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

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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.,

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

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EFFECT OF SHIP SECTION SCANTLINGS AND TRANSVERSE POSITION OF LONGITUDINAL BULKHEADS ON SHEAR STRESS DISTRIBUTION AND SHEAR CARRYING CAPACITY OF MAIN HULL GIRDER.

by M.A. Shama, B.Sc., Ph.D.*).

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 side longitudinal bulkheads to the shear carrying capacity of the main hull girder is also investigated.

The analysis is limited to tankers having twin longitudinal bulkheads and is carried out in the form of a parametric study using 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 side longitudinal bulkhead plating has the major effect on the magnitude of the maximum shear stress in and the participation of the longitudinal bulkheads to the shear carrying capacity of the main hull girder. It is also concluded that the ratio of effective thickness of bottom plating to effecting thickness of side shell plating and the transverse position of side longitudinal bulkheads have an appreciable influence on the maximum shear stress and on the shear carrying capacity of the main hull girder.

Further, it is shown that it is possible to determine, from a series of curves the maximum shear force or the relationship between ship section parameters that will not induce shear stresses greater than a maximum allowable value. A sample of these curves is given in the paper together with a numerical example.

Introduction.

The economic structural design of ships is mainly based on the optimum distribution of the hull material to carry efficiently the different types of internal and external loads. This, in fact, infers that the optimum design should aim at increasing the strength/weight ratio or reducing the weight/strength ratio of the structure. The first approach could be achieved by using high strength materials whereas the second could be fulfilled by optimizing the distribution of the available material in the structure. The optimization procedure could be carried out either for some particular structural elements or for the whole assembly of the hull girder. The former case is a local strength problem and could easily be solved when the various types of loadings are known. The latter case is a three dimensional problem which may best be solved using the finite element technique. However, the optimization procedure of the main hull girder could be applied separately to the longitudinal strength material and to the transverse strength material. A lot of work has been done in this direction particularly towards the optimization of the local, transverse and longitudinal hull material within the rules of classification societies.

In this paper, an attempt is made to analyse and optimize the shear carrying material i.e. side shell and longitudinal bulkheads, of oil tankers having twin-longitudinal bulkheads. This is because in large tankers the shear forces on

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the hull girder must be taken into account when deciding the thicknesses and the stability characteristics of the plating in ship side and in longitudinal bulkheads.

In order to carry out the optimization procedure, the shear flow distribution around a ship section due to a longitudinal vertical shear force is calculated. From this shear flow distribution, the maximum shear stresses and the distribution of the longitudinal vertical shear force between the side shell and longitudinal bulkheads are determined. These calculations are based on the general assumptions that the ship section is symmetrical and the section is not subjected to any torsional moments.

The optimization procedure is aimed at determining the best distribution of the shear carrying material in a ship section of a twin-bulkhead oil tanker. This is achieved by carrying out a parametric study using the main parameters which may affect the distribution of the shear flow around the ship section. These parameters are:

1. Effective thickness of longitudinal bulkheads/effective thickness of side shell.
2. Effective thickness of deck/effective thickness of side shell.
3. Effective thickness of bottom/effective thickness of side shell.
4. Distance of longitudinal bulkheads from ship longitudinal vertical centre line/ship breadth.
5. Breadth/depth ratio.

The effective thickness is in effect the thickness which takes into account the contribution of the stiffening material to the shear carrying capacity of the member. These five non-dimensional parameters are used to compute the distribution of the shear flow around the ship section and subsequently the maximum shear stresses in and the shear carrying capacity of side shell and longitudinal bulkheads. The results of these calculations are presented in the form of non-dimensional coefficients representing the shear flow, shear stress and shear carrying capacity. The effect of variation of each of the above mentioned parameters on the magnitude of the maximum shear stress in and on the shear carrying capacity of the side shell and longitudinal bulkheads are computed and analysed.

Using Lloyds Register of Shipping Rules for 1968 and the computed shear stress non-dimensional coefficients, a set of curves is obtained giving the relationship between the maximum shear force (as obtained from longitudinal strength calculations) and ship depth. These curves are determined for different values of the above-mentioned ship section 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.

