and by the hydrostatic forces acting over the immersed surfaces of the hulls. All of these except propeller torque (which separate analysis proved to be inconsequential) were applied to the models in producing the results discussed in this paper. Three general cases were applied, they being (1) ship at maximum draft ("loaded"), (2) ship at minimum operating ballast draft, and (3) propulsion thrust only. Because of the linearity of the modeling, the third case results can be added to either of the other two to produce total results. The major interest is in the changes that occur in deflections when the ships go from one extreme of

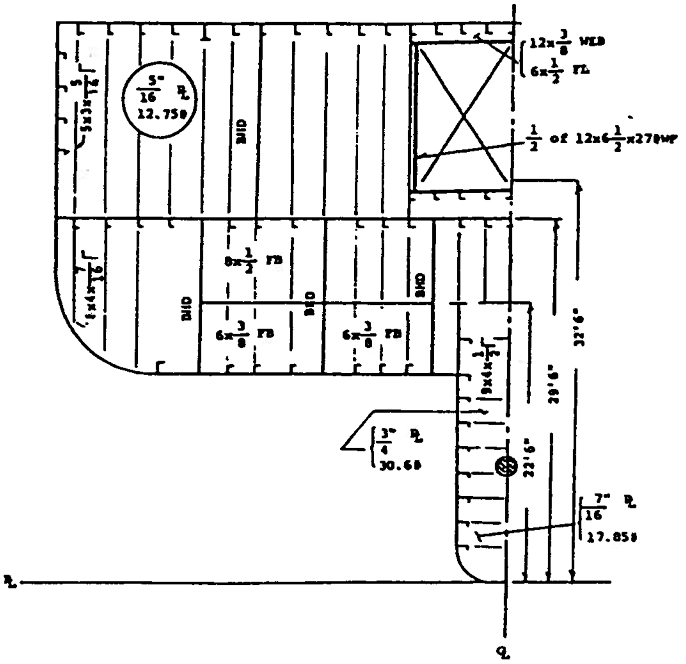

FIGURE 3 ·Simplified Drawing of Bulkhead, Frame 82, Ship A

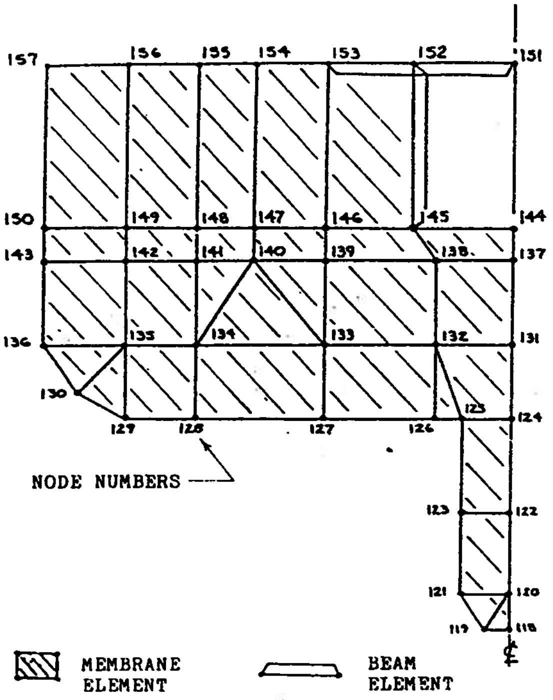

FIGURE 4 Nodes and Elements Representing Bulkhead at Frame 82, Ship A

operating draft to the other, or the difference between (1) and (2). The subsequent presentation of results is centered on the differences in deflections between these two cases.

GRAPHICS

Figures 5, 6, and 7 are graphical representations of the finite element models. They show three views of the membrane elements for Ship A. They were developed by a computer routine auxiliary to MSAP, principally as an aid to error checking (an error in typing the coordinates of a node would produce an obvious unfairness). They serve here to give an overall impression of the finite element model.

Similar graphics were generated for the beam elements and truss elements.

DEFLECTIONS

The results of the analysis (i.e. output of MSAP) are typical of any structural analysis -- deflections, moments, stresses, and forces at joints. Our interest lies with the deflections at points of interest, and hence with the print-out giving the deflection in six degrees of freedom, repeated for each load case, for each of the 669 nodes of Ship A and the 829 nodes of Ship B. A lot of numbers, that, and incomprehensible at casual glance. The person using the results must pick out a few deflections of interest, such as those at nodes lying close to the propulsion shaft bearings. Even so, there may be a large set of numbers to digest. Here, as samples, we have picked some deflections of possible interest, mostly vertical movements occurring between loaded and ballasted drafts, but because even this sample is large, have placed them in the Appendix.

Figures 8 and 9 provide a summary of a significant part of the results. They show, for Ship A and Ship B respectively, plots of propulsion shafting and machinery foundation movements between loaded and ballasted conditions. The figures give a qualitative view of the consequences of hull deflection on the propulsion machinery.

COMPARISON WITH MEASUREMENTS

Measurements of hull deflections in way of propulsion machinery were made in 1979 and 1980 on both Ship A and Ship B by a contractor of Bay Shipbuilding, and furnished to us by that firm for use in assessing the validity of our calculated deflections.

