April 13, 1956

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Naval Architecture

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WEIGHT-STRENGTH ANALYSIS OF A MODERN DESTROYER
WITH VARYING FRAME SPACINGS

by
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SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREES OF MASTER OF SCIENCE
IN NAVAL ARCHITECTURE AND MARINE ENGINEERING
AND NAVAL ENGINEER

at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1957

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Department of Naval Architecture and Marine Engineering, May 20, 1957

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1
ABSTRACT

By superimposing two series of grids, one longitudinal and one transverse, on a typical bulkhead-deck arrangement of a destroyer, an analysis of the effect of stiffener spacing on the total weight of structure has been made. Assuming normal design criteria, the weight of longitudinal structure and the weight of transverse web frames have been calculated for nine possible arrangements with the same strength as measured by the design criteria.

From analysis of the results, it is concluded that there is a minimum number of longitudinalss necessary to give the minimum structural weight. This number provides the arrangement which results in the maximum spacing of longitudinals at which the minimum required section modulus is obtained. Beyond this, any increase in the number of longitudinals serves to increase the complexity (hence cost)
of structure at no decrease in weight.

The variation in web spacing produces very little change in weight. There is a small advantage in decreasing the spacing in the ends of the midships three fifths length to provide a gradual transition to end framing conditions. There is a slight penalty introduced in the total structural weight, when excessive web spacing is used amidships. As a practical matter, web frame spacing appears to be best governed by arrangement advantages and not weight considerations.

The critical factor in determining least weight of structure seems to be the design criteria. Small changes in the required section modulus, $1/r$ of deck longitudinals, and degree of fixity assumed in calculating buckling strength, could lead to far greater changes in the weight of structure than variations in stiffener spacing. Further research into the reduction of ship structural weight might better be applied to evaluating design criteria rather than evaluating framing systems.

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Assistant Professor of Naval Architecture
Cambridge, Massachusetts
May 20, 1957

Professor Leicester F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Professor Hamilton:

In accordance with the requirements for the Degrees of Naval Engineer and Master of Science in Naval Architecture and Marine Engineering, we submit herewith a thesis entitled: "Weight-Strength Analysis of a Modern Destroyer with Varying Frame Spacings."

Respectfully yours,

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Lieutenant, U.S. Coast Guard
ACKNOWLEDGEMENTS

The authors are indebted to Professor A. M. D'Arcangelo of the Department of Naval Architecture, Massachusetts Institute of Technology, for his advice and guidance as thesis supervisor, and to Professor J. H. Evans of the Department of Naval Architecture, Massachusetts Institute of Technology, for his advice and guidance as thesis advisor.
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NOTATION

A  Cross-sectional area

a  Length of plating (in the longitudinal direction)

B  Plating Width Factor = b/t \( \sqrt{\frac{c y}{E}} \)
  Ratio of bending to shear stress in Bleich and Ramsey buckling formula

b  width of plating (in the transverse direction)

a/b aspect ratio of plating panel (in considering shear stress a/b is the long dimension over the short dimension.)

C  Any coefficient

D  Flexural rigidity of a plate = Et\(^3\)/12(1-\(u^2\))

E  Modulus of elasticity

H  Hydrostatic head

I  Moment of Inertia of ship or longitudinal

K  Coefficient of buckling in Bryan formula or coefficient of hydrostatic stress in normal loading

L  Length of vessel

l  Length of beam

l/r  Slenderness ratio of longitudinals

M  Bending moment

Q  First moment of area about the neutral axis

r  Radius of gyration of a longitudinal

SF  Safety factor

s  Spacing of longitudinals

t  Thickness of plate

UCS  Ultimate compressive stress

u  Poisson's ratio

V  Vertical shearing force
\( w \)  pounds per foot of water pressure

\( x \)  A function of aspect ratio in the Bleich and Ramsey buckling formula

\( y \)  Distance from neutral axis to extreme fiber

\( Z = \frac{I}{y} \)  - Section modulus of ship or longitudinal

\( \Delta \)  Displacement of the ship

\( \rho \)  Density of water

\( \eta \)  Ratio of Young's modulus to tangent modulus in Bleich and Ramsey buckling formula.

\( \sigma_1 \)  Primary bending stress = \( \frac{M}{Z} \) _ship_

\( \sigma_2 \)  Secondary or line stress = \( \frac{M}{Z} \) _longitudinal-plate combination_

\( \sigma_3 \)  Tertiary or point stress = \( \frac{M}{Z} \) _plate under normal load_

\( \sigma_i \)  Indicated stress in Bleich and Ramsey buckling formula

\( \sigma_{cr} \)  Critical buckling stress in compression

\( \tau \)  Shear stress

\( \tau_{cr} \)  Critical buckling stress in shear

**Subscripts**

act  Actual

all  Allowable

cr  Critical

h  Hogging

hyd  Hydrostatic

inst  Instability

max  Maximum

min  Minimum

r  Reduced

rqd  Required

s  Sagging

y  Yield point
I. INTRODUCTION

To most naval architects it has become increasingly apparent that the science of ship structural design and analysis has lagged behind that of hydrodynamics, propulsion, and newer fields. Advances in ship structure have been made through improvements in building techniques and materials, but we have not advanced correspondingly in our ability to analyze the relative adequacy of ship structures. Midship Section Design has remained largely a matter of designing an adequate structure from strength considerations, which is, at once, comparatively light in weight, compatible with the desired arrangements, and relatively cheap to construct.

The heart of the design problem lies in the evaluation of the term "adequate strength" in relation to the other factors. To say that a ship which does not exhibit structural weakness is adequate, does not evaluate how over-adequate she may be at a cost to the other factors, particularly weight. There has been an understandable reluctance on the part of structural designers to arrive at a minimum design criteria by trial and error, for error in ship structures is not usually correctable in the trial ship. Only after conclusive experience or in the face of necessity have bold departures been made from past practice.

In no single type of ship has more structural experience been gained, more valuable experimentation been carried out, or has necessity pushed harder than in the destroyer type. Since their inception in the late
nineteenth century, destroyers have been critical in most every design sense, much moreso than other types. The measure of success in destroyer design has been the degree to which the desired military characteristics have been obtained in relation to the overall size of the ship. Thus every design characteristic must, in the destroyer type, be evaluated more in terms of weight and space than in other types. With smaller safety factors, closer tolerances, and lighter scantlings, they represent the maximum yet achieved in the reduction of weight in ship structural design.

It was with these factors in mind that we decided to use a modern destroyer as our guinea pig in the analysis of the relation between the weight, strength, and, to a lesser degree, the arrangements, in a longitudinally framed ship. It was our feeling that perhaps if there were some knowledge of the relative effect upon weight in using a given arrangement of structural members, the arrangements might, at an early stage of the design, be compromised to the least weight structure. We at least hoped to determine what relative magnitude of weight saving is possible purely through the variation in the spacing of the stiffening members. At the same time of course, we are determining what penalty is paid in departing in any direction from the least weight solution.
II. PROCEDURE

2.1 Layout

Having decided to base the calculations on a destroyer type, some typical dimensions were picked and the necessary shell expansion and the shell cross-sections were drawn. It was decided that in order to eliminate the effect of bow and stern framing (not related to the problem of ship girder stresses with which this work is concerned) only the midship three-fifths length of this hypothetical destroyer would be considered. The ends of this section are very close to the points where close-spaced transverse frames are introduced at either end in most destroyers.

In drawing the sections, some typical bulkhead locations and platform deck arrangements were picked and the required main deck openings which would normally be present in a destroyer deck were laid out. This provided the minimum number of invariable factors which it was felt would normally confront the structural designer. The only variation which was later allowed was a two foot movement of transverse bulkheads in the longitudinal direction, to fit the various standard web frame spacings which were later introduced.

Thus, a series of large panels of shell, which were to be stiffened against the loads which were imposed by design criteria, were established. It was determined that in the deck it was impractical to vary the spacing of longitudinals, as the large number of openings made any systematic variation incompatible with arrangement problems. One average
arrangement of longitudinals for the deck, to be used in all studies, was therefore selected. On the sides and bottom, however, a series of grids, longitudinal and transverse, which could be superimposed, one on the other, was established. Thus, the effect of (a) variation of longitudinal spacing on a given web spacing and (b) variation of web spacing on a given longitudinal spacing, could be measured.

For the web systems, a variation from the spacing amidships to a smaller spacing at the ends was established, in order to effect a more gradual transition from midship section scantlings to bow and stern framing scantlings. For consistency a ratio of two to three between the end and midship spacing of web frames was chosen. It was decided that an eight foot spacing amidships, in conjunction with the reduced spacing in the ends, was as close as web frames could be placed without encountering unrealistic arrangement problems in the ends. The spacing amidships was increased by first a small amount (one foot) and than a large amount (four feet) to measure the effect of small and large changes in the longitudinal spacing of webs. Thus, three grid systems of 12'/8', 9'/6', and 8'/5.34' web spacings were established, each of which were plotted on the shell expansion and adjusted for compatibility with the established bulkhead locations.

For longitudinal systems, the spacing was varied from a specified amount at the neutral axis to a closer spacing at the bottom and at the sheer strake. Rather than decide on spacings, the number of longitudinals to be spaced around
the girth and the ratio between the spacing at the neutral axis and the spacing at the bottom and sheer strake plating was selected. A constant value of 1.17 was used for this ratio. Judging from existing designs, twelve longitudinals seemed to be the most likely number for the girth which had been chosen. Accordingly, 15, 12, and 9 longitudinals were chosen to give a variation of 33% more or less than the normal.

The decision to space the longitudinals closer at the bottom and at the sheer strake was based on a suspicion that they would contribute more to the moment of inertia at these locations than at the neutral axis. On the other hand, it was realized that they reduce the required scantlings of the bottom and sheer strake plating, while increasing the minimum thickness of plating at the neutral axis. The relative merits of varying the longitudinals in this manner, against reversing the procedure, are discussed in the appendix.

In a similar manner to that used in adjusting web frames for compatibility with the shell expansion, each longitudinal system was adjusted to the ship. First, the longitudinals were spaced around the girth of the ship. An effort was made to keep the total girth of wide spaced longitudinals at the neutral axis constant in all three longitudinal schemes. Next the strakes were laid out in such a manner that seams were placed within six inches of the transition from narrow to wide spacing. This work was done on a cross-section of the midship section. The girth
readings were then transferred to a shell expansion and the seams and longitudinals were marked off. The longitudinals and strakes could then be run from end to end utilizing platform decks and longitudinal bulkheads as points of longitudinal support, thus eliminating some longitudinals in the ends.

In numbering and tabulating the nine separate schemes, the following nomenclature was chosen:

a) Web Frame Grids
   i. 8' spacing amidships, 5.34' spacing at ends----A
   ii. 9' " " 6' " " " ----B
   iii. 12' " " 8' " " " ----C

b) Longitudinal Frame Grids
   i. 9 longitudinals --------1
   ii. 12 " " --------2
   iii. 15 " " --------3

Thus, nine separate schemes (1A, 2A, 3A, 1B, 2B, etc.) were calculated, each representing a possible framing system. For each of the nine schemes, there were three calculations of scantlings and weight per foot (one amidships, one forward and one aft) and a web frame weight for each web frame in each scheme.
2.2 Design Criteria

Though it was recognized that many of the design criteria in use in structural design are of questionable merit, it was felt that any great departures from the accepted criteria would tend to detract from the primary purpose of our work, i.e. to determine the relative weight saving which can be obtained solely from variation of stiffener spacings. Therefore, a set of design criteria was established which represented reasonable values of the parameters normally established in destroyer design. In some cases, particularly in designing the end sections, a lack of existing design criteria upon which to base a decision as to what was structurally adequate was found. In these cases, criteria which gave satisfactory results when applied to known successful ships were established.

The important dimensions and design criteria are briefly as follows:

1. Dimensions Assumed: LPB = 410', $\Delta = 3200$ tons

2. $M_h$ (midships) = $\frac{\Delta x L}{C}$ (C = 18) $M_h$ (midships) = 73,500 tons-ft.