Method of calculation.

The method of calculation used in this analysis is given in references [1, 2, 3] and therefore only a brief summary of the method, as applied to three cell box girders, is given here. In reference [2], the method is used to study the effect of variation of the thickness of longitudinal bulkheads on the magnitude of the maximum shear stress. The calculations are based on the assumption that the neutral axis of the ship section is at mid-depth.

It is assumed here that a ship section is subjected only to longitudinal vertical shear force which in turn is assumed to be uniformly distributed in the transverse direction. When a ship is inclined (due to bilging or unsymmetrical loading), the resultant shear force will be inclined to the longitudinal vertical plane. The distribution of the shear stresses, in this case, should be calculated in the vertical and horizontal directions and the resultant distribution could be obtained by superposition.

It is also assumed that the longitudinal vertical shear force is only carried by the side shell plating and longitudinal bulkheads, i.e.

$$F = 2\,F_L + 2\,F_s$$

Further, it is assumed that the whole structure (or any part of it) should not experience any angle of twist as it is not subjected to any torsional moments.

The following additional assumptions, which are valid for tankers, are also necessary for the analysis:

1. The plating thickness is very small compared with the dimensions of the ship cross-section.
2. The stress is uniform across the plating

thickness.

3. The cross-sectional dimensions of the sections (stiffeners, longitudinals and girders) are small compared with those of the ship cross-section. Their effect could be taken into consideration by changing actual thickness of plating by effective thickness as follows:

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

   where:

   t_a and t_e are the actual and effective thicknesses of member

   a = total sectional area of girders and all longitudinals fitted to the member

   l = length of member.

4. The main ship section parameters which may affect the shear flow distribution are as follows:

   a. Effective thicknesses of side shell plating and longitudinal bulkheads
   b. Effective thickness of bottom and deck platings
   c. Breadth/depth ratio
   d. Transverse position of side longitudinal bulkheads.

A. Calculation of the distribution of shear flow and maximum shear stresses.

Using the above assumptions, the shear flow distribution, in a simplified box shape of twin bulkhead tankers, and the maximum shear stresses are calculated as follows:

a. Shear flow distribution.

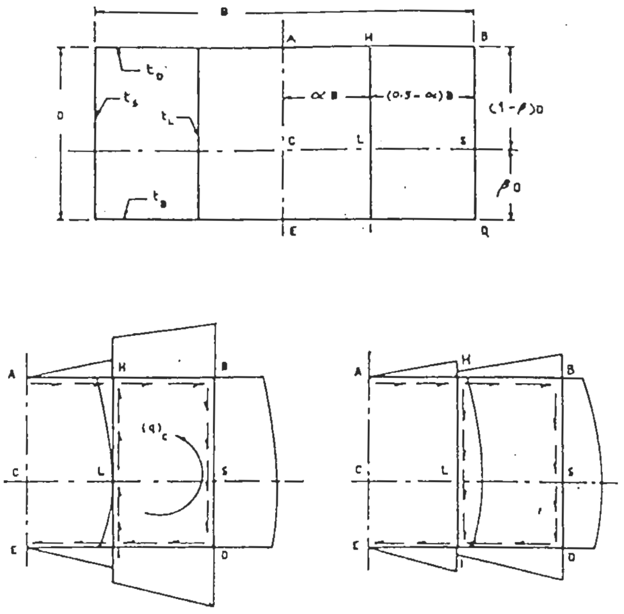
1. Shear flow at points A and E, see Figure 1, are zero because of symmetry and absence of a centre line longitudinal bulkhead

2. A zero shear flow is assumed at point L.

3. The continuity equation for the shear flow is valid at any joint.

4. A shear flow distribution is assumed as follows:

   $$q_i = \frac{F}{I} \cdot Q_i \qquad (2)$$



ASSUMED SHEAR FLOW RESULTANT SHEAR FLOW

Figure 1.