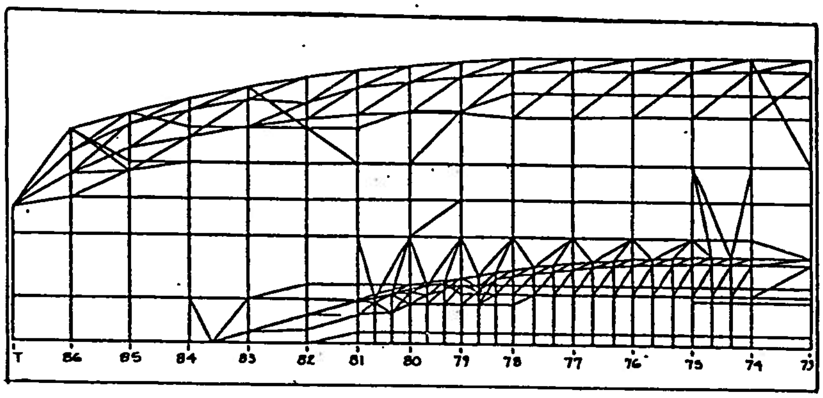

FIGURE 5 Membrane Elements, Ship A

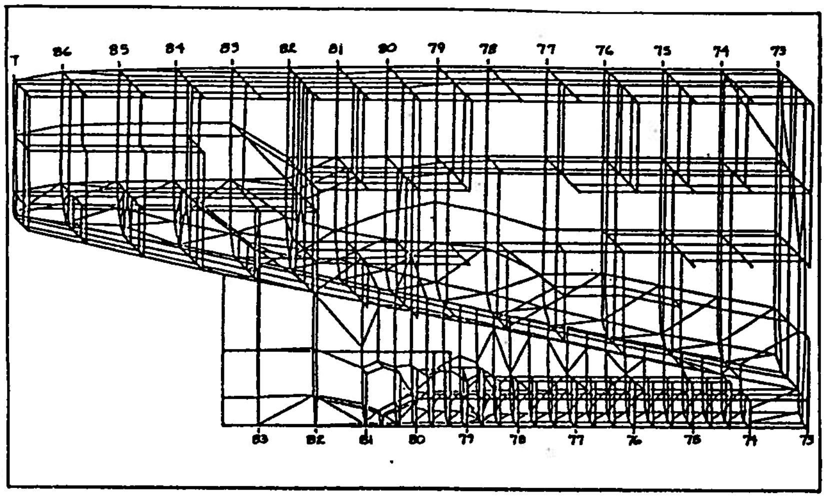

FIGURE 6 Membrane-Elements, Ship A

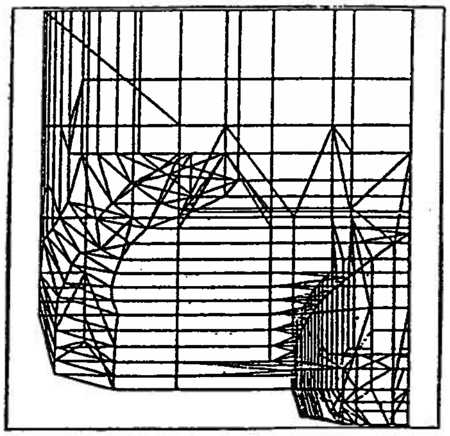

FIGURE 7 Membrane Elements, Ship A

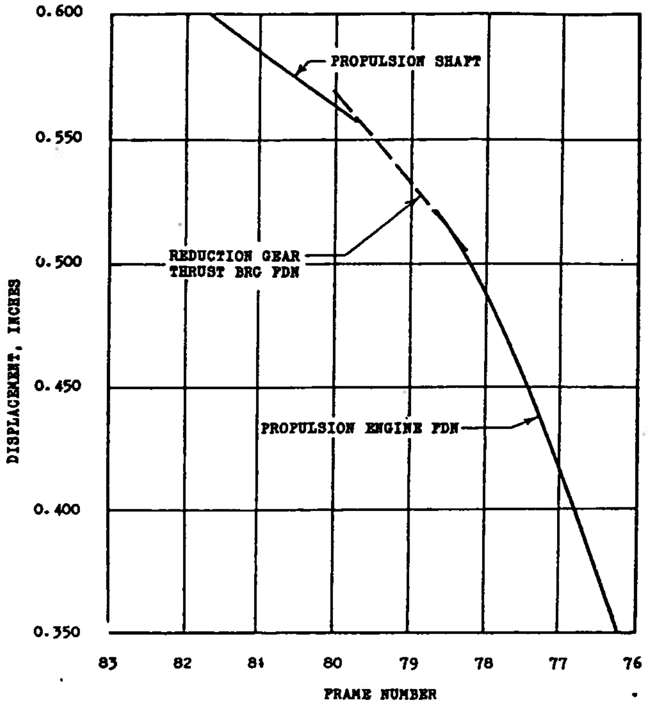

FIGURE 8 Plot of Vertical Displacements, Loaded to Ballast, Ship A Propulsion Components