3. $M_s$ (midships) = .75 $M_h$ = 55,100 tons-ft.

4. $G_1$ hog = 19,500 psi

5. $G_1$ sag = 14,650 psi

6. required $I/y$ to bottom = $M_h/G_1 h$ = 8,440 in$^2$ft.

7. required $I/y$ to deck = $M_s/G_1 s$ = 6,340 in$^2$ft. (in compression)

8. Material: HTS throughout. Yield strength = 45,000 psi.

9. $M_h$ at after 3L/5 point = .30 $M_h$ amidships = 22,100 tons-ft.
10. Mh at forward 3L/5 point = $.15 Mh amidships = 11,050 tons-ft.

11. Shear Force forward, \( V = \frac{\Delta}{C} (C = 8) = 400 \) tons.

12. Shear Force aft, \( V = \frac{\Delta}{C} (C = 6\frac{1}{4}) = 520 \) tons.

13. \((L/r)\) max of bottom longitudinals = 30.

14. \((L/r)\) max of deck longitudinals and side longitudinals down to the neutral axis = 55. (See Fig. I)

15. \((L/r)\) max of side longitudinals from neutral axis to bottom-straight line variation with depth from 30 on the bottom to 55 at the neutral axis. (See Fig. I).

16. Hydrostatic Head - a head of water of 4' above the main deck is assumed on all plating amidships and aft, and a variation to 8 feet at the forward end is assumed.

17. All structural members, normally determined by local considerations, are kept constant throughout the design. These include the intercostal docking longitudinal, the center vertical keel, and the side longitudinal normally reserved for spur shores.

18. \( \frac{f}{\sigma_{cr}} + \left( \frac{r}{r_{cr}} \right)^{1.5} < 1 \) for all plating subjected to combined shear and direct compression. (See Fig. II)

19. The ultimate compression strength of each panel must be greater than \( 1\frac{1}{4} \) times \( \sigma_{cr} \).

20. All plating is considered fully effective in compression except that in the deck only 60 thicknesses of plating associated with each stiffener are considered as effective.

21. All plating under a head of water greater than 15' is assumed to have fully clamped edges. All plating under 6' of water or less is assumed to have simply supported edges.
Figure I
Design Criteria for Minimum $l/r$ of Longitudinals
For the determination of the safety factor choose the formula:

\[ \frac{F \cdot \delta}{\bar{P}} = \bar{S} \]

**Key:**
- \( F \): Factor of safety
- \( \bar{P} \): Applied load
- \( \delta \): Deflection
- \( \bar{S} \): Safety factor

Figure II
22. No corrosion allowance will be added as such. The uncertainty in choosing the corrosion allowance will serve only to distort the relative effect of variations of parameters.

23. Special design criteria used in end sections appear in Procedure Section under subtitle End Sections, (Section 2.4).

2.3 Midship Section

The midship section design was carried out in a manner similar to that outlined by M. St. Denis in DTMB Report C-555 (On the Structural Design of the Midship Section). Realizing that this method is not necessarily followed in its pure form in most design agencies, we were satisfied that it gives results consistent with those obtained by other methods under similar design criteria. It has the advantage of flexibility for its application to varying sections, such as we have considered. It further lends itself to simplification when dealing with many schemes having similar characteristics.

Starting at the bottom and working up in a girthwise direction, each strake was sized on the basis of hydrostatic load, instability, and ultimate compressive strength, considering both longitudinal and girthwise stresses. The deck plating was also sized for the fixed longitudinal spacing in this manner.

Longitudinals were sized on the basis of limiting $\ell/r$ and required section modulus of each longitudinal. The docking longitudinal (near the turn of the bilge) was considered invariant and one longitudinal above the neutral
axis was made oversized for spur shore support. In all cases, the lightest standard structural shape of reasonable dimensions was used. No depths greater than 14" were considered.

Section modulus was checked to verify that the assumed value of $\sigma_1$ was actually not exceeded. Where section modulus resulted in a value higher than the minimum required, plates which had been slightly over a certain standard plate size were reduced to this plate size (since it was apparent that $\sigma_1$ would not be as high as allowed, hence allowed $\sigma_3$ would be greater in the refined stress schedule). Where the section modulus resulted in a value lower than the required minimum, the plates in the bottom and/or the sheer strakes were increased in conjunction with the longitudinals which stiffened them. The purpose here, of course, was to add weight where it would do the most good in increasing the section modulus and where the plate was most highly stressed.

2.4 End Sections

On the forward and after ends of the vessel, the scantlings were sized by actual computation. A gradual decrease in the midship scantlings was not used. The design method used at this station was the same basic method as that used amidships. However, some very important variations were necessary. The most important variation made in the design approach was necessary in order to consider the effect of the high shear force in these sections.

In establishing stress schedules for these sections, some means of arriving at a reduced value of $\sigma_1$ was
necessary. During the design process this value was selected as:

\[ \sigma_{1R} = \sigma_1 \text{all} \left( \frac{M_1}{M_2} \right) \left( \frac{Z_2}{Z_1} \right) \]  

(1)

where \( \sigma_{1R} \) = Reduced value of \( \sigma_1 \) or the allowable \( \sigma_1 \) value to be designed for.

\( M_1 \) = Bending moment at the station.

\( M_2 \) = Bending moment at midship station.

\( \sigma_1 \text{all} = 8.7 \text{ tons per sq. in.} \)

\( \frac{Z_2}{Z_1} \) was assumed to equal unity.

Using this value of \( \sigma_1 \), the stress schedules were drawn up in the usual manner, and the shell plating was sized for two different cases. First, the thickness required for ultimate strength under hydrostatic load was computed from

\[ t_{\text{hyd}} = 0.473b \sqrt{\frac{KH}{\sigma_3}} \]  

(2)

This calculation was made for all strakes of shell and deck plating. The second calculation made from the stress schedule was to size the plate for instability, assuming that the plate panels were acted upon only by an edge compressive loading.

\[ t_{\text{inst}} = 1.92 \times 10^{-4} b \sqrt{\frac{\sigma_1}{K}} \]  

(3)

In order to give due consideration to the effect of the shearing force, the shell plating was sized a third time using the following criteria:

Simply for the purpose of sizing the shell, it was assumed that shear is the only force system acting on the shell. A value of \( \tau_{cr} \) was then assumed.
In making this assumption, the critical value was related to the yield value in shear, which was a known quantity, by the relationship.

\[ \tau_{cr} = \tau_y \frac{1}{S.F.} \]

where \( \tau_y = 22,800 \text{ psi} \)

S.F. = safety factor

When making this assumption, it was recognized that this value of \( \tau_{cr} \) does not, in fact, represent the actual critical value. Other parameters, notably the panel aspect ratio, and the value of \( \frac{b}{t} \) will effect the critical. However, in this stage of the design, it was found that the above approximation produced fairly reliable values of the critical stress, compared to those which were later calculated.

In further refinements of the design process, a closer estimate of the critical value of shear can be obtained by using a method of successive approximations. Once the scantlings have all been sized, it is possible to calculate the value of the critical and this value can be used for the second cycle of calculations. At the forward section the actual values of the critical shear stress intensity at the stringer strake for schemes A, B and C are as follows:

- Scheme A, \( \tau_{act} = 18,250 \text{ psi} \)
- Scheme B, \( \tau_{act} = 17,650 \text{ psi} \)
- Scheme C, \( \tau_{act} = 16,750 \text{ psi} \)
In arriving at the original assumption of $\tau_{cr}$ an arbitrary value of 1.5 was assigned as a safety factor. The safety factors implied by the actual values of $\tau_{cr}$ can be found from

$$\text{Factor of Safety} = \frac{22,800}{\tau_{cr}}$$

(5)

Which gives for

<table>
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<th>S.F.</th>
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<td>A</td>
<td>1.25</td>
</tr>
<tr>
<td>B</td>
<td>1.29</td>
</tr>
<tr>
<td>C</td>
<td>1.36</td>
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By using the assumed value of $\tau_{cr}$ the thickness of plating required to satisfy the shear force, acting by itself, can be found from

$$\tau_{cr} = K_s \frac{\pi D}{tsb^2}$$

(6)

$$t = b \sqrt{\frac{\tau_{crit}}{(26.75 \times 10^6) K_s}}$$

let $\tau_{cr} = 15,300$

$$t = 2.38 \times 10^{-2}b\sqrt{\frac{1}{K_s}}$$

Having obtained the plate thickness required by each of three separate and independent criteria, the shell plate size was selected as the smallest standard plate which was necessary to satisfy all three cases. It was possible to size longitudinals in accordance with standard methods, in the same manner as at the midship section. Inertia calculations were carried out after all scantlings had been sized. In making the inertia calculations for all of the schemes, the values of area, moment, and lever arm for the
platforms were considered as constants and entered as such.

Once the inertia calculations were completed, it was possible to check the entire section by established design criteria. At this point, however, new design criteria were necessary, in order to give due regard to the interaction of shear and edge compression on the panels. Two separate criteria were used for this analysis. The first was based upon an interaction formula given by St. Denis [10], and the second was based upon the work of Bleich and Ramsey.[3]

First Method.

The interaction formula given by St. Denis considers the case of plate panels under combined shear and edge compression, stressed in compression across the short sides. This formulation is stated as follows:

$$ R_s \cdot 5 + R_c = \frac{1}{f} $$

where

$ R_s = \frac{\text{Intensity of applied shear stress}}{\text{Critical shear for simple loading}} $  

$ R_c = \frac{\text{Intensity of applied edge compression}}{\text{Critical stress for simple loading}} $  

$ f = \text{Factor of safety}.$

By applying this criterion to similar existing vessels, the value of $f$ was found to vary between 1.25 and 2.0. Accordingly, in the designs of the various schemes, the safety factor was maintained within these limits.

Second Method

This criterion was based upon "A Design Manual or the Buckling Strength of Metal Structure" by Bleich and Ramsey, pg. 41. By using this method the values of $\sigma_{cr}$ and $\tau_{cr}$ can
be determined. These values represent the criticals under the combined effects of both edge compression and shear, and differ from the values of the criticals in the first method in this respect. Consequently, by using the second method an instability failure will occur when either $\sigma_1 = \sigma_{\text{crit}}$ or $\tau = \tau_{\text{crit}}$. Thus the second method can be expressed as

$$\frac{\sigma_1}{\sigma_{cr}} = \frac{\tau}{\tau_{cr}} = \frac{1}{S.F.}$$

Previous designs indicated that by using this method, the safety factors are slightly higher than the first method and range between 1.4 and 2.4.

The description of the design procedure for the quarter point stations given above and the use of the design criteria specified was the basis for all of the calculations on the end stations. This procedure is one of successive approximations and it may be necessary to carry out a second or even third cycle of calculations. However, the method converges rapidly.

2.5 Web Frame Calculations

Due to the limited time available for this particular phase of the study, it was impractical to attempt nine separate ring frame calculations to determine web frame size. Since one web frame from a ring frame calculation was available for an eight foot spacing on a similar existing ship, it was felt that this could be used as a base, with a suitable percentage variation in weight, as spacing departed from eight feet. This approach, though not exact, was considered to yield results which would not vary appreciably from those derived from nine ring frame
calculations.

The method used to obtain the percentage variation in weight was based on the procedure outlined in Section 28 of the 1954 edition of American Bureau of Shipping Rules. Where departure was made from the rules in regard to depth of web to length ratio, appropriate modification was made to the formulation for the Frame Numeral. The depth of web was chosen to be compatible with the transverse section concerned and such that the Frame Numeral would lie in or near the tabulated range. The web thicknesses were chosen in conformance with Section 28, American Bureau of Shipping Rules, but the hydrostatic head used was that shown in the original design criteria. This departure from Rule procedure was necessary for consistency in design criteria.