Assuming that $B/D = \gamma$, $t_D/t_B = x$, $t_B/t_s = z$, $t_L/t_s = y$ and substituting for Q_i and I in terms of B, D, t_B, t_D, t_s and α we get:

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

and

$$Q_i = \varphi_i \cdot D^2 t_s$$

were φ_i and ψ are non-dimensional coefficients.

The shear flow distribution is calculated only for half ship section as given in Appendix (II).

5. The angle of twist θ, in cell HBDI, resulting from the assumed distribution of shear flow is calculated from:

   $$\theta = \frac{1}{2\,AG} \oint q \cdot \frac{\Delta s}{t} \qquad (3)$$

   In order to satisfy the condition that the angle of twist should be zero, a correcting shear flow $(q)_c$ given by:

   $$(q)_c = \frac{\oint q \frac{\Delta s}{t}}{\oint \frac{\Delta s}{t}} \qquad (4)$$

   should be applied for each cell.

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

$$(q)_c = (w)_c \cdot \frac{F}{D} \qquad (5)$$

where $(w)_c$ = non-dimensional coefficient.

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

$$(q_i)_r = q_i - (q)_c \qquad (6)$$

b. Maximum shear stress.

The maximum values of the shear flow occur at points L and S, on the neutral axis, and are given by:

$$q_L = w_L \cdot \frac{F}{D} \qquad (7)$$

and

$$q_s = w_s \cdot \frac{F}{D} \qquad (8)$$

where

$$w_L = \varphi_L / \psi \qquad (9)$$

$$w_s = \varphi_s / \psi \qquad (10)$$

$$\varphi_L = \frac{\frac{1+y}{2}[\beta^3+(1-\beta)^3]+\frac{\gamma^2}{2}[\frac{1}{4}-\alpha^2]+\frac{\gamma z}{2}[\beta^2+x(1-\beta)^2]}{\frac{y+1}{y}+\frac{\gamma}{yz}(\frac{1}{2}-\alpha)(1+x)} + \frac{\frac{\gamma y}{2z}[\frac{1}{2}-\alpha][\beta^2+\frac{(1-\beta)^2}{x}]}{\frac{y+1}{y}+\frac{\gamma}{yz}(\frac{1}{2}-\alpha)(1+x)} \qquad (11)$$

$$\psi = (1+y)[\frac{1}{6}+2(\frac{1}{2}-\beta)^2]+\gamma Z[\beta^2+x(1-\beta^2)] \qquad (12)$$

$$\beta = \frac{\gamma x Z + y + 1.0}{2(y+1)+\gamma Z(1+x)} \qquad (13)$$

and

$$\varphi_S = \frac{\beta}{2}[\beta(1+y)+\gamma Z] - \varphi_L \qquad (14)$$

The maximum values of the shear stress also occur at points L and S where the shear flow is maximum and are given by:

$$\tau_L = \frac{q_L}{\bar{t}_L}$$

$$\tau_s = \frac{q_s}{\bar{t}_s}$$

Assuming that:

$$\frac{t_L}{t_s} = \frac{\bar{t}_L}{\bar{t}_s} = y$$

Hence

$$\tau_L = \varsigma_L \cdot \frac{F}{D\,\bar{t}_s} \qquad (15)$$

and

$$\tau_s = \varsigma_s \cdot \frac{F}{D\,\bar{t}_s} \qquad (16)$$

where

$$\varsigma_s = w_s \text{ and } \varsigma_L = \frac{w_L}{y}$$

B. Calculation of the participation of longitudinal bulkheads to the shear carrying capacity of the main hull girder.

The shear load carried by one side shell plating i.e. F_s and one side longitudinal bulkhead i.e. F_L are given by:

$$F_s = \int_{-\beta D}^{(1-\beta)D} (q_s)_y \cdot dy = (q_s)_m \cdot D \qquad (17)$$

and

$$F_L = \int_{-\beta D}^{(1-\beta)D} (q_L)_y \cdot dy = (q_L)_m \cdot D \qquad (18)$$

where

$$(q_s)_m = \frac{1}{3}[\beta\, q_{DS} + (1-\beta)\, q_{BS} + 2\, q_s] \qquad (19)$$

and

$$(q_L)_m = \frac{1}{3}[\beta\, q_{IL} + (1-\beta)\, q_{HL} + 2\, q_L] \qquad (20)$$