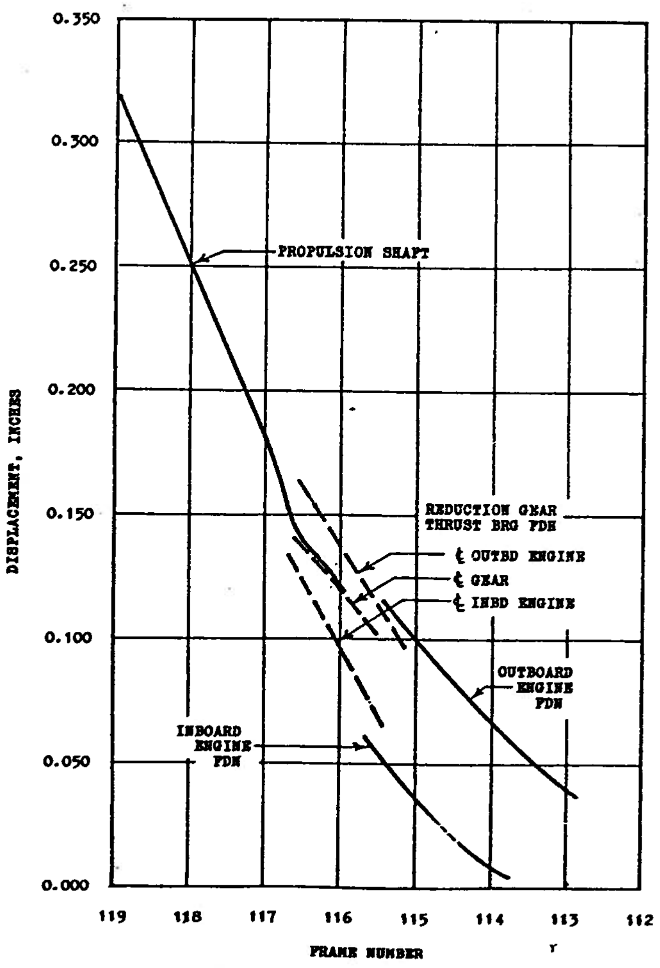

FIGURE 9 Plot of Vertical Displacements, Loaded to Ballast, Ship B Propulsion Components

Measurements were made relative to a taut wire stretched between frame 73 and frame 82 on Ship A, and between frame 111 and frame 123 on Ship B. For comparison, our deflections must be adjusted to suit the conditions of measurement. This adjustment is illustrated for Ship B by Figure 10. In the figure the vertical deflection of the tank top at frame 111 is adjusted to zero for loaded, ballasted, and base (empty) conditions. A straight line is drawn for each of the three conditions to the calculated displacement at frame 123, relative to the calculated displacement at frame 111. These straight lines thus represent a wire stretched in our model. The calculated deflections -- also relative to frame 111 deflections -- are plotted over the span of the figure. The differences between these plots and the "wire" are therefore equivalent to the actual measurements. Vertical arrows drawn in at frame 119 illustrate what the measurements should be.

Figures 11 and 12 demonstrate how well these calculated "measurements" agree with the actual measurements. We are pleased to see that the shapes of measured and calculated curves are similar, and that with one exception the magnitudes are close. The exception is obviously the loaded-to-empty comparison in Figure 12. The cause of the discrepancy is not known, but we believe it to lie in a misunderstanding over the meaning of "empty." Since the ship was in service when the measurements were made, it is unlikely to have been devoid of all liquids, for example. Log information in our possession is not sufficient for an unambiguous comparison of the measured and calculated conditions.

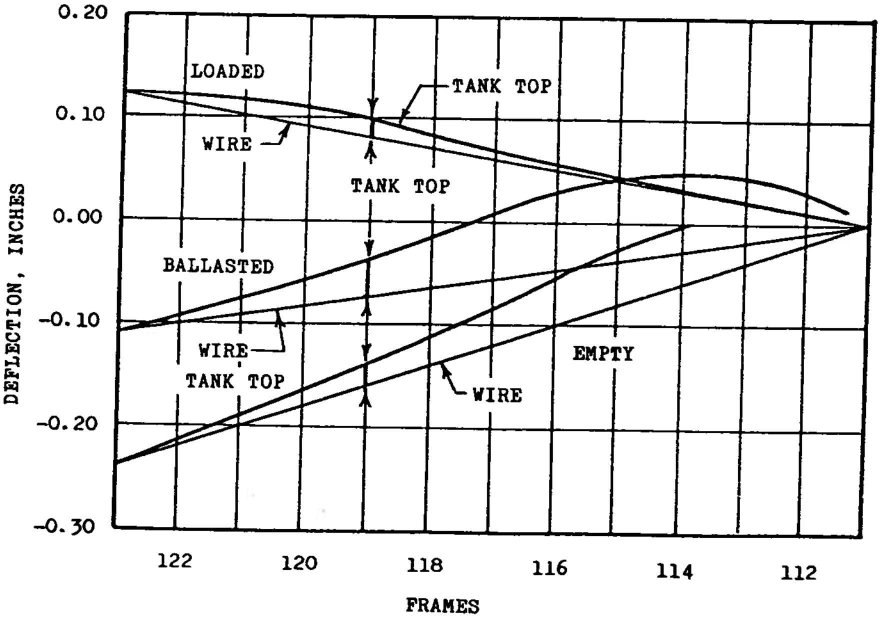

FIGURE 10 Converting Calculated Deflections into the Equivalent of Measurements Relative to a Fixed Wire

