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SHIP HULL

EFFECT OF VARIATION OF SHIP SECTION PARAMETERS ON SHEAR FLOW DISTRIBUTION, MAXIMUM SHEAR STRESSES AND SHEAR CARRYING CAPACITY DUE TO LONGITUDINAL VERTICAL SHEAR FORCE

By

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Summary

The paper examines the effect of varying the different ship section parameters on the shear flow distribution and maximum shear stresses at the section neutral axis due to longitudinal vertical shear force. The contribution of the centre line longitudinal bulkhead to the shear carrying capacity of the main hull girder is also investigated.

The analysis is limited to small tankers having one centre line longitudinal bulkhead, and is carried out in the form of a parameteric study on the University IBM 1620 digital computer. The results are given in terms of ship depth, thickness of side shell plating and the applied shear force and are represented in tabular and graphical forms.

It is concluded that the thickness of longitudinal bulkhead plating and the ratio of the sectional area of the shear carrying members to the total sectional area of the hull longitudinal material are the most important parameters which affect the shear flow distribution, maximum shear stresses, and shear carrying capacity of the centre line longitudinal bulkhead and side shell plating.

Further, it is concluded that it is possible to check graphically the shear carrying capacity of a ship section under the action of a known shear force.

List of Symbols

t = thickness
t_B = effective thickness of bottom plating
t_D = « « « deck plating
t_s = « « « side shell plating
t_c = « « « centre line longitudinal bulkhead
B = breadth
D = depth
I = second moment of area of ship section about its own neutral axis
γ = B/D
x = t_D/t_B
y = t_c/t_s
z = t_B/t_s
γ, x, y, z, are independent parameters
β = the normalised distance of the neutral axis from the base line
ψ = coefficient of midship section second moment of are ($I = \psi D^3 t_s$)
R_W = ratio of sectional area of shear carrying members (side shell plating + longitudninal bulkhead) to the total sectional area of the hull longitudinal material
R_L = ratio of sectional area of centre line longitudinal bulkhead to the total sectional area of the hull longitudinal material

R_W and R_L are dependent parameters
Q = first moment of area about neutral axis $= \Sigma A_p \cdot \bar{y}$
A_p = sectional area of plating
$\bar{y}$ = height of centroid of area above neutral axis
Q_s = $\varphi_s D^2 t_s$
φ_c = coefficient of first moment of area for the centreline longitudinal bulkhead
w = φ/ψ
q = shear flow in tons/cm
$\bar{q}$ = mean shear flow
q_{ij} = shear flow at point i in diretcion ij
$(q)_c$ = correcting shear flow
q_i = shear flow at point i
q_r = resultant shear flow
$(q_c)_m$ = mean shear flow for the centre line longitudinal bulkhead
$(q_s)_m$ = mean shear flow for side shell plating
$(q_c)_y$ = shear flow at a depth y from the neutral axis for the centre line longitudinal bulkhead
$(q_s)_y$ = shear flow at a depth y from the neutral axis for the side shell plating
η_c = maximum shear stress for the centre line longitudinal bulkhead
η_s = maximum shear stress for the side shell plating
F_H = horizontal longitudinal shear force
F = vertical longitudinal shear force
F_c = shear force carried by the centre line longitudinal bulkhead $= k_c \cdot F$
k_s = coefficient of the shear force carried by one side shell plating

G = modulus of rigidity
ζ_s & ζ_c = coefficients of the maximum shear stress η_s & η_c
ζ_c = w_c/y
ζ_s = w_s

Method of Calculation

The method of calculation used in this analysis is given in references [1, 2, 3] and is based on the idea that the structure is allowed to distort under an assumed set of shear forces. A correction is then introduced to satisfy the existing conditions of geometry. The resultant shear flow distribution must satisfy the following conditions of equilibrium [2]:

a. sum of horizontal shear forces must be zero
b. sum of vertical shear forces must equal the resultant shear force F
c. the angle of twist must be zero for each cell and for the whole structure since it is assumed that no torsional moments are applied.

Condition (a) above is valid since we are dealing with a structure subjected only to longitudinal vertical shear force.

Condition (b) implies that the shear force carried by the centre line longitudinal bulkhead and the two sides of a ship must equal the applied longitudinal vertical shear force, i.e.:

$$F = F_c + 2\,F_s \qquad \dots (1)$$

In this analysis it is assumed that F is uniformly distributed in the transverse direction.

Condition (c) is satisfied, for each cell, by applying an opposite uniform shear flow so that the angle of twist Θ, resulting from the assumed shear flow distribution, vanishes. This angle of twist is given by:

$$\Theta = \frac{1}{2AG} \cdot \oint q \frac{\Delta s}{t} \qquad \dots (2)$$

where: Δs is taken round the cell
A = sectional area of the cell under consideration.