Using American Bureau of Shipping Rules, as modified above, the web frame scantlings at a particular transverse section were determined for web spacings from 5.34 feet through 12 feet. Web frame volumes, which correspond to web frame weight, were calculated and this information was placed on a percentage basis with the eight foot web spacing being the base of 100%. Thus, a curve of percentage of 8 foot web frame weight vs. web frame spacing was obtained. This information, in conjunction with a designed web frame, was used to determine total web frame weight. This procedure is detailed in section 2.7 and sample calculations appear in the appendix.

2.6 Determination of Hull Steel Weight between the Forward and After Sections

The only weights included in this analysis were those
which were dependent on design calculations made in this thesis. These were:

1. Main deck plating
2. Main deck longitudinals
3. Shell plating
4. Shell longitudinals
5. Web frames

The inclusion of the weights of items which had been previously determined to be invariant would serve to detract from the relative merit of the various spacing schemes which were calculated. Thus, platform decks and longitudinal bulkheads were included for inertia calculations, where effective, but not in weight calculations.

2.7 Method of Summation of Weights

In determining the total weight of the hull steel in the length considered, it was apparent that items one through four in Section 2.6 lent themselves to a calculation of weight per foot of length in the longitudinal direction. Similarly, item five lent itself to a computation on the basis of weight per foot of girth.

2.7.1 Longitudinal Material

From the inertia calculations, it was one additional step to compute, at each of the stations considered, the weight per foot of longitudinal material.

With three values of weight per foot for each scheme, some method of summation was necessary. Since it was impractical, through lack of time, to obtain additional points on the weight per foot curve, it was decided that some form
of approximate integration would be used to obtain the total weight of longitudinal material. Although it was desirable to obtain representative weights, this study is primarily one of comparison, and it was felt that a small inaccuracy in total weight, through approximate integration, would not materially alter the value of the results; provided, of course, that the method was consistent.

In arriving at the shape of the weight per foot curve, the following items were considered; 1) girth, 2) waterline form, and 3) the shape of the bending moment curves between the three points. All of these factors indicated a parabolic shape, and it was decided that no better method of summation could be made than that resulting from the assumption of a second order parabola for the weight curve. Simpson's first rule was therefore used to integrate the longitudinal weight per foot curve between the three calculation points.

2.7.2 Transverse Material

From the web frame calculations, a curve was derived which showed, on a percentage basis, the weights of web frames spaced at other than eight feet. From the shell expansion, a summation of girths was made for each web spacing for each scheme. With the total girth at each spacing and the weight per foot of girth at each spacing, it was possible to calculate the summation of web frame weight for each scheme. Sample calculations are included in the Appendix.
III. RESULTS

The results of the calculations performed on the various schemes are most easily shown and interpreted by plots of the total weight of the structure vs. the number of longitudinals in the shell. Separate plots showing the weight of shell plating, weight of webs, and weight of longitudinals are included to indicate where any weight saving is possible and its magnitude. A plot of total weight, using a constant eight foot web spacing, is included to show the effect of variations in web spacing. These plots embody the general results of all calculations.
### TABLE I

**Weight Summary**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Wgt/ft. forward</th>
<th>Wgt/ft. midships</th>
<th>Wgt/ft. aft</th>
<th>Total wgt. of long'l material</th>
<th>Web Frame Weight</th>
<th>Total Weight</th>
<th>% of 2A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>2174</td>
<td>3390</td>
<td>2316</td>
<td>734,094</td>
<td>52,234</td>
<td>786,328</td>
<td>1.072</td>
</tr>
<tr>
<td>1B</td>
<td>2239</td>
<td>3447</td>
<td>2368</td>
<td>748,084</td>
<td>49,176</td>
<td>797,260</td>
<td>1.085</td>
</tr>
<tr>
<td>1C</td>
<td>2313</td>
<td>3577</td>
<td>2423</td>
<td>774,576</td>
<td>38,438</td>
<td>813,014</td>
<td>1.109</td>
</tr>
<tr>
<td>2A</td>
<td>1811</td>
<td>3231</td>
<td>2036</td>
<td>682,077</td>
<td>52,234</td>
<td>734,311</td>
<td>1.000</td>
</tr>
<tr>
<td>2B</td>
<td>1867</td>
<td>3247</td>
<td>2039</td>
<td>687,172</td>
<td>49,176</td>
<td>738,348</td>
<td>1.005</td>
</tr>
<tr>
<td>2C</td>
<td>1943</td>
<td>3327</td>
<td>2090</td>
<td>705,055</td>
<td>38,438</td>
<td>743,492</td>
<td>1.012</td>
</tr>
<tr>
<td>3A</td>
<td>1825</td>
<td>3265</td>
<td>1884</td>
<td>681,995</td>
<td>52,234</td>
<td>734,229</td>
<td>1.000</td>
</tr>
<tr>
<td>3B</td>
<td>1876</td>
<td>3280</td>
<td>1892</td>
<td>688,462</td>
<td>49,176</td>
<td>737,638</td>
<td>1.006</td>
</tr>
<tr>
<td>3C</td>
<td>1949</td>
<td>3342</td>
<td>1941</td>
<td>701,883</td>
<td>38,438</td>
<td>740,320</td>
<td>1.009</td>
</tr>
</tbody>
</table>
Figure V

Percentage in weight of:
- Plates
- Longitudinals
- Web frames

For various schemes.
IV. DISCUSSION OF RESULTS

4.1 Evaluation of work

From the plots included in the results there are three main facts which are evident.

a) From the plot of per cent increase in weight (Fig. III), the most immediate conclusion to be drawn is that only one per cent of total structural weight can be saved by departing from the use of a standard and constant eight foot web spacing. This small saving was achieved by reducing the web frame spacing in the end sections from 8 feet to 5.34 feet and using a total of twelve shell longitudinals.

b) The plot showing the total weight of structure vs. the number of longitudinals indicates that for all schemes there exists a minimum number of longitudinals which will yield a minimum structural weight. Increasing this number of longitudinals has negligible effect upon the total structural weight. The web spacing has some effect upon this minimum number of longitudinals, although this effect is slight. For our hypothetical ship and our design criteria this number appears to be 10 or 11.

c) The indication of all plots is that by decreasing the web spacing toward the ends some weight saving, for a given number of longitudinals, is possible.
4.2 Significance of Results

The significance of the results stated above can be analysed from the point of view of their overall effect on the design approach which is to be used by the structural designer and the effect this approach will have on the final design.

Item (a) in the evaluation indicates that there is nothing sacred about the traditionally constant web spacing. In fact, by using a variable spacing of webs, a structural weight which is smaller than the constant spacing weight is possible. The calculations made, however, indicate that this weight saving is small and the structural designer may not desire to change his spacing merely to gain one per cent in structural weight. Perhaps the most significant point to be borne in mind concerns the spacing of webs from an arrangement point of view. The calculations have shown that it is to the advantage of the designer to have a larger web spacing amidships and narrow this spacing at the ends of the vessel. This type of web space variation can be used advantageously by the arrangement designer. Within the machinery spaces where webs are used to provide proper foundations for machinery, and where large items of equipment are placed between webs, the larger spacing is desirable. However, outside of the machinery spaces there is no need for such a large spacing. In these areas, since no large pieces of equipment must be fitted between webs, it is possible that the web frames can be spaced in accordance with the dictates of the arrangement studies. In doing so,
the problem of arriving at an efficient arrangement will be somewhat simplified and at the same time the structural weight will decrease.

Item (b) in the evaluation indicates that considerable care must be taken in selecting the number of side longitudinals to be used. For example, if only nine longitudinals had been used, a sacrifice in weight of ten per cent would be incurred. By using more than the minimum number of longitudinals, no weight advantage of importance is gained. However, by using more than the minimum amount, construction costs increase due to the additional amount of welding necessary, and the internal arrangements problem is made somewhat more difficult. Accordingly, from a design viewpoint, it is of the utmost importance to use the minimum number of side longitudinals. This number is a function of the girth of the ship amidships, the material and the web spacing amidships. It represents the maximum spacing of longitudinals with which plate scantlings do not become so large that the minimum required section modulus is exceeded. No formulation for arriving at this number was derived as a result of this thesis and it is recommended that additional work be carried out along these lines because of the importance and significance attached to it.

Item (c) indicates that by decreasing the web spacing, weight saving is realized. This fact, however, has little significance because there is a lower limit under which webs should not be spaced, simply from a practical construction or arrangement point of view. The only significance which
can be attached to this is that if a choice is to be made between two web frame spacings, especially in the end sections of the vessel, the smaller spacing should be selected.
V. CONCLUSIONS

a) The designer has considerable latitude in varying the web frame spacing along the length of the ship, without appreciably affecting the total weight of structure. A constant spacing offers no advantage.
b) Some weight saving is accomplished by reducing the web spacing at the ends from that amidships.
c) Arrangement requirements and studies can dictate the web spacing without sacrificing structural weight.
d) All other things being equal, when a decision regarding the selection of one of two web frame spacings is to be made, the smaller spacing should be selected for it will give the least weight.
e) The number of shell longitudinals used is a critical item and its determination should be made with care.
f) In order to arrive at any weight reduction of structural material, a reanalysis of the existing design criteria seems to be the most promising field.
VI. RECOMMENDATIONS

The calculations which were carried out indicate that the designer has a considerable amount of latitude in varying the spacing of stiffeners without appreciably affecting the total weight of structure. In the design approach and procedure used, however, specific design criteria appeared to have a considerable influence on specific areas where weight might have been saved. This, in fact, is the purpose of design criteria. However, since such importance has been attached to their use and the limitations which they force upon the designer, it may well be worth while to reevaluate the validity of some design criteria. Of paramount importance is the choice of the proper wave characteristics to be used in arriving at the bending moments. Actually, there is little certainty in the present methods of defining the wave profile, and the effect upon the weight and structural design is out of proportion to the trust placed in the original assumption.

A second criteria of design which requires investigation, and a field in which over-design may well be eliminated, deals with the end conditions of those plate panels and longitudinals normally sized from instability considerations. The assumption that fully clamped conditions exist in any panel subjected to more than 15 feet of hydrostatic head neglects the many other factors which have perhaps a greater influence on the degree of fixity which exists. Many panels under no hydrostatic head appear to have a greater degree of fixity than others under heavy
water pressure. In panels normally sized on the basis of instability, considerable weight saving seems feasible through an accurate evaluation of end conditions.

Investigation along the same line could be directed toward the design criteria regarding the limiting value of \( \frac{1}{r} \) for longitudinals with the goal of either modifying the existing limits or introducing a new approach to the problem. Limiting the \( \frac{1}{r} \) of longitudinals at the neutral axis, for example, seems to be an illogical design criteria in an area where compressive stress is of insignificant magnitude.

These three specific design criteria play a large part in limiting the flexibility of the over-all design approach. Any refinements in these criteria should lead to a design of reduced weight.