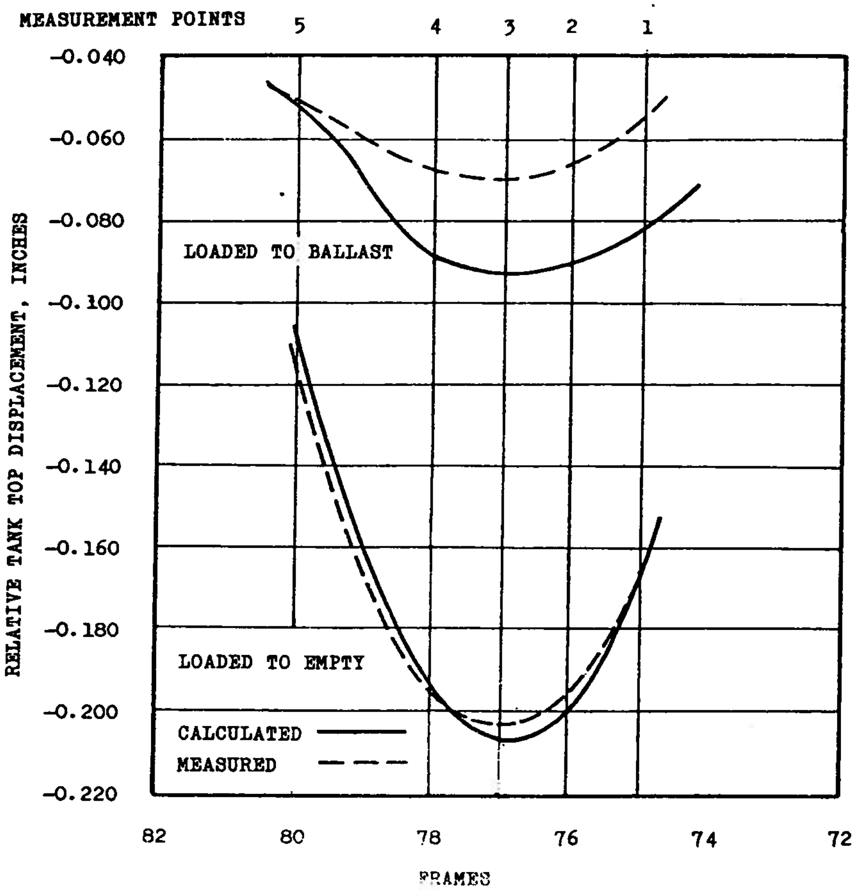

FIGURE-11-Calculated-and-Measured-Displacements,-Ship-A

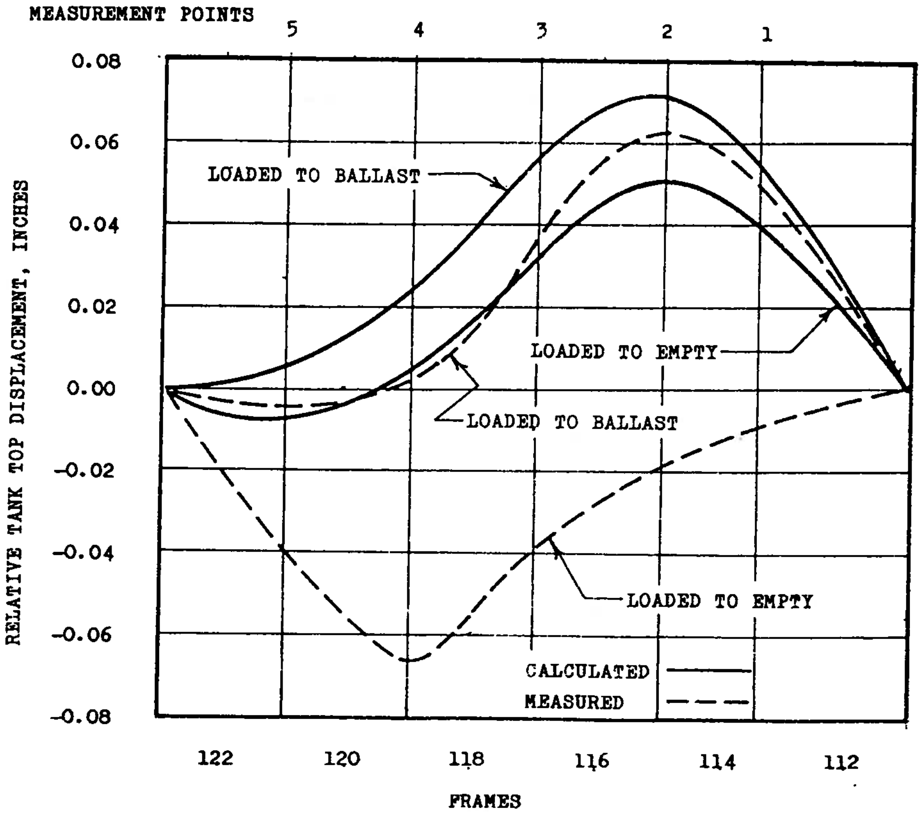

FIGURE 12 Calculated and Measured Displacements, Ship B

On the whole, we feel that the measurements tend to confirm the validity of the finite element models.

SHAFT BEARING INFLUENCE COEFFICIENTS

Since our finite element results give the vertical deflections of many points in the machinery spaces, one may select the deflections of nodes at the shaft bearings, and then by combining these with bearing influence coefficients in the conventional manner, calculate the changes in bearing loads caused by the deflections. This we shall not do in this paper. However, the influence coefficients themselves are possibly calculated to a better accuracy if our hull deflections are included, and we note following how that can be.

The conventional calculation of shaft bearing influence coefficients is based on rigidity of the structure that supports the bearings. In actuality, the act of raising a bearing (by inserting a shim, say) pushes that structure down, so that the change in bearing load is not as great as the calculation states. The calculated influence coefficient is therefore too large.

Our Ship B model contains a vertically-oriented contact element at each shaft bearing, making it possible to run a calculation in which a specified displacement of the bearing relative to its foundation is imposed. The output contains the resulting forces at all nodes; the determination of influence coefficients is then a simple matter of reading off these forces at the nodes located at bearing centers. The deflections of the hull have also occurred in the calculation, and in consequence the influence coefficients include the flexibility of the hull as well as of the shaft system.

Tables 2 and 3 illustrate the influence coefficients. Table 2 lists conventional influence coefficients (also obtained by the finite element analysis, but with hull nodes fixed). Table 3 lists influence coefficients obtained with the hull deflections allowed. The latter coefficients are indeed less than the former, but by no more than about five percent.

