STRUCTURAL OPTIMIZATION OF A PANAMA AND SUEZ CANAL BULK CARRIER

By

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ABSTRACT

The present structural study, as a part of an integrated basic design problem, optimizes the longitudinal and transverse strength members throughout a cargo hold of an ocean going bulk carrier. It is an implementation of an approach proposed by the Author (2) for ship structural design using a non-linear programing technique.

In order to give the obtained results a potential value for practical utilization, a hold arrangement suited to a wide range of dry bulk cargoes is selected. Environmental constraints at Panama Canal and the Suez Canal are recognized in a computer program, which generates a midship section configuration suitable for prospective commodities.

The trade-offs of the structural optimization are the transverse frame spacing, the spacing of topside wing-tank longitudinals, the spacing of longitudinals in ship sides and the spacing of deck longitudinals. The objective function for the optimization process is cost, weight, or the required freight rate.

The goal of this paper is to describe basic features of the study giving few examples of its possible applications.

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HISTORICAL REVIEW

Evans and Khoushy (6) have attempted an optimization design of midship section for a family of general cargo ships ranging in length from 300 to 800 ft. The basic design variables for each ship is the transverse frame spacing. They have carried out the weight optimization and the cost optimization separately; and concluded that the most economical solution lies between those of least weight and minimum cost of production. Thus, they claimed that neither revenue earning power nor initial investment by itself is a sufficient criterion. From this study and reference (5), one can conclude that the ABS rule spacing is not far from the optimum frame spacing associated with minimum weight; also a little deviation from the minimum weight frame spacing may give a considerable saving in the initial cost with an acceptable increase in hull weight.

Buxton (4) used the computer in evaluating a specific design or making a systematic calculation of the structural design. In this respect, he selected a midship cargo tank of an oil tanker and applied the LR rules. Although his work has not handled an optimization attempt of the whole cargo hold, but only parts of it, the work emphasized the importance of sub-optimizing characteristics of different structural components such as the transverse girders. The measure of merit of Buxton's study is the weight minimization.

Lund and Moe (9) have developed a general method of optimization based on a non-linear programing procedure with special emphasis on longitudinal strength members of tankers. The free design variables of that study are spacing of deck and side longitudinals, thickness of plates in deck and bottom, and section moduli of deck and bottom longitudinals. The study takes into account varying levels of wages, steel prices as well as different types of steel. In a more recent development, Moe (10) recognized the weakness in disregarding the coupling which exists between the design of the longitudinal members and what he called the three-dimensional grillage system consisting of transverse and longitudinal frames. He then presented an approach for optimizing a selected topology of a cargo tank of a tanker taking into account as many as twelve free design variables.

Aldwinkel (1) outlined an analysis for computer-aided structural design of bulk carriers using the LR rules. He has preferred to publish many output results for different parametric variations of the principal dimensions, than to optimize using a well-defined measure of merit.

In the area of basic ship design which forms the background of the present study, Nowacki, Brusis and Swift (11), have explored two optimization techniques for tankers preliminary design. One of these techniques is adapted in the present research.

From all the foregoing and other work done in this area by Benford (2), one can see the need for a rational, consistent and integrated approach in ship design, to evaluate different alternatives using sound criteria.

In fact, this lenghy historical review puts the reader where the present study starts. Thus, the study is a continuation of the research outlined in the review but also implements research of other reports which will be referred to wherever used in this paper.

SCOPE AND BACKGROUND

The general problem which forms the domain of the structural study is illustrated in Figure 1. The chart shown may be more complicated than those used in conventional design offices but is typical to the modeling formulation of advanced work as in research centers. One may note here the interference that exists between the structural design

