1- Publications in Ship Structural Analysis and Design (1969-2002)

1- " Effect of Variation of Ship Section Parameters on Shear Flow Distribution, Maximum Shear Stresses and Shear Carrying Capacity Due to Longitudinal Vertical Shear Forces", European Shipbuilding, Vol. 18. (Norway-1969), Shama, M. A.,

2- "Effect of Ship Section Scantlings and Transverse Position of Longitudinal Bulkheads on Shear Stress Distribution and Shear Carrying Capacity of Main Hull Girder", Intern. Shipb. Progress, Vol. 16, No. 184, (Holland-1969), Shama, M. A.,

3- "On the Optimization of Shear Carrying Material of Large Tankers", SNAME, J.S.R, March. (USA-1971), Shama, M. A.,

4- " An Investigation into Ship Hull Girder Deflection", Bull. of the Faculty of Engineering, Alexandria University, Vol. XII., (Egypt-1972), Shama, M. A.,

5- "Effective breadth of Face Plates for Fabricated Sections", Shipp. World & Shipbuilders, August, (UK-1972), Shama, M. A.,

6- " Calculation of Sectorial Properties, Shear Centre and Warping Constant of Open Sections", Bull., Of the Faculty of Eng., Alexandria University, Vol. XIII, (Egypt-1974), Shama, M. A.

7- "A simplified Procedure for Calculating Torsion Stresses in Container Ships", J. Research and Consultation Centre, AMTA, (EGYPT-1975), Shama, M. A.

8- "Structural Capability of Bulk Carries under Shear Loading", Bull., Of the Faculty of Engineering, Alexandria University, Vol. XIII, (EGYPT-1975), Also, Shipbuilding Symposium, Rostock University, Sept. (Germany-1975), Shama, M. A.,

9- "Shear Stresses in Bulk Carriers Due to Shear Loading", J.S.R., SNAME, Sept. (USA-1975) Shama, M. A.,

10- "Analysis of Shear Stresses in Bulk Carriers", Computers and Structures, Vol.6. (USA-1976) Shama, M. A.,

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On The Optimization of Shear Carrying Material of Large Tankers

By M. A. Shama[1]

The effect of longitudinal material distribution in a ship section, on shear stresses in and shear deformations of side shell and longitudinal bulkheads, is investigated and discussed. The investigation is concerned with large tankers having three longitudinal bulkheads and is carried out in the form of a parametric study. The results are given in terms of ship depth, thickness of side shell plating and the longitudinal vertical shear force of the main hull girder. An optimization procedure for calculating the optimum distribution of the shear carrying material of a hull girder is presented together with a numerical example. The calculated optimum distribution of the shear carrying material satisfies both strength and stiffness requirements. It is concluded that the relative values of the effective thicknesses of side shell and longitudinal bulkheads, as well as the transverse position of side longitudinal bulkheads, have a marked influence on the magnitude of the maximum shear stress and deformation in a ship section. It is also shown that an optimization procedure for the shear carrying material of large tankers could be achieved without violating the requirements of Lloyd's Register of Shipping Rules for 1968.

Introduction

THE STRUCTURAL DESIGN of a ship section is mainly governed by the various forces and moments resulting from the local and general loads acting on the main hull girder. The accurate assessment of these various types of loads is a difficult task and has not yet been fully solved. This is simply because the nature and causes of some of these loads have not been accurately determined, such as the residual stresses resulting from cutting, welding and assembly operations.

However, this problem has been partly solved by the classification societies, which have produced rules for the structural design of several types of steel ships. Nevertheless, the design of a ship section, according to these rules, neither gives the least weight structure nor how much extra material has been put in the structure. Much research work has been carried out in this direction aimed at the determination of the optimum design of a ship section without violating the requirements of classification societies.

The optimum structural design of a ship section should yield the lightest structure satisfying both strength and stiffness requirements, under the assumed worst loading condition. The optimization process, therefore, results in an efficient distribution of all the effective material in a ship section with a subsequent valuable saving in the required amount of steel.

The optimization procedure could be carried out for:

i. several local structural details, and/or
ii. a ship section, or
iii. a certain length of the ship (e.g., a cargo tank length in an oil tanker).

The first problem is a simple one, but may not result in the optimum design of the main hull girder. The second problem is a two-dimensional one and could be easily solved using a parametric study. This problem could be simplified by optimizing, separately, the material required to carry the local and general bending stresses and the material required to sustain the shear stresses of the main hull girder. However, the resulting optimum ship section may necessitate increasing the scantlings of the supporting transverse members. In order to overcome this problem, the optimization procedure should be carried out for the three-dimensional form of the structure, such as for a cargo tank length of an oil tanker. This problem could best be solved using the finite-element technique.

In this paper, the effect of material distribution in a ship section of a tanker having three longitudinal bulkheads has been investigated with reference to:

a. Shear flow distribution around the ship section.
b. Magnitude of the maximum shear stresses at the neutral axis of the ship section.

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c. Participation of longitudinal bulkheads to the shear carrying capacity of main hull girder.
d. Shear deflection of side shell and longitudinal bulkheads.

The results of this investigation are used to determine the optimum distribution of the shear carrying material of the main hull girder. This optimum distribution, is, in effect, a compromise between the configuration having least shear area and that yielding equal vertical shear deflections for side shell and longitudinal bulkheads.

The optimized shear carrying material not only provides adequate effective shear area but it also provides sufficient effective material to carry the local and bending loads. This has been achieved by satisfying the requirements of Lloyd's Register of Shipping Rules for 1968.

In order to carry out the optimization procedure, the shear flow distribution around a half ship section due to a longitudinal vertical shear force is computed. Subsequently the maximum shear stresses in and shear deflections of side shell and longitudinal bulkheads are calculated. These calculations are based on the assumptions that a ship section is symmetrical about the vertical centerplane, that the section is not subjected to any torsional moments, and that the longitudinal vertical shear force is uniformly distributed in the transverse direction.

The calculations were carried out in the form of a parametric study using the Alexandria University IBM 1620 computer. The actual plate thickness is replaced by an effective thickness so as to take the contribution of the stiffening members into account. The main parameters used are: the effective thicknesses of side shell, longitudinal bulkhead, bottom and deck plating, transverse position of side longitudinal bulkheads, and the breadth/depth ratio. From this parametric study the shear flow, shear stress, shear deflection and shear carrying capacity of side shell and longitudinal bulkheads are represented by nondimensional coefficients. The effect of variation of each individual parameter on the magnitude of the maximum shear stress in, on the shear deflection of, and on the shear carrying capacity of side shell and longitudinal bulkheads is computed and analyzed.

Using Lloyd's Register Rules for 1968, and the computed nondimensional coefficients for the shear stress and shear deflection, a relationship between the longitudinal vertical shear force and ship depth is obtained. This relationship is represented graphically for several values of the chosen parameters. From these curves, the optimum distribution of the shear carrying material could be determined without violating the requirements of Lloyd's Register Rules for 1968. A numerical example is presented to show the importance of the optimization procedure.

No attempt is made here to investigate the effect of shear deflection of side shell and longitudinal bulkheads on the strength of transverse members.

The importance of this investigation arises from the fact that the recent increase in tanker size is effectively achieved by increasing ship breadth, since the increase in ship depth is controlled by the draft limitations and the increase in ship length is controlled by, among other factors, building costs as well as dry docking. However, the increase in tanker size is associated with a corresponding increase in shear force, bending moment, hull girder deflection in addition to the increase in the local hydrostatic loading. Therefore, it is of utmost importance to provide adequate effective material in the deck, bottom, sides and longitudinal bulkheads to carry the local hydrostatic loading as well as the shear force and bending moment of the main hull girder. The provision of this effective material in the deck and bottom is catered for by the increase in ship breadth and also by increasing the plating thicknesses and associated longitudinal stiffeners. On the other hand, because of the limited increase in ship depth, the provision of adequate effective material in the sides and longitudinal bulkheads could be achieved either by increasing the thicknesses of plating and associated longitudinal stiffeners or by optimizing the distribution of the shear carrying members. The latter approach is the main objective of this investigation as the increase in plating thicknesses and associated longitudinal stiffeners, for side shell and longitudinal bulkheads, may produce an inefficient and heavy structure.

Calculation of the Shear Flow Distribution in a Ship Section of a Large Tanker

The main assumptions and method of calculation of shear flow distribution in multicell box-girders are given in detail by Williams [1].[2] The application of these methods to the structural design of oil tankers is given in reference [2] for tankers having one centerline longitudinal bulkhead and in reference [3] for tankers having two longitudinal bulkheads. The following analysis is concerned with large tankers having three longitudinal bulkheads:

In order to calculate the shear flow distribution in a complicated structure such as a ship section, the stiffened plating in the section (deck, bottom, sides and longitudinal bulkheads, which will be designated by D, B, S, C and L respectively) is idealized by an effective plating. The thickness of the latter is defined as "effective thickness" and in fact takes all the longitudinal continuous stiffening material into account. The idealized ship section (see Fig. 1) is therefore a 4-cell box girder made of unstiffened panels. The geometrical properties of the ship section should be maintained in the idealized 4-cell box girder. The computation of the effective thicknesses of the idealized structure is as follows:

$$t_j = l_j + \left[\sum_{i=1}^{n} \frac{a_i}{l_i} \right],$$

where

$j = D, B, S, C$ or L
t_j = effective thickness of member j

[2] Numbers in brackets designate References at end of paper.

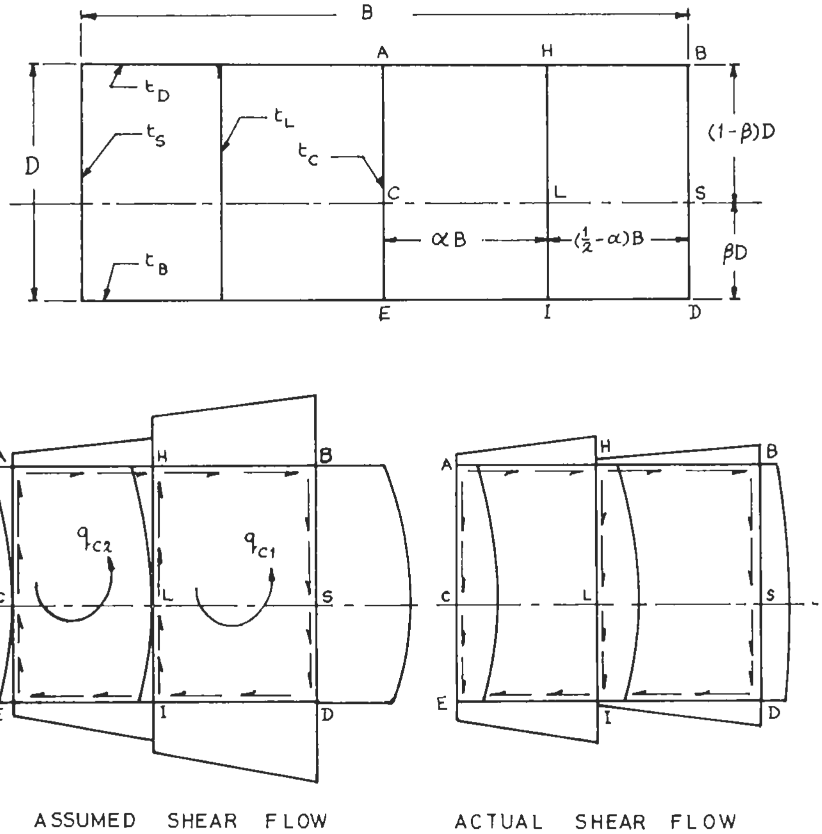

Fig. 1

$\bar{t}_j$ = mean thickness of member j

$$= \left[\bar{t}_i l_i \Big/ \sum_{i=1}^{n} l_i\right]_j$$

n = number of strakes in member j
$\bar{t}_i$ = true thickness of strake i, (i = 1, 2...n)
l_i = length of strake i in plane of ship section (i = 1, 2...n)
a_i = total sectional area of all longitudinal stiffeners attached to strake i, (i = 1, 2...n)

It is shown in reference [4] that the errors resulting from this idealization are very small, and in fact could be neglected in the course of this parametric study.

The shear flow at any point i in a ship section is given by

$$q_i = \frac{F}{I} Q_i \tag{1}$$

Using nondimensional coefficients, the first and second moments of area of a ship section are given by:

$Q_i = \phi_i D^2 t_s$ see Appendix 3
$I = \psi D^3 t_s$ see Appendix 1

Substituting these two values of Q_i and I into equation (1), we get

$$q_i = w_i \frac{F}{D} \tag{2}$$

where ϕ_i, ψ and w_i are nondimensional coefficients for the first and second moments of area of a ship section and for the shear flow respectively. Their values are entirely dependent on the geometry and scantlings of the ship section.