Since the calculations which were performed pointed out the importance of initially selecting the minimum number of shell longitudinals, it is recommended that further investigation along this line be carried out. A simple formula which could relate the governing parameters in order to give the designer the number of longitudinals to be used during the first stages of design would be extremely helpful and would by-pass the present method of carrying out additional investigations to determine the optimum number. As a starting point in this investigation, some insight into the method of approach may be gained from the work of St. Denis and Timoshenko. St. Denis deals with the case of a flat unstiffened plate and states that the
required number of stiffeners in the direction of compression can be expressed as

\[ n > \sqrt{\frac{\sigma_v}{\sigma_{cr}}} - 1 \]

An approach of this type may well be modified to include the effects of shape and varying thickness.
VII. APPENDIX
APPENDIX A

SAMPLE CALCULATIONS

Part I Midship Section - Scheme 2C

Assumed neutral axis: 13' above M.B.L.
(Final calculated neutral axis was 12.91')

(1) Stress Schedule - Strake A

Web Spacing (a) = 12'. Longitudinal Spacing (b) = 36'.
a/b = 4.  H = 20'

Inner Plate Surface
Hogging
σ1 = -19,500 (see design criteria # 4) +14,500
σ2 = + 2,000 (to be verified) + 2,000
σ3 = -27,500 +28,500
σy = -45,000 +45,000

Outer Plate Surface
Sagging

K = .685

\[ t = \frac{b}{12} \sqrt{\frac{KH}{2\sigma_3}} = \frac{b}{12} \sqrt{\frac{64}{2}} \sqrt{\frac{KH}{\sigma_3}} \]

\[ = .473 \ b \sqrt{\frac{KH}{\sigma_3}} = 17.05 \sqrt{\frac{19.85}{27,500}} = .463'' \]

Instability check: ends are assumed fixed  K = 7.4

\[ t = \frac{(1-u^2)}{E} \frac{c_{cr}b^2}{\pi^2K} = \frac{b}{\pi} \sqrt{\frac{(1-u^2)}{E}} \sqrt{c_{cr}/K} \]

\[ = 1.92 \times 10^{-4} \times b \sqrt{\frac{19,500}{7.4}} = .355'' \quad (OK) \]

U.C.S. Check:

\[ B = \frac{b}{t} \sqrt{\frac{c_{y}}{E}} = 0.03878 \times \frac{36}{.463} = 2.81 \quad USR = .620 \]

U.C.S. = 0.620 x 45,000 = 27,900

1.25 x 19,500 = 24,400 - OK

Therefore: t = .463'' is the minimum required thickness
(ultimately used .625'' Plate for I/y considerations)
(2) Strake B

\[ WS = 12', \quad LS = 36'' \quad a/b = 4 \quad H = 2.83 \text{ (scaled)} \]

\[
\begin{align*}
\text{I. P. S.} & \quad (\text{Hogging}) & \text{O. P. S.} & \quad (\text{Sagging}) \\
\sigma_1 & = -19,500 \times \frac{12.3}{13} = -18,500 & & +13,500 \\
\sigma_2 & = +2,000 & & +2,000 \\
\sigma_3 & = -28,500 & & +29,500 \\
\sigma_y & = -45,000 & & +45,000 \\
\end{align*}
\]

\[ K = .685 \]

\[ t = .473b \sqrt{\frac{KH}{\sigma_3}} = .445'' \]

Instability check and U.C.S. check - okay by inspection with strake A.

(Ultimately used .5625" plate for I/y considerations)

(3) Strake C

\[ WS = 12', \quad LS = 42'' \quad a/b = 3.43 \quad H = 26.3 \text{ (scaled)} \]

\[
\begin{align*}
\text{I. P. S.} & \quad (\text{Hogging}) & \text{O. P. S.} & \quad (\text{Sagging}) \\
\sigma_1 & = 19,500 \times \frac{10.3}{13} = -15,400 & & +11,500 \\
\sigma_2 & = +2,000 & & +2,000 \\
\sigma_3 & = -31,600 & & +31,500 \\
\sigma_y & = -45,000 & & +45,000 \\
\end{align*}
\]

\[ K = .685 \]

\[ t = .473b \sqrt{\frac{KH}{\sigma_3}} = 19.85 \sqrt{\frac{.685 \times 26.3}{31,500}} = .474'' \]

Instability Check

\[ t = 1.92 \times 10^{-4} \times 42 \sqrt{\frac{15,400}{7.4}} = .370'' \quad - \quad \text{OK} \]

U.S.C. Check

\[ B = .03878 \times \frac{42}{.504} = 3.23 \quad \text{U.S.R.} = .587 \]

\[ \text{U.C.S.} = .587 \times 45,000 = 26,400 \]
1.25 \times 15,400 = 19,250

t = .474" is the minimum required thickness

(Ultimately used .50" plate as indicated by the stress schedule)

(4) Strake D

\[
\begin{align*}
WS &= 12' \\
LS &= 42" \\
a/b &= 3.43 \\
H &= 21.6
\end{align*}
\]

I. P. S. (Hogging) \quad O.P.S. (Sagging) \quad Girthwise

\[
\begin{align*}
\sigma_1 &= 19,500 \times \frac{5.6}{13} = -8,400 + 6,250 = 0 \\
\sigma_2 &= +2,000 + 2,000 + 3,000 \\
\sigma_3 &= -36,600 + 36,750 + 42,000 \\
\sigma &= -45,000 + 45,000 + 45,000
\end{align*}
\]

**Longitudinal Criteria**

\[
t = .473 \times 42 \sqrt{\frac{.685 \times 21.6}{36,750}} = .394"
\]

**Girthwise Criteria**

\[
t = .473 \times 42 \sqrt{\frac{1 \times 21.6}{42,000}} = .430" - \text{(controls)}
\]

Instability and U.C.S. Check - okay by inspection with strake A.

(Ultimately used .4375" plate as indicated by stress schedule)

(5) Strake E

\[
\begin{align*}
WS &= 12' \\
LS &= 42" \\
a/b &= 3.43 \\
H &= 14.8'
\end{align*}
\]

I. P. S. (Hogging) \quad O.P.S. (Sagging) \quad Girthwise

\[
\begin{align*}
\sigma_1 &= 19,500 \times \frac{2}{12} = -3,000 + 1,800 = 0 \\
\sigma_2 &= +2,000 + 2,000 + 3,000 \\
\sigma_3 &= -44,000 + 41,200 + 42,000 \\
\sigma &= -45,000 + 45,000 + 45,000
\end{align*}
\]

Obviously girthwise stress controls

\[
t = .473 \times 42 \sqrt{\frac{14.9 \times 1}{42,000}} = .370"
\]
(Ultimately used \( .375'' \) plate as indicated by stress schedule)

(6) Strake F

\[
WS = 12', \quad LS = 36'' \quad a/b = 4 \quad H = 7
\]

I.P.S. (Hogging)  
\[
\sigma_1 = 19,500 \times \frac{11}{13} = +16,500
\]
\[
\sigma_2 = +2,000
\]
\[
\sigma_3 = +26,500
\]
\[
\sigma_3 = +45,000
\]

\[
K = .685
\]
\[
t = 17.05 \sqrt{\frac{4.1}{26,500}} = .218''
\]

**Instability Check**

Since \( H \) is 7' maximum, only simply supported edges can be assumed.

\[
t = 1.92 \times 10^{-4} x 36 \sqrt{\frac{13,300}{4}} = .398'' \quad \text{(controls)}
\]

**U.C.S. Check**

\[
B = .03878 \times \frac{36}{.398} = 5.18 \quad \text{USC} = .600
\]
\[
U.C.S. = .600 \times 45,000 = 27,000
\]
\[
1.25 \times 12,300 = 15,400 \quad \text{OK}
\]

(Ultimately used \( .50'' \) plate to match stringer plate and for I/y)

(7) Deck Plating - Strake G (Stringer Plate)

In all deck plating \( \sigma_1 \) is assumed as \( \sigma_1(\text{max}) \).

As head is small, instability controls.

Criteria: \( \sigma_{cr} = \sigma_1 + \frac{\sigma_2}{2} = -15,500 \)

\[
WS = 12' \quad LS = 37.5'' \quad K = 4 \quad \text{(edges simply supported)}
\]
\[
t = 1.92 \times 10^{-4} \times 37.5 \sqrt{\frac{15,500}{4}} = .480''
\]

(Ultimately \( .5625'' \) plate for I/y)
(8) Deck Plating - Strakes H-K

WS = 12'  LS = 37''  K = 4  a/b = 3.89

Instability controls

\[ t = 1.92 \times 10^{-4} \times 37 \times \sqrt{\frac{15,500}{4}} = 0.472 \]

(used .50" plate as indicated by instability requirements)

(9) Longitudinals (1)-(4) in bottom

A. First Design - Based on \( t = .50" \) (20.4# Plate)

\[ \sigma_1 = -19,500 \]
\[ \sigma_2 = -16,500 \]
\[ \sigma_y/1.25 = -36,000 \]

\[ r(\text{min}) = \frac{12' \times 12}{30} = 4.8 \]

\[ M_{\text{max}} = \frac{wL^2}{12} = \rho Hs1^2/12 = 5.33 \times 29 \times 144 = 802,000\# \text{ in.} \]

\[ Z_{\text{min}} = \frac{M_{\text{max}}}{\sigma_{2\text{max}}} = \frac{802,000}{16,500} = 48.5 \]

try 10 x 8 x 39# I-T (25.7#) \[ 7.56 \text{ in}^2 \]

\[ Z = 49 \ I = 370 \ A = 15+7.56 = 22.56 \]
\[ r = \sqrt{370/22.56} = 4.05 \text{ - too low} \]

try 12 x 8 x 40# I-T (26.9#) \[ 7.92 \text{ in}^2 \]

\[ Z = 60 \ I = 540 \ A = 15+7.92 = 22.92 \]
\[ r = \sqrt{540/22.92} = 4.86 \text{ - OK} \]

B. Ultimate Design based on \( t = .625" \) (28.05# plate)

For 1 & 2, and .5625" plate (22.95# Pl.) for 3 & 4

try 12 x 8 x 45# I-T (30.4#) \[ 8.95 \text{ in}^2 \]

\[ Z = 70 \ I = 690 \ A = 23.4+8.95 = 32.4 \]
\[ r = \sqrt{690/32.4} = 4.59 \text{ - too low} \]
try T-14 x $\frac{63}{4} \times 34$\# (24.43\#) $[7.19 \text{ in}^2$]

\[ Z = 74 \quad I = 705 \quad A = 23.4 + 7.2 = 30.6 \]

\[ r = \sqrt{\frac{705}{30.6}} = 4.80 \quad \text{good} \]

therefore \#1 & \#2 longitudinals are T-14 x $\frac{63}{4} \times 34$\#

For 3 & 4 \[ t = 0.5625" \ (22.95\#) \]

required \[ r = \frac{144}{32} = 4.5 \]

try T-12 x $\frac{61}{2} \times 31$\# (21.51\#) 6.32 in\^2

\[ Z = 66 \quad I = 500 \quad A = 19 + 6.3 = 25.3 \]

\[ r = \sqrt{\frac{500}{25.3}} = 4.45 \quad \text{OK} \]

(10) Longitudinal No. 6 - (No. 5 is intercostal docking longitudinal)

\[ \sigma_1 = 19,500 \times \frac{8.8}{13} = -13,300 \quad H = 25' \]

\[ \sigma_2 = \underline{-22,700} \quad t = 20.4\# \ (0.50") \]

\[ 45,000/1.25 = -36,000 \]

\[ M_{\text{max}} = 5.33 \times 25 \times 144 = 691,000 \text{ in.}\# \]

\[ Z_{\text{min}} = \frac{691,000}{22,700} = 30.4 \]

try 12 x 4 x 22\# I-T (16.9\#) $[4.98 \text{ in}^2$]

\[ Z = 32.1 \quad I = 336 \quad A = 15 + 5 = 20 \]

\[ r = \sqrt{I/A} = \sqrt{336/20} = 4.10 \]

\[ t = 144/4.10 = 35 \quad \text{OK} \]

(11) Longitudinals No. 7 & 8

\[ \sigma_1 = 19,500 \times \frac{6.5}{13} = -9,750 \quad H = 22.5 \]

\[ \sigma_2 = -26,250 \quad t = 17.85\# \ (0.4375") \]

\[ M_{\text{max}} = 5.33 \times 22.5 \times 42 \times 144 = 726,000 \]

\[ Z_{\text{min}} = \frac{726,000}{25,850} = 27.0 \]
try 12 x 4 x 19# I-T (14.9#) \[4.39 \text{ in}^2\]

\[Z = 27.2 \quad I = 153 \quad A = 11.5 + 4.4 = 15.9\]

\[r = \sqrt{\frac{158}{15.9}} = 3.10 \quad L/r = \frac{144}{3.10} = 46 - \text{OK}\]

(12) Longitudinal No. 9

\[\sigma_1 \approx 0 \quad \sigma_2 = 36,000 \quad H = 17\]

\[M_{max} = 5.33 \times 17 \times 43.4 \times 144 = \frac{569,000 \text{ in.}\#}{t = 15.30\# \ (375\")}\]

required \[Z = \frac{569,000}{36,000} = 15.8\]

try 10 x 4 x 15# I-T (11.7#) \[3.45 \text{ in}^2\]

\[Z = 17.5 \quad I = 144 \quad A = 8.41 + 3.45 = 11.86\]

\[r = \sqrt{\frac{144}{11.86}} = 3.5 \quad L/r = 41.2 - \text{OK}\]

(13) Longitudinals No. 11 & 12 (No. 10 is invariable)

\[\sigma_1 = -14,500 \times \frac{9}{13} = -10,900 \quad H = 10\]

\[\sigma_2 = -25,100 \quad t = 20.40\# \ (50\")\]

\[M_{max} = 5.33 \times 10 \times 36 \times 144 = 276,000 \]

\[Z_{min} = \frac{276,000}{25,000} = 12.7\]

try 8 x 4 x 13# I-T (10.0#) \[2.94 \text{ in}^2\]

\[Z = 12.9 \quad I = 95 \quad A = 15 + 2.9 = 17.9\]

\[r = \sqrt{\frac{95}{17.9}} = 2.3 \quad L/r = 63 - \text{too high}\]

try 10 x 4 x 11.5# I-T (9.1#) \[2.67 \text{ in}^2\]

\[Z = 13.8 \quad I= 125 \quad A = 15 + 2.67 = 17.7\]

\[r = \sqrt{\frac{125}{17.7}} = 2.68 \quad L/r = 54 - \text{OK}\]

(14) Deck Longitudinals

Obviously \[L/r\] will control as \[H\] is only 4'.