Using the above three conditions of equilibrium, the shear flow distribution, in a simplified box shape of small tankers having one centre line longitudinal bulkhead, is calculated as follows:

1. The shear flow at point c, see fig. (1), is assumed zero i.e. q_c = zero

2. At joint A, the shear flow must satisfy the continuity equation i.e.

$$q_{AC} = q_{AB} + q_{BG} \qquad \dots (4)$$

But $q_{AB} = q_{AG}$ because of symmetry

Hence $q_{AC} = 2q_{BG}$

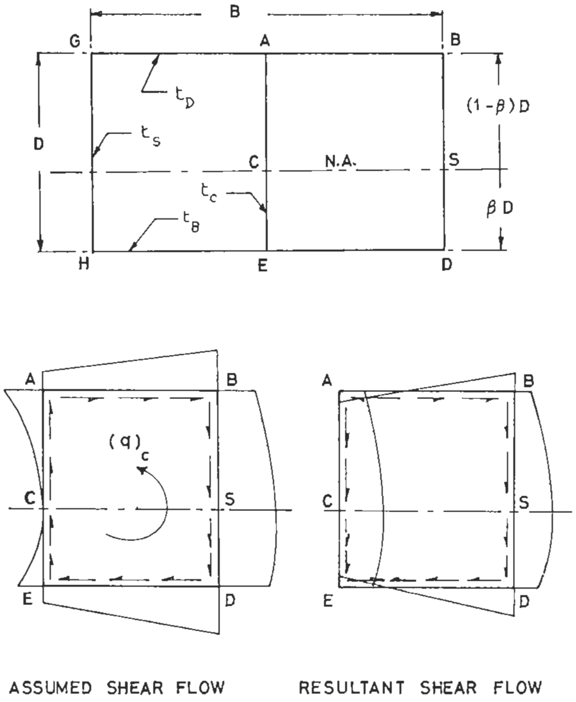

Fig. 1.

3. A shear flow distribution is assumed as follows:

$$q_i = \frac{F}{I} \cdot Q_i \qquad \dots (5)$$

where: Q_i = first moment of the area above point i about the neutral axis of the section and is calculated in terms of ship depth, thickness of side shell plating and the different independent parameters as given in Appendix (1).

i.e. $Q_i = f(B, D, t_s, t_B, t_D, t_c)$

I = the second moment of area about section neutral axis and is calculated in terms of ship depth, thickness of side shell plating and the different independent parameters as given in Appendix (1).

i.e. $I = F(B, D, t_s, t_B, t_D, t_c)$

Substituting for Q_i and I in terms of γ, x, y and z, we get:

$$Q_i = \varphi_i \; D^2 t_s \qquad \dots (6)$$
$$I = \psi \; D^3 t_s \qquad \dots (7)$$

where φ_i = non-dimensional coefficient of the first moment of area and depends on the position of the point i and the different independent parameters

ψ = non-dimensional coefficient of the second moment of area and depends on the different independent parameters.

It should be noted that, since the plating thicknesses are relatively small in comparison to the section dimensions, the concept of shear flow is used. It should also be noted that the effect of longitudinals and girders are taken into consideration by replacing the actual thickness of any member by an effective thickness calculated as follows:

$$t_e = t_a + \frac{a}{l}$$

where: t_e = effective thickness of member

t_a = actual thickness of member

a = total sectional area of all other longitudinal materials fitted to the member

l = length of member.

4. Because of symmetry of structure, the shear flow distribution and the correcting shear flow are calculated only for cell ABDE. Using equation (2), the correcting shear flow is calculated as follows:

$$(q_c \left\{ \sum \frac{\Delta s}{t} \begin{bmatrix} E—D \\ D—B \\ B—A \end{bmatrix} + 2 \sum \frac{\Delta s}{t} [A—E] \right\} — \oint q \frac{\Delta s}{t} = 0$$

$$\text{i.e. } (q)_c = \frac{\oint q \frac{\Delta s}{t}}{\int_E^A \frac{\Delta s}{t} + 2 \int_A^E \frac{\Delta s}{t}} \qquad \ldots . (8)$$

The correcting shear flow is calculated in terms of the different independent parameters, see appendix (II), and is given by:

$$(q)_c = (w)_c \cdot \frac{F}{D}$$

where: $(w)_c$ is a non-dimensional coefficient

5. The resultant shear flow at any point i in each cell is given by:

$$(q_i)_r = q_i — (q)_c \qquad \ldots . (9)$$

This method of calculation has been applied to small tankers having one centre line longitudinal bulkhead to calculate the maximum values of shear stress and the shear loads carried by the centre line longitudinal bulkhead and side shell plating in addition to the shear flow distribution. The calculations are summarised as follows:

a) Maximum values of the shear flow occurs at points C & S, see fig. (1), on the neutral axis and are given by:

$$q_c = 2\,(q)_c = w_c \cdot \frac{F}{D} \qquad \ldots . (10)$$

$$\text{and } q_s = w_s \cdot \frac{F}{D} \qquad \ldots . (11)$$

where $w_s = \varphi_s / \psi$

$w_c = 2\,(w)_c$

φ_c and φ_s are calculated in Appendix (II) and are given by:

$$\varphi_c = \frac{[0.5+0.25y][\beta^3+(1—\beta)^3]+\frac{3\gamma y}{16Z}[\beta^2+\frac{(1—\beta)^2}{x}]+\frac{\gamma Z}{2}[\beta^2+x(1—\beta)^2]+\frac{\gamma^2}{8}}{\frac{\gamma}{2Z}(1+\frac{1}{x})+\frac{2}{y}+1.0} \qquad \ldots . (12)$$

$$\varphi_S = \frac{\gamma xz}{2}(1-\beta)+0.25(y+2)(1-\beta)^2-\varphi_C \quad .\ (13)$$

$$\psi = (2+y)\left[\frac{1}{12}+(0.5-\beta)^2\right]+\gamma z[\beta^2+x(1-\beta)^2] \quad (14)$$

$$\beta = \frac{1+0.5y+\gamma xz}{2+y+\gamma z\ (1+x)} \quad \ldots.\ (15)$$

The definitions of ψ and β are given in Appendix (I).