The assumed shear flow distribution around the idealized structure, as given by equation (2), distorts the cells $HBDI$ and $AHIE$ by angles θ_1 and θ_2 respectively, Fig. 1. Since it is assumed that the ship section is not subjected to any torsional moments, correcting shear flows $(q_c)_1$ and $(q_c)_2$ should be applied to these two cells in order to satisfy the geometry of the structure. The calculation of these correcting shear flows is given in Appendix 2 and is given by:

$$(q_c)_i = w_i \frac{F}{D} \quad (i = 1, 2) \tag{3}$$

where w_1 and w_2 are nondimensional coefficients.

The actual value of the shear flow at any point i in a ship section is the resultant of the assumed shear flow, as given by equation (2), and the correcting shear flow, as given by equation (3). For members HB, BD and DI, the resultant shear flow is given by:

$$(q_i)_r = q_i - (q_c)_1$$

For member *HI*, it is given by:

$$(q_i)_r = q_i - (q_c)_1 + (q_c)_2$$

For members *AH* and *IE*, it is given by:

$$(q_i)_r = q_i - (q_c)_2$$

For member *AE*, it is given by:

$$(q_i)_r = q_i - 2(q_c)_2$$

Therefore, for points *C*, *S* and *L*, Fig. 1, the shear flow is given by:

$$q_C = 2(q_C)_2 = w_C \frac{F}{D} \qquad (4a)$$

$$q_L = (q_C)_1 - (q_C)_2 = w_L \frac{F}{D} \qquad (4b)$$

$$q_S = q_{SB} - (q_C)_1 = w_S \frac{F}{D} \qquad (4c)$$

where w_C, w_L and w_S are nondimensional coefficients, and are given by

$$w_C = 2w_2$$

$$w_L = w_1 - w_2$$

$$w_S = \frac{\phi_s}{\psi} - w_1$$

and

$$\phi_s = \frac{\gamma z\beta}{2} - \frac{\beta^2}{4}(y_C + 2y_L + 2) \qquad \text{see Appendix 3}$$

Calculation of the Maximum Shear Stress in a Ship Section

Although the calculation of shear flow distribution around a ship section is based on the concept of an effective thickness, the computation of shear stresses is, in fact, based on the true thickness of plating.

The maximum shear stress occurs at the neutral axis of the ship section, i.e., where the shear flow is maximum. From Fig. 1, it is shown that the highest values of the shear stress will be at points *C*, *L* and *S* and are given by:

$$\tau_i = \frac{q_i}{\bar{t}_i} \qquad (i = C, L, S) \qquad (5)$$

Nomenclature

A = area of a section
A_w = web area of a ship section
d_A = elementary area
B = ship breadth
D = ship depth
d = ship draft
F = longitudinal vertical shear force
F_C, F_L, F_S = shear force carried by centerline longitudinal bulkhead, side longitudinal bulkhead and side shell respectively
G = modulus of rigidity
I = second moment of area of a ship section about its own neutral axis
K_C, K_L, K_S = nondimensional coefficients of shear forces carried by centerline and side longitudinal bulkheads and by side shell respectively
L = length of ship
Q_i = first moment of area above point i about neutral axis of ship section
q_i = shear flow at point i
$(q_i)_r$ = resultant shear flow at point i
q_{ij} = shear flow at point i in member ij
$(q_C)_1$, $(q_C)_2$ = correcting shear flows
$(q_C)_m$, $(q_L)_m$, $(q_S)_m$ = mean shear flows for centerline and side longitudinal bulkheads and for side shell plating respectively
$(q_i)_y$ = shear flow for member i at a distance y from ship section neutral axis
R = $A_w/D\bar{t}_S$
ΔS = elementary length on perimeter
t = thickness
t_D, t_B, t_L, t_C, t_S = effective thicknesses of deck, bottom, side longitudinal bulkhead, centerline longitudinal bulkhead and side shell plating respectively
$\bar{t}_L$, $\bar{t}_C$, $\bar{t}_S$ = actual thicknesses of side longitudinal bulkhead, centerline longitudinal bulkhead and side shell plating respectively
v = rate of shear deflection
v_L, v_C, v_S = rate of shear deflection for side and centerline longitudinal bulkheads and for side shell respectively
w = nondimensional coefficient of shear flow
x = t_D/t_B
y_L = t_L/t_S
y_C = t_C/t_S
Z = t_B/t_S
α = normalized distance of side longitudinal bulkhead from the longitudinal centerline of ship
β = normalized distance of section neutral axis from baseline
γ = B/D
ψ = nondimensional coefficient of second moment of area
ρ = nondimensional coefficient for shear stress
τ_i = shear stress at point i
φ = nondimensional coefficient for first moment of area
η_1, η_2 = nondimensional coefficients
θ = angle of twist due to assumed shear flow
θ_c = correcting angle of twist
Δ = vertical shear deflection
δ_s = nondimensional coefficient
λ = nondimensional coefficient
μ_L, μ_C, μ_S = shear deflection coefficients for side and centerline longitudinal bulkheads and for side shell respectively

In order to determine the nondimensional coefficients of the shear stresses in side shell and longitudinal bulkheads, it is assumed that:

$$\bar{t}_C/\bar{t}_S = y_C \tag{6a}$$

and

$$\bar{t}_L/\bar{t}_S = y_L \tag{6b}$$

This assumption does not have any effect on the subsequent calculations and analysis, and in fact its main purpose is to reduce the number of the parameters used in this investigation.

Substituting equations (4) and (6) into (5), we get

$$\tau_i = \rho_i \frac{F}{D\bar{t}_S} \qquad (i = C, L, S) \tag{7}$$

where ρ_C, ρ_L, and ρ_S are nondimensional coefficients for the maximum shear stress in the centerline longitudinal bulkhead, side longitudinal bulkheads, and side shell plating, and are given by:

$$\rho_C = w_C/y_C \tag{8a}$$

$$\rho_L = w_L/y_L \tag{8b}$$

$$\rho_S = w_S \tag{8c}$$

The values of ρ_C, ρ_L, and ρ_S are entirely dependent on the geometry and scantlings of the ship section. The effect of variation of the various ship section parameters on ρ_i, $(i = C, L, S)$ is shown in Figs 2, 3, and 4.

From the shear-stress distribution over the side shell and longitudinal bulkheads, it is possible to calculate the participation of the longitudinal bulkheads in the shear carrying capacity of the main hull girder; see Appendix 4.

The shear forces carried by side shell and longitudinal bulkheads are given by:

$$F_i = K_i F \; (i = S, L, C) \tag{9}$$

The values of K_i, $(i = S, L, C)$ are entirely dependent on the geometry and scantlings of the ship section. The effects of variation of the various ship section parameters on K_i, $(i = S, L, C)$ are shown in Figs. 5, 6, and 7.

Calculation of the Vertical Shear Deflection of Shear Carrying Members

The bending deflection of the main hull girder, in the longitudinal vertical plane, depends mainly on the distribution of load and stiffness of hull girder throughout the ship length. This deflection could be assumed to be uniform throughout the ship breadth. On the other hand, the shear deflection of the hull girder, in the longitudinal vertical plane, is not uniform in the transverse direction, since this deflection depends on the magnitude and distribution of the shear stresses in side shell and longitudinal bulkheads. The difference in the vertical deflection of side shell and longitudinal bulkheads may cause the ship section to distort as shown in Fig. 8. The distorted shape, however, depends mainly on the relative magnitude of shear deflections of the shear carrying members and the stiffnesses of the intersecting transverse members [5]. Therefore the nonuniform transverse vertical deflection may induce additional forces and moments to the attached transverse members.

Reference [6] indicates that the shearing deformation of transverse rings induces stresses in the lower transverse members on the order 20–30 percent of those induced by direct loading. In fact this percentage could be higher under certain conditions of loading. Consequently, in order to have a rigorous solution for the strength of transverse rings of tankers, the vertical deflection of the shear carrying members should be taken into account. This particular problem is outside the scope of this paper and should be investigated separately. In the following analysis, however, the relative vertical shear deflections of side shell and longitudinal bulkheads are determined and the influence of the various ship section parameters on these shear deflections is studied.

The shear deflection of a member is calculated using the energy method as follows [1]:

$$\frac{1}{2}F\Delta = \int_0^x \int_0^A \frac{1}{2}\left(\frac{\tau^2}{G}\right) dA \; dx$$

Hence

$$\Delta = \frac{1}{FG}\int_0^x \int_0^A \tau^2 dA \; dx$$

and

$$v = \frac{1}{FG}\int_0^A \tau^2 dA$$

where

Δ = vertical shear deflection

$$v = \frac{d\Delta}{dx}$$

The shear strain for side shell and longitudinal bulkhead is given by:

$$v_i = \mu_i \frac{F}{GA_w} \qquad (i = S, L, C) \tag{10}$$

where μ_C, μ_L and μ_S are nondimensional coefficients given by:

$$\mu_i = \frac{\lambda_i \cdot K_i}{A_i/A_w} \qquad (i = S, L, C) \tag{11}$$

where λ_i, $(i = C, L, S)$ are coefficients depending on the shear stress distribution along the member, A_S, A_C, A_L are the effective shear areas for side shell and longitudinal bulkheads respectively, and

$$A_w = 2A_L + 2A_S + A_C$$

K_S, K_L and K_C are shear force coefficients and are given in Appendix 4.

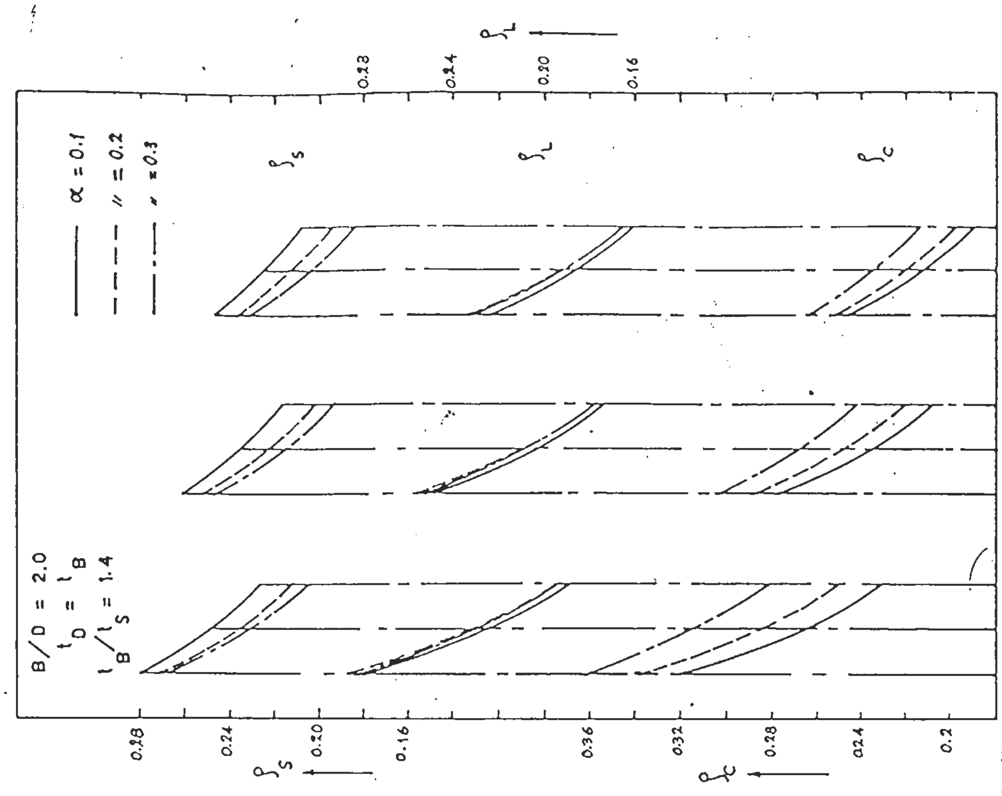
B/D = 2.0
$t_D = t_B$
$t_B/t_S = 1.4$
α = 0.1
" = 0.2
" = 0.3
ρ_S
ρ_L
ρ_C
$t_L/t_S =$
$t_C/t_S =$