TABLE 2 Shaft Bearing Influence Coefficients, Rigid Structure

	1	2	3	4
1	192.0	-246.9	63.16	- 8.293
2	-246.9	324.8	-93.35	15.41
3	63.16	- 93.35	40.72	-10.54
4	- 8.293	15.41	-10.54	3.414

TABLE 3 Shaft Bearing Influence Coefficients, with Hull Deflections

	1	2	3	4
1	182.5	-234.4	59.69	- 7.152
2	-234.4	308.5	-88.79	14.70
3	59.63	- 88.79	39.41	-10.32
4	- 7.752	14.70	-10.32	3.377

Notes for TABLES

1. Number 1 bearing is forward
2. Units are pounds force per 0.001 inch

USE OF THE FINITE ELEMENT MODELS

Our major purpose in doing the work reported here was to demonstrate the use of finite element analysis in calculating the details of hull deflections in way of propulsion machinery. The most valuable practical use of the models is in studying the effects of design changes on deflections. The file of input data can be edited to change scantlings, say, or to add or delete structural elements. Many of the possible design changes would require only a few minutes each of editing to effect the corresponding change in the model. Computer runs are expensive (on the order of $100 per run at Michigan), but many alternatives can be evaluated quickly.

The models can also be used to analyze proposed changes in the modeled ship at any time during its life. For example, the builder proposed to add a pair of stanchions to the machinery space of Ship A after it had been in service for approximately six years, this for the purpose of reducing hull deflections in way of the propulsion machinery. Figure 13 illustrates the proposed change. It is similar to Figure 3, being one of the many simplified structural drawings made as an step in preparation of the finite element model. Added to it is a truss element representing the proposed stanchion.

The Ship A input data file was recoved from a tape where it had languished for several years, then edited by addition of a line to describe the nodal connections of an additional truss element, by the addition of a line giving the material properties and scantlings of the new element, and by change of the number 180 to 181 in the line that told MSAP how many truss elements to treat.

Results are sampled by Tables 4, 5, and 6. The left

TABLE 4 Vertical Displacements of Bottom Shell

Frame No.	Node No.	Max. Load	Min. Bal't	Thrust Alone	Frame No.	Node No.	Max. Load	Min. Bal't	Thrust Alone
T	1	+ 0.31492	- 0.43112	- 0.00039	T	1	+ 0.2847	- 0.4292	-
86	17	+ 0.30967	- 0.41434	- 0.00019	86	17	+ 0.2801	- 0.4124	-
85	37	+ 0.30147	+ 0.39776	- 0.00000	85	37	+ 0.2727	- 0.3959	-
84	59	+ 0.29367	- 0.37545	+ 0.00022	84	59	+ 0.2658	- 0.3736	-
83	87	+ 0.29455	- 0.33772	+ 0.00062	83	87	+ 0.2685	- 0.3360	-
82	118	+ 0.30232	- 0.30766	+ 0.00120	82	118	+ 0.2699	- 0.3055	-
81	158	+ 0.31304	- 0.27901	+ 0.00238	81	158	+ 0.2745	- 0.2764	-
80	214	+ 0.32565	- 0.24615	+ 0.00330	80	214	+ 0.2785	- 0.2385	-
79	284	+ 0.33607	- 0.19821	- 0.00216	79	284	+ 0.2777	- 0.1942	-
78	352	+ 0.33643	- 0.15275	- 0.00266	78	352	+ 0.2672	- 0.1480	-
77	411	+ 0.31561	- 0.10265	- 0.00181	77	411	+ 0.2386	- 0.0973	-
76	472	+ 0.26418	- 0.06077	- 0.00100	76	472	+ 0.1924	- 0.0558	-
75	535	+ 0.18277	- 0.03011	- 0.00046	75	535	+ 0.1317	- 0.0266	-
74	600	+ 0.08689	- 0.00522	- 0.00024	74	600	+ 0.0658	- 0.0038	-
73	635	0	0	0	73	635	+ 0.0000	- 0.0000	-

TABLE 5 Displacements of Propulsion Shaft

FRAME NO.	NODE NO.	VERTICAL DISPL. BAL to LD	VERTICAL DISPL. THRUST	LATERAL DISPL. BAL to LD	LATERAL DISPL. THRUST	FRAME NO.	NODE NO.	VERTICAL DISPL. BAL to LD	VERTICAL DISPL. THRUST	LATERAL DISPL. BAL to LD	LATERAL DISPL. THRUST
83 5/8	85	+0.64494	+0.00033	0	0	83 5/7	85	+0.6211	-	-	-
83	91	+0.63124	+0.00061	0	0	73	91	+0.6045	-	-	-
82	122	+0.60644	+0.00116	0	0	82	122	+0.5722	-	-	-
81	166	+0.58472	+0.00237	0	0	81	166	+0.5426	-	-	-
80	226	+0.56341	+0.00400	0	0	80	226	+0.5123	-	-	-
79 2/3	264	+0.55636	+0.00460	0	0	79 2/3	264	+0.5021	-	-	-

TABLE 6 Displacements of Reduction Gear Foundation

FRAME NO.	NODE NO.	VERTICAL DISPL. BAL to LD	VERTICAL DISPL. THRUST	LATERAL DISPL. BAL to LD	LATERAL DISPL. THRUST	LONGITUD'L BAL to LD	FRAME NO.	NODE NO.	VERTICAL DISPL. BAL to LD	VERTICAL DISPL. THRUST	LATERAL DISPL. BAL to LD	LATERAL DISPL. THRUST	LONGITUD'L BAL to LD
80	222	+0.56761	+0.00389	0	0	+0.00145	80	222	+0.5173	-	-	-	-
"	223	+0.56770	+0.00402	-0.00009	+0.00027	+0.00132	"	223	+0.5174	-	-	-	-
79 2/3	263	+0.55635	+0.00351	-0.00002	-0.00006	+0.00137	79 2/3	263	+0.5021	-	-	-	-
79 1/3	276	+0.54526	-0.00269	0	0	+0.00144	79 1/3	276	+0.4870	-	-	-	-
"	277	+0.54508	-0.00165	-0.00011	+0.00005	+0.00153	"	277	+0.4868	-	-	-	-
"	278	+0.54507	+0.00014	-0.00116	-0.00037	+0.00082	"	278	+0.4869	-	-	-	-
79	295	+0.53243	-0.00067	+0.00129	-0.00150	+0.00155	79	295	+0.4701	-	-	-	-
78 2/3	331	+0.52034	-0.00267	0	0	+0.01250	78 2/3	331	+0.4540	-	-	-	-
"	332	+0.51930	-0.00211	-0.00030	-0.00033	+0.00773	"	332	+0.4744	-	-	-	-
"	333	+0.51991	-0.00140	-0.00083	-0.00078	+0.00796	"	333	+0.4534	-	-	-	-