For \[t = .5625\"]
try \( 8 \times 4 \times 15\# \) I-T \((11.3\#) \) \( [3.33 \text{ in}^2] \)

\[
Z = 15.3 \quad I = 116 \quad A = 18 + 3.3 = 21.3 \\
r = \sqrt{\frac{116}{21.3}} = 2.34 \quad L/r = 61 \quad \text{too high}
\]

try \( 10 \times 4 \times 15\# \) I-T \((11.7\#) \) \( [3.45 \text{ in}^2] \)

\[
Z = 18.2 \quad I = 170 \quad A = 18 + 3.5 = 21.5 \\
r = \sqrt{\frac{170}{21.5}} = 2.82 \quad L/r = 51 \quad \text{OK}
\]

For \( t = 0.500" \)

The \( 10 \times 4 \times 11.5\# \) I-T will satisfy design criteria but the \( 10 \times 4 \times 15\# \) I-T is required for I/y. Therefore all deck longitudinals are the same.

**Part II - Forward Section - Scheme 2C**

Assumed Neutral Axis: 16' above M.B.L.  
(Final calculated neutral axis was 15.77')

(1) Stress Schedule - Strake A

Web Spacing \((a) = 8'\). Longitudinal Spacing \((b) = 37"\).
\[
a/b = 2.6 \quad H = 35.9
\]

Reduced \( \sigma_1 = 19,500 \left(\frac{M_1}{M_2}\right)^{\frac{Z_2}{Z_1}} = 3,050 \text{ psi. (see procedure)} \)

<table>
<thead>
<tr>
<th>Inner Plate Surface Hoggig</th>
<th>Outer Plate Surface Sagging</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_1 )</td>
<td>- 3,050</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>+ 2,000 (to be verified)</td>
</tr>
<tr>
<td>( \sigma_3 )</td>
<td>-43,950</td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>-45,000</td>
</tr>
</tbody>
</table>

\[
K = 0.685 \\
K = \frac{b}{12} \sqrt{\frac{K \rho H}{\sigma_3}} = 0.473b \sqrt{\frac{KH}{\sigma_3}} \\
t = 0.434 \text{ in.}
\]
Instability check: (ends assumed fixed, \( K = 7.85 \))

\[
t = 1.92 \times 10^{-4} b \sqrt{\frac{\sigma_1}{K}} = 0.140''
\]

Therefore, the thickness calculated checks for instability.

**U.C.S. Check**

\[
B = \frac{b}{t} \sqrt{\frac{\sigma_Y}{E}} = 3.84
\]

From Chart \( F = 0.500 \)

\[\text{U.C.S.} = 0.50 \times (45,000) = 22,500\]

\[1.25 \times (3,050) = 3,920\]

Therefore, the minimum required thickness is

\[t = 0.434\] for Strake A.

(Ultimately used 17.85\# Plate, .4375 in.)

(2) Strake B.

\[
\text{WS} = 8' \quad \text{LS} = 36'' \quad a/b = 2.6 \quad H = 33'
\]

**I.P.S. (Hogging)**

\[
\sigma_1 = -3,050 \left(\frac{12.5}{16.6}\right) = -2,300
\]

\[
\sigma_2 = +2,000
\]

\[
\sigma_3 = -44,700
\]

\[
\sigma_Y = -45,000
\]

\[K = 0.685\]

\[t = 0.473b \sqrt{\frac{KH}{\sigma_3}} = 0.400\text{ in.}\]

Instability and U.C.S. check by inspection and comparing with Strake A.

(3) Strake C.

\[b = 36 \quad K = 0.685 \quad H = 28.40\]
I.P.S. (Hogging)

\[
\begin{align*}
\sigma_1 &= -3,050 \left( \frac{7.8}{16.0} \right) = -1,430 \\
\sigma_2 &= +2,000 \\
\sigma_3 &= -45,570 \\
\sigma_4 &= -45,000 \\
t &= .473b \sqrt{\frac{KH}{\sigma_3}} = 0.378
\end{align*}
\]

(4) Strake D (Neutral Axis)

\[
b = 36'' \quad K_B = .685 \quad H = 18.65 \quad a/b = 2.6
\]

Girthwise criteria controls plating size.

\[
t = \frac{36}{12} \sqrt{\frac{0.5(64)(18.65)}{42,000}} = 0.357 \text{ in.}
\]

(5) Strake E.

\[
b = 36 \quad H = 16.15 \quad a/b = 2.6
\]

I.P.S. (Hogging)

\[
\begin{align*}
\sigma_1 &= -3,050 \left( \frac{4.5}{14.6} \right) = -940 \\
\sigma_2 &= +2,000 \\
\sigma_3 &= -46,060 \\
\sigma_4 &= -45,000 \\
t &= .473(36) \sqrt{\frac{(0.685)(16.15)}{42,060}} = 0.275 \text{ in.}
\end{align*}
\]

(6) Strake F (Shear Strake)

\[
H = 10.15
\]

I.P.S. (Hogging)

\[
\begin{align*}
\sigma_1 &= -3,050 \\
\sigma_2 &= +2,000 \\
\sigma_3 &= -43,950 \\
\sigma_4 &= -45,000 \\
t &= .473(36) \sqrt{\frac{(0.685)(10.15)}{39,050}} = .228
\end{align*}
\]
(7) Main Deck, sized for edge compression alone
Stress Schedule same as Strake F.

\[ b = 31" \quad H = 8' \]

\[ t = 0.196 \text{ in.} \]

(8) After sizing all strakes of plate as above, it was again sized, assuming plate panels were acted upon simply by a shearing force, and the minimum thickness required to resist critical buckling was computed.

\[ \tau_{cr} = 15,300 \text{ (see procedure)} \]

\[ \tau_{cr} = 26,750,000 \left( \frac{t}{b} \right)^2 K_s \]

\[ t = 0.0238 b \sqrt{\frac{1}{K_s}} \]

Summarizing the shear calculations, the following results were obtained:

<table>
<thead>
<tr>
<th>Strake</th>
<th>a/b</th>
<th>(K_s)</th>
<th>(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>3.1</td>
<td>6.2</td>
<td>0.296 in.</td>
</tr>
<tr>
<td>H</td>
<td>3.55</td>
<td>5.9</td>
<td>0.264</td>
</tr>
<tr>
<td>J</td>
<td>3.2</td>
<td>6.0</td>
<td>0.291</td>
</tr>
<tr>
<td>K</td>
<td>3.69</td>
<td>5.9</td>
<td>0.254</td>
</tr>
<tr>
<td>F</td>
<td>2.68</td>
<td>6.5</td>
<td>0.336</td>
</tr>
<tr>
<td>E</td>
<td>2.74</td>
<td>6.4</td>
<td>0.326</td>
</tr>
</tbody>
</table>

Strake A, B, C, and D were governed by hydrostatic conditions, while all other strakes were governed by the shear condition.

(9) Longitudinals (1)-(4) in bottom.
A. Designed on base of \(t = 0.4375"\) (17\# plate)

\[ \sigma_1 = -3,050 \]

\[ \sigma_2 = -32,950 \]

\[ \frac{\sigma_y}{1.25} = -36,000 \]

\[ r_{\text{min}} = \frac{96}{30} = 3.2 \]
\[ M_{\text{max}} = \frac{-wl^2}{12} = \frac{\rho Hz^2}{12} = 428,000 \text{ psi.} \]

\[ Z_{\text{min}} = \frac{M_{\text{max}}}{\sigma_2} = \frac{428,000}{32,950} = 13. \]

Using a 10" x 4" x 11.5" I-T

\[ Z = 13.65 \quad A = 2.67 + 11.48 = 14.15 \]

\[ I = 121 \]

\[ r = \sqrt{\frac{121}{14.15}} = 2.92 \]

Therefore, a 10" x 4" x 11.5" I-T should be used for longitudinals 1, 2, 3, and 4.

(10) Longitudinal 6 (Note that No. 5 is intercostal)

\[ M_{\text{max}} = 334,000 \]

\[ Z_{\text{req}} = 9.65 \]

Using an 8 x 4 x 10# I-T

\[ Z = 9.89 \quad A = 2.23 + 8.44 = 10.67 \]

\[ I = 72 \quad r = \sqrt{\frac{72}{10.67}} = 2.6 \]

\[ \frac{1}{r} = 36.8 \text{ which is acceptable.} \]

(11) Longitudinals 8 and 9

\[ \sigma_1 = 0 \quad H = 19 \quad t = 15\# \text{ plate} \]

\[ \sigma_3 = 36,000 \quad S = 35 \]

\[ M_{\text{max}} = 226,000 \quad Z_{\text{req}} = \frac{226,000}{36,000} = 6.3 \]

Using a 6" x 4" x 6.2# I-T

\[ I = 34 \quad A = 10.26 \]

\[ K = 1.8 \quad \frac{1}{r} = 53.5 \]

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(12) Longitudinals 11 and 12.

At these positions the \( \frac{1}{r} \) criterion governs

Using a \( \frac{1}{2} - 12'' \times 3'' \times 11.8'' \) Jr Bm. (5.9#)

\[
\begin{align*}
I &= 32 \\
A &= 8.815 \\
\frac{1}{r} &= 51
\end{align*}
\]

(13) The same size longitudinal was used throughout the deck.

(14) After sizing all scantlings inertia calculations were made and the stringer plate checked for instability by two methods.