Fig. 3

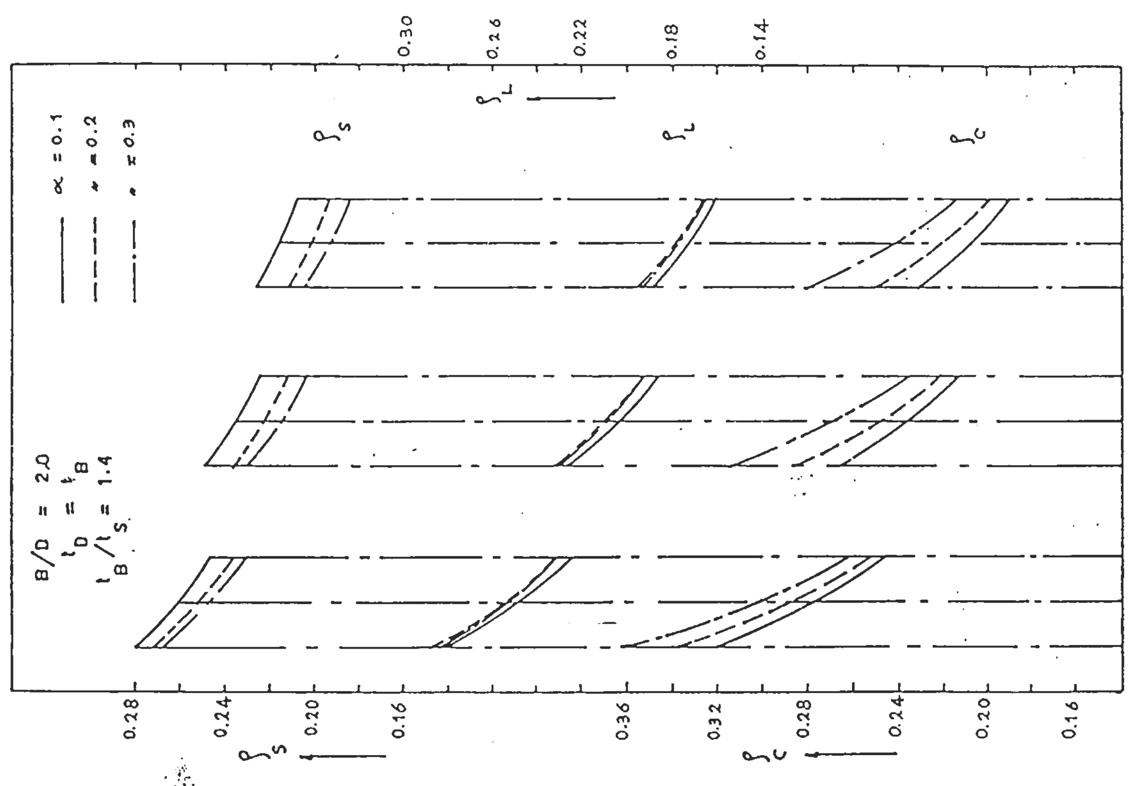
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Fig. 2

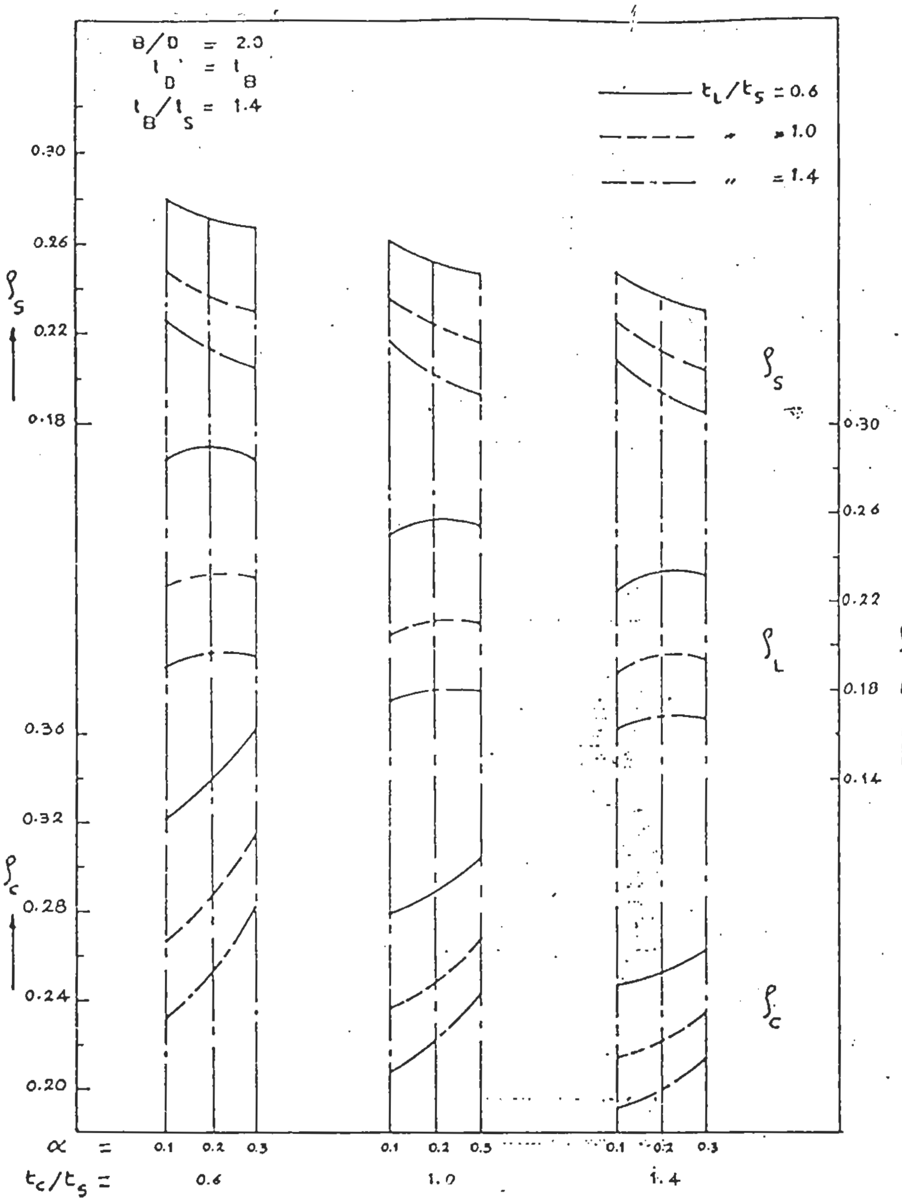


Fig. 4

The effect of variation of the various ship section parameters on μ_i, ($i = C, L, S$) is shown in Figs. 9, 10, 11.

Optimization of Shear Carrying Material

The optimization procedure is aimed at the calculation of the minimum total sectional area of the shear carrying material, such that:

i. The maximum shear stress in the ship section does not exceed a certain allowable value.
ii. The vertical shear deflections for side shell and longitudinal bulkheads are equal.

The optimization procedures according to items (i) and (ii) are treated separately, as follows:

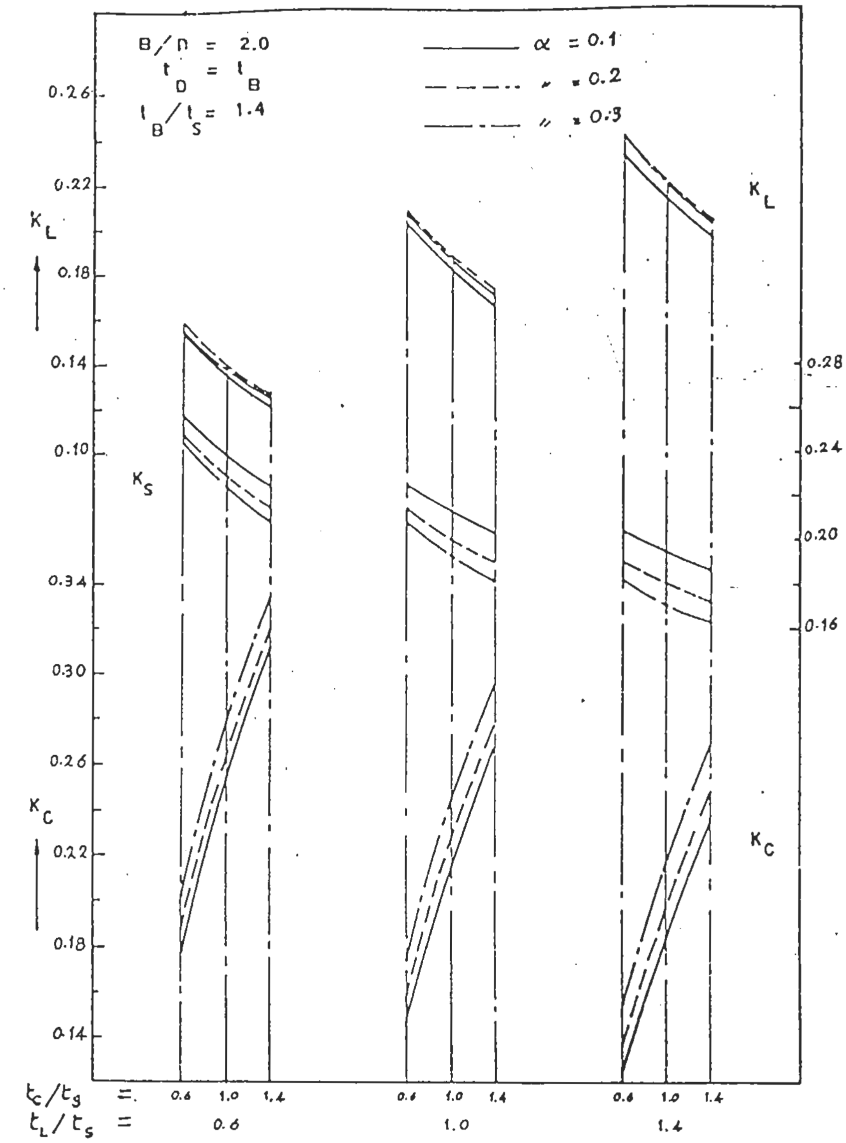
(a) Optimization of the Shear Carrying Material Using an Upper Limit for the Maximum Shear Stress

This could be achieved by satisfying condition (i) only, i.e.

$$\tau_i \leqslant \tau_a \qquad (i = S, L, C) \tag{12}$$

where τ_a is the maximum allowable shear stress (it varies between 6.0 and 7.0 kg/sq mm).

Fig. 5



From equations (S), substituting τ_a for the shear stress, we get:

$$F_{max} \leqslant \frac{\tau_a}{\rho_i} D\bar{l}_S \qquad (i = S, L, C) \qquad (13)$$

The minimum thickness of side shell plating is determined from the rules of classification societies. Using Lloyd's Register Rules for 1968, the minimum thickness of side shell plating, within 0.4 L amidships, when longitudinally framed, is given by (D 5301) as follows:

$$\bar{l}_S = \frac{S + 150}{640}\sqrt{\frac{dL}{D}} \quad \text{mm}$$

where

$$S \nless 559 + 1.11\,L$$

S = spacing of longitudinals

Hence

$$D\bar{l}_S = \frac{S + 150}{640}\sqrt{dLD} \quad \text{m.mm} \qquad (a)$$

The relationship between the ship depth D and the product $D\bar{l}_s$ could be determined from expression (a) as follows:

$$D\bar{l}_S = mD\sqrt{fD} \qquad (b)$$

where

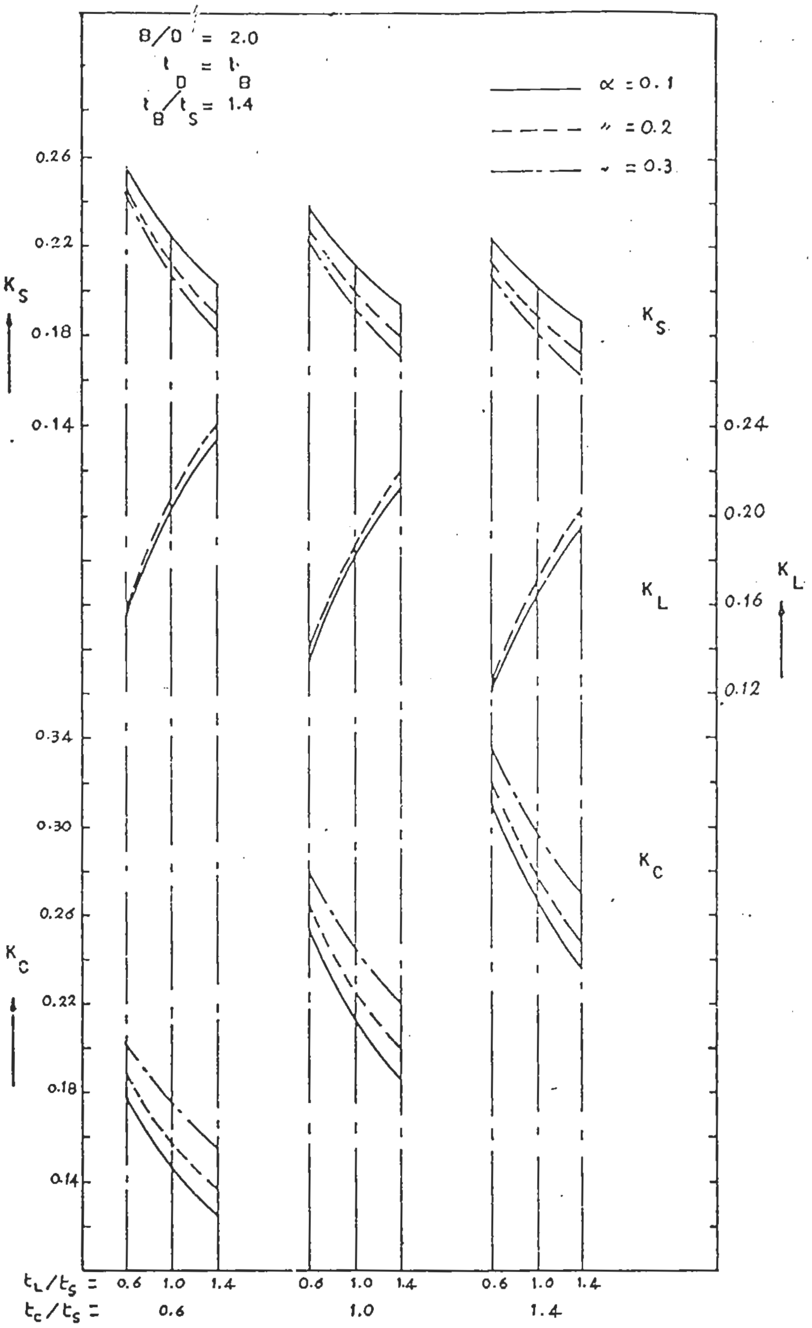


Fig. 6

$$m = \frac{(559 + 1.11\,L) + 150}{640}$$

and

$$f = \frac{d}{D} \cdot \frac{L}{D}$$

Substituting for $D\bar{t}_S$ from (*b*) into (13), we get:

$$F_{max} = \frac{\tau_a}{\rho_i} m D \sqrt{fD} \qquad (i = S, L, C) \qquad (14)$$