Substituting for the shear flow values from Appendix (II) in equation (20), we get:

$$(q_L)_m = \left\{ -\varphi_L + \frac{y}{6}[\beta^3 + (1-\beta)^3] \right\} \frac{F}{\psi D} \qquad (21)$$

Substituting equation (21) into equation (18) we get:

$$F_L = K_L\, F \qquad (22)$$

where

$$K_L = \frac{\frac{y}{6}[\beta^3 + (1 - \beta)^3] - \varphi_L}{\Psi} \qquad (23)$$

The shear force carried by the side shell plating is calculated from equation (1) as follows:

$$F_S = \frac{1}{2}\,(F - 2\,F_L)$$

Hence

$$F_S = K_S\,F$$

where

$$K_S = 0.5 - K_L$$

The participation of the side shell and longitudinal bulkheads is therefore represented by the coefficients K_S and K_L respectively.

It is to be noted that the side shell plating and side longitudinal bulkheads should be adequately stiffened against instability in order to ensure their contribution to the shear carrying capacity (5).

Ranges of the different parameters.

The above calculations are performed on the University IBM 1620 computer. The different 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 sheil 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 0.6 to 1.4 every 0.4.
5. Transverse position of side longitudinal bulkhead, i.e. the normalized distance $\alpha = 0.1$, 0.2 and 0.3.

The programme is carried out to investigate the effect of variation of the above different parameters on:

a. Shear flow distribution.
b. Maximum shear flow and shear stress at the neutral axis for both side shell plating and longitudinal bulkheads.
c. Shear loads carried by side shell plating and longitudinal bulkheads.

Results of calculations.

The effect of variation of each parameter on the maximum shear flow, maximum shear stress and on the participation of the side longitudinal bulkheads to the shear carrying capacity of the main hull girder is presented in tabular and graphical forms. The percentage change in any computed quantity is referred to its initial value. These results are summarized as follows:

1. Effect of B/D ratio:
   The effect of increasing B/D ratio from 1.5 to 3.0 is shown in Figure 5 for the different conditions of t_B/t_S, α and t_L/t_S.
   For the special case when $t_D = t_B$, $t_B/t_S = 1.4$, and for $\alpha = 0.1$ and 0.2, the effect of increasing B/D ratio from 1.5 to 3.0 for three values of t_L/t_S ratio are given in the following table:

t_L/t_S	Percentage change in							
	q_L and τ_L		q_S and τ_S		F_L		F_S	
	α							
	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2
0.6	+3.85	+5.74	-9.71	-11.20	+8.22	+10.26	-5.93	-7.60
1.0	-1.54	+0.77	-8.00	-10.82	+3.28	+ 5.70	-3.61	-6.60
1.4	-4.62	-2.16	-5.77	- 9.55	+0.51	+ 3.13	-0.73	-4.82

2. Effect of t_D/t_B.
   It is shown that t_D/t_B has a slight effect on the different quantities (q, τ, F). For the special case when $B/D = 2.0$, $t_B/t_s = 1.4$ and for two values of α, the effect of increasing t_D/t_B ratio from 0.6 to 1.4 for three values of t_L/t_s is given in the following table:

t_L/t_s	Percentage change in							
	q_L and τ_L		q_s and τ_s		F_L		F_s	
	α							
	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2
0.6	-5.17	-5.84	-1.34	-0.73	-2.83	-3.59	+2.21	+2.95
1.0	-3.96	-4.58	-2.55	-1.73	-0.94	-1.71	+1.07	+2.13
1.4	-3.61	-4.10	-3.43	-2.64	-0.14	-0.84	+0.19	+1.35