(15) First the shear in the stringer plate was found.

\[
\tau = \frac{VQ}{It}
\]

\( V = 406 \) tons (Design Criteria)

\( I = 81,372 \) ft\(^2\)in\(^2\) (from Inertia Calculation)

\( t = 0.3125 \) in. (from Plating Calculations)

\( Q = 15.67 (82.04) = 1,289 \) (\( Q = y \times A \))

Then

\[
\tau = 4,040 \text{ psi.}
\]

From interaction formula (see Procedure).

\[
\frac{\sigma_l}{\sigma_{cr}} + \left( \frac{\tau}{\tau_{cr}} \right)^{1.5} = \frac{1}{S.F.}
\]

\[
\begin{align*}
\sigma_{cr} &= K \frac{\tau^2D}{tb^2} \\
\tau_{cr} &= K \frac{I^2D}{tb^2}
\end{align*}
\]

\[
\begin{align*}
D &= 83,840 \\
b &= 31 \\
K_s &= 6.07 \\
t &= 0.3125 \\
K_o &= 4
\end{align*}
\]

\[
\begin{align*}
\sigma_{cr} &= 11,050 \\
\tau_{cr} &= 16,750
\end{align*}
\]

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\[
\frac{c_1}{\sigma_{cr}} + \left(\frac{\tau}{\tau_{cr}}\right)^{0.5} = \frac{1}{\text{S.F.}}
\]
\[
\frac{4,900}{11,050} + \left(\frac{4,040}{16,750}\right)^{1.5} = \frac{1}{\text{S.F.}}
\]
S.F. = 1.45

(16) Using the method of Bleich & Ramsey (See Procedure)

\[
\frac{a}{b} = 3.1
\]

\[
B = \frac{c_1}{\tau} = \frac{3,050}{4,040} = 0.75
\]

\[
X = \frac{4}{3} + \frac{1}{(a/b)^2} = 1.43
\]

\[
K = 2x^2 B \sqrt{B^2 + 3} \left[ -1 + \sqrt{1 + \frac{4}{B^2 x^2}} \right]
\]

K = 6.45

\[
\frac{c_1}{\eta} = 26,750,000 \left(\frac{t}{b}\right)^2 K
\]

\[
\frac{c_1}{\eta} = 17,420 \ (\eta = 1)
\]

\[
\tau_{cr} = \frac{c_1}{\sqrt{B^2 + 3}} = 9,240
\]

Then

\[
\frac{c_1}{\sigma_{cr}} = \frac{\tau}{\tau_{cr}} = \frac{1}{\text{S.F.}}
\]

\[
\frac{4,040}{9,240} = \frac{3,050}{6,920} = \frac{1}{2.28}
\]
S.F. = 2.28
Part III  After Section - Scheme 2C

Assumed N.A.: 14.5' above M.B.L.

Final Calculated N.A. was 13.89' above M.B.L.

(1) Strake A (between #1 and #2 longitudinal)

Web Spacing (a) = 8'  Long. spacing (b) = 35"

\[
a/b = 2.74  \quad H = 26'\]

Stress Schedule - Assume 6.5 tons/in² in keel

(ie. 14,600 psi)

\[
\sigma_1 = \frac{11.5}{14.5} \times 14,600 = +11,600
\]

\[
\sigma_2 = + 2,000
\]

\[
\sigma_3 = +31,400
\]

\[
+45,000
\]

Hydrostatic

\[
t = 0.473(b)\sqrt{\frac{KH}{c_3}} = 0.473(35)\sqrt{\frac{-685(26)}{31,400}} = 16.59(2.38 \times 10^{-2}) = 0.394"
\]

Instability

\[
t = 1.92 \times 10^{-4}(b)\sqrt{\frac{c_1}{K}} = 1.92 \times 10^{-4}(35)\sqrt{\frac{11,600}{7.75}} = 67.2 \times 10^{-4}(38.7) = 0.26"
\]

Girthwise  \(c_1 + c_2 + c_3 = 0 + 3000 + 42000 = 45,000\)

\[
t = 0.473(35)\sqrt{\frac{1.0 (26)}{42,000}} = 0.414"
\]

(Used .4375" plate, 17.85#)

Ult. Comp. Strength Check

\[
B = 0.03878 \frac{b}{t} = 0.03878 \frac{35}{4375} = 3.1 \quad \text{Ratio} = 0.60
\]

U.C.S. = .60 (45,000) = 27,000

\[
1.25\sigma_1 = 1.25 (11,600) = 14,500 \quad (OK)\]
(2) Strake B - between #2 and #3 longitudinal

WS = 8'  LS = 35"  H = 29'-5' = 24'

\[ \sigma_1 = \frac{9.5}{14.5} \times 14,600 = 9,600 \]

\[ \sigma_2 = 2,000 \]

\[ \sigma_3 = 33,400 \]

Hydrostatic

\[ t = 0.473(35) \sqrt{\frac{685(24)}{33,400}} = 16.59(2.22 \times 10^{-2}) = 0.372 \]

Girthwise

\[ t = 16.59 \sqrt{\frac{1.0(24)}{42,000}} = 0.396" \text{ controls} \]

Instability and Ult. Compr. Strength OK by inspection with Strake A. (Used 17.85# plate, .4375")

(3) Strake C

WS = 8'  LS = 35"  H = 29'-7' = 22'

\[ \sigma_1 = \frac{7.5}{14.5} \times 14,600 = 7,600 \]

\[ \sigma_2 = 2,000 \quad a/b = 2.74 \]

\[ \sigma_3 = 35,400 \quad K_s = 6.20 \]

Hyd:

\[ t = 16.59 \sqrt{\frac{685(22)}{35,400}} = 0.342" \]

Girth:

\[ t = 16.59 \sqrt{\frac{1.0(22)}{42,000}} = 0.380" \text{ controls} \]

Shear Instab:

\[ t = 2.38 \times 10^{-2}(35) \frac{1}{\sqrt{6.20}} = 0.334" \]

(Used 15.3#, .375" - This was OK since N.A. was lower than assumed 14.5'.)
(4) Strake D

\[ WS = 8', \quad LS = 35'', \quad H = 20.25 \]

Girth:
\[ t = 0.473(35) \sqrt{\frac{1.0(20.25)}{42,000}} = 0.364'' \text{ controls} \]

Shear instability same as Strake C.

Instability & Ult. Comp. Str. OK by inspection

(Used 15.3#, .375'')

(5) Strake E - between #9 longitudinal and platform.

\[ WS = 8', \quad LS = 35'', \quad H = 13.5 \]

Girthwise:
\[ t = 16.59 \sqrt{\frac{1.0(13.5)}{42,000}} = 0.298 \]

Shear Instability
\[ t = 2.38 \times 10^{-2}(35) \frac{1}{\sqrt{6.20}} = 0.334'' \text{ controls} \]

(Used 14.02#, .3437'')

(6) Strake F - between #12 longitudinal and deck

\[ WS = 8', \quad LS = 31.5'', \quad H = 5.75' \]

\[ \sigma_1 = \frac{9.25}{14.5} \times 14,600 = 9,200 \]

\[ \sigma_2 = 2,000 \]

\[ \sigma_3 = \frac{33,800}{45,000} \]

Instability
\[ t = 1.92(31.5) \times 10^{-4} \sqrt{\frac{9200}{4}} = 0.290'' \]

Shear Instability
\[ t = 2.38 \times 10^{-2}(31.5) \frac{1}{\sqrt{6.09}} = 0.304 \text{ controls} \]

\[ K_s = 6.09 \]

(Ultimately use 15.3# plate, .375'' for closer match to deck and for I/y considerations)
(7) Deck Plating

\[ \sigma_1 = \frac{10.5}{14.5} \times 14,600 = 10,600 \]

Strake C - largest spacing of longitudinals

WS = 8' \quad LS = 38" \quad a/b = 2.52

Instability

\[ t = 1.92 \times 38 \times 10^{-4} \sqrt{\frac{10,600}{4}} = 0.375 \]

Shear Instability \( K_s = 6.3 \)

\[ t = 2.38 \times 10^{-2}(38) \times \frac{1}{\sqrt{6.3}} = 0.36" \]

(Used 15.3#, .375")

Strake D - Stringer plate - On the basis of the above, since \( b = 35" \), 15.3# plate would be OK.

Later, a check of combined stress and I/y required an increase to 17.85# plate.

Strake B.

Instab: \[ t = \frac{34.5}{38} \times 0.375 = 0.340" \]

could use 14.02# on the basis of above, but this strake was increased to 15.3# for I/y.

Strake A

(Used 14.02#)

(9) Longitudinals #1 and #2

(#3 and #4 terminated well forward of this station)

\[ \sigma_1 = \frac{14.5-2}{14.5} \times 14,600 = 12,600 \quad H = 27' \quad l = 8' \]

\[ \sigma_2 = \frac{23,400}{36,000} \quad s = 35" \]
A. #1 long.

\[ M = 5.33 \, Hs_1^2 = 5.33(8)^2Hs = 341 \, Hs = 322,000 \]
\[ Z = \frac{M}{\sigma^2} = 13.78 \quad t = .4375'' \quad Ap_1 = 11.48'' \]
\[ \left(\frac{1}{r}\right)_{\text{rqd}} = 34.2 \quad r_{\text{rqd}} = \frac{96}{34.2} = 2.8 \]
\[ r^2A \approx 110 \]

Try \( 10 \times 4 \times 11.5'' \) I-T \((9.1'')(2.67'')\) \( I = 121 \quad Z=13.7 \)

\[ r = \sqrt{\frac{121}{14.5}} = 2.93 \quad L/r = \frac{96}{2.93} = 32.8 \quad OK \]

B. #2 same

Note: Bulkhead runs in way of #3 longitudinal
Shafting runs in way of #4 longitudinal

(10) Longitudinals #5 through #7 \( t = .375'' \quad Ap = 8.44 \)

\[ \sigma_1 = \frac{14.5-7}{14.5} \times 14,600 = 7,600 \quad H = 29-7 = 22' \]
\[ \sigma_2 \]
\[ 28,400 \quad s = 35'' \]
\[ Z = \frac{262,200}{28,400} = 9.25 \]

\[ L/r_{\text{rqd}} = 43.2 \quad r_{\text{rqd}} = \frac{96}{43.2} = 2.22 \quad r^2A \approx 54 \]

Try \( 8 \times 4 \times 10'' \) I-T \((7.6'')(2.23'')\) \( I = 67 \quad Z = 9.8 \)

\[ r = 2.51 \quad L/r = 33.2 \quad OK \]

(11) Longitudinals #8 and #9

\[ \sigma_1 = \frac{14.5-11.5}{14.5} \times 14,600 = 3,100 \quad H = 29-13.5 = 15.5' \]
\[ \sigma_2 \]
\[ 31,900 \quad t = .375'' \quad Ap = 8.44 \]
\[ 36,000 \]

\[ M = 341Hs = 185,000 \quad Z = \frac{185,000}{31,900} = 5.83 \]

\[ \left(\frac{1}{r}\right)_{\text{rqd}} = 52 \quad r_{\text{rqd}} = \frac{96}{52} = 1.85 \quad r^2A \approx 38 \]
Try $\frac{1}{2} - 12 \times 4 \times 14\#$ Joist (7.0#)(2.07")

I = 39.7  \quad Z = 6.09  \quad A_T = 10.51
\n\quad r = 1.945  \quad \frac{1}{r} = 49.4  \quad \text{OK}
\n#10 longitudinal ties into platform
\n(12) Longitudinal #11 and #12
\n\sigma_1 = \frac{22-14.5}{14.5} \times 14,600 = 7,600  \quad H_m = 9.5'
\n\sigma_2 = \frac{28,400}{36,000}  \quad t = .375''  \quad A_p = 8.44
\nUse the head for #11 longitudinal and the above stress schedule based on #12 longitudinal.
\nM = 341 Hs = 341(9.5)(31.5) = 102,000
\nZ = \frac{102,000}{28,400} = 3.6  \quad (\frac{1}{r})_{rqd} = 55 :.
\n\quad r_{rqd} = 96/55 = 1.745
\n\quad r^2 A \approx 33 \text{ or } 34
\nTry $\frac{1}{2} - 12 \times 3 \times 11.8\#$ Jr. Bm (5.9#)(1.725")
\nI = 33  \quad r = 1.802  \quad \frac{1}{r} = 53  \quad \text{OK}
\n(13) Deck Longitudinals
\n\sigma_1 = \frac{25-14.5}{14.5} \times 14,600 = 10,600
\n\sigma_2 = \frac{25,400}{36,000}  \quad H = 4'
\nFor #13 and 14  \quad s = 36 \frac{1}{2}
\nM = 341 Hs = 49,700  \quad Z = \frac{M}{\sigma_2} = 1.92
\n\quad 1/\frac{r_{rqd}}{r_{min}} = 55  \quad . \quad \frac{r_{min}}{r_{rqd}} = 96/55 = 1.75
\n\quad t = .375''  \quad (15.3#)  \quad A_p = 8.44
Try \( \frac{1}{2} - 12 \times 3 \times 11.8\# \) Jr. Bm. (5.9\#) (1.72\"

\[
Z = 6.1 \quad I = 33.5 \quad A_T = 10.52
\]

\[
V = \sqrt{\frac{33.5}{10.52}} = 1.784 \quad \frac{1}{r} = \frac{96}{1.784} = 53.7\# \quad \text{OK}
\]

If plate boosted to .4375

\[
\frac{1}{2} - 12 \times 3 \times 11.8\# \) Jr Bm.
\]

\[
Z = 6.2 \quad I = 35.5 \quad A_{pl} = 11.48
\]

\[
r = \sqrt{\frac{35.5}{13.20}} = 1.64 \quad A_t = 13.20
\]

Try \( \frac{1}{2} - 12" \times 4" \times 14\# \) Joist (7.0\#) (2.07\"

\[
Z = 7.7 \quad I = 42
\]

\[
r = \sqrt{\frac{I}{A}} = \sqrt{\frac{42}{13.55}} = 1.76 \quad \frac{1}{r} = 54.5 \quad (\text{OK})
\]

Use \( \frac{1}{2} - 12" \times 4" \times 14\# \) Joist for #13 and #14

Use \( \frac{1}{2} - 12" \times 3" \times 11.8\# \) Jr. Bm. for #15, 16, 18, 19.