Therefore, for any ship section configuration having a depth D the maximum allowable shear force which will not induce shear stresses in side shell or in the longitudinal bulkheads greater than the maximum allowable value could be determined from (14). However, expressions

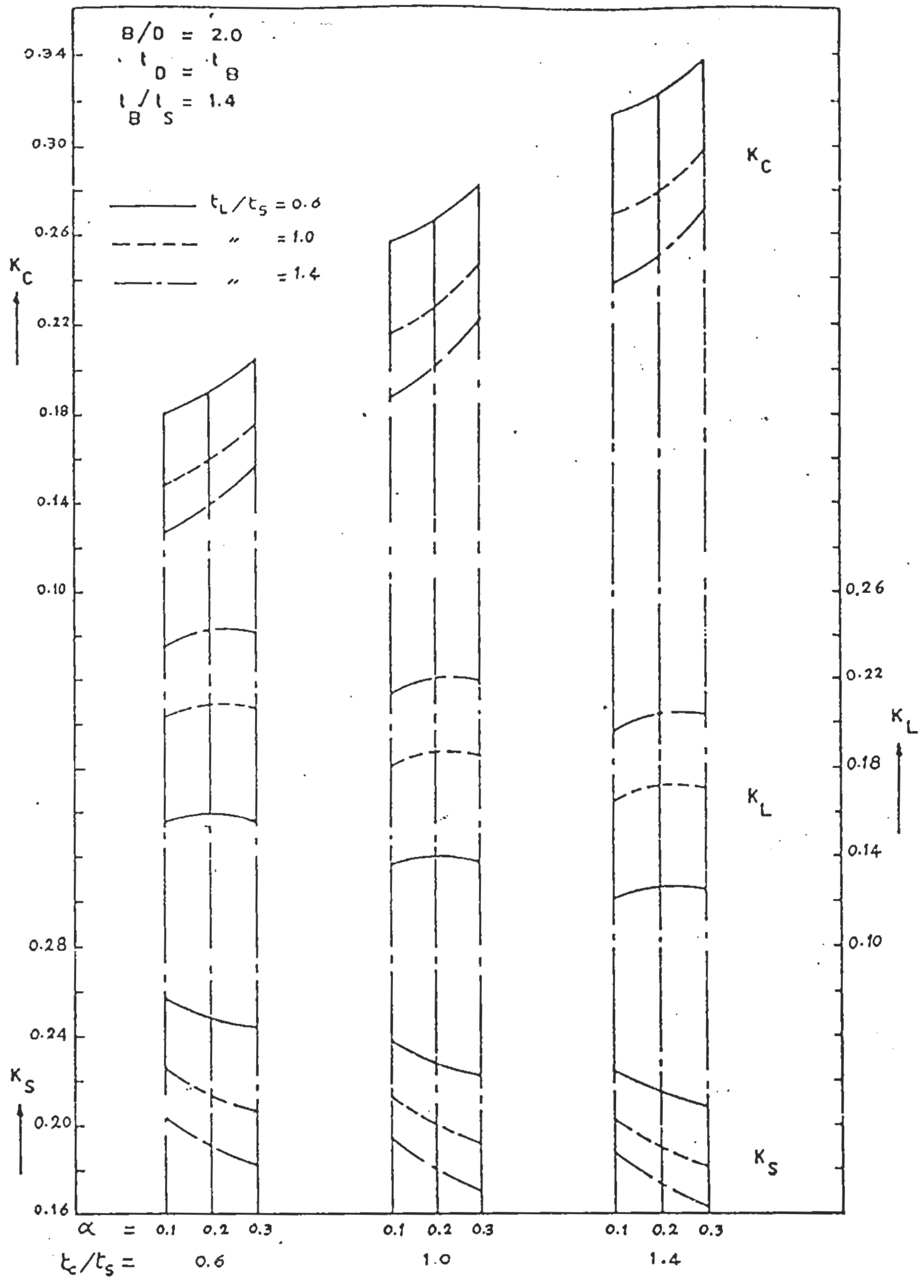


Fig. 7

(14) could be represented graphically for several conditions of the ship section. The optimum configuration for a ship having a depth D and subjected to a maximum shear force F_{max} could be determined from these curves. A sample of these curves is shown in Figs. 12, 13 for the following conditions:

Fig. 12: $B/D = 2.0$, $t_D = t_B$, $t_B/t_S = 1.4$, $t_C/t_S = 1.0$ and 1.4, $\alpha = 0.2$, $f = 10.0$, $t_L/t_S = 0.6$, 1.0 and 1.4

Fig. 13: $B/D = 2.0$, $t_D = t_B$, $t_B/t_S = 1.4$, $t_C/t_S = 1.0$ and 1.4, $\alpha = 0.3$, $f = 10.0$, $t_L/t_S = 0.6$, 1.0 and 1.4

In these curves, if $f \neq 10.0$, the magnitude of the shear force should be corrected as follows:

$$(F)_{corrected} = F\sqrt{\frac{f}{10}}$$

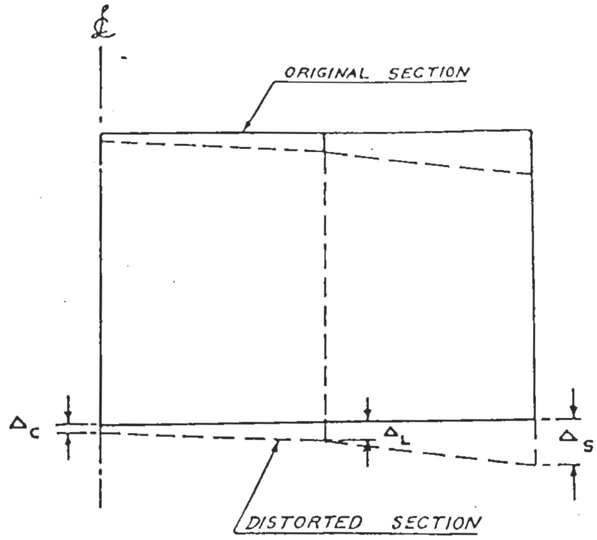


Fig. 8

These curves are very useful to determine the optimum ship section configuration that will not induce shear stresses greater than a maximum allowable value. In addition, these curves could be used to determine, for any ship section configuration, the maximum allowable shear force which will not induce shear stresses in side shell or in longitudinal bulkheads greater than a maximum allowable value.

(b) Optimization of the Shear Carrying Material with Regard to Vertical Shear Deflection

This could be achieved by satisfying condition (ii) only. This condition infers that the vertical shear deflections of side shell and longitudinal bulkheads must be equal. Assuming that:

$$A_w = R \cdot Dt_S$$

and then substituting in equations (10), we get:

$$\frac{v_i}{F} = \frac{\mu_i}{GRDt_S} \qquad (i = S, L, C) \tag{15}$$

where R = nondimensional coefficient > 1.0.

Substituting expression (b) in (15), we get:

$$\frac{v_i}{F} = \frac{\mu_i}{GRmD\sqrt{fD}} \qquad (i = C, L, S) \tag{16}$$

Therefore, for any ship section configuration having a depth D the vertical shear deflection per unit length of side shell and longitudinal bulkheads could be calculated from (16), when the shear force F is known. Expressions (16) could be represented graphically for several conditions of the ship section. The optimum configuration could be determined from these curves for any ship having a depth D, length L, and draft d.

A sample of these curves is shown in Figs. 14, 15, and 16 for the following conditions:

Fig. 14 $B/D = 2.0$, $t_D = t_B$, $t_B/t_S = 1.4$, $t_C/t_S = 0.6$, $t_L/t_S = 0.6$, 1.0 and 1.4, $\alpha = 0.2$ and 0.3, $\delta_s = 1.0$, $R = 2.0$, $f = 10.0$

Fig. 15 $B/D = 2.0$, $t_D = t_B$, $t_B/t_S = 1.4$, $t_C/t_S = 1.0$, $t_L/t_S = 0.6$, 1.0 and 1.4, $\alpha = 0.2$ and 0.3, $\delta_s = 1.0$, $R = 2.0$, $f = 10.0$

Fig. 16 $B/D = 2.0$, $t_D = t_B$, $t_B/t_S = 1.4$, $t_C/t_S = 1.4$, $t_L/t_s = 0.6$, 1.0 and 1.4, $\alpha = 0.2$ and 0.3, $\delta_s = 1.0$, $R = 2.0$, $f = 10.0$

where

$$\delta_s = A_s/A_w$$

If $\delta_s \neq 1.0$, the rate of shear deformation obtained from the foregoing curves should be corrected as follows:

$$\left(\frac{v}{F}\right)_{\text{corrected}} = \left(\frac{v}{F}\right)/\delta_s$$

and if $R \neq 2.0$, the rate of shear deformation should be corrected as follows:

$$\left(\frac{v}{F}\right)_{\text{corrected}} = \left(\frac{v}{F}\right) \times \frac{2}{R}$$

These curves are very useful to determine the ship section configuration which will approximately induce equal vertical shear deflections for side shell and longitudinal bulkheads. On the other hand, these curves could be used to determine, for any ship section configuration, the relative vertical shear deflections for side shell and longitudinal bulkheads.

A numerical example for an oil tanker is given in Appendix 5, showing the calculation of the optimum distribution of shear carrying material from the viewpoints of shear stress and shear deflections.

Ranges of the Different Parameters

The foregoing calculations were performed on the Alexandria University IBM 1620 digital computer. The different parameters were varied as follows:

1. Breadth/depth ratio; i.e., B/D varies from 1.5 to 3.0 every 0.5.
2. Effective thickness of deck plating/effective thickness of bottom plating; i.e., t_D/t_B varies from 0.6 to 1.4 every 0.4.
3. Effective thickness of bottom plating/effective thickness of side shell plating; i.e., t_B/t_S varies from 0.6 to 1.4 every 0.4.
4. Effective thickness of side longitudinal bulkhead plating/effective thickness of side shell plating; i.e., t_L/t_S varies from 0.6 to 1.4 every 0.4.