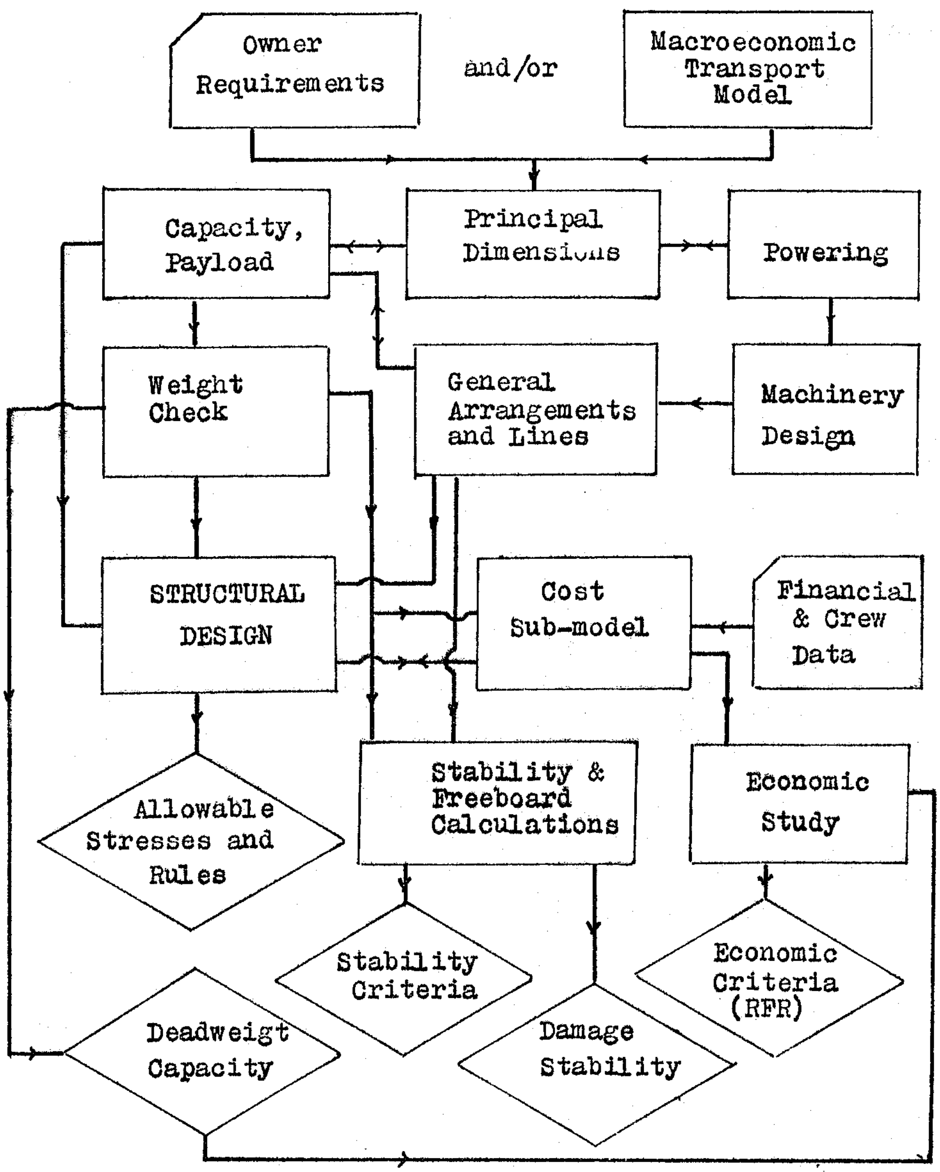


Fig. 1 Basic ship design flow chart

and many other aspects of ship design. In the past, difficulties from such interference were tackled by going into design loops using emperical formulas. Now, the computer would offer a more comprehensive approach.

With respect to the structural design, Figure 2 shows a flow chart for steps which have been done in this study. The broken lines indicate some work left for a future development. Thus, one can correct inaccuracy in the preliminary design solution due to the use of conventional weight and/or cost estimation techniques by introducing the output of the structural design solution. Eventually, finding the optimum solution of a structural problem is the major task of this research.

PROBLEM FORMULATION

The optimum solution of the structural problem, is the best set of design variables according to a specified measure of merit. Four of these design variables are considered, and their limits of variation are assigned for a Suez and Panama Canal bulk carrier, whose midship section arrangement is shown in Figure 3.

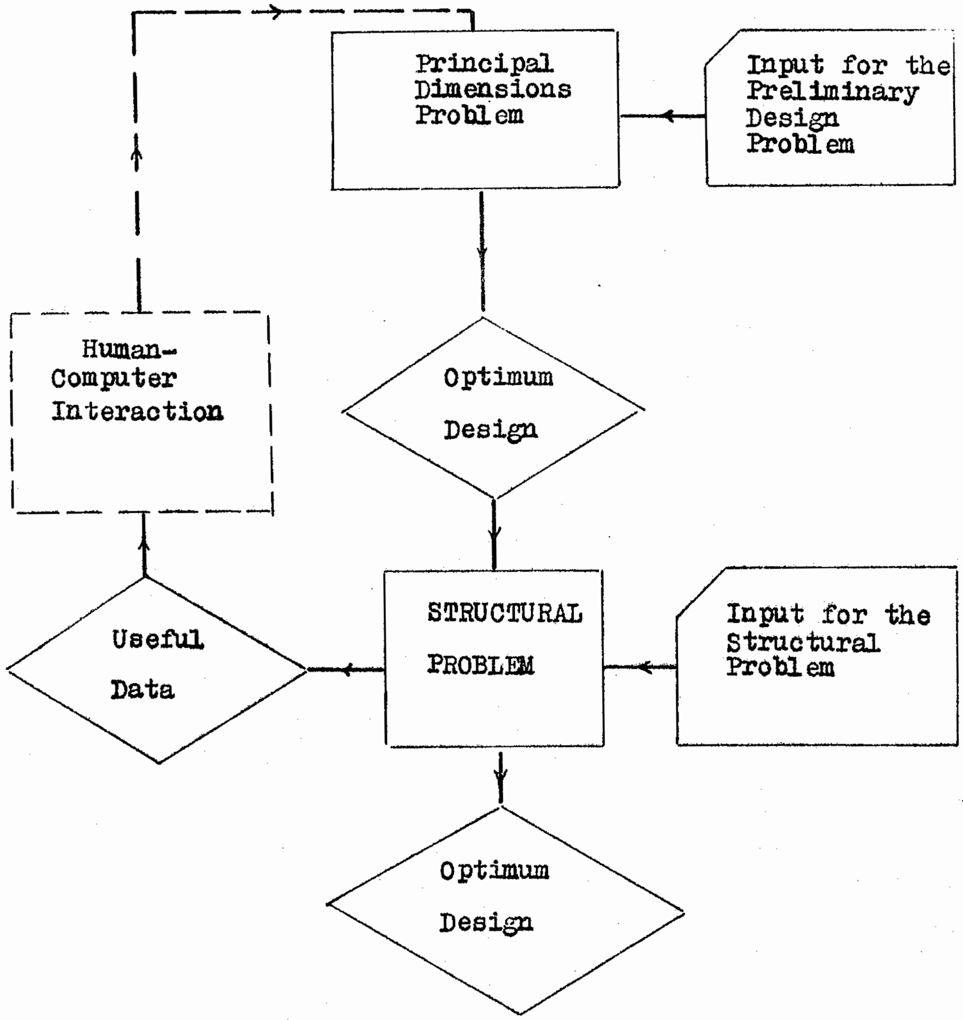


Fig. 2 Simplified flow chart illustrating possible implementation of output of the computerized structural problem in improving the preliminary design.