half of each of these tables is taken from Appendix A, and shows the deflections before addition of stanchions. The right half repeats the left half, but the deflections are those occurring after addition of the stanchions. The dashes indicate cases or coordinates in which no significant change is imposed by the stanchions. Otherwise, reductions in deflections are evident. Loads imposed on the stanchion by change from ballasted to loaded draft were also produced. The shipbuilder therefore had in hand an accurate (so we believe) estimate of the consequences of adding the stanchions.

At the time that this paper was written (summer 1982) the shipbuilder had not publically stated its decision on adding the stanchions.

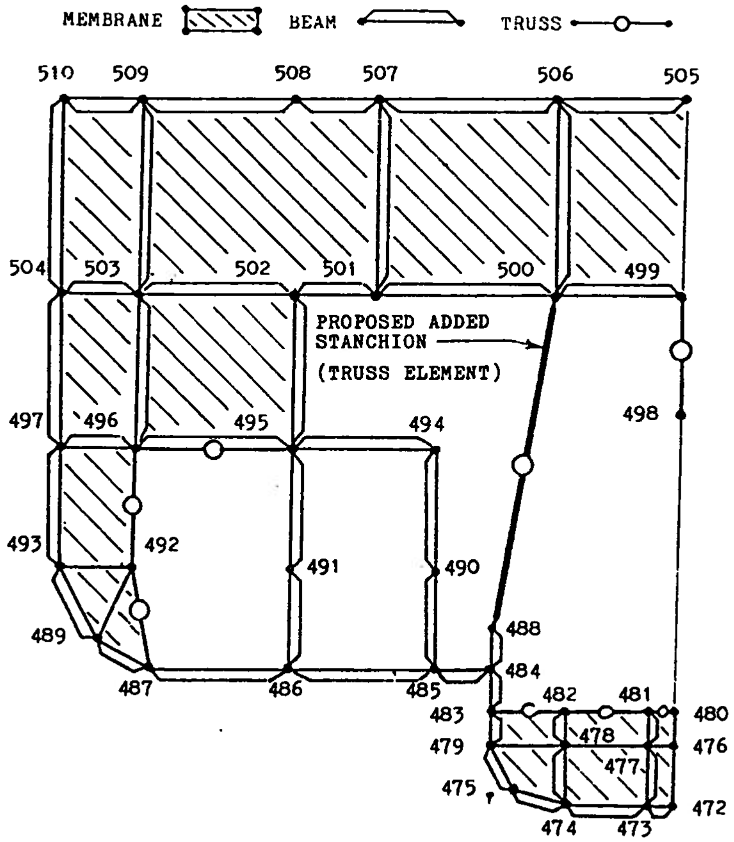

FIGURE 13 Finite Element Model of Bulkead at Frame 76, Ship A, Showing Proposed Addition of a Stanchion

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APPENDIX A

The tables in this appendix present a sampling of deflections calculated for Ship A.

Frame No.	Node No.	Max. Load	Min. Bal't	Thrust Alone
T	1	+ 0.31492	- 0.43112	- 0.00039
86	17	+ 0.30967	- 0.41434	- 0.00019
85	37	+ 0.30147	+ 0.39776	- 0.00000
84	59	+ 0.29367	- 0.37545	+ 0.00022
83	87	+ 0.29455	- 0.33772	+ 0.00062
82	118	+ 0.30232	- 0.30766	+ 0.00120
81	158	+ 0.31304	- 0.27901	+ 0.00238
80	214	+ 0.32565	- 0.24615	+ 0.00330
79	284	+ 0.33607	- 0.19821	- 0.00216
78	352	+ 0.33643	- 0.15275	- 0.00266
77	411	+ 0.31561	- 0.10265	- 0.00181
76	472	+ 0.26418	- 0.06077	- 0.00100
75	535	+ 0.18277	- 0.03011	- 0.00046
74	600	+ 0.08689	- 0.00522	- 0.00024
73	635	0	0	0

A1 Vertical Displacements of Bottom Shell

Frame No.	Node No.	Max. Load	Min. Bal't	Thrust Alone
T	11	+ 0.31271	- 0.42396	- 0.00042
86	31	+ 0.29279	- 0.38712	- 0.00032
85	52	+ 0.27603	- 0.35890	- 0.00019
84	75	+ 0.25832	- 0.33057	- 0.00062
83	110	+ 0.23921	- 0.30154	+ 0.00006
82	143	+ 0.21818	- 0.27158	+ 0.00015
81	184	+ 0.19356	- 0.23987	+ 0.00016
80	244	+ 0.16846	- 0.20730	+ 0.00014
79	308	+ 0.14390	- 0.17413	+ 0.00011
78	375	+ 0.11908	- 0.14179	+ 0.00008
77	434	+ 0.09095	- 0.10644	+ 0.00005
76	497	+ 0.06126	- 0.07048	+ 0.00004
75	562	+ 0.03823	- 0.04367	+ 0.00003
74	622	+ 0.01632	- 0.01966	+ 0.00001
73	657	0	0	0