3. Effect of t_B/t_s.
   The effect of increasing t_B/t_s from 0.6 to 1.4 when $t_D = t_B$ and for different values of B/D, α and t_L/t_s are shown in Figures 2, 3, 4. For the special case when $t_D = t_B$, $B/D = 2.0$, $\alpha = 0.2$ and for different values of t_L/t_s, the effect of increasing t_B/t_s from 0.6 to 1.4 is given in the following table:

t_L/t_s	Percentage change in			
	q_L and τ_L	q_s and τ_s	F_L	F_s
0.6	-10.92	-2.59	-6.36	+5.68
1.0	- 8.88	-4.81	-2.80	+3.62
1.4	- 8.05	-6.41	-1.22	+2.01

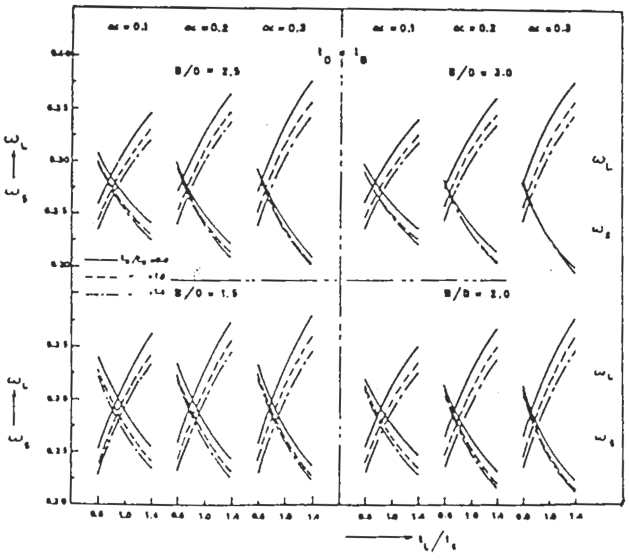


Figure 2.

4. Effect of t_L/t_s.
   It is shown that t_L/t_s is the most effective parameter in the calculation of q_s, τ_s, q_L, τ_L, F_s and F_L. The effect of increasing t_L/t_s from 0.6 to 1.4 when $t_D = t_B$ and for different values of B/D, t_B/t_s and α are shown in Figures 2, 3, 4.

For the special case when $t_D = t_B$, $B/D = 2.0$, $t_B/t_s = 1.4$ and for $\alpha = 0.2$, the effect of increasing t_L/t_s from 0.6 to 1.4 is as follows:

a. q_L is reduced by about 44.0 %
b. τ_L is reduced by about 38.3 %
c. q_s and τ_s are reduced by about 29 %
d. F_L is increased by about 39 %
e. F_s is reduced by about 30.8 %

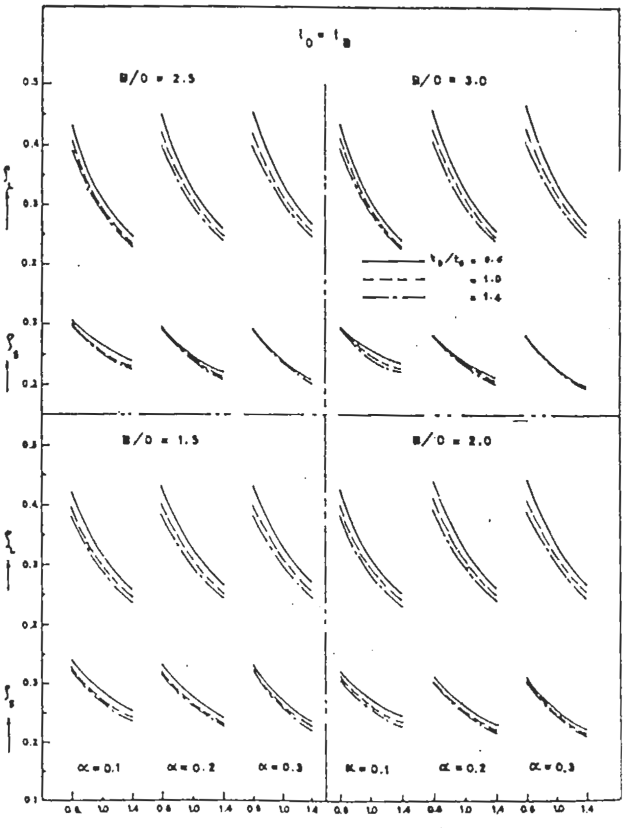


Figure 3.