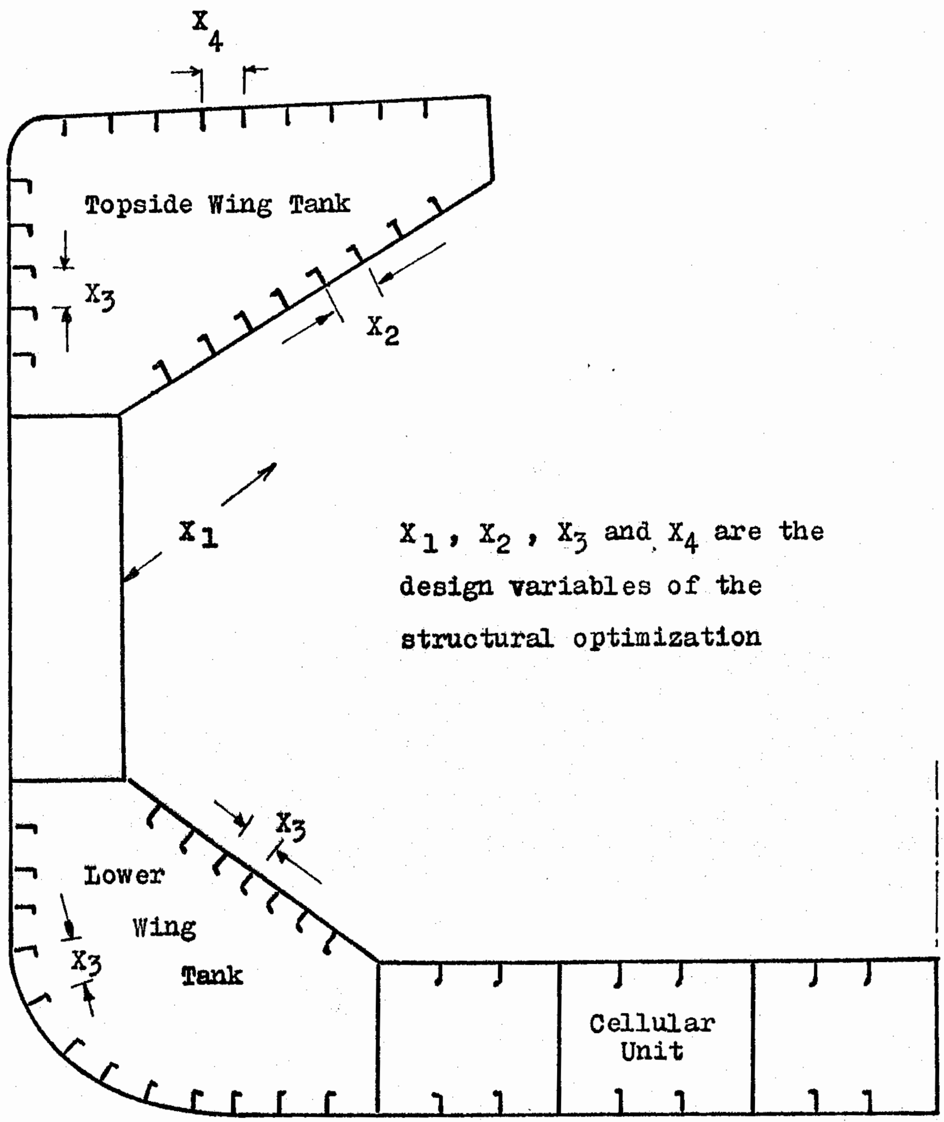


Fig. 3 Midship Section Arrangement

Design Variables

1. Transverse frame spacing, X_1 (inches)

$$33.0 \le X_1 \le 42.0 \ ,$$

2. Spacing of topside wing-tank sloping bulkhead longitudinals, X_2 (inches)

$$30 \le X_2 \le 40 \ ,$$

3. Spacing of longitudinals in ship sides, X_3 (inches)

$$30 \le X_3 \le 36 \quad \text{and}$$

4. Spacing of deck longitudinals, X_4 (inches)

$$30 \le X_4 \le 40 \ .$$

Constraints

In addition to the limits which control the fluctuation of the design variables in search for the optimum solution, there are other constraints which also ensure proper stress limits and satisfy ABS rules as well as other practical considerations. Both of primary bending and shear stresses of the main hull girder are recognized as important factors in bulk carriers structural design.

For the present optimization technique, the constraints must be expressed in a normalized form $g_i \geq 0$. The following is a summary of all constraints considered :

$$g_1 = \frac{X_1}{33} - 1 \geq 0,$$

$$g_2 = \frac{42}{X_1} - 1 \geq 0,$$

$$g_3 = \frac{X_2}{30} - 1 \geq 0,$$

$$g_4 = \frac{38}{X_2} - 1 \geq 0,$$

$$g_5 = \frac{X_3}{30} - 1 \geq 0,$$

$$g_6 = \frac{36}{X_3} - 1 \geq 0,$$

$$g_7 = \frac{X_4}{25} - 1 \geq 0,$$

$$g_8 = \frac{40}{X_4} - 1 \geq 0,$$

$$g_9 = \frac{SM_B}{SM_{BC}} - 1 \geq 0 \quad \text{and}$$

$$g_{10} = \frac{SM_T}{SM_{TC}} - 1 \geq 0$$

where SM_B and SM_T are rule section moduli to the bottom and top respectively;

SM_{BC} and SM_{TC} are the corresponding calculated moduli;

$$g_{11} = \frac{T_m}{T} - 1 \geq 0$$

where T_m = maximum practical deck thickness, inches;

T = calculated thickness of the deck plating, inches;

$$g_{12} = \frac{4.75}{S_1} - 1 \geq 0,$$

$$g_{13} = \frac{6.3}{S_2} - 1 \geq 0 \quad \text{and}$$

$$g_{14} = \frac{4.0}{S_3} - 1 \geq 0$$

where S_1 = maximum calculated shearing stress amidships, in still water condition, tons per square inch;

S_2 = maximum calculated shearing stress for the governing loading condition, tons per square inch and

S_3 = maximum calculated bending stress in the still water condition, tons per square inch.

Measure of Merit

The objective function for the optimization process is cost, weight or the required freight rate. The later criterion combines effects of the weight and cost as well as a change in the payload.