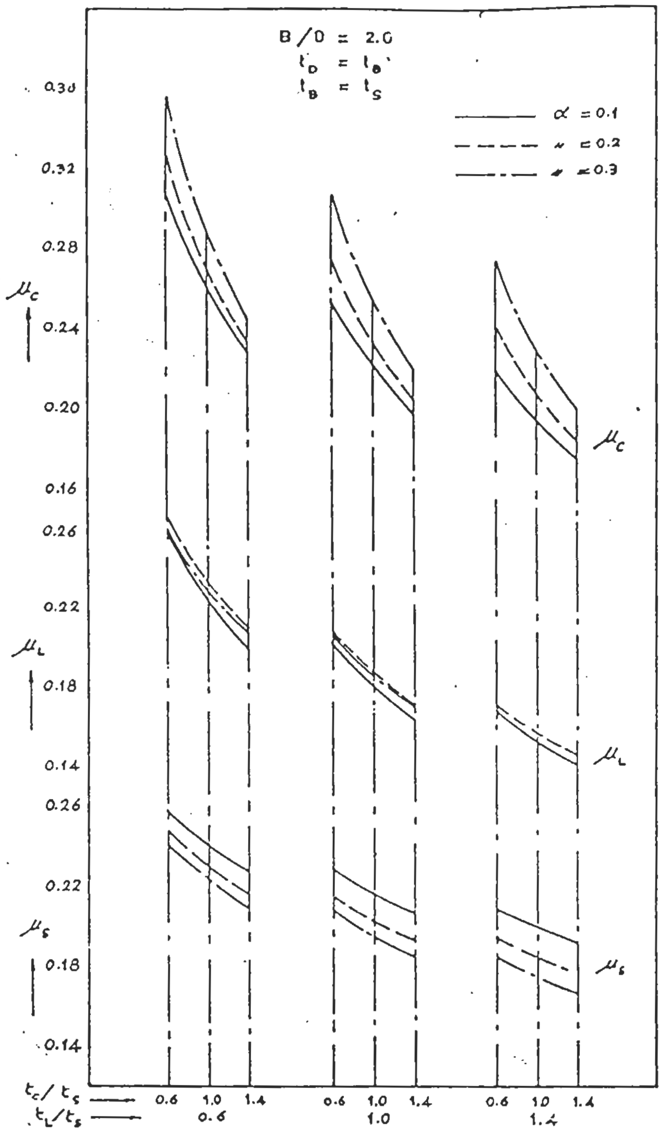


Fig. 9

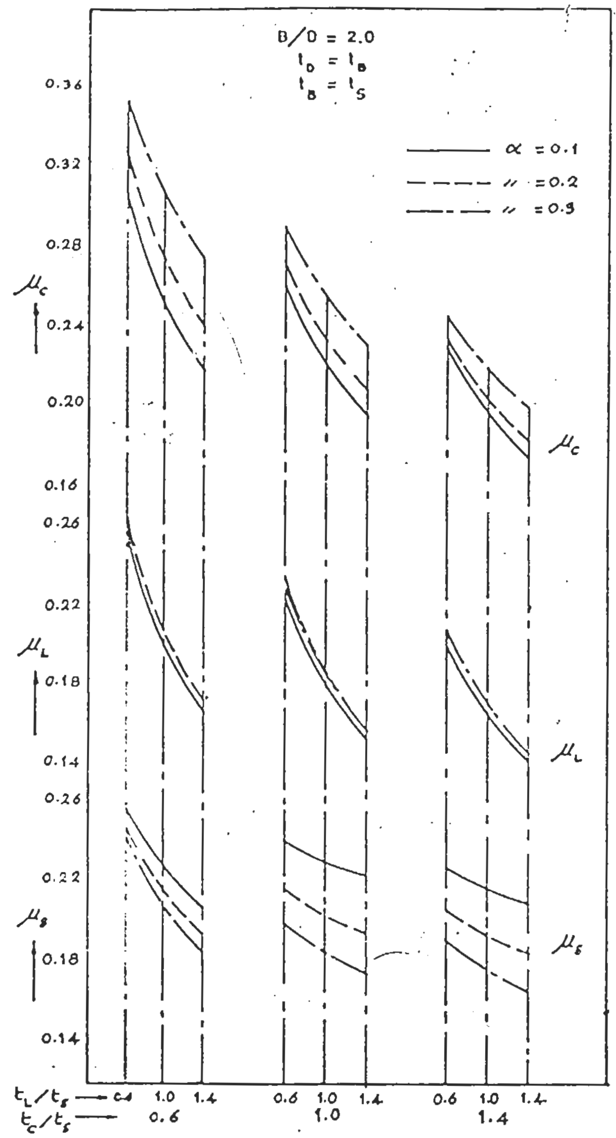


Fig. 10

5. Effective thickness of centerline longitudinal bulkhead plating/effective thickness of side shell plating; i.e., t_C/t_S varies from 0.6 to 1.4 every 0.4.

6. Transverse position of side longitudinal bulkhead from ship centerline; i.e., the normalized distance α varies from 0.1 to 0.3 every 0.1.

The parametric study was carried out to investigate the effect of varying each parameter, within the ranges indicated in the foregoing, on the following:

a. Shear flow distribution in the ship section.

b. Maximum shear stress in side shell and longitudinal bulkheads.

c. Participation of side shell and longitudinal bulkheads in the shear carrying capacity of main hull girder.

d. Vertical shear deflection of side shell and longitudinal bulkheads.

Discussion of Results

In order to simplify the presentation of this parametric study, only part of the results is represented graphically in Figs. 2–7 and 9–11. These figures indicate the effect of variation of the relevant parameters on:

i. The magnitude of the maximum shear stress in side shell and longitudinal bulkheads; i.e., τ_S, τ_L and τ_C.

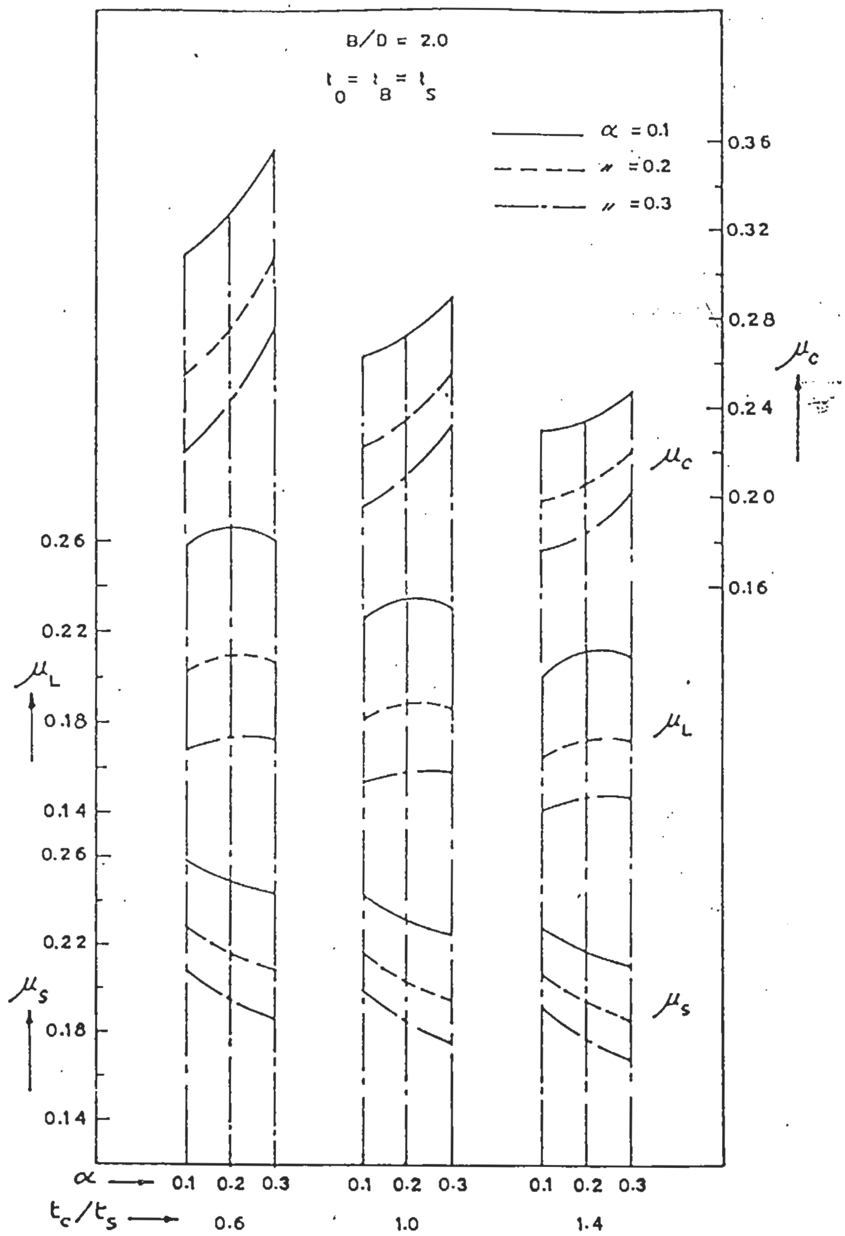


Fig. 11

ii The participation of side shell and longitudinal bulkheads in the shear carrying capacity of main hull girder; i.e., K_S, K_L and K_C.

iii. The magnitude of the vertical shear deflection of side shell and longitudinal bulkheads; i.e., v_S, v_L and v_C.

From the parametric study, it was found that the chosen parameters could be divided into (i) parameters having major effects, and (ii) parameters having minor effects. The former parameters include t_C/t_S, t_L/t_S and α, whereas the latter parameters include t_D/t_B, t_B/t_S and B/D.

The effects of increasing each relevant parameter on τ_i, K_i, and v_i, ($i = C, L, S$) are as follows:

1 Effect of t_C/t_S

The effect of variation of the parameter t_C/t_S on τ_i, K_i, v_i, ($i = C, L, S$) is shown in Figs. 2, 3, and 4 respectively. From these figures, it is evident that increasing the thickness of centerline longitudinal bulkhead has the following effects:

(*a*) The maximum shear stresses in C, L and S are reduced; see Fig. 2.

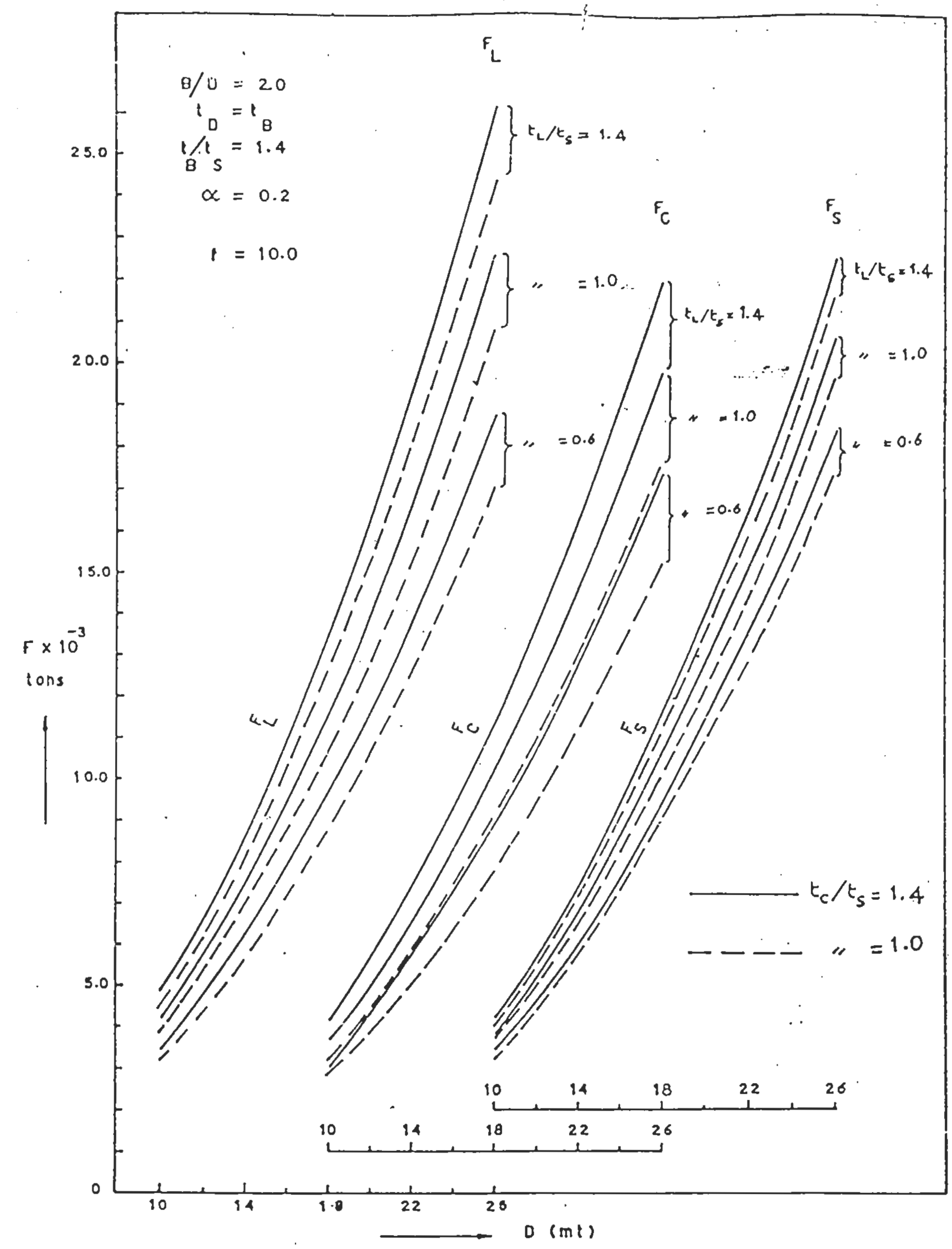


Fig. 12

(*b*) The contribution of the centerline bulkhead to the shear carrying capacity of the main hull girder increases very rapidly. This has the advantage of reducing the shear loads carried by the side shell and side longitudinal bulkheads; see Fig. 3.

(*c*) The vertical shear deflections of C, L and S are reduced; see Fig. 4.