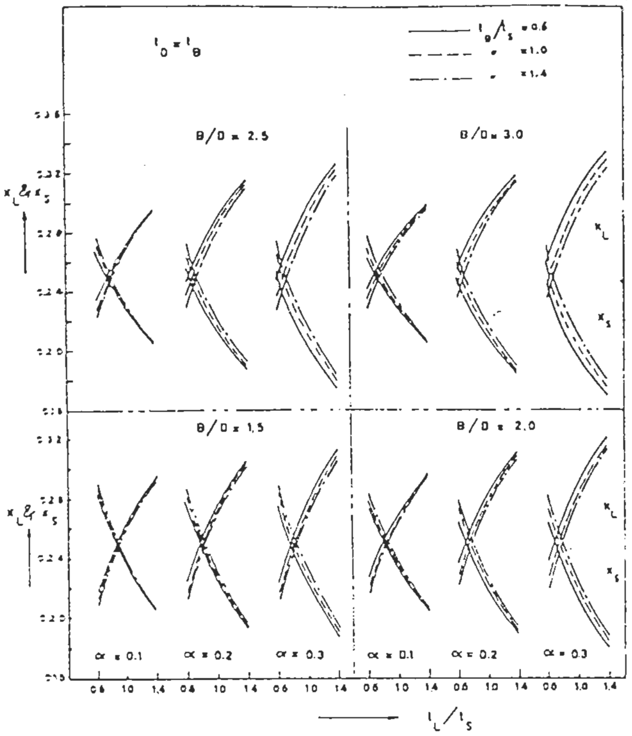


Figure 4.

5. Effect of transverse position of side londitudinal bulkheads i.e. α.
   The effect of increasing α from 0.1 to 0.3 when $t_D = t_B$ and for different values of B/D, t_B/t_s and t_L/t_s are shown in spacing Figure 6. For the special case when $t_D = t_B$, $t_B/t_s = 1.4$ and for two values of B/D, the effect of increasing α from 0.1 to 0.3 for the two values of t_L/t_s are given in the following table:

	Percentage change in							
	q_L and τ_L		q_s and τ_s		F_L		F_s	
t_L/t_s	B/D							
	2.0	3.0	2.0	3.0	2.0	3.0	2.0	3.0
0.6	+1.38	+2.87	-1.02	- 2.34	+1.48	+3.00	-1.11	- 2.50
1.4	+5.67	+8.43	-8.07	-12.37	+6.29	+9.13	-9.00	-13.05

6. Effect of R_w and/or R_L.
   Increasing R_w and/or R_L, by reducing t_B/t_s ratio from 1.4 to 0.6 while keeping the same value for t_L/t_s, has a slight effect on τ_L and τ_s whereas K_L and K_s are hardly affected. On the other hand, increasing R_w and/or R_L by increasing t_L/t_s ratio from 0.6 to 1.4 while keeping the same value of t_B/t_s reduces τ_L, τ_s, K_s considerably whereas K_L is increased, see Figures 7, 8.

Analysis of results.

The results of these calculations are analysed in terms of:

a. Effect of different parameters on the maximum shear stress and on the participation of the side longitudinal bulkheads to the shear carrying capacity of the main hull girder.

b. The conditions of the different parameters which will not induce shear stresses at the neutral axis, for both side shell and longitudinal bulkheads, greater than a maximum allowable value.

Considering each item in detail we have:

A. Effect of different parameters.

1. Effect of B/D ratio.

   Increasing B/D ratio has the following effects:
   1. q_s, τ_s, F_s are reduced
   2. q_L, τ_L, F_L are increased for low values of t_L/t_s and are reduced for high values of t_L/t_s.

2. Effect of t_D/t_B

   Increasing t_D/t_B ratio has the following effects:
   1. q_L, τ_L, q_s, τ_s, F_L are reduced
   2. F_s is slightly increased.