The maximum weight has long been sought by ship designers as a criterion for optimization. The reason may be the fact that it is simple and conventional. For high speed vessels and some types of naval ships such as catamarans, the weight criterion can be justified because of the need to minimize displacement, hence increase the deadweight/ displacement ratio.

Every shipyard probably has its own formulation for cost modeling. A model would depend on many factors some of which may not be related even the building operation itself. But for the purpose of the present work, the cost model considers only those items which influence the production cost of the cargo holds' structural elements.

Detailed cost and weight models are formulated. Differences among shipyards' cost estimates may be accounted for by adjusting the cost model input parameters.

Mathematical Format

The objective function can be expressed in terms of the design variables as :

$$F = f(X_1, X_2, \ldots, X_n), \; n = 4$$

The function F is non-linear in most ship structural optimization problems similar to the present study. It is defined numerically rather than in a mathematical form for which derivatives are obtainable.

There are several 'direct search' methods using digital computers to find the optimum of such unconstrained function. The search is always done sequentially, exploiting information from previous trials, hence, reducing the computer time required.

But in the present case, as well as many other problems, the design variables are subjected to inequality constaints which can be written as :

$$G_m = g_m(x_1, X_2, \ldots X_n) \geq 0,$$

m = 14 in the present case.

Now the search for the optimum solution would be limited to the 4-dimensional space domain bounded by the 14 equations which are explained in the previous section. The boundary of such domain is also non-linear in its most common form.

For such constrained problem that may also be subjected to equality constraints, Moe and Kavlie (8) introduced the use of a penalty function to transform the problem into a format that is suitable to be treated using the well-defined sequential unconstrained optimization techniques.

Nowacki and his co-workers (11) at the University of Michigan, defined a new object function similar to Moe's as :

$$\bar{F}(x, r_k) = F(x) + r_k \sum_{i=1}^{m} \frac{1}{g_i(x)} ;$$

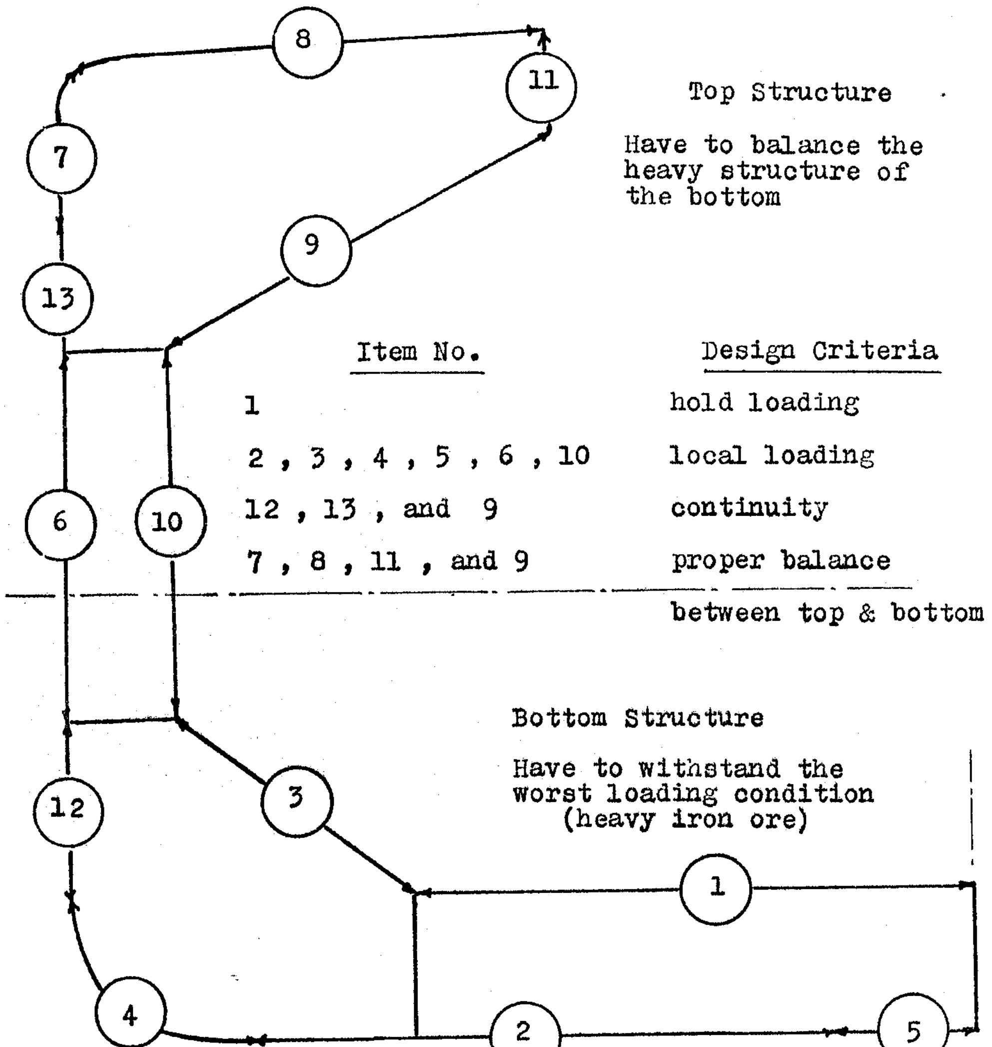
r_k = a parameter approaching zero in successive approximate steps.

The above function is used successfully in connection with a direct search method originated by Hooke and Jeeves for a tanker optimization study. It is also used in the present research after a slight modification so that the program will handle only integer values of the design variables.

DESIGN PROCEDURE

As pointed out earlier, there is an interaction between the basic design problem and the structural optimization. But since solving the first problem is beyond the scope of the present work, arbitrary input is used to carry out the structural optimization using results of a research by Gilfillan (7), wherein he has investigated the principal dimensions problem of a similar bulk carrier. A second group of the input will specify requirements and limitations such as a maximum practical thickness of deck plating, slope of the topside and lower wing tank bulkheads, load intensities and cost parameters.