b) Maximum shear stresses occur at points C and S and are given by see fig. (1):

$$\tau_S = \frac{q_S}{\bar{t}_S} = \rho_S \cdot \frac{F}{D\bar{t}_S} \quad \ldots.\ (16)$$

$$\tau_C\ \frac{q_C}{\bar{t}_C} = w_C \cdot \frac{F}{D\bar{t}_C} \quad \ldots.\ (17)$$

Assuming that $\bar{t}_C/\bar{t}_S = y$

Hence, $\tau_C = \rho_C \cdot \frac{F}{D\bar{t}_S}$

where $\bar{t}_S$ and $\bar{t}_C$ are actual thicknesses of side shell plating and centre line longitudinal bulkhead respectively.

c. Shear load carried by the centre line longitudinal bulkhead is given by:

$$F_C = \int_{-\beta D}^{(1-\beta)D} (q_C)_y \cdot dy = (q_C)_m \cdot D \quad \ldots.\ (18)$$

where: $(q_C)_m$ = mean shear flow for the centre line longitudinal bulkhead

$(q_C)_y$ = shear flow at any depth y from the neutral axis.

The mean shear flow $(q_C)_m$ is calculated on the assumption that the shear flow distribution is parabolic across the depth of side shell plating and centre line longitudinal bulkhead and is given by:

$$(q_C)_m = \frac{1}{3}[\beta q_{EC} + (1-\beta)q_{AC} + 2q_C] \cdot \frac{F}{I} \quad \ldots.\ (19)$$

Substituting for q_{EC}, q_{AC} and q_C from Appendix (II), into equation (19), we get:

$$(q_C)_m = \left\{\frac{y}{6}[\beta^3+(1-\beta)^3]-2\varphi_C\right\}\frac{F}{D} \quad \ldots.\ (20)$$

Hence: $F_C = K_C \cdot F$ .... (21)

$$\text{where: } K_C = \frac{\frac{y}{6}\ [\beta^3+(1-\beta)^3]-2\varphi_C}{\psi} \quad \ldots.\ (22)$$

F_C = shear force carried by the centre line longitudinal bulkhead

It should be realised that the participation of the centre line longitudinal bulkhead to the shear carrying capacity will only be fulfilled when the bulkhead is adequately stiffened against instability (4).

d. Shear force carried by the side shell plating is calculated from the equilibirum condition given by equation (1) i.e.:

$$F_S = (F-F_C)/2 = 0.5\,(1-k_C)\cdot F = k_S \cdot F \quad \ldots.\ (23)$$

where: $k_S = 0.5\,(1-k_C)$

It should be noted that F_S could be calculated in the same way as F_C using the concept of the mean shear flow $(q_S)_m$.

These calculations are performed on the University IBM 1620 computer. The parameters are varied as follows:

1. Breadth/depth ratio i.e. B/D from 1.5 to 3.0, every 0.5.
2. Thickness ratio of effective deck plating/effective bottom plating i.e. t_D/t_B from 0.6 to 1.4, every 0.4.
3. Thickness ratio of effective bottom plating/side shell plating i.e. t_B/t_S from 0.6 to 1.4, every 0.4.
4. Thickness ratio of effective longitudinal bulkhead plating/side shell plating. i.e. t_C/t_S from 0.5 to 2.0, every 0.5.

For every condition of the above independent parameters, the programme computes the following:

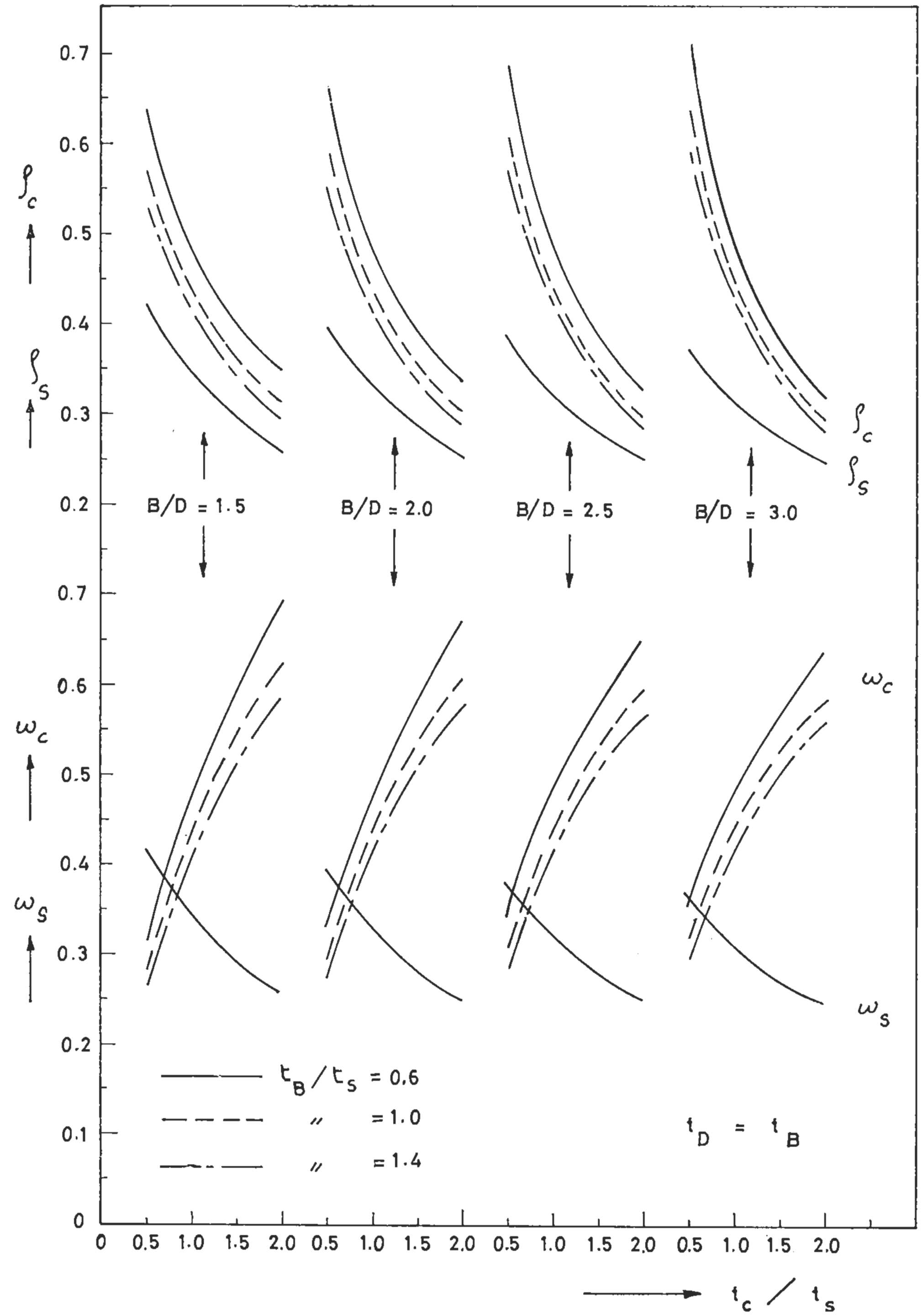

Fig. 2.

i. A set of dependent parameters, as given in Appendix (I).
ii. Maximum shear flow and shear stress at ship section neutral axis for both the centre line longitudinal bulkhead and side shell.
iii. Shear loads carried by the longitudinal bulkhead and side shell.

Results of calculations

In these results the effect of varying each independent parameter, while keeping the other ship section parameters constant, on the maximum shear flow, maximum shear stress and on the shear loads carried by the side shell and longitudinal bulkheads are given. The results are presented in tabular and graphical form and are given in terms of both the

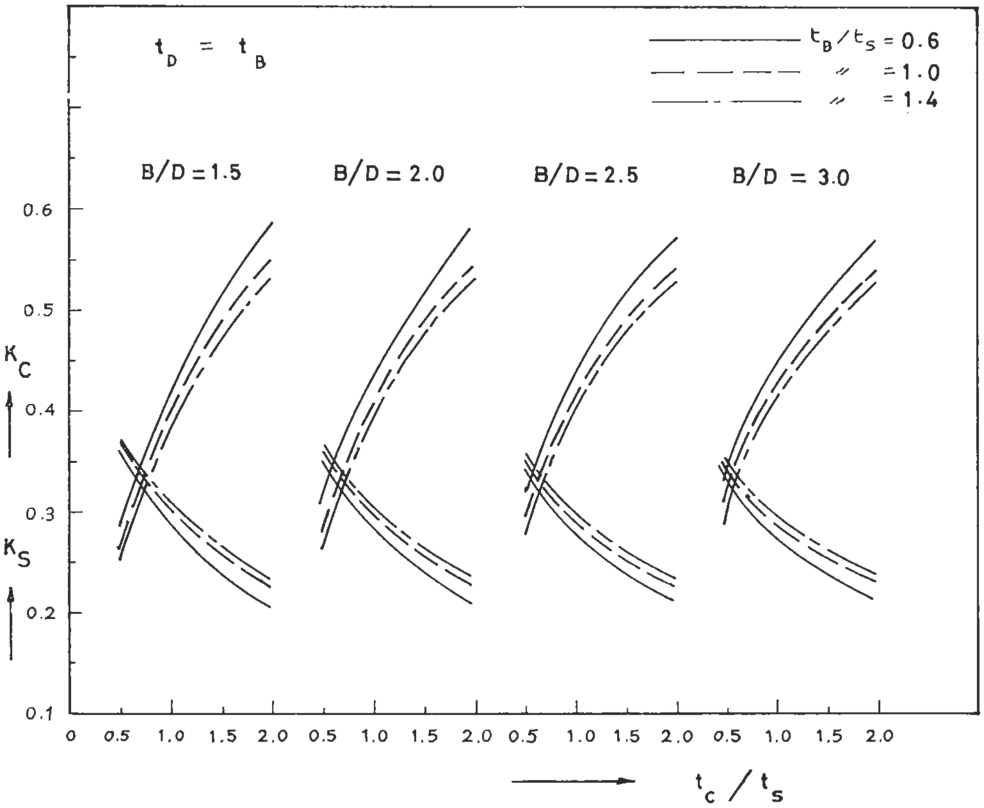

Fig. 3.