2 *Effect of t_L/t_S*

The effects of variation of the parameter t_L/t_S on τ_i, K_i, v_i, ($i = C, L, S$) are shown in Figs. 5, 6, and 7 respectively. From these figures it is evident that increasing the thickness of side longitudinal bulkheads has the following effects:

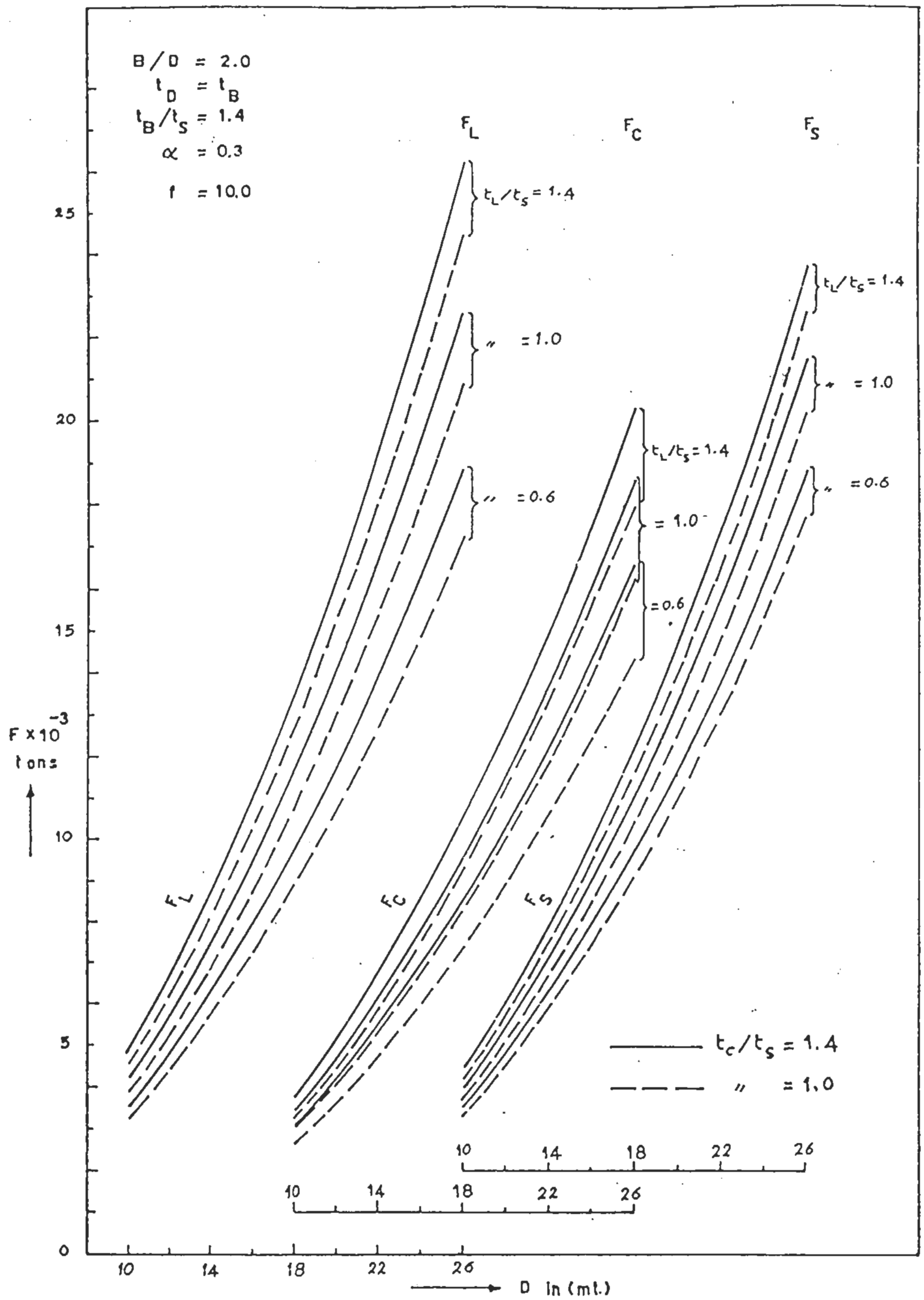


Fig. 13

(*a*) The maximum shear stresses in C, L and S are reduced; see Fig. 5.

(*b*) The contribution of the side longitudinal bulkheads to the shear carrying capacity of the main hull girder increases very rapidly. Consequently, the shear loads carried by the centerline longitudinal bulkhead and side shell are reduced; see Fig. 6.

(*c*) The vertical shear deflections of C, L and S are reduced; see Fig. 7.

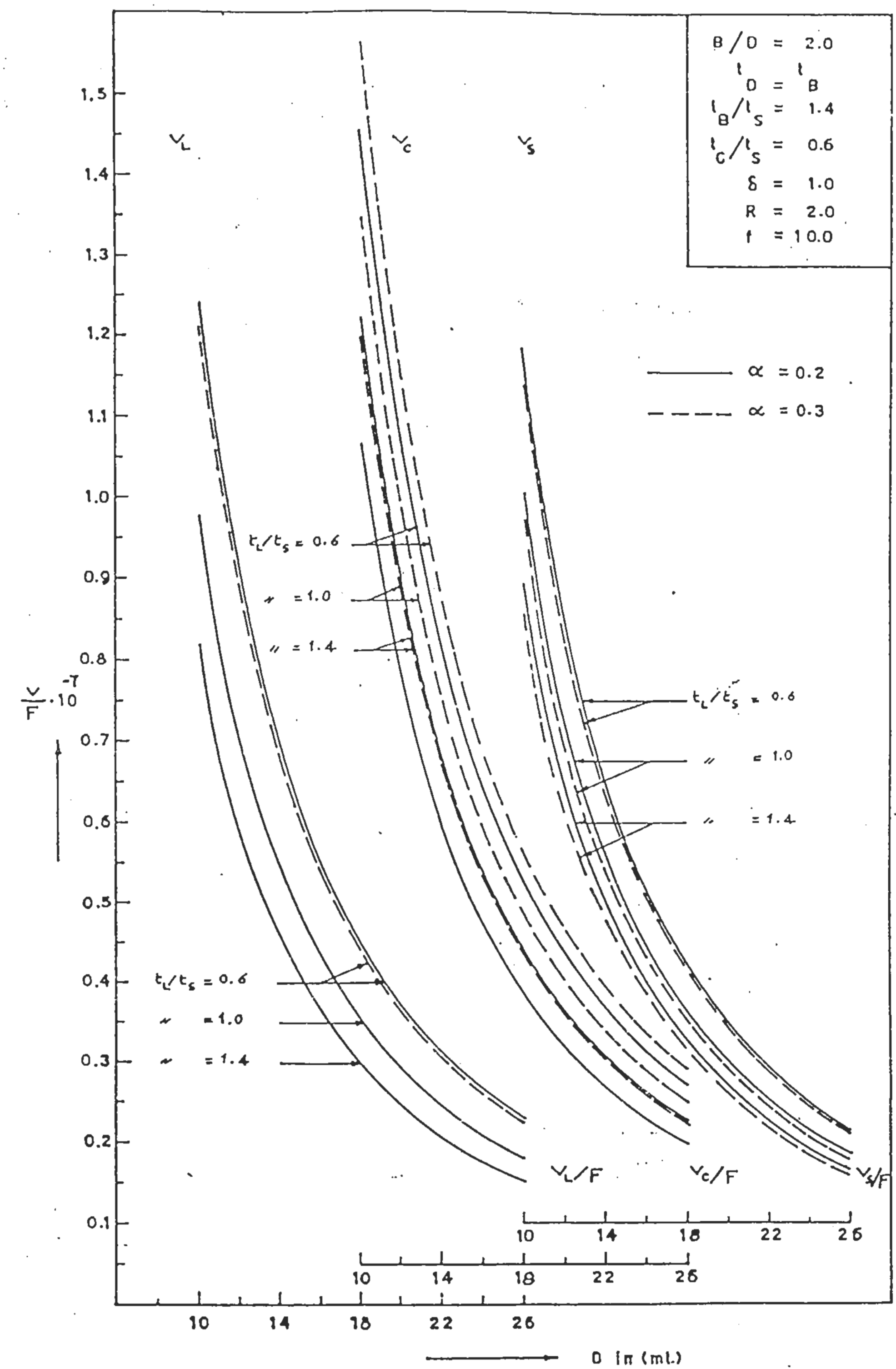

B/D = 2.0
$t_D = t_B$
t_B/t_S = 1.4
t_C/t_S = 0.6
δ = 1.0
R = 2.0
f = 10.0
α = 0.2
α = 0.3
V_L
V_C
V_S
t_L/t_S = 0.6
" = 1.0
" = 1.4
V_L/F
V_C/F
V_S/F
$\frac{V}{F} \cdot 10^{-7}$
D in (ml.)

Fig. 14

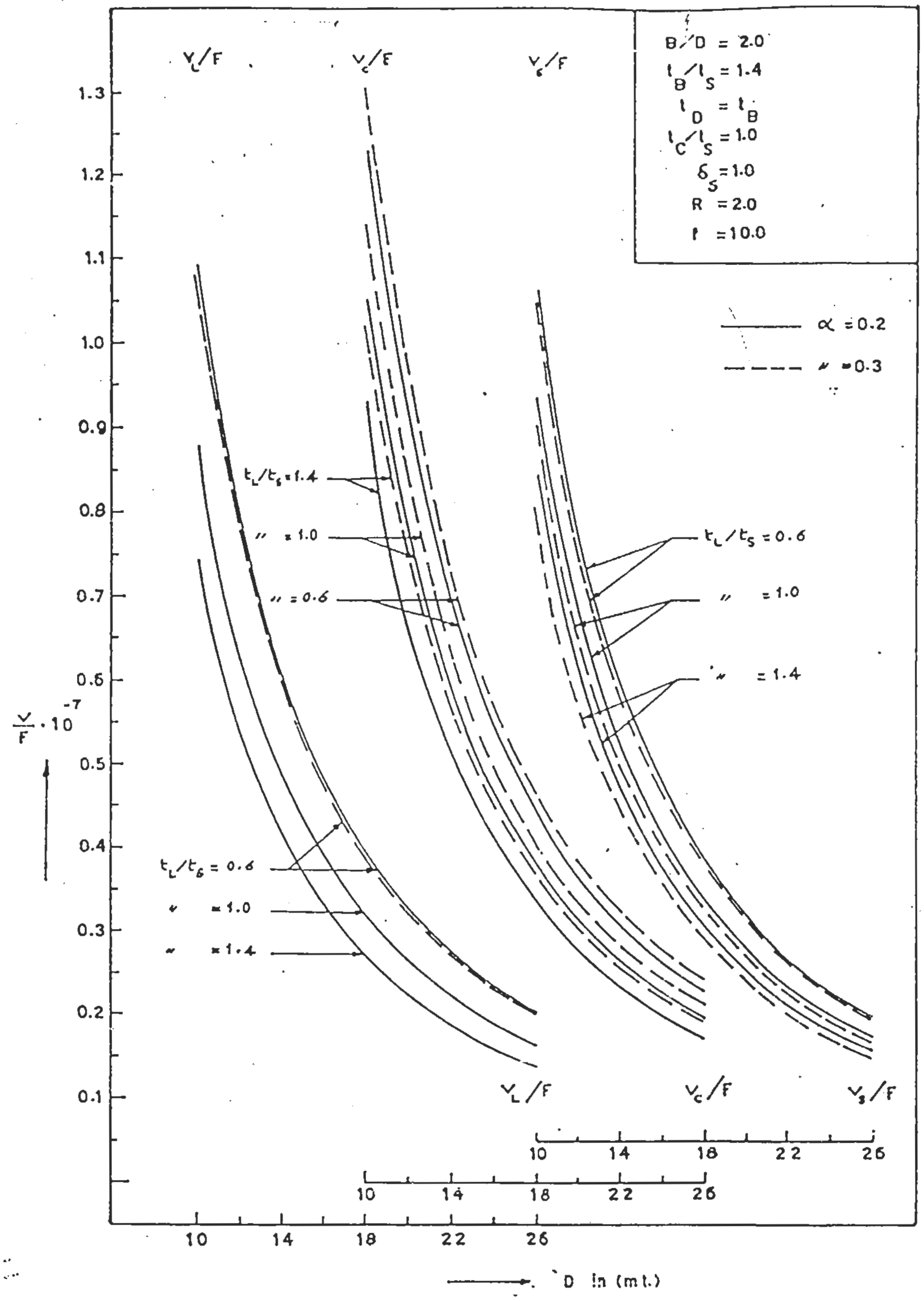


Fig. 15

3 Effect of the Transverse Position of Side Longitudinal Bulkheads from the Ship Centerline; i.e. α

The effects of variation of the parameter α on τ_i, K_i and v_i (i = C, L and S) are shown in Figs. 9, 10 and 11 respectively.

From these figures, it is evident that the transverse positions of the side longitudinal bulkheads have a marked influence on τ_i, K_i and v_i, ($i = C, S$), whereas its influence on τ_L, K_L and v_L is not very significant.