All midship section structural members are designed to satisfy the ABS rule requirements but with different design criteria. An example, showing how the shell plating thickness is calculated, is given in Figure 4.



Item No.	Design Criteria
1	hold loading
2 , 3 , 4 , 5 , 6 , 10	local loading
12 , 13 , and 9	continuity
7 , 8 , 11 , and 9	proper balance between top & bottom

Computer storage arrays : Plate thickness $\left.\begin{matrix}T(I)\\W(I)\end{matrix}\right\}$, I=1,13
Plate Width

Fig.4 Design criteria of shell plating

Before going further in summarizing the design steps, one may focus the attention on a problem of importance especially when heavy cargoes are intended to be carried in alternate holds. This problem is the position of the hull girder neutral axis.

Position of the Neutral Axis

A critical area in the midship section design is that of the upper flange of the hull girder. In order to obtain a satisfactory balance between bottom and deck structures, the ABS rules relate the section modulus to the bottom SM_B to that of the top SM_T. The rule requires a 10% increase in SM_B over SM_T for bulk carriers less than 700 ft long. Although the difference is not required for ships of 1000 ft in length and over, interpolation would be used to find the percentage for vessels between 700 and 1000 ft. Reasons behind such increase are the high secondary stresses at the bottom due to heavy local load intensities; and corrosion that would happen more rapidly in the under-water portion of the vessel.

If the scantlings of the midship section are assigned using secondary and tertiary stresses as criteria, the bottom structure will be almost always heavier than the deck structure.

The corresponding position of the hull girder neutral axis will be even closer to the bottom than what the ABS rule does allow.

Therefore, for given scantlings of the bottom structure as determined from local strength calculations, one can minimize the longitudinal material by assigning the minimum height of the neutral axis above the midship base-line. This procedure is unique in case of large hatch openings as in the case considered.

Steps of Design

After determining the position of the neutral axis, the following steps are carried out for each set of the design variables :

1. Area, first and second moments of area about the neutral axis are calculated using the minimum ABS rule requirements for local strength. This is done for each of the longitudinally continuous members below and above the neutral axis separately.
2. If the moment of area of the bottom members is greater than that of the top, the latter will receive incremental adjustments, which will achieve the proper balance between the top and the bottom flanges of the hull girder.

3. The design of transverse webs in the topside and lower wing tanks is then done according to a sub-optimization process to wisely distribute the cross-sectional area of each member between its web and flanges.

COMPUTER ANALYSIS

A reader of this paper may not be quite familiar with the computer language, but it simply consists of statements that give instructions to the machine. One may note here a resemblance between music and computer programing for both are human languages. In music, a development may be defined as the elaboration of a theme by rhythmic, harmonic, and melodic changes. In computer programing our developments are called subroutines which are composed of statements and functions. The subroutines, as the developments, are not very significant unless they are integrated together to achieve certain goals.

Five subroutines are written to divide the work of this study into five individual jobs. The following explains briefly the task of every subroutine.

Subroutine GEOMT

This subroutine is concerned with the geometric configuration of the midship section. Figure 5 shows how GEOMT calculates and stores the midship dimensions in single arrays. Practical considerations are implemented in the construction of cellular units in the double bottom and the location of the tank top knuckle.

Subroutine SCANT

The job assigned to this subroutine is very similar to what may be required from a preliminary structural design group in a classical-type shipyard. The main difference is that the time needed to do a complete midship section calculation using electronic calculators is about 8 man-days, while SCANT performs the same task in few seconds.

After calculating the scantlings of all midship section structural components, the computer divides the weight of the hull material amidships into 3 main categories :

a) Longitudinally continuous material.
b) Transverse framing comprising floors, side or web frames, and wing tanks' transverses.
c) Other remaining weight items which are not affected by the design variables, hence can be determined emperically.