**Summary of Inertia Calculations**

**Scheme 2C**

\[
I = 46,991 \text{ in}^2\text{ft}^2
\]

N.A. above baseline = 13.89'

y deck = 11.11'

Max Stresses

- Compr. Deck 5.25 tons/in²
- Keel 6.55 "

(14) Stringer Plate Check

**First Method:**

\[
A_{\text{deck}} = \begin{cases} 
144 \times 0.375 = 54.0 \\
76 \times 0.4375 = 32.2
\end{cases} = 86.2 \text{ in}^2
\]

\[
A_{\text{along}} = 15.73 \text{ in}^2 \quad I = 46,911 \text{ in}^2\text{ft}^2.
\]
$$Q = 86.2(11.11) + 15.73(10.8) = 957 + 170 = 1127 \text{ in}^2\text{ft}.$$ 

$$\tau = \frac{VQ}{tI} = \frac{520.3(2240)(1127)}{(46991)(.4375)} = 6400 \text{ psi}.$$ 

$$\sigma_1 = 5.25 \times 2240 = 11,720 \text{ psi}.$$ 

$$\sigma_{cr} = 4 \times \frac{\pi^2 \times 230050}{(35)^2 \times .4375} = 16,950 \text{ psi}.$$ 

$$\tau_{cr} = \frac{6.2}{4} \times 16,950 = 26,300 \text{ psi}.$$ 

$$\frac{\sigma_1}{\sigma_{cr}} + \left(\frac{\tau}{\tau_{cr}}\right)^{1.5} = \frac{11,720}{16,950} + \left(\frac{6,400}{26,300}\right)^{1.5} = .691 + .120 = .811$$ 

$$\text{S.F.} = 1.23$$ 

**Second Method:** 

$$I = 46,911 \text{ in}^2\text{ft}^2$$ 

$$V = 520.3 \text{ tons} \quad t = .4375''$$ 

$$Q = 1127 \text{ in}^2\text{ft}. \quad b = 35''$$ 

$$\tau = 6,400 \text{ psi}.$$ 

$$\sigma_1 = 11,720 \quad B = \frac{\sigma_1}{\tau_{xy}} = \frac{11,720}{6,400} = 1.835$$ 

$$B^2 = 3.365 \quad \sqrt{B^2 + 3} = 2.52$$ 

$$a/b = 96/35 = 2.74 \quad X = \frac{4}{3} + \frac{1}{(2.74)^2} = 1.46$$ 

$$x^2 = 2.135$$ 

$$K = 2X^2 B \sqrt{B^2 + 3} \left[-1 + \sqrt{1 + \frac{4}{B^2x}}\right]$$ 

$$K = 2(2.135)(1.835)(2.52) \left[-1 + \sqrt{1 + .814}\right]$$ 

$$K = 6.84$$ 

$$\frac{\sigma_1}{\eta} = 26,750,000 \quad \frac{t^2}{b^2} K = 28,550 \text{ psi} \quad \eta = 1$$
Neutral Axis Check:

Method I:
\[ \frac{a}{b} = \frac{96}{35} = 2.74 \]  
\[ \text{S.F.} = 1.76 \]

\( Q_{\text{deck}} = 1127 \text{ in}^2\text{ft.} \)
\[ V = 520.3 \text{ tons} \]

Strake E (Panel just above N.A.)

A platform and its longitudinals = 25.03+8.28 = 33.31 in^2

Q side shell

Strake F (68")(.375)(21.5-13.88) = 194

Strake E (39")(.3437)(1.5) = 20.1

Q side longitudinals

#12 (1.725) (8.0) = 13.8

#11 (1.725) (5.5) = 9.5

Platform 33.31 (16.83-13.89) = 97.4

Q total = 1127 + 194 + 20.1 + 13.8 + 9.5 + 97.4 = 1462

\[ \tau = \frac{VQ}{tI} = \frac{520.3(2240)(1462)}{(0.3437)(46,911)} = 10,620 \text{ psi.} \]

\[ \tau_{cr} = K_s \frac{\sigma_D^2}{t b^2} = 6.2 \frac{\sigma_D^2(111,650)}{(0.3437)(35)^2} = 16,200 \text{ psi.} \]

\( K_s = 6.2 \) (pure shear simply supported)

assume \( \sigma \) very small

\[ \frac{\tau}{\tau_{cr}} = \frac{10,620}{16,200} = .657 \quad \text{S.F.} = 1.52 \]

Method II:

\[ \frac{a}{b} = 2.74 \]

\[ \frac{\sigma_1}{H} = 26,750,000 \left( \frac{t}{b} \right)^2 K \]
\[ K = \left( \frac{1}{3} \left( 5.34 + 4\left(\frac{a}{b}\right)^2 \right) \right) = \sqrt{3} \left( 5.34 + 0.534 \right) = \sqrt{3} \left( 5.87 \right) \]

\[ \tau_{cr} = \frac{\sigma_{1}}{\sqrt{3}} = 26,750,000 \left( \frac{0.3437}{35} \right)^2 \left( 5.87 \right) = 15,100 \text{ psi.} \]

\[ \frac{\tau}{\tau_{cr}} = \frac{10,620}{15,100} = 0.705 \quad \text{S.F.} = 1.42 \]

**Part IV - Web Frame Weight**

(1) Nomenclature for web frame calculations

- **A** = area
- **B** = maximum breadth of ship
- **d** = depth of beam
- **h** = head of water
- **l** = length as defined in American Bureau of Shipping Rules for Building and Classing Steel Vessels.
- **M** = Frame Numeral, ABS Rules
- **s** = web frame spacing
- **t** = thickness

**Subscripts**

- **F** = Flange
- **W** = Web
- **T** = Total
(2) Summary of Web Frame Percentage Calculations

<table>
<thead>
<tr>
<th>Section</th>
<th>5.34</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>122</td>
<td>130</td>
<td>155</td>
<td>178.5</td>
<td>202</td>
</tr>
<tr>
<td>4</td>
<td>61.6</td>
<td>64</td>
<td>76.9</td>
<td>88</td>
<td>100.8</td>
</tr>
<tr>
<td>5</td>
<td>246</td>
<td>270</td>
<td>342</td>
<td>383.0</td>
<td>423.0</td>
</tr>
<tr>
<td>6</td>
<td>96</td>
<td>102.5</td>
<td>122.5</td>
<td>141.8</td>
<td>150.8</td>
</tr>
<tr>
<td>Total</td>
<td>525.6</td>
<td>566.5</td>
<td>696.4</td>
<td>791.3</td>
<td>876.6</td>
</tr>
<tr>
<td>% of 8' spacing</td>
<td>75.5%</td>
<td>81.4%</td>
<td>100%</td>
<td>113.8%</td>
<td>126%</td>
</tr>
</tbody>
</table>

(3) Calculation of Upper Deck Beam

\[ \text{h = 4' } \]

Using \( d = 1' \) Rules require \( t = 0.40'' \), \( l = 14 \)

\[ M = 0.004s1^2h = (0.004)(14)^2(4)s = 3.14s \]

<table>
<thead>
<tr>
<th>s</th>
<th>8</th>
<th>6</th>
<th>5.34</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>25.2</td>
<td>18.8</td>
<td>16.8</td>
</tr>
<tr>
<td>( A_t )</td>
<td>2.6</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>( A_w )</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>( A_T )</td>
<td>7.4</td>
<td>6.2</td>
<td>5.8</td>
</tr>
<tr>
<td>Vol 21(( A_T ))</td>
<td>155</td>
<td>130</td>
<td>122</td>
</tr>
</tbody>
</table>

(4) Calculation of Upper Side Transverse

\( h = 8' \) \( t = .45'' \) web

\[ M = 0.0045s1^2h = .0045(49)(8)s = 1.405s \]

Rules say depth = .25 l. We shall use 1' and increase \( M \) accordingly by a length ratio squared.

\[ M = \left( \frac{7}{4} \right)^2 1.405s = 4.3s \]
Calculation of Middle Side Transverse

\[ l = 9.75 - .3(9) + 3 = 10' \quad h = 16' \quad d = 20'' \]

\[ M = \left( \frac{10}{6.66} \right)^2 (0.0045)(100)(16)s = 7.2s(2.25) = 16.2s \]

\[
\begin{array}{ccc}
M & 130 & 97.3 & 86.5 \\
A_F & 11.5 & 7.2 & 5.8 \\
A_W & 9.0 & 9.0 & 9.0 \\
A_T & 20.5 & 16.2 & 14.8 \\
\end{array}
\]

\( L = 14' - 8'' \quad A \times L = \text{Vol.} \quad 342 \quad 270 \quad 246 \)

Calculation of Bottom Transverse

\[ l = 8' \quad t = .47'' \quad h = 25' \]

\[ M = \left( \frac{8}{4} \right)^2 (64)(25)s(.0036) = 4(5.77s) = 23s \]

\[
\begin{array}{ccc}
M & 82.1 & 61.6 & 54.9 \\
A_F & 6.8 & 4.3 & 3.5 \\
A_W & 8.5 & 8.5 & 8.5 \\
A_T & 15.3 & 12.8 & 12.0 \\
\text{Vol.} & 122.5 & 102.5 & 96.0 \\
\end{array}
\]
Figure - VI

WEB FRAME DELINEATION
Fig VII

Weight of Web Frame
Weight of Web Frame at various spacing for various web spacings

Percent of 8' Web Frame Wgt

62
APPENDIX B

SUMMARY OF DESIGNED SECTIONS
Scheme 1-A FWD.

Web Spacing - 5.34 ft
Longitudinals - 9
I - 84,216
N.A. - 15.02 ft Above B
FIG. X

ALL DECK LONGITUDINALS 8x4x10#I-T(7.6#)
5/8 x 5 1/2 x 5/8"

8x4x10#I-T(7.6#)
8"
Strap

12x4x22#I-T(16.9#)
"E"
17.8#

6x4x12#I-T(8.7#)
69

8x4x15#I-T(11.3#)
"D"
25.50#

24x12x100#I-T(70#)

INTERCOSTAL DOCKING LONGL

12x4x19#I-T(14.9#)

"A"
25.50#

"B"
25.50#

"C"
25.50#

WEB SPACING 8FT
9 LONGITUDINALS
N.A. 12.44' ABOVE B
I = 112,853 ft^2 in^2

SCHEME 1A - CC

0 2 4 6 8
FEET

66
FIG XI

SCHEME 1A AFT

WEB SPACING 5.71 FT.
9 LONGITUDINALS
NEUTRAL AXIS 13.03" ABOVE B
MOMENT OF INERTIA 53,120 FT²-IN

67
FIG-XII

OK LONG.  
1/2 - 9" x 2 3/8" x 7.5" JR. BM (3.75")

PLAT FORM

1/2 - 11" x 2 7/8" x 10.3" JR. BM.

PLAT FORM

Docking Long.