dependent and independent parameters. The percentage change in any calculated quantity is computed as follows:

$$\text{percentage change} = \frac{\text{final value—initial value}}{\text{initial value}} \times 100$$

The results of these calculations are summarised as follows:

1. Effect of B/D ratio:
   The effect of increasing B/D ratio from 1.5 to 3.0 is shown in figs. (2, 3, 4) for the different values of t_B/t_S and t_C/t_S. For the special case, when $t_D = t_B$, $t_B/t_S = 1.4$, the effect of B/D ratio for different values of t_C/t_S is given in the following table:

t_C/t_S	Percentage change			
	q_C & η_C	q_S & η_S	F_C	F_S
0.5	+11.0	—8.3	+15.0	—5.0
1.0	+ 2.6	—7.9	+ 6.5	—4.0
2.0	— 5.2	—4.0	— 0.9	+ 1.0

2. Effect of t_D/t_B ratio:
   The effect of increasing t_D/t_B from 0.6 to 1.4 when B/D = 2.0 and t_B/t_S = 1.4 for different values of t_C/t_S is given in the following table:

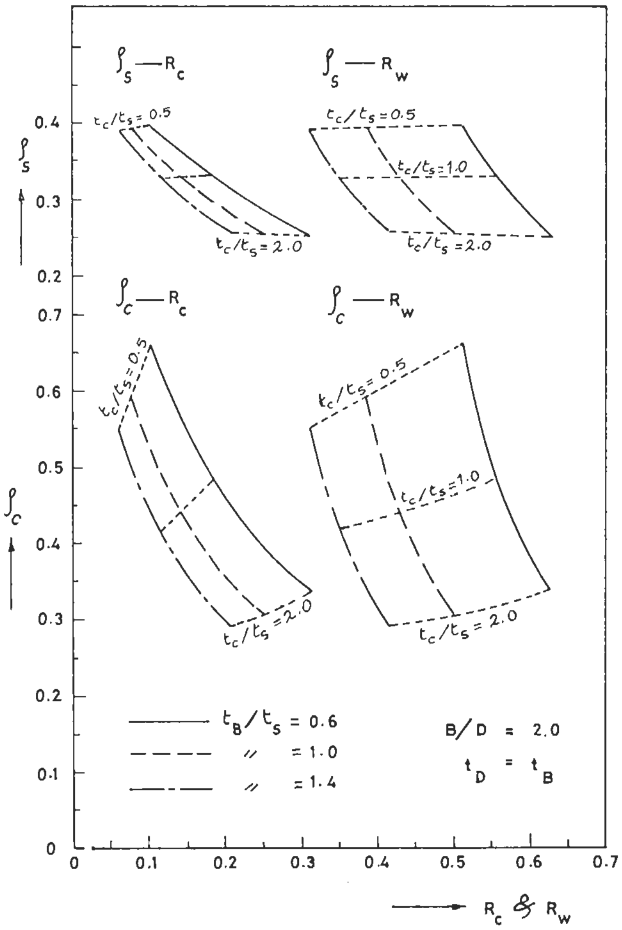

Fig. 4.

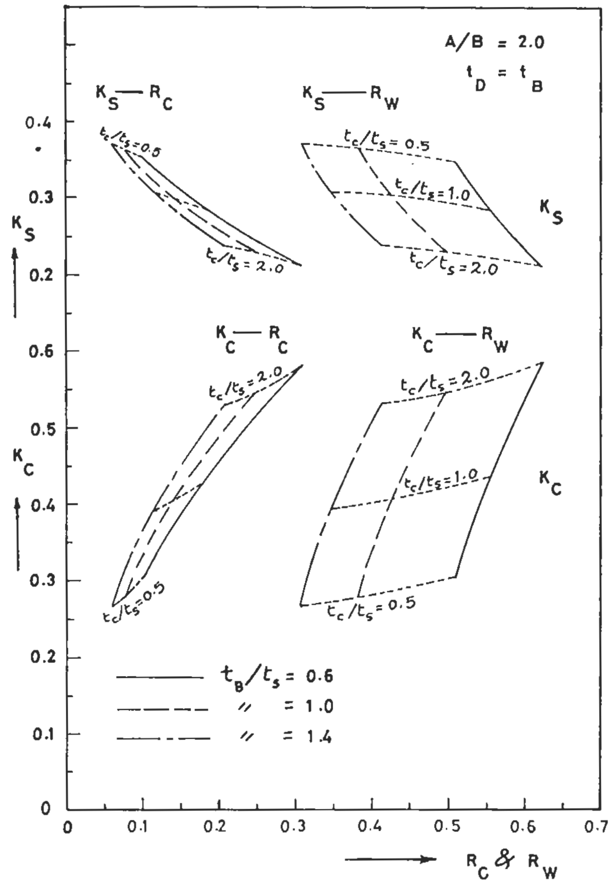

Fig. 5.