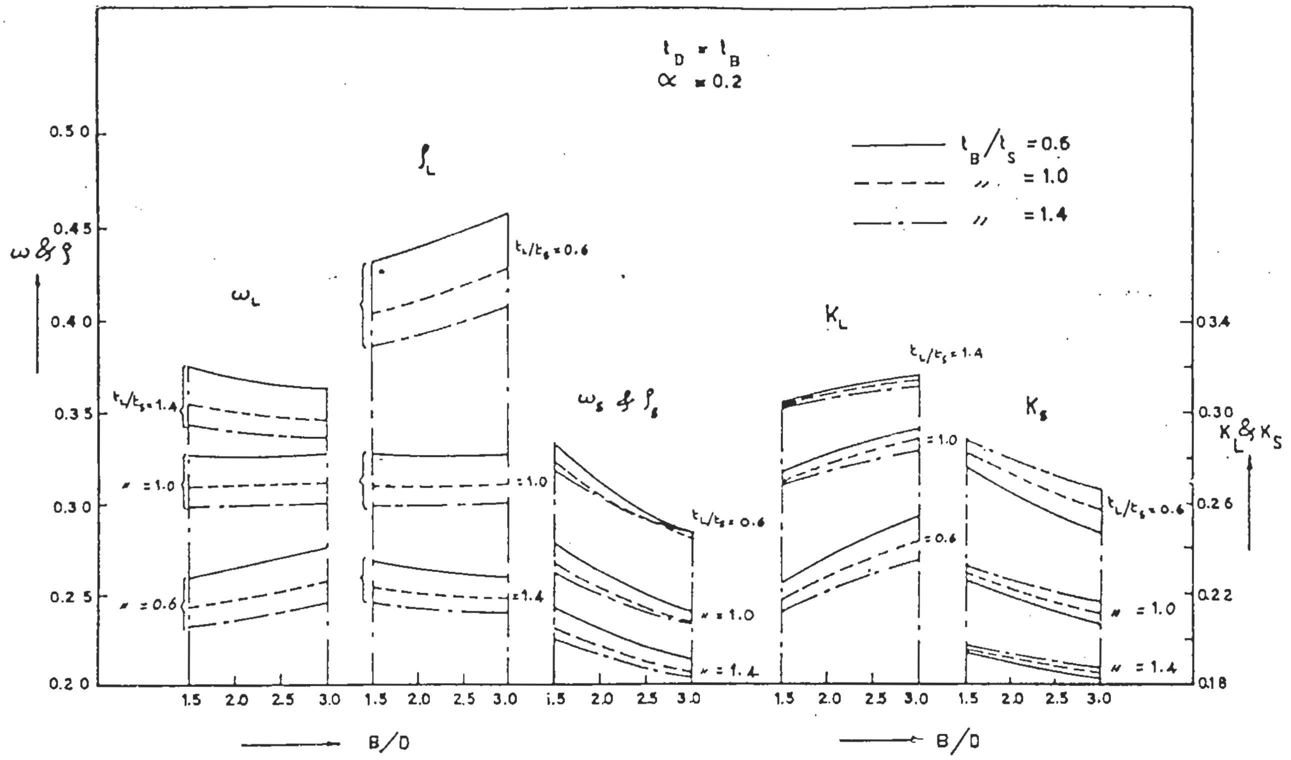


Figure 5.