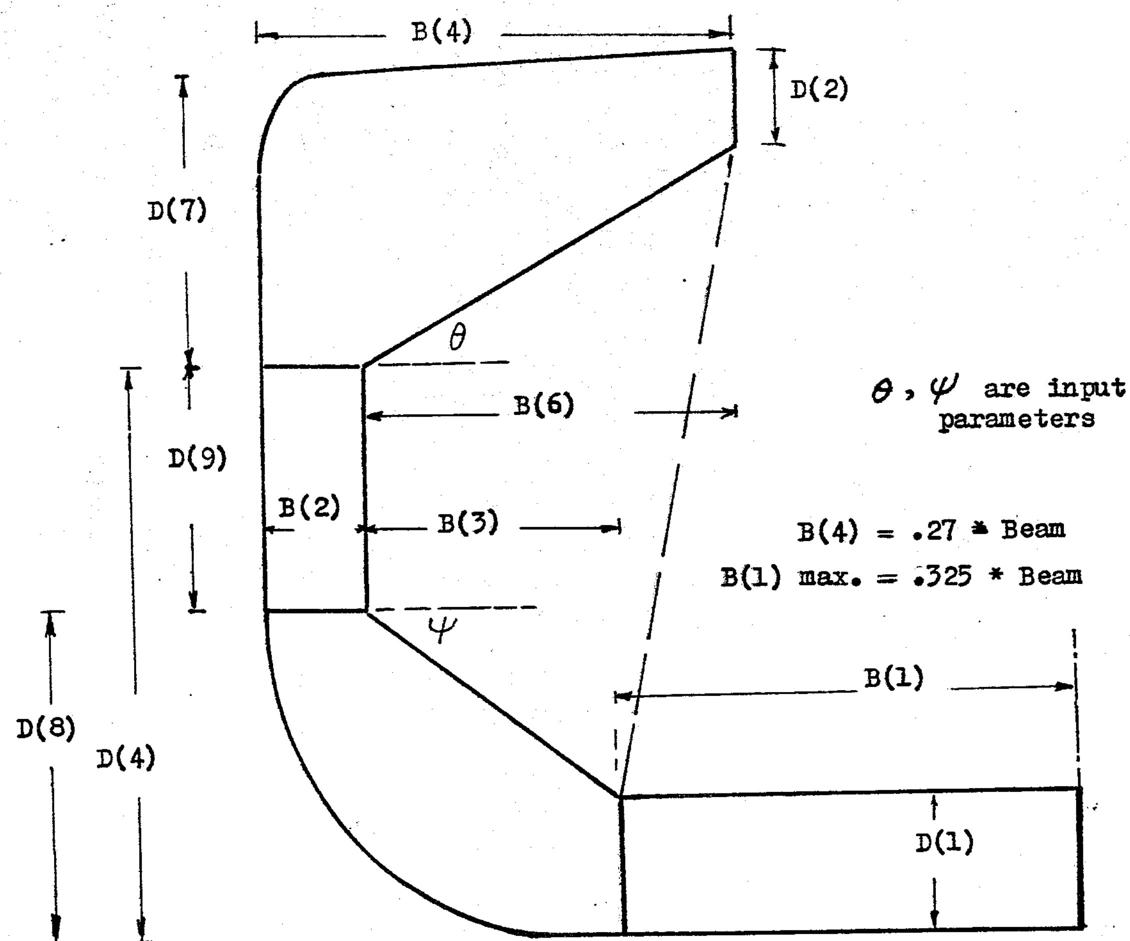


Fig. 5 Computer's definition of midship section dimensions

Subroutine SUMT

This subroutine carries the mathematical task of the optimization process by minimizing the objective function and thus finding the optimum solution.

Subroutine CONSTR

If for a set of the design variables any of the 14 constraints, mentioned previously, is violated; CONSTR will pick up the violated constraint and report it to the subroutine SUMT which will bring the search for the optimum back to the feasible side of the domain's boundary.

Subroutine FUN

The organization of FUN is done so that it computes the required objective function which would be selected from the available options via a code specified, as an input parameter, by the computer program user.

The following is a brief summary of how the objective function is calculated :

a) The Minimum Weight Criterion

If the weight is to be optimized, the computer will minimize a function F which is given by :

$$F_w = W - D$$

where W = an estimated hull steel weight,

$D = W_x + T_x - W_o - T_o$

W_x= weight of the longitudinally continuous material, tons,

T_x= weight of the transverse framing systems, tons,

W_o and T_o are the same as the above except that they are those of an initial guess on the design variables.

In fact, a slight inaccuracy in estimating W using emperical methods will not affect, to any degree, the results of the optimization.

b) The Minimum Cost Criterion

Steel material and labor costs are considered. The steel labor cost may be divided into :

- Cost of mounting and welding deck, bottom, side shell, sloping bulkheads and inner bottom longitudinals;
- Cost of fabrication, welding, erection, and assembling the transverses;
- Cost which is independent of the design variables such as blocking and stagging.

The objective function in this case is :

$$F_c = C - LD * LF - MD * MF$$

where C = An estimated initial cost of the ship, \$;

LD = Decrease in labor cost from that calculated for the initial guess on the design variables;

LF = Labor factor;.

MD = Decrease in the material cost from that calculated for the initial guess, \$ and

MF = Material factor;

The asterisk '*' stands as a multiplication sign.

c) RFR Criterion

In this case, the subroutine FUN sets the objective function as :

$$F_R = \frac{Y + P\ (CRF - 15\% - 25)}{C}$$

where Y = annual operating cost, \$;

$P = P_o - F_c$,

$C = C_o + N * Fw$,

P_o = initial cost corresponding to the initial guess;

C_o = cargo per year for the initial guess;

N = number of round voyages per year,

CRF= capital recovery factor based on 15% yield and 25 years.

The Program MAIN

This program reads the input data which include initial step widths and error tolerance needed for the optimization process.

Flow Chart

Figure 6 shows the flow chart of the computer work. The main program calls the subroutine GEOMT which outlines the midship section. Main then calls SUMT which runs the optimization process. SUMT has two main mechanisms, one to keep the search inside the feasible space, and another to search for the optimum. It calls CONST which in turn gets all the required scantling from SCANT. CONST checks the constraints and if one is violated, it will report the violation to SUMT which will bring the search back to the feasible side. If not, the search for the optimum would start.

The optimization loops are continued until the minimum value of the objective function is found. The computer will then print out the optimum set of the design variables.