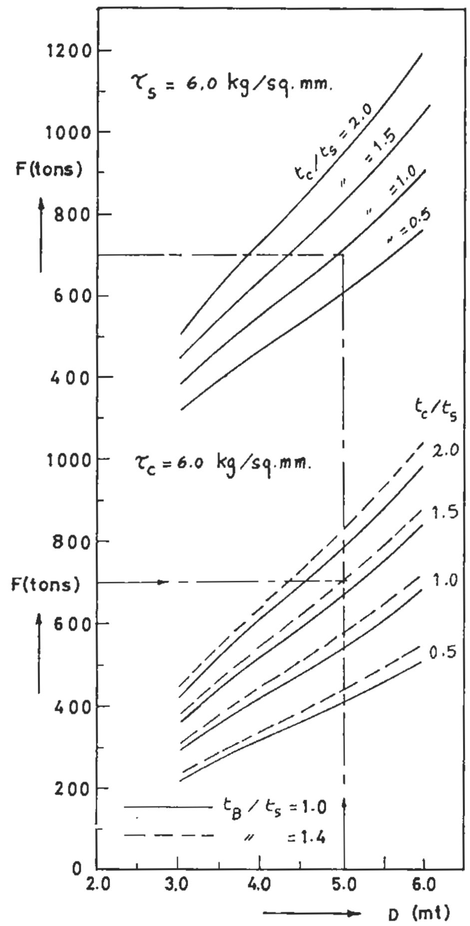

Fig. 6.

t_c/t_s	Percentage change			
	q_c & η_c	q_s & η_s	F_c	F_s
0.5	— 8.7	— 0.40	— 7.2	+ 2.7
1.0	— 7.0	— 0.27	— 4.8	+ 3.3
2.0	— 6.6	+ 0.50	— 4.0	+ 4.8

3. Effect of t_B/t_s ratio:

The effect of increasing t_B/t_s ratio from 0.6 to 1.4 is shown in figs. (2, 3, 4) for different values of B/D, t_c/t_s. For the special case, when B/D = 3.0, $t_D = t_B$, the effect of t_B/t_s ratio, for different values of t_c/t_s is given in the following table:

t_c/t_s	Percentage change			
	q_c & η_c	q_s & η_s	F_c	F_s
0.5	— 17.0	— 1.40	—15.0	+ 7.5
1.0	— 12.5	+ 0.84	— 9.5	+ 7.7
2.0	— 12.0	+ 2.50	— 8.0	+10.7

4. Effect of t_c/t_s ratio:

It is shown that t_c/t_s ratio is the most effective parameter as it has the greatest influence on the magnitude and distribution of shear stresses in the structure. The results of increasing t_c/t_s from 0.5 to 2.0 are shown in figs. (2, 3, 4) for different values of B/D and t_B/t_s ratios. For the special cases when $t_D = t_B$, $t_B/t_s = 1.4$ and for two values of B/D, the effect of t_c/t_s is given in the following table:

t_c/t_s	Percentage change									
	q_c		η_c		q_s & η_s		F_c		F_s	
	B/D									
	2.0	3.0	2.0	3.0	2.0	3.0	2.0	3.0	2.0	3.0
0.5—1.0	+51.0	+44.0	—24.5	—28.0	—16.5	—16.5	+49.0	+42.2	—17.4	—17.0
1.0—2.0	+ 38.8	+32.0	—30.5	—34.0	—21.4	—19.5	+35.0	+29.5	—22.8	—20.0

5. Effect of R_W ratio:
The effect of R_W, when B/D = 2.0, is shown in figs. (5, 6). It is shown that increasing R_W by 20 % has the following effects:
a. η_c is reduced by more than 50 %
b. η_s is reduced by about 34 %
c. F_c is increased by about 90 %
d. F_s is reduced by about 66 %

6. Effect of R_L ratio:
The effect of R_L when B/D = 2.0, is shown in figs. (5, 6). It is shown that increasing R_L by 100 % gives the following results:
a. η_c is reduced by about 31 %
b. η_s is reduced by about 19 %
c. F_c is increased by about 50 %
d. F_s is reduced by about 100 %.

Analysis of Results

For a certain value of the longitudinal vertical shear force, the effect of the different parameters on q_s, η_s, q_c, η_c, F_s and F_c are analysed and discussed. The analysis is intended mainly to examine the configuration of the ship section which brings the lowest shear stressses in both side shell plating and longitudinal bulkhead. Further, these analyses will make it possible to differentiate between the most and least effective parameters, regarding the shear carrying capacity of the ship hull girder.

a. *Effect of different parameters:*
1. Increasing B/D ratio always tends to reduce q_s, η_s & F_s when t_c/t_s ratio is low and has a negligible effect when t_c/t_s ratio is high.
2. Increasing B/D ratio always tends to increase/decrease q_c, η_c & F_c when t_c/t_s ratio is low/high.
3. Increasing t_D/t_B ratio always tends to reduce q_c, η_c, F_c & F_s
4. t_D/t_B ratio has a negligible effect on q_s and η_s
5. Increasing t_B/t_s ratio always tends to reduce q_c, η_c and F_c and increases F_s
6. t_B/t_s ratio has, in general, a small effect on q_s and η_s
7. Increasing t_c/t_s ratio always tends to increase q_c and F_c and reduce, η_c, q_s, η_s and F_s
8. Increasing R_L and/or R_W always tends to increase F_c and reduce η_s, η_c and F_s

Consequently, in order to keep down the maximum shear stress in both side shell plating and centre line longitudinal bulkhead, the following parameters should be varied as follows:
i. t_D/t_B and t_B/t_s ratios should be increased
ii. B/D ratio should be decreased
iii. t_c/t_s should be increased
iv. R_L and/or R_W should be increased.