1/2 - 12" x 3" x 11.8" (5.9")

PLAT FORM

10" x 4" x 11.5" I-T (3.1")

B - 20.4 ft

A - 20.4 ft

D - 22.95 ft

E - 20.4 ft

F - 20.4 ft

0 1 2 3 4 5

FEET

Scheme 1-B FWD
Web Spacing - 6 FT
Longitudinals - 9
I = 49,022
N.A = 16.52 ft A.B.U.E.
\textbf{FIG. XIV}

\begin{align*}
F & \quad 17.85^\circ \text{R} \\
E & \quad 17.85^\circ \text{R} \\
D & \quad 20.4^\circ \text{R} \\
C & \quad 20.4^\circ \text{R} \\
B & \quad 25.5^\circ \text{R} \\
A & \quad 25.5^\circ \text{R} \\
\end{align*}

\textbf{Scheme 1B Aft}

\begin{itemize}
\item Web spacing 6.0 ft
\item 9 Longitudinals
\item Neutral Axis 130\text{'} above \&
\item Moment of Inertia 53,441
\end{itemize}
FIG - XV

12"X 5"X80 JR. 8/4

F' 20.4" Fl

8"x 4" X 10" I-T

8"x 4" X 10" I-T

D" 22.95" Fl

10"x 4" X 15" I-T (5.8")

Docking Long

C" 20.4" Fl 0 1 2 3 4 5 6 7

FEET

Scheme 1-C FWD

WEB SPACING - 8 FT
LONGITUDINALE - 9
I = 54,728
N.A. = 16.97 FT AB

71
ALL DECK LONGITUDINALS 10 x 4 x 15 ft I-T (11.7 ft)
5/8 x 5/8 x 5/8 in

10 x 4 x 15 ft I-T (11.7 ft)

12 x 4 x 22 ft I-T (16.9 ft)

10 x 4 x 11.5 ft I-T (9.1 ft)

12 x 4 x 22 ft I-T (16.9 ft)

24 x 12 x 100 ft I-T (70 ft)

14 x 6 3/4 x 38 ft I-T (27.4 ft)

SCHEME C
WEB SPACING 12 ft
9 LONGITUDINALS
N.A. 12.64' ABOVE BE
I = 113.186 ft² in³
SCHEME 1 C AFT

WEB SPACING 8.0 FT.
9 LONGITUDINALS
NEUTRAL AXIS 13.04' ABOVE 5
MOMENT OF INERTIA 54,418 FT²•IN
FIG-XIX

DECK LONGS - 8 x 4 x 10# (7.6#) I-T 1/2

5 1/8 x 5 1/8 x 98" L

8 x 4 x 10# (7.6#) IT

12 x 4 x 16.5# (13.3#) IT

6 x 4 x 12# I-T (8.7#)

6 x 4 x 10# (11.2#) IT

10 x 4 x 11.5# (9.9#) INTERCOSTAL DOCKING LONGS

12 x 8 x 10# (26.9#)

12 x 4 x 22# I-T (16.9#)

24 x 12 x 100# I-T (70#)

"A" 10" Strap 28.05#

"B" 10" Strap 22.95#

"C" 17.85#

"D" 15.3#

WEB SPACING 8 FT.

12 LONGITUDINALS

N.A. 12.99" ABOVE B

I = 110,058 ft^2-in^2

SCHEME 2 A- X

75
SCHEME 2A AFT
WEB SPACING 5.71 FT.
12 LONGITUDINALS
NEUTRAL AXIS 15.81 FT ABOVE B
MOMENT OF INERTIA 45,557 FT$^2$-°
FIG. XXI

$\frac{1}{2} - 9" \times 2\frac{3}{4}" \times 7.5^\circ$ Jr. Bm (3.75\textdegree) [110\textdegree]

"F" - 14.02\textdegree RN

"E" - 14.02\textdegree RN

"C" - 15.8\textdegree RN

"B" - 17.85\textdegree RN

"A" - 17.85\textdegree RN

Scheme 2-B, Fwd.
Web Spacing - 6 FT
Long. - 12
Mom. of Inertia - 72,970
Neutral Axis - 15.24
Scheme 2B

Web spacing 9 ft.
12 longitudinal
N.A. 12.91' above $
FIG. XXIII

\[ \frac{1}{2} - 10 \times 2^{\frac{3}{4}} \times 9^2 \text{in. Bu. (45\degree)} \] \(1.93^\circ\)

\[ \frac{1}{2} - 12 \times 4 \times 14^2 \text{Joist (7.0\degree)} \] \(2.07^\circ\)

**Scheme 2B Aft**

**Web spacing 6 ft.**

12 Longitudinal

**Neutral axis 13.84' above**

**Moment of Inertia 45,919 ft-lb**
Scheme Z-C FWD.
Web Spacing - 8 FT
Long's - 12
Mom. of Inertia 81,372
Neutral Axis - 15.77 FT
Scheme 2C Aft

Web spacing 8 ft
12 Longitudinals
Neutral axis 13.89' above B
Moment of Inertia = 46,991 ft²·lb
Scheme 3-A Fwd.
Web Spacing - 5.34 ft.
Longitudinals - 15
Moment of Inertia - 77,468
Neutral Axis - 15.15 ft.
ALL DECK LONGITUDINALS

8x4x10# IT (7.6#)

5/8 x 5'1/8 x 5/8" L

1/2-12x4x14# Joist (7.0#)

12x4x22# IT (16.3#)

1/2-12x4x14# Joist (7.0#)

8x4x10# IT (7.6#)

12x4x19# IT (14.3#)

12x8x40# IT (30.4#)

12x8x50# IT (33.4#)

"D" 17.85#

"C" 20.9#

"B" 22.95#

"A" 25.50#

WEB SPACING = 8 FT.

15 LONGITUDINALS

NA = 12.25' ABOVE B

I = 103,846 Ft² in²

SCHEME 3A
FIG. XXIX

DECK LENGTH

\[ \frac{1}{2} \times 10 \times 2 \frac{3}{4} \times 9.0 \text{ IBE} (6.50') [1.32'] \]

\[ \frac{1}{2} \times 9 \times 2 \frac{3}{4} \times 7.5 \text{ IBE} (3.75') [1.40'] \]

\[ \frac{1}{2} \times 12 \times 4 \times 14 \text{ Joint (10') [6.07']} \]

WEB SPACING 5.71 FT.
15 LONGITUdINALS
NEUTRAL AXIS 14.43' ABOVE E
MOMENT OF INERTIA 43.554 ft^2-in

SCHEME 3A AFT

85
DECK LONG'L5
\[ \frac{1}{2} - 9' \times 2\frac{1}{8} \times 7.5' \text{ Jr. BM (3.75')} \]

\[ \frac{1}{2} - 10' \times 2\frac{1}{4} \times 9' \text{ Jr. BM (4.5')} \]

PLATFORM

PLAT FORM

\[ \frac{1}{2} - 10' \times 2\frac{1}{4} \times 9' \text{ Jr. BM (4.5')} \]

PLATFORM

DOCKING LONGITUDINAL

8"x4"x10" IT (7.6")

PLATFORM

\[ \text{C} - 17.85' \text{ of } \]

\[ \text{B} - 15.3' \text{ of } \]

\[ \text{A} - 15.3' \text{ of } \]

SCHEME 3-B FWD.
WEB SPACING - 6 FT
LONG'L5 - 15
MOM. INERTIA - 75,705
NEUTRAL AXIS - 15.27
Scheme 3B Aft

Web spacing 6.0 ft.
15 longitudinals
Neutral axis 14.44" above B
Moment of inertia 43,567 ft²-in
FIG. XXXIII

DECK LONG'Ls
1/2 - 12"x3" x 11.8" Jr. Bm. (5.9°)

1/2 - 12"x3" x 11.8" Jr. Bm. (5.9°)

PLATFORM

F - 15.3°@E

1/2 - 12"x4" x 16.5 L.8. (8.25")

Docking LONG'L

8"x4" x 10" I-T (7.6°)

PLATFORM

10"x4" x 11.5" I-T (9.1°)

8" - 15.3°@E

A - 15.3°@E

G - 12.75°@E

Scheme 3-C Fwd.
Web Spacing - 8 ft.
Long'Ls - 15
Mom. of Inertia - 81,484
Neutral Axis - 15.81 ft
All Deck Longitudinals
10 x 4 x 15# I-T (11.71#)

5\text{/}8 \times 5\text{/}8 \times 5\text{/}8

10 x 4 x 11.5# I-T (9.14#)

12 x 4 x 22# I-T (16.9#)

12 x 4 x 19# I-T (14.9#)

10 x 4 x 11.5# I-T (9.1#)

12 x 4 x 22# I-T (16.9#)

12 x 4 x 22# I-T (16.9#)

12 x 4 x 22# I-T (16.9#)

12 x 8 x 40# I-T (26.9#)

12 x 8 x 45# I-T (30.8#)

12 x 8 x 50# I-T (33.8#)

A

B

C

D

E

F

G

15 Longitudinals

N.A. - 12.58 above B

I = 106,933 ft^2 in^2

Scheme 3C - 12

Web spacing 12 ft
**Fig. XXXV**

### Scheme 3C Aft

**Web Spacing** 8.0 FT

**15 Longitudinals**

**Neutral Axis** 14.46' Above B

**Moment of Inertia** 44,016 ft²-in

---

FPK 153 in
CVK 24 x 12 x 100 in

---

$A$ 15.3 ft
$B$ 12.75 ft
$C$ 12.75 ft
$D$ 11.47 ft
$E$ 11.47 ft

---

$1/2 - 12.3 \times 11.8$ in, (5.9 in) $[1.725]$ in

$1/2 - 12 \times 4 \times 14.0$ Joint (10°) $[2.07]$ in

$1/2 - 12.3 \times 11.8$ Joint, (5.9 in) $[1.725]$ in

---

14 x 6.4 x 7.6 in - T (21.8°) $[2.45]$ in

8 x 4 x 10 in - T (16°) $[2.23]$ in

---

6.87 ft

---

10 x 4 x 11.5 in - T (9.1°) $[2.61]$ in
APPENDIX C

Discussion of Alternate Method of Spacing Longitudinals

The assumption of a fixed ratio, greater than unity, between the spacing of longitudinals at the neutral axis and the spacing at the top and bottom of the ship girder flange, was based on nothing more than a suspicion that the longitudinals would thereby contribute more to the moment of inertia of the section than they would with an even spacing. As mentioned in the procedure section, however, it was realized that there might possibly be an advantage in plate distribution by use of the reverse ratio. To investigate this possibility, a cross section was laid out with the reverse ratio, all other criteria remaining constant, for the 12 longitudinal scheme with 8', 10' and 12' web spacings. A group of graduate students studying the basic method of midship section design which was used in this study, determined the scantlings and weight per foot of longitudinal material for each of these alternate schemes. Their calculations were not in all respects comparable with those in this investigation, but a study of their scantlings indicates that the difference in weight is very small, being less than 1%, more or less than the weights calculated in this study. Thus, there appears to be no overall advantage in either a closer or a wider spacing of longitudinals at the neutral axis compared to the rest of the girth, at least in the range of the small ratio of space variation used in these studies (this ratio was 1.17:1).

Nevertheless, there appears to be an advantage in
using the neutral axis as a starting point in the design procedure. The plating at the neutral axis is limited by local considerations since it is normally close to the water line and subjected to unpredictable loadings in docking, excessive corrosion due to alternate wetting and drying, and other conditions peculiar to the center of the web of the ship girder. It would therefore seem logical to determine the minimum acceptable thickness of the plating at the neutral axis on the basis of local loadings and then determine the maximum allowable stiffener spacing based on instability at the quarter points. Then the remaining number of stiffeners could be equally spaced about the remaining girth. In most cases this procedure will result in a wider spacing at the neutral axis than elsewhere, substantiating the assumption made in this investigation.
APPENDIX D - BIBLIOGRAPHY


6. HOVGAARD, W., "Structural Design of Warships" - Annapolis, Maryland, 1940.