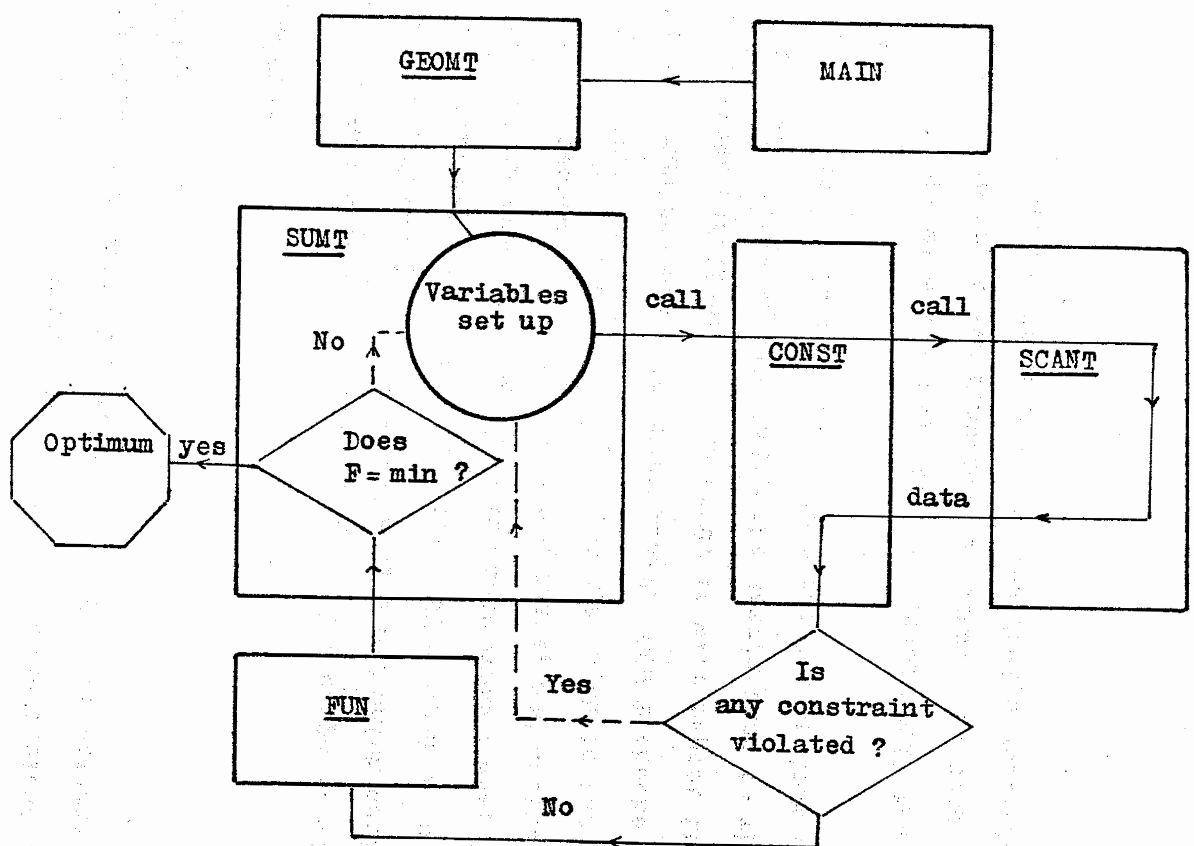


Fig. 6 Flow chart of the computer program

SAMPLE RESULTS

The computer program written for the bulk carriers structural optimization can be used to handle quite a few problems in practical applications as well as research and development.

The results presented here are for a Panama and Suez Canal carrier, 720 ft long, 105 ft in breadth, has 63 ft depth and 40 ft draft. The optimum value of the design variables are shown in the following table.

TABLE 1

Optimum Values of the Design Variables

Design variable	Criterion for optimization		
	Weight	Cost	RFR
X_1	33	36	36
X_2	38	38	38
X_3	30	30	30
X_4	37	39	38

The results shown in table 1 do agree with logical considerations. In general one can say that the RFR optimum solution lies somewhere between those of weight and cost but much closer to the later. The minimum weight criterion gives smaller values for almost all spacings of the stiffening systems and this is a well known fact.

The spacing of longitudinals in ship sides X_3 converges to 30 inches for all the optimization criteria considered, i.e., just on a boundary of the search domain created by X_3. This may be justified by the fact that an increase in X_3 for the longitudinals below the neutral axis, will lead to a heavier bottom structure which will consequently need more material in the top to balance it. The result is a double increase in the weight which will penalize every of the three criteria considered.

One may also note that the spacing of the topside wing tank sloping bulkhead longitudinals is 38 inches for all the criteria. This is not right on the search domain but is actually the greatest permissible value of X_2 because the number of the longitudinals is an integer; hence reducing it by one would bring the value of X_2, which is also an integer, outside the search domain. The explanation of such convergence may be that large spacing will lead to heavier cross-sectional area of the top structure, which is needed to balance the heavier bottom flange of the hull girder, while it also decreases the labor cost. The impact of these two effects is good for all the criteria considered. In other words, the material which would be saved from decreasing X_2 should go elsewhere in the top structure to obtain a satisfactory top flange area, hence, no gain in weight saving will be obtained. This would show that the optimization of separate ship pannels, by itself, is in some cases not very meaningful.

SENSITIVITY STUDY

In some cases, one may desire to investigate the effect of varying one design variable on the objective function. This would show the magnitude by which the function will be affected. Two examples illustrating the effect of X_1 variation on the two optimum solutions obtained for the weight and cost criteria, as given in table 1, will be discussed.

Effect of X_1 Variation on Weight

In the present study, the weight of the holds portion doesn't include the transverse bulkheads and hatch covers, because the weight of these items is not affected, to a considerable degree, by the design variables. Thus the portion of the ship optimized is found to be about 50% of the total steel weight of the hull.

Figure 7 shows the weight of transverses versus frame spacing, while Figure 8 shows the variation of the longitudinally continuous material. The net result of combining these two effects is given in Figure 9. It should be noted here that the incremental weight change in Figure 9 is calculated as a deviation from a design corresponding to an initial guess on the design variables wherein X_1 is taken as 36 inches.

Effect of X_1 Variation on Cost

The reduction in the total production cost versus frame spacing is shown in Figure 10. The base-line is considered at a 30 inches spacing, i.e., in comparison with a vessel whose spacing is 30 inches.

Two important things can be learnt from Figure 10. Firstly, there are two peaks along the curve but SUMT has picked the right global maxima in the optimization process. Secondly, the ABS rule frame spacing of 38 inches is close to the optimum frame spacing according to the minimum cost criterion.