It should be realised that B/D, t_D/t_B and t_B/t_s ratios have a minor effect on η_c & η_s whereas t_c/t_s, R_L and/or R_W ratios have the major effect on the magnitude of η_c & η_s

b. *Maximum Allowable Shear Force*

The results of this investigation could also be used to calculate the maximum shear force which will not induce shear stresses in the side shell plating and/or the centre line longitudinal bulkhead greater than a maximum allowable value.

The maximum shear stress in the side shell plating and centre line longitudinal bulkhead due to a longitudinal vertical shear force are given by:

$$\eta_s = \zeta_s \cdot \frac{F}{D\,\bar{t}_s}$$

and

$$\eta_c = \zeta_c \cdot \frac{F}{D\,\bar{t}_s}$$

The corresponding shear force is therefore given by:

$$F = \frac{\eta_s \cdot D\,\bar{t}_s}{\zeta_s}$$

or

$$= \frac{\eta_c \cdot D\,\bar{t}_s}{\zeta_c}$$

If $\eta_s \leqslant \eta_a$
and $\eta_c \leqslant \eta_a$
where η_a = maximum allowable shear stress and varies between 6.0 and 7.0 kg/sq. mm.

Hence;
$$F_{max} \leqslant \frac{\eta_a \cdot D\,\bar{t}_s}{\zeta_s} \qquad \text{.... (a)}$$

or
$$\leqslant \frac{\eta_a \cdot D\,\bar{t}_s}{\zeta_c} \qquad \text{.... (b)}$$

where: F_{max} = maximum value of shear force obtained from longitudinal strength calculation.

The calculation of F_{max} from either (a) or (b) can only be performed when the thickness of side plating i.e. $\bar{t}_s$ is known.

Using G.L. Rules (1963) for small tankers (length $\leqslant$ 80 m.), the thickness of side shell plating when longitudinally framed is given by:

$$s = \frac{a_1}{110}\sqrt{\frac{0.85\,T + 0.025\,L}{2.2 + 0.01\,L}}$$

where s = thickness of side shell plating in mm.
a_1 = spacing of longitudinals in mm.
L = length of ship in m.
T = draft of ship in m.

It is to be noted that: $a_1 < 0.9\,(2L+500)$
and minimum thickness $\geq 0.04\,L + 5.3$ mm.

Consequently, using the above expressions, a relationship between the ship depth D and the product $D\,\bar{t}_s$ could be determined either analytically or in numerical form.

Substituting $D\,\bar{t}_s$ into expressions (a) and (b), we get:

$$F_{max} = f_s\,(\eta_a\,,\ \zeta_s\,,\ D) \quad \ldots.\ (c)$$

$$\text{or} \quad = f_L\,(\eta_a\,,\ \zeta_c,\ D) \quad \ldots.\ (d)$$

where: f_s and f_c : are the functions relating η_a, ζ, D with F_{max}.

Expressions (c) and (d) could be represented graphically as shown in Fig. (6). From these curves, at any depth D of a ship, the maximum allowable shear force which will not induce shear stress, in either the side shell plating or the centre line longitudinal bulkhead, greater than a maximum allowable value, could be determined. Alternatively, for any depth D and maximum shear force F, the different ratios of t_B/t_s and t_c/t_s which will not induce shear stresses greater than η_a could be determined.

Several curves could be obtained for the different conditions of B/D, t_D/t_B, t_B/t_s and t_c/t_s ratios for both transverse and longitudinal framing systems.

As an example, for a longitudinally framed tanker having:

D = 5.0 m. B/D = 2.0
η_a = 6.0 kg/sq. mm.

and assuming that the maximum shear force obtained from longitudinal strength calculations is 700 tons.

In order to satisfy the condition:

$$\eta_s \leqslant \eta_a \quad \ldots.\ (e)$$

$$\text{and} \quad \eta_c \leqslant \eta_a \quad \ldots.\ (f)$$

the following section parameters are obtained from Fig. (6).

i. In order to satisfy condition (e), we have: $t_c/t_s \geq 1.0$

ii. In order to satisfy condition (f), we have: $t_c/t_s \geq 1.7$ when $t_B/t_s = 1.0$
or ≥ 1.5 when $t_B/t_s = 1.4$

Since the minimum value of $\bar{t}_s$ is determined from the G.L. Rules, the minimum thickness of the centre line longitudinal bulkhead which will satisfy conditions (e) and (f) can be calculated. This type of study will be most useful in the case of large tankers having twin or three longitudinal bulkheads since the efficient use of the bulkhead material will certainly lead to an appreciable saving in the total steel weight.

Conclusions

Longitudinal bulkheads, apart from dividing the hull into water-tight compartments, are important structural elements of the main hull girder. The contribution of these bulkheads to longitudinal bending and shear forces depends mainly on their resistance to local buckling.

However, when these bulkheads are adequately stiffened to prevent local buckling, it is possible to increase their contribution to the basic loads of the main hull girder. As a result, the thickness of side shell plating could be reduced since it will be subjected to a reduced bending and shear loads. The reduced thickness should be checked for instability resistance, excessive deflections and high stresses due to normal hydrastatic pressure and hydrodynamic loading.