A2 Vertical Displacements of Hull Side at Waterline

Frame No.	Node No.	Max. Load	Min. Bal't	Thrust Alone
82	120	+ 0.30198	- 0.30794	+ 0.00122
81	161	+ 0.31316	- 0.27874	+ 0.00232
80 2/3	195	+ 0.31660	- 0.26941	+ 0.00312
80 1/3	206	+ 0.32179	- 0.25560	+ 0.00336
80	218	+ 0.32552	- 0.24174	+ 0.00358
79 2/3	256	+ 0.32867	- 0.22789	+ 0.00245
79 1/3	272	+ 0.33[illegible]	- 0.21338	- 0.00085

A3 Vertical Displacements of Tank Top iwo Shaft

FRAME NO.	NODE NO.	VERTICAL DISPL. BAL to LD	VERTICAL DISPL. THRUST	LATERAL DISPL. BAL to LD	LATERAL DISPL. THRUST	LONGITUD'L DISPL. BAL to LD	LONGITUD'L DISPL. THRUST
83 5/8	85	+0.64494	+0.00033	0	0	-0.00795	+0.00149
83	91	+0.63124	+0.00061	0	0	-0.00799	+0.00150
82	122	+0.60644	+0.00116	0	0	-0.00085	+0.00700
81	166	+0.58472	+0.00237	0	0	+0.00539	+0.01181
80	226	+0.56341	+0.00400	0	0	+0.01164	+0.01663
79 2/3	264	+0.55636	+0.00460	0	0	+0.01372	+0.01823

A4 Displacements of Propulsion Shaft

FRAME NO.	NODE NO.	VERTICAL DISPL. BAL to LD	VERTICAL DISPL. THRUST	LATERAL DISPL. BAL to LD	LATERAL DISPL. THRUST	LONGITUD'L DISPL. BAL to LD	LONGITUD'L DISPL. THRUST
80	222	+0.56761	+0.00389	0	0	+0.00145	+0.00933
"	223	+0.56770	+0.00402	-0.00009	+0.00027	+0.00132	+0.00864
79 2/3	263	+0.55635	+0.00351	-0.00002	-0.00006	+0.00137	+0.00901
79 1/3	276	+0.54526	-0.00269	0	0	+0.00144	+0.00953
"	277	+0.54508	-0.00165	-0.00011	+0.00005	+0.00153	+0.00823
"	278	+0.54507	+0.00014	-0.00116	-0.00037	+0.00082	+0.00365
79	295	+0.53243	-0.00067	+0.00129	-0.00150	+0.00155	+0.00343
78 2/3	331	+0.52034	-0.00267	0	0	+0.01250	+0.00807
"	332	+0.51930	-0.00211	-0.00030	-0.00033	+0.00773	+0.00444
"	333	+0.51991	-0.00140	-0.00083	-0.00078	+0.00796	+0.00328

A5 Displacements of Reduction Gear Foundation

Nodes 222, 276, 331 are on centerline; nodes 223, 263, 277, 332 are 19" off centerline; nodes 278, 295, 333 are 64" off centerline

FRAME NO.	NODE NO.	VERTICAL DISPL. BAL to LD	VERTICAL DISPL. THRUST	LATERAL DISPL. BAL to LD	LATERAL DISPL. THRUST	LONGITUD'L DISPL. BAL to LD	LONGITUD'L DISPL. THRUST
78 2/3	-	+0.51941	-0.00148	-0.00159	-0.00038	+0.00116	+0.00316
78 1/3	-	+0.50476	-0.00204		-0.	+0.00041	+0.00244
78	-	+0.48811	-0.00187	-0.00175	-0.00042	+0.00282	+0.00212
77	-	+0.41786	-0.00144	-0.00220	-0.00020	+0.01323	+0.00134
76	-	+0.32520	-0.00084	-0.00333	-0.00007	+0.02519	+0.00089
75	-	+0.21315	-0.00038	-0.00323	-0.00000	+0.03537	+0.00064
74 1/3	-	+0.13288	-0.00031	-0.00167	+0.00002	+0.03758	+0.00062

AVERAGE OF INB'D & OUTB'D

A6 Displacements of Engine Foundation

APPENDIX B

The tables in this appendix present a sampling of deflections calculated for Ship B.

FRAME NO.	NODE NO.	MAX. LOAD	MIN. BAL'T	THRUST ALONE (FWD)
126	1	+0.46463	-0.19541	-0.00044
125	20	+0.44821	-0.17363	-0.00036
124	45	+0.43496	-0.15200	-0.00021
123	77	+0.41358	-0.12673	-0.00007
122	126	+0.41182	-0.08920	+0.00008
121	170	+0.40608	-0.05089	+0.00025
120	215	+0.38201	-0.01810	+0.00044
119	264	+0.33089	+0.00728	+0.00058
118	318	+0.25612	+0.02876	+0.00063
117	378	+0.16521	+0.04631	+0.00050
116	473	+0.10947	+0.08015	+0.00028
115	588	+0.05904	+0.09444	+0.00007
114	645	+0.02713	+0.09534	-0.00006
113	703	+0.01459	+0.07767	-0.00010
112	754	+0.01145	+0.03904	-0.00007
111	796	0	0	0

B1 Vertical Displacements of Bottom Shell

FRAME NO.	NODE NO.	MAX. LOAD	MIN. BAL'T	THRUST ALONE (FWD)
126	7	+0.38828	-0.21409	-0.00060
125	31	+0.35904	-0.20037	-0.00047
124	54	+0.33277	-0.18591	-0.00034
123	96	+0.30287	-0.16844	-0.00021
122	143	+0.27262	-0.15133	-0.00007
121	188	+0.24354	-0.13333	+0.00006
120	234	+0.21579	-0.11485	+0.00121
119	288	+0.18653	-0.09684	+0.00034
118	345	+0.15543	-0.07808	+0.00045
117	411	+0.12343	-0.06689	+0.00046
116	524	+0.09355	-0.04877	+0.00036
115	623	+0.06566	-0.03675	+0.00021
114	678	+0.04258	-0.02654	+0.00013
113	734	+0.022945	-0.01607	+0.00008
112	780	+0.00795	-0.00733	+0.00004
111	809	0	0	0