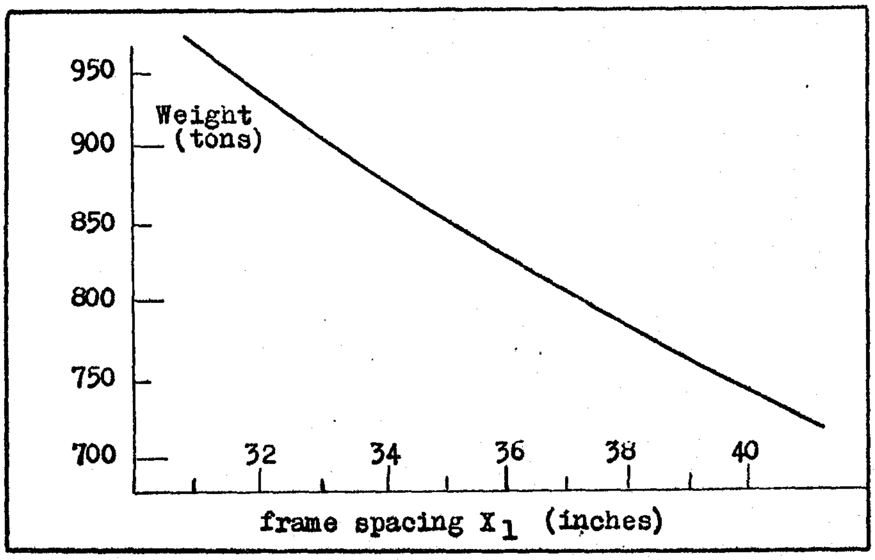


Fig. 7 Effect of X_1 variation on weight of the transverse stiffening systems

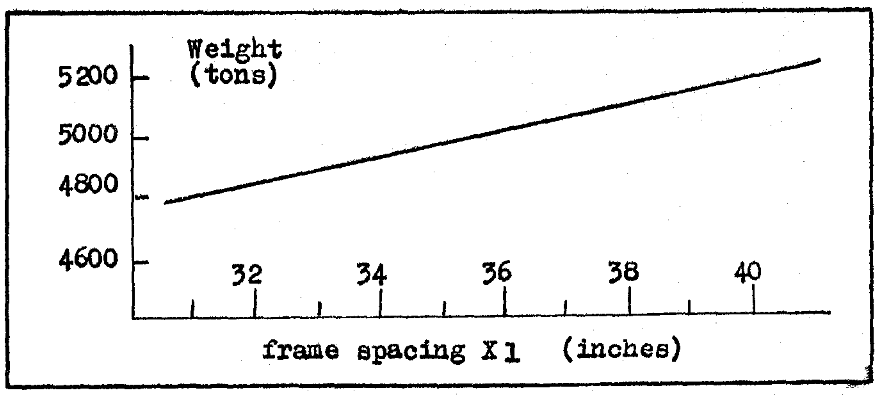


Fig. 8 Effect of X_1 variation on weight of the longitudinally continuous material

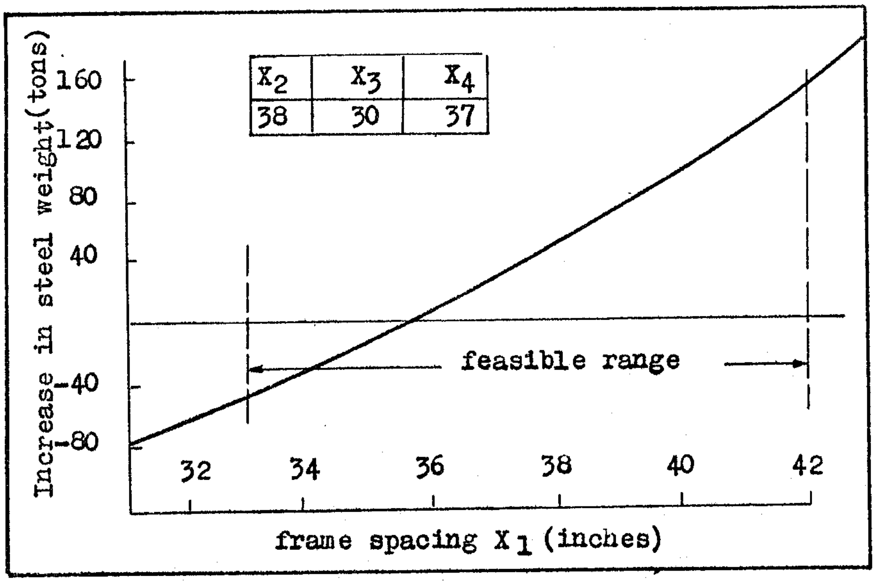


Fig. 9 Net increase in steel weight

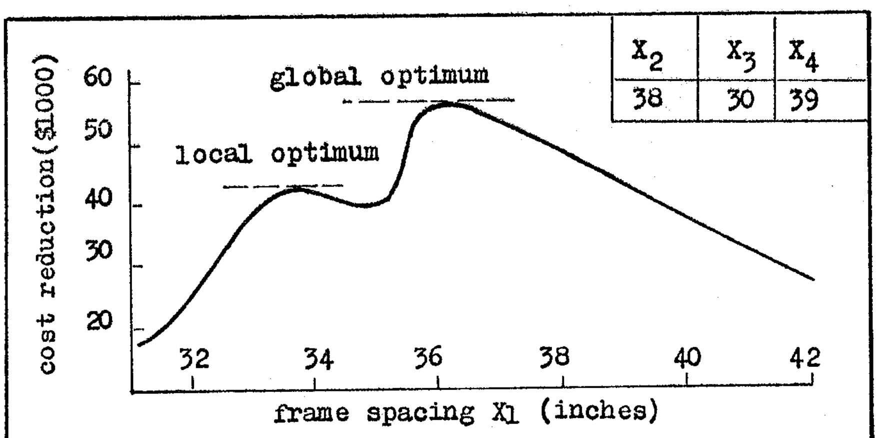


Fig. 10 Net reduction in material and labor cost

CONCLUDING REMARKS

The application of non-linear programing techniques to solve fairly complicated ship structural problems is proved to be feasible. The organization of the computer program is done economically in such a way that permits it to handle variety of problems.

Examples are the impact of environmental considerations on structural features of vessels and corresponding improvements or expansion in the classification rules. One may mention here that, the project for the Suez Canal developing will allow a permissible draft of 67 ft while it is now only 40 ft. This may lead to a need for a new class of ocean bulk carriers. The research presented in this paper will be helpfull in developing such new class.

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