4 Effect of B/D ratio

The effect of variation of the parameter B/D, within

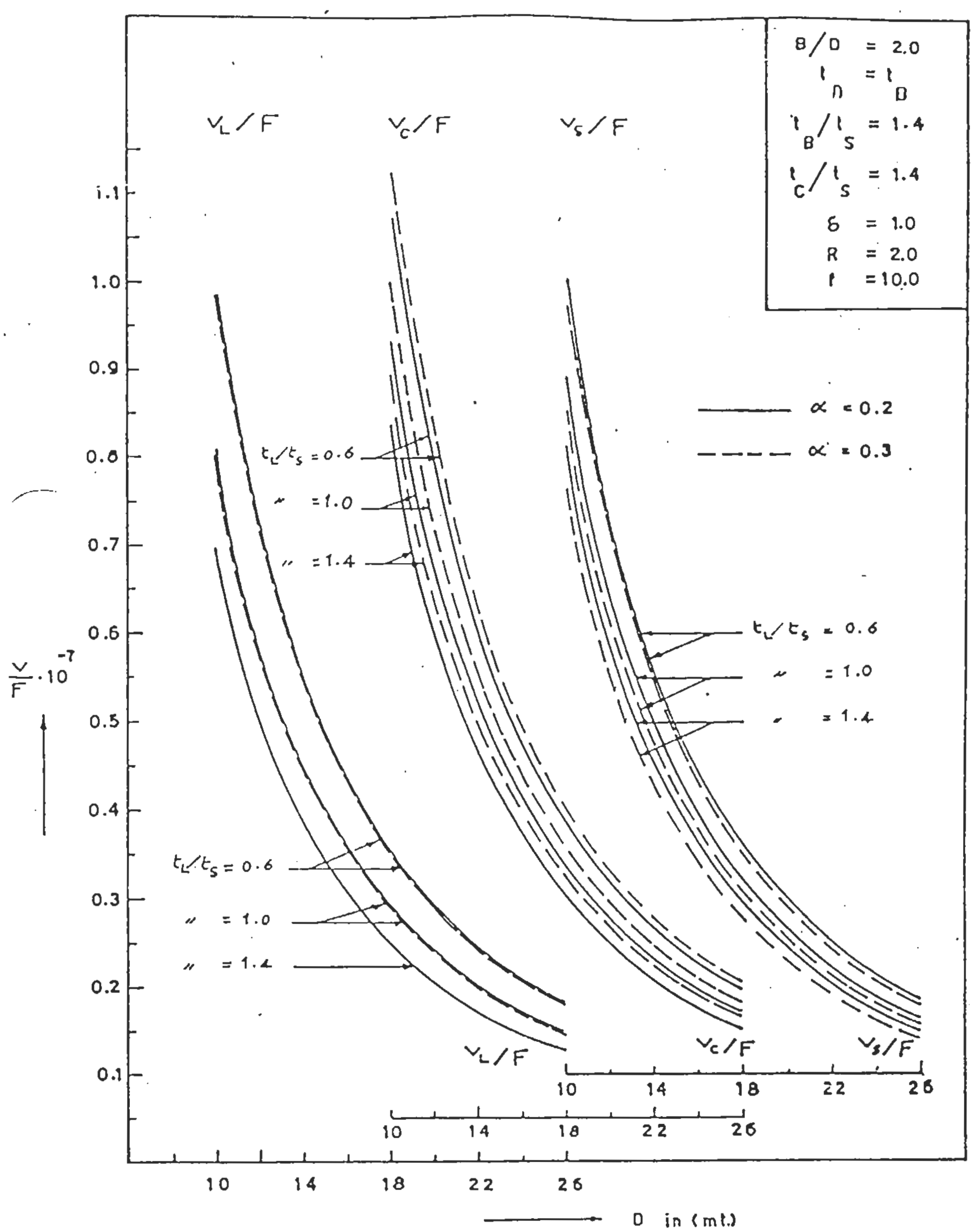


Fig. 16

the limits adopted in practice, on τ_i, K_i and v_i, (i = (C, L and S) was found to be insignificant. The influence of B/D becomes significant only when this ratio varies considerably.

5 Effect of t_B/t_S and t_D/t_B

The variation of either of t_B/t_S or t_D/t_B causes insignificant changes in τ_i, K_i and v_i, (i = C, L and S). This infers that the variation in the deck or bottom thicknesses has virtually no effects on τ_i, K_i and v_i; (i = C, L and S).

From the foregoing results and analysis it is concluded that, in order to keep down the maximum shear stresses and shear deflections in side shell and longitudinal bulkheads, the following conditions should be maintained:

1. The thicknesses of longitudinal bulkheads should be increased.
2. The transverse position of the side longitudinal bulkhead, i.e., α, should satisfy the following conditions:

(i) $\tau_i \leqslant \tau_a$ $(i = C, L, S)$
(ii) The relative vertical shear deflections between side shell and longitudinal bulkheads should be minimum.

The importance of the latter conditi·· arises from the fact that the variation in vertical shear deflection between side shell and longitudinal bulkheads may have an adverse effect on the attached transverse members [5, 6].

In order to satisfy conditions (i) and (ii), design curves are presented in Figs. 12–16. From these figures, given the maximum shear force (stillwater component + wave component) and ship section configuration, the maximum shear stresses in and deflections of side shell and longitudinal bulkheads could be determined. On the other hand, these design curves could be used for determining the ship section configuration that will induce shear stresses and deflections in side shell and longitudinal bulkheads lower than a predetermined allowable value.

However, these curves are based on an idealized structure and the simple theory of shear flow in multicell box girders. The effects on the results of the parametric study of transverse members and bulkheads, warping constraints, and the nonuniform distribution of the loading in the transverse direction, have not been considered. The neglect of these factors and the degree of structure idealization may impose some limitations on the use of these curves.

No attempt is made here to investigate the validity of these design curves, but this could be achieved by carrying out either a 3-dimensional analysis using FEM or by running a series of full-scale tests. The results of the 3-D FEM and/or the full-scale tests should establish the limitations of these curves as design tools.

Conclusion

From the foregoing results and analysis, it is concluded that:

1. The effective thickness of side shell and longitudinal bulkheads and the transverse position of side longitudinal bulkheads from ship centerline are the relevant parameters having a significant effect on:

(*a*) Shear flow distribution around a ship section.
(*b*) Magnitude of maximum shear stress in side shell and longitudinal bulkheads.
(*c*) Magnitude of vertical shear deflection of side shell and longitudinal bulkheads.
(*d*) Shear carrying capacity of main hull girder.

2. The determination of the optimum transverse position of side longitudinal bulkheads should take into account the following effects:

(*a*) Magnitude of maximum shear stress in side shell and longitudinal bulkheads.
(*b*) Relative vertical shear deflection between side shell and longitudinal bulkheads.
(*c*) Local and general strength of transverse members.
(*d*) Free-surface effects and also constructional requirements.

3. For any ship section configuration, it is possible to determine graphically:

(*a*) The shear carrying capacity of the section; i.e., the maximum allowable shear force.
(*b*) The relative vertical shear deflections between side shell and longitudinal bulkheads.

4. It is possible to determine, from a series of curves, the optimum distribution of the shear carrying material. This optimum distribution satisfies both strength and stiffness requirements as well as Lloyd's Register Rules for 1968.

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5 M. Mori et al., "On the Transverse Strength of Oil Tankers," *Journal of the Society of Naval Architects of Japan*, vol. 121, 1967.
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Appendix 1

(a) Independent Parameters

i. $t_D/t_B = x$

ii. $t_B/t_S = z$

iii. $t_L/t_S = y_L$

iv. $t_C/t_S = y_C$

v. $B/D = \gamma$

vi. Normalized distance of side longitudinal bulkhead from ship centerline $= \alpha$.

(b) Dependent Parameters

i. Distance of the neutral axis from baseline. This is defined by the normalized distance β (see Fig. 1) and is given by:

$$\beta = \frac{1 + y_L + 0.5y_C + \gamma xz}{2(1 + y_L) + y_C + \gamma_z(1 + x)}$$

ii. Second moment of area about section neutral axis. This is given by:

$$I = \psi D^3 t_S$$

where ψ is a nondimensional coefficient and is given by:

$$\psi = \gamma_z[\beta^2 + x(1 - \beta)^2] + \tfrac{1}{3}[1 + y_L + 0.5y_C] + (0.5 - \beta)^2[y_C + 2(y_L + 1)]$$

Appendix 2

Calculation of the Correcting Shear Flows

Due to the assumed distribution of shear flow, the cells $HBDI$ and $AHIE$ will be twisted by the angles θ_1 and θ_2 respectively. Since it is assumed that there are no torsional moments, correcting shear flows $(q_c)_1$ and $(q_c)_2$ are applied in order to satisfy the geometry of the section. These correcting shear flows are calculated from the condition that the angle of twist in each cell should be zero, i.e.

$$\theta_1 - \theta_{c1} = 0 \qquad (a)$$

$$\theta_2 - \theta_{c2} = 0 \qquad (b)$$

where θ_{c1} and θ_{c2} are the correcting angles of twists resulting from the correcting shear flows $(q_c)_1$ and $(q_c)_2$, respectively. Assuming that A_1 and A_2 are the areas of cells $HBDI$ and $AHIE$ respectively, and G is the modulus of rigidity, then we have:

$$\theta_1 = \frac{1}{2A_1G}\oint_H^I q\frac{\Delta s}{t}$$

$$\theta_2 = \frac{1}{2A_2G}\oint_A^E q\frac{\Delta s}{t}$$

$$\theta_{c1} = \frac{(q_c)_1}{2A_1G}\oint_I^H \frac{\Delta s}{t} - \frac{(q_c)_2}{2A_1G}\int_H^I \frac{\Delta s}{t}$$

$$\theta_{c2} = \frac{(q_c)_2}{2A_2G}\oint_A^E \frac{\Delta s}{t} + \frac{(q_c)_2}{2A_2G}\int_A^E \frac{\Delta s}{t} - \frac{(q_c)_1}{2A_2G}\int_H^I \frac{\Delta s}{t}$$

Assume the following notations:

$$\oint_H^I \frac{\Delta s}{t} = \left[1 + \frac{1}{y_L} + \frac{\gamma}{z}\left(\frac{1}{2} - \alpha\right)\left(1 + \frac{1}{x}\right)\right]\frac{D}{t_S} = p_1\frac{D}{t_S}$$

$$\int_H^I \frac{\Delta s}{t} = \frac{1}{y_L}\cdot\frac{D}{t_S} = p_{12}\frac{D}{t_S}$$

$$\oint_A^E \frac{\Delta s}{t} = \left[\frac{1}{y_L} + \frac{1}{y_C} + \frac{\alpha\gamma}{z}\left(1 + \frac{1}{x}\right)\right]\frac{D}{t_S} = p_2\frac{D}{t_S}$$

$$\int_A^E \frac{\Delta s}{t} = \frac{1}{y_C}\frac{D}{t_S} = p_{23}\frac{D}{t_S}$$

and

$$(q_c)_1 = w_1\frac{F}{D}$$

$$(q_c)_2 = w_2\frac{F}{D}$$

$$\oint_H^I q\frac{\Delta s}{t} = \eta_1\frac{F}{t_S}$$

$$\oint_A^E q\frac{\Delta s}{t} = \eta_2\frac{F}{t_S}$$

where w_1, w_2, η_1 and η_2 are nondimensional coefficients [η_1 and η_2 are calculated in Appendix 3].

Substituting these terms into equations (a) and (b), we get:

$$\eta_1 - w_1p_1 + w_2p_{12} = 0 \qquad (c)$$

$$\eta_2 - w_2p_2 + w_2p_{23} + w_1p_{12} = 0 \qquad (d)$$

Solving equations (c) and (d) for w_1 and w_2, we get:

$$w_2 = \frac{\eta_1p_{12} + \eta_2p_1}{p_1(p_2 + p_{23}) - (p_{12})^2}$$

$$w_1 = \frac{\eta_1}{p_1} + \frac{\eta_1(p_{12})^2 + \eta_2p_1p_{12}}{(p_2 + p_{23})(p_1)^2 - p_1(p_{12})^2}$$

Since the maximum shear flow occurs at points C, L and S, we have:

$$q_C = 2(q_c)_2 = 2w_2\frac{F}{D}$$

$$q_L = (q_c)_1 - (q_c)_2 = (w_1 - w_2)\frac{F}{D}$$

$$q_S = q_{SB} - (q_c)_1 = \left(\frac{\varphi_{SB}}{\psi} - w_1\right)\frac{F}{D}$$

where φ_{SB} is as given in Appendix 3.