It is also concluded that t_c/t_s and R_L or R_W are the most important parameters which affect the maximum shear stress in the side shell plating and centre line longitudinal bulkhead in addition to affecting the contribution of the latter to the shear carrying capacity of the main hull girder.

Further, it is shown that it is possible to obtain from a series of curves, the conditions of the ship section which, under a maximum longitudinal vertical shear force, will not induce shear stress in the side shell plating or centre line longitudinal bulkhead greater than a maximum allowable value.

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Appendix (I)

a) Independent Parameters

i. $t_D/t_s = x$

ii. $t_B/t_s = z$

iii. $t_c/t_s = y$

iv. $B/D = \gamma$

where t is the effective thickness.

b) Dependent Parameters

i. Total sectional area of all longitunal material $= A_T$

A_T = sectional area of deck, bottom, longitudinal bulkhead and side shell plating

$A_T = [2+y+\gamma z(1+x)] \cdot D\, t_s$

ii. Sectional area of shear carrying members $= A_W$

A_W = sectional area of longitudinal bulkhead and side shell plating

$A_W = [2+y] \cdot D\, t_s$

iii. Sectional area of centreline longitudinal bulkhead $= A_C$

$A_C = y \cdot D\, t_s$

iv. $A_W/A_T = \dfrac{2+y}{2+y+\gamma z(1+x)} = R_W$

v. $\dfrac{A_C}{A_T} = \dfrac{y}{2+y+\gamma z(1+x)} = R_C$

vi. Position of neutral axis from base line.

This is defined by the normalised distance β, see fig. (1) and is given by:

$$= \frac{(1+0.5y)+\gamma x z}{2+y+\gamma z(1+x)}$$

vii. Second moment of area I, $(I = \psi D^3 t_s)$

This is defined by the non-dimensional coefficient ψ which is given by:

$$\psi = (2+y)\left[\frac{1}{12}+(0.5-\beta)^2\right]+\gamma z[\beta^2+x(1-\beta)^2]$$

APPENDIX II

SHEAR FLOW DISTRIBUTION

MEMBER OR POINT	$A\bar{y}/D^2 t_s$	$\omega_i = q_i / \frac{F}{D}$	$\bar{q} / \frac{F}{D}$	$\frac{\Delta s}{t} / \frac{D}{t_s}$	$\bar{q}\frac{\Delta s}{t} / \frac{F}{t_s}$	$(q_i)_r$
C	–	–	$y(1-\beta)^2/6$	$(1-\beta)/y$	$(1-\beta)^3/6$	$-2(q)_c$
AC	$(y(1-\beta)^2/2$	$y(1-\beta)^2/2$				$q_{AC}-(q)_c$
AB	$\gamma x z(1-\beta)/2$	$y(1-\beta)^2/4$	$3y(1-\beta)^2/8+\gamma z x(1-\beta)/4$	$\gamma/2xz$	$3\gamma y(1-\beta)^2/16xz+\gamma^2(1-\beta)/8$	$q_{AB}-(q)_c$
BA		$y(1-\beta)^2/4+\gamma x z(1-\beta)/2$				$q_{BA}-(q)_c$
BS	$(1-\beta)^2/2$		$(\frac{y}{4}+\frac{1}{3})(1-\beta)^2+\gamma x z(1-\beta)/2$	$1-\beta$	$(\frac{y}{4}+\frac{1}{3})(1-\beta)^3+\gamma x z(1-\beta)^2/2$	$q_{BS}-(q)_c$
SB		$(\frac{y}{2}+1)(1-\beta)^2/2+\gamma x z(1-\beta)/2$				$q_{SB}-(q)_c$
EC	$y\beta^2/2$	$y\beta^2/2$	$y\beta^2/6$	β/y	$\beta^3/6$	$q_{EC}-(q)_c$
ED	$\gamma z\beta/2$	$y\beta^2/4$	$3y\beta^2/8+\gamma z\beta/4$	$\gamma/2z$	$3\gamma y\beta^2/16z+\gamma^2\beta/8$	$q_{ED}-(q)_c$
DE		$\gamma z\beta/2+y\beta^2/4$				$q_{DE}-(q)_c$
DS	$0.5\beta^2$		$(\frac{y}{4}+\frac{1}{3})\beta^2+\gamma z\beta/2$	β	$(\frac{y}{4}+\frac{1}{3})\beta^3+\gamma z\beta^2/2$	$q_{DS}-(q)_c$
SD		$(\frac{y}{2}+1)\beta^2/2+\gamma z\beta/2$				$q_{SD}-(q)_c$

$$(q)_c = \frac{\oint q\frac{\Delta s}{t}}{\int_A^E \frac{\Delta s}{t}+2\int_E^A \frac{\Delta s}{t}} = \left\{\frac{(\frac{1}{2}+\frac{y}{4})[\beta^3+(1-\beta)^3]+3\gamma y[\beta^2+(1-\beta)^2/x]/16z+\gamma z[\beta^2+x(1-\beta)^2]/2+\gamma^2/8}{\gamma(1+1/x)/2z+2/y+1.0}\right\}\frac{F}{I}\cdot D^2 t_s$$

Substituting for $I = \psi \cdot D^3 t_s$

and $(\Phi)_c$ for the term between brackets

$\therefore (q)_c = (\omega)_c \cdot \frac{F}{D}$

where $(\omega)_c = (\Phi)_c/\psi$.