B2 Vertical Displacements of Hull Side at Waterline

FRAME NO.	NODE NO.	MAX. LOAD	MIN. BAL'T	THRUST ALONE (FWD)
119	275	+0.25260	-0.06590	+0.00085
118	328	+0.20548	-0.04460	+0.00199
117	400	+0.16529	-0.01613	+0.00312
116 2/3	444	+0.14714	-0.00655	+0.00271
116 1/3	465	+0.13686	-0.00051	+0.00232
116	512	+0.12720	+0.00603	+0.00230
115 2/3	559	+0.11949	+0.01124	-0.00508
115 1/3	585	+0.10924	+0.01861	-0.00376

B3 Vertical Displacements of Tank Top iwo Shaft

FRAME NO.	NODE NO.	VERTICAL DISPL.		LATERAL DISPL.		LONGITUD'L DISPL.	
		BAL to LD	THRUST	BAL to LD	THRUST	BAL to LD	THRUST
123	87	+0.51359	-0.00030	-0.03652	-0.00008	+0.01141	+0.04107
122	136	+0.47187	-0.00045	-0.02790	-0.00012	+0.01228	+0.03936
121	180	+0.42731	-0.00042	-0.02098	-0.00015	+0.01321	+0.03764
120	225	+0.37713	-0.00005	-0.01743	-0.00018	+0.01426	+0.03592
119	274	+0.31850	+0.00085	-0.01896	-0.00019	+0.01548	+0.03419
118	335	+0.25045	+0.00225	-0.02250	-0.00017	+0.01689	+0.03245
117	401	+0.17988	+0.00309	-0.02720	-0.00010	+0.01836	+0.02981
116 2/3	447	+0.14401	+0.00258	-0.02860	-0.00005	+0.01911	+0.02836
116 1/3	472	+0.13375	+0.00217	-0.03000	-0.00002	+0.01933	+0.02783
116	519	+0.12139	+0.00152	-0.03050	+0.00001	+0.01958	+0.27217
115 2/3	532	+0.11458	+0.00112	-0.03050	+0.00003	+0.01971	+0.02687

B4 Displacements of Propulsion Shaft

FRAME NO.	NODE NO.	VERTICAL DISPL.		LATERAL DISPL.		LONGITUD'L DISPL.	
		BAL to LD	THRUST	BAL to LD	THRUST	BAL to LD	THRUST
	442	+0.11585	+0.00238	-0.3086	+0.00016	+0.01169	+0.00373
	443	+0.12396	+0.00243	-0.03070	+0.00008	+0.01166	+0.00384
116 2/3	444	+0.14059	+0.00271	-0.02963	-0.00010	+0.00614	+0.00251
	445	+0.17698	+0.00225	-0.02946	-0.00037	-0.00034	+0.00313
	446	+0.18084	+0.00216	-0.02965	-0.00045	-0.00111	+0.00326
	467	+0.09485	+0.00172	-0.03096	+0.00113	+0.01221	+0.00374
116 1/3	468	+0.10292	+0.00162	-0.03082	+0.00120	+0.01194	+0.00399
	470	+0.16049	+0.00155	-0.02756	-0.00128	+ .00032	+0.00362
	471	+0.16467	+0.00166	-0.02767	-0.00121	-0.00103	+0.00328
	509	+0.07264	+0.00057	-0.03273	+0.00012	+0.01302	+0.00351
	510	+0.08475	+0.00043	-0.03192	+0.00020	+0.01208	+0.00463
	511	+0.11334	+0.00253	-00.3106	+0.00021	+0.00877	+0.01026
116	512	+0.12099	+0.00248	-0.03058	+0.00003	+0.00638	+0.01072
	513	+0.12857	+0.00254	-0.02986	-0.00017	+0.00447	+0.01015
	514	+0.14701	+0.00048	-0.02621	+0.00025	+0.00016	+0.00424
	515	+0.15122	+0.00066	-0.02394	+0.00019	-0.00097	+0.00303
	558	+0.09968	+0.00143	-0.02812	-0.00092	+0.00889	+0.01044
115 2/3	559	+0.10825	-0.00508	-0.02789	+0.00011	+0.00660	+0.01090
	560	+0.11678	-0.00482	-0.02749	+0.00112	+0.00450	+0.01032

B5 Displacements of Reduction Gear Foundation

FRAME NO.	NODE NO.	VERTICAL DISPL.		LATERAL DISPL.		LONGITUD'L DISPL.		
		BAL to LD	THRUST	BAL to LD	THRUST	BAL to LD	THRUST	
115	-	+0.03764	-0.00281	-0.04134	+0.00040	-0.00361	+0.00131	AVERAGE INB'D ENG.
114	-	+0.00511	-0.00192	-0.04026	+0.00017	-0.00618	+0.00036	
113	-	-0.01011	-0.00104	-0.03509	-0.00008	-0.00884	+0.00017	
115	-	+0.10061	-0.00233	-0.02434	-0.00052	-0.000188	+0.00126	AVERAGE INB'D ENG.
114	-	+0.06628	-0.00152	-0.02424	-0.00020	-0.00508	+0.00181	
113	-	+0.03932	-0.00078	-0.02038	-0.00003	-0.00178	+0.00016	
112	-	+0.01808	-0.00030	-0.00993	-0.00000	+0.00102	+0.00006	

B6 Displacements of Engine Foundation