Appendix 3

Shear Flow Distribution

MEMBER OR POINT	$Q_i/D^2 t_s$	$\mathcal{P}_i = Q_i/D^2 t_s$	$\bar{q}/\frac{F}{I} D^2 \cdot t_s$	$\frac{\Delta s}{t}/\frac{D}{t_s}$	$\bar{q}\frac{\Delta s}{t}/\frac{F}{I}D^3$
AC	$y_c(1-\beta)^2/2$	$y_c(1-\beta)^2/2$	$y_c(1-\beta)^2/6$	$(1-\beta)/y_c$	$\frac{1}{6}(1-\beta)^3$
AH	$\alpha\gamma x z(1-\beta)$		$y_c(1-\beta)^2/4 + \alpha\gamma x z(1-\beta)/2$	$\alpha\gamma/xz$	$\alpha\gamma y_c(1-\beta)^2/4xz + \frac{\alpha^2\gamma^2}{2}(1-\beta)$
HA		$\alpha\gamma x z(1-\beta) + y_c(1-\beta)^2/4$			
HL	$y_L(1-\beta)^2/2$	$y_L(1-\beta)^2/2$	$y_L(1-\beta)^2/6$	$(1-\beta)/y_L$	$\frac{1}{6}(1-\beta)^3$
HB		$\alpha\gamma x z(1-\beta)+(y_c+2y_L)(1-\beta)^2/4$	$(y_c+2y_L)(1-\beta)^2/4 + \frac{\gamma x z}{2}(1-\beta)(\frac{1}{2}+\alpha)$	$\frac{\gamma(\frac{1}{2}-\alpha)}{xz}$	$\frac{\gamma}{4xz}(y_c+2y_L)(\frac{1}{2}-\alpha)(1-\beta)^2 + \frac{\gamma^2}{2}(1-\beta)(\frac{1}{4}-\alpha^2)$
BH	$(1-\beta)(\frac{1}{2}-\alpha)\gamma x z$				
BS		$\gamma x z(1-\beta)/2 + (y_c+2y_L)(1-\beta)^2/4$	$\frac{\gamma x z}{2}(1-\beta)+(y_c+2y_L+\frac{4}{3})(1-\beta)^2/4$	$(1-\beta)$	$\frac{\gamma x z}{2}(1-\beta)^2 + (y_c+2y_L+\frac{4}{3})(1-\beta)^3/4$
S		$\gamma x z(1-\beta)/2 + (y_c+2y_L+2)(1-\beta)^2/4$			
EC	$\beta^2 y_c/2$	$\beta^2 y_c/2$	$y_c\beta^2/6$	β/y_c	$\frac{1}{6}\beta^3$
EI		$y_c\beta^2/4$	$y_c\beta^2/4 + \alpha\gamma z\beta/2$	$\alpha\gamma/z$	$\alpha\gamma y_c\beta^2/4z + \frac{1}{2}\alpha^2\gamma^2\beta$
IE	$\alpha\gamma z\beta$				
IL	$y_L\beta^2/2$	$y_L\beta^2/2$	$y_L\beta^2/6$	β/y_L	$\frac{1}{6}\beta^3$
ID		$\alpha\gamma z\beta + (y_c+2y_L)\beta^2/4$	$(y_c+2y_L)\beta^2/4 + \gamma z\beta(\frac{1}{2}+\alpha)/2$	$\frac{\gamma(\frac{1}{2}-\alpha)}{z}$	$\frac{\gamma\beta^2}{4z}(y_c+2y_L)(\frac{1}{2}-\alpha)+\frac{\beta\gamma^2}{2}(\frac{1}{4}-\alpha^2)$
DI	$\gamma z\beta(\frac{1}{2}-\alpha)$				
DS		$\gamma z\beta/2 + (y_c+2y_L)\beta^2/4$	$\gamma z\beta/2+(y_c+2y_L+\frac{4}{3})\beta^2/4$	β	$\frac{1}{2}\gamma z\beta^2 + \frac{\beta^3}{4}(y_c+2y_L+\frac{4}{3})$
S		$\gamma z\beta/2 + (y_c+2y_L+2)\beta^2/4$			

From the table, we have: $\oint^{I}_{H} q\frac{\Delta s}{t} = \eta_1 \cdot \frac{F}{t_s}$ and $\oint^{E}_{A} q\frac{\Delta s}{t} = \eta_2 \cdot \frac{F}{t_s}$

where, $\eta_1 = \left\{\frac{1}{4}(y_c+2y_L+\frac{2}{3})[\beta^3+(1-\beta)^3] + \frac{\gamma}{4z}(y_c+2y_L)(\frac{1}{2}-\alpha)[\beta^2+\frac{(1-\beta)^2}{x}] + \frac{\gamma z}{2}[\beta^2+x(1-\beta)^2] + \frac{\gamma^2}{2}(\frac{1}{4}-\alpha^2)\right\}/\psi$

$\eta_2 = \left\{\frac{1}{3}[\beta^3+(1-\beta)^3] + \frac{\alpha\gamma y_c}{4z}[\beta^2+\frac{(1-\beta)^2}{x}] + \frac{1}{2}\alpha^2\gamma^2\right\}/\psi$

The assumed shear flow i.e. q_i, at any point i, is given by:

$q_i = \mathcal{P}_i \cdot D^2 t_s \cdot \frac{F}{I} = (\mathcal{P}_i/\psi)\cdot\frac{F}{I}$

ex. $q_{SB} = (\mathcal{P}_{SB}/\psi)\cdot\frac{F}{D}$ where $\mathcal{P}_{SB} = \frac{\gamma x z}{2}(1-\beta) + (1-\beta)^2(y_c+2y_L+2)/4$

Appendix 4

Calculation of the Participation of Side Shell and Longitudinal Bulkheads in the Shear Carrying Capacity of Main Hull Girder

The longitudinal vertical shear force is assumed to be carried by the side shell and the longitudinal bulkheads. Hence

$$F = 2F_S + 2F_L + F_C$$

where

$$F_S = K_S F$$
$$F_L = K_L F$$
$$F_C = K_C F$$

The participation of the shear carrying members, i.e., F_C, F_L and F_S, is given by:

$$F_C = \int_{-\beta D}^{(1-\beta)D} (q_C)_v dy = (q_C)_m D$$

$$F_L = \int_{-\beta D}^{(1-\beta)D} (q_L)_v dy = (q_L)_m D$$

$$F_S = \int_{-\beta D}^{(1-\beta)D} (q_S)_v dy = (q_S)_m D$$

where $(q_C)_m$, $(q_L)_m$ and $(q_S)_m$ are the mean values of the shear flows for members IH, DB, and EA, respectively and are given by (see Fig. 1):

$$(q_C)_m = \tfrac{1}{3}[\beta(q_{EC}) + (1-\beta)(q_{AC}) + 2(q_C)_r]$$
$$(q_L)_m = \tfrac{1}{3}[\beta(q_{JL}) + (1-\beta)(q_{HL}) + 2(q_L)_r]$$
$$(q_S)_m = \tfrac{1}{3}[\beta(q_{DS}) + (1-\beta)(q_{BS}) + 2(q_S)_r]$$

Substituting for the shear flow values from Appendix 3 we get:

$$(q_C)_m = -\frac{y_C}{6\psi}\left\{[\beta^3 + (1-\beta)^3] - w_C\right\}\frac{F}{D}$$

$$(q_L)_m = \left\{w_L - \frac{y_L}{6\psi}[\beta^3 + (1-\beta)^3]\right\}\frac{F}{D}$$

$$(q_S)_m = \left\{\left(\frac{\gamma_s}{6}[\beta^2 + x(1-\beta)^2] + \left(\frac{y_C + 2y_L}{12}\right) \times [\beta^3 + (1-\beta)^3] + \frac{\gamma_t\beta}{3} + \frac{\beta^2}{6}(y_C + 2y_L + 2)\right)\frac{1}{\psi} - w_1\right\}\frac{F}{D}$$

Hence, the shear load coefficients for side shell and longitudinal bulkheads are given by:

$$K_S = \left\{\frac{\gamma_s}{6}[\beta^2 + x(1-\beta)^2] + \left(\frac{y_C + 2y_L}{12}\right) \times [\beta^3 + (1-\beta)^3] + \frac{\gamma_t\beta}{3} + \frac{\beta^2}{6}(y_C + 2y_L + 2)\right\}\frac{1}{\psi} - w_1$$

$$K_C = w_C - \frac{y_C}{6\psi}[\beta^3 + (1-\beta)^3]$$

$$K_L = w_L - \frac{y_L}{6\psi}[\beta^3 + (1-\beta)^3]$$

Appendix 5

Calculation of the optimum distribution of the shear carrying material for an oil tanker having the following particulars:

$L = 270.0$ m, $B = 41.5$ m, $D = 21.6$ m,
$d = 15.9$ m, $c_b = 0.815$, dwt $= 120{,}000$ tons,
$\Delta = 149{,}000$ tons

Assuming the maximum shear force $F = 13{,}000$ tons

$$f = \frac{15.9}{21.6} \times \frac{270}{21.6} = 9.29$$

Hence, corrected shear force $F_1 = 13{,}000\sqrt{\frac{10}{9.29}}$

$= 13470$ tons

$$B/D = \frac{41.5}{21.6} = 1.92$$

Assuming that $\tau_a = 6.0$ kg/sq mm

$$t_D = t_B \text{ and } t_B/t_S = 1.4$$

(a) Optimum Ship Section Having Least Shear Area

The optimum ship section having least shear area should satisfy the following condition:

$$\tau_S = \tau_L = \tau_C \leqslant \tau_a$$

and could be obtained from Figs. 12 and 13 as given in Table 1.

Table 1

τ	t_C/t_S			
	1.0		1.4	
	$\alpha = 0.2$	$\alpha = 0.3$	$\alpha = 0.2$	$\alpha = 0.3$
	t_L/t_S			
$\tau_S \leqslant \tau_a$	0.60	0.80	0.700	0.60
$\tau_L \leqslant \tau_a$	0.65	0.78	0.615	0.60
$\tau_C \leqslant \tau_a$	0.97	1.50	0.850	1.07
$(t_C + 2t_L)/t_S$	2.94	4.0	3.1	3.54

From the foregoing table it is shown that the optimum ship section configuration having least shear area is achieved when:

$$t_C/t_S = 1.0,\ t_L/t_S = 0.97 \text{ and } \alpha = 0.2$$

(b) Optimum Ship Section Configuration Inducing Equal Vertical Shear Deflections for Shear Carrying Members.

The ship section configuration that induces equal vertical shear deflections for side shell and longitudinal bulkheads could be obtained from Figs. 14, 15 and 16 as given in Table 2.

Table 2

$v \times (1/F \times 10^7)$	t_L/t_S	t_C/t_S = 0.6, α = 0.2	0.6, α = 0.3	1.0, α = 0.2	1.0, α = 0.3	1.4, α = 0.2	1.4, α = 0.3
v_S	0.6	0.302	0.296	0.278	0.275	0.260	0.252
v_L		0.322	0.316	0.286	0.287	0.255	0.255
v_C		0.380	0.406	0.318	0.341	0.277	0.290
v_S	1.0	0.260	0.250	0.242	0.236	0.231	0.220
v_L		0.255	0.252	0.230	0.230	0.208	0.207
v_C		0.317	0.350	0.275	0.296	0.241	0.257
v_S	1.4	0.232	0.249	0.220	0.210	0.212	0.198
v_L		0.212	0.209	0.193	0.195	0.178	0.178
v_C		0.278	0.313	0.242	0.268	0.215	0.235

From the foregoing table it is shown that the ship section configuration that produces, approximately, equal vertical shear deflections for side shell and longitudinal bulkheads is given by:

$$t_C/t_S = 1.4,\ t_L/t_S = 0.6 \text{ and } \alpha = 0.2$$

From the results obtained from (*a*) and (*b*) it is shown that the ship section having least shear area is not necessarily the ship section that gives equal vertical shear deflections for the shear carrying members.

Nevertheless, the optimum ship section that satisfies, approximately, the strength and deflection requirements, is given by:

$$t_C/t_S = 1.4,\ t_L/t_S = 0.85 \text{ and } \alpha = 0.2$$

It should be noted that the foregoing values are obtained on the assumption that the maximum allowable shear stress τ_a = 6.0 kg/sq mm. However, the corresponding values for different values of τ_a are as follows:

i. τ_a = 7.0 kg/sq mm

$$t_C/t_S = 1.2,\ t_L/t_S = 0.73 \text{ and } \alpha = 0.2$$

ii. τ_a = 8.0 kg/sq mm

$$t_C/t_S = 1.05,\ t_L/t_S = 0.638 \text{ and } \alpha = 0.2$$

iii. τ_a = 9.0 kg/sq mm

$$t_C/t_S = 0.935,\ t_L/t_S = 0.567 \text{ and } \alpha = 0.2$$

However, the minimum thicknesses of side shell and longitudinal bulkheads determined from Lloyd's Register Rules for 1968 are as given in Table 3.

Table 3

Frame or Longitudinal Spacing, mm	l_S mm	l_C and l_L mm	l_C/l_S and l_L/l_S
800	20.9	13.3	0.637
900	23.1	14.4	0.625
1000	25.3	16.0	0.632
1100	27.4	17.6	0.642

From this table the mean value of $\bar{l}_C/\bar{l}_S$ and $\bar{l}_L/\bar{l}_S$ is approximately 0.635.

Assuming that $\bar{l}_L/\bar{l}_S = t_L/t_S$ and $\bar{l}_C/\bar{l}_S = t_C/t_S$, then, according to Lloyd's Register Rules, we have

$$t_L/t_S = t_C/t_S = 0.635$$

Consequently, for the tanker under consideration, if the maximum shear force is 13,000 tons and τ_a = 6.0 kg/sq mm, the effective thickness of the centerline longitudinal bulkhead should be increased in order to reduce the maximum shear stress in the centerline longitudinal bulkhead, and also to reduce the relative vertical shear deflections between the side shell and longitudinal bulkheads.

A comparison between the vertical shear deflections, computed from the thicknesses obtained from the optimum ship section and from Lloyd's Register Rules, is given in Table 4.

Table 4

v mm/m	From Optimum Ship Section	From Lloyd's Register (1968)
v_S	0.323	0.344
v_L	0.303	0.346
v_C	0.339	0.409

From the foregoing results it is evident that in order to obtain equal vertical shear deflections, the effective thickness of centerline longitudinal bulkhead should be increased. However, the corresponding increase in the weight of this bulkhead should be balanced with the corresponding savings in the weight of the transverses.