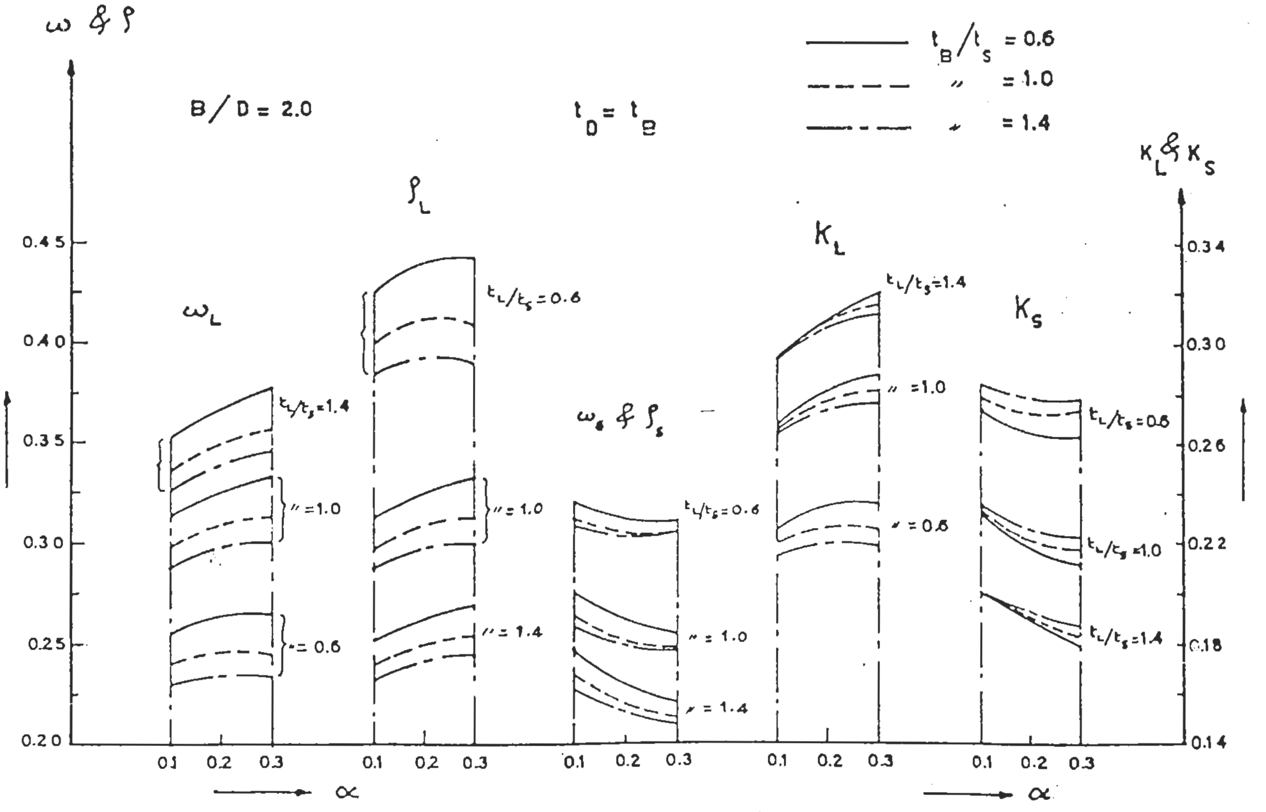


Figure 6.

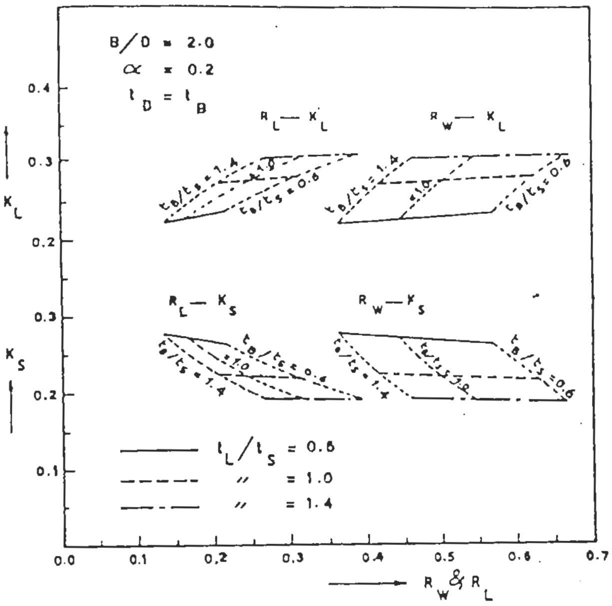


Figure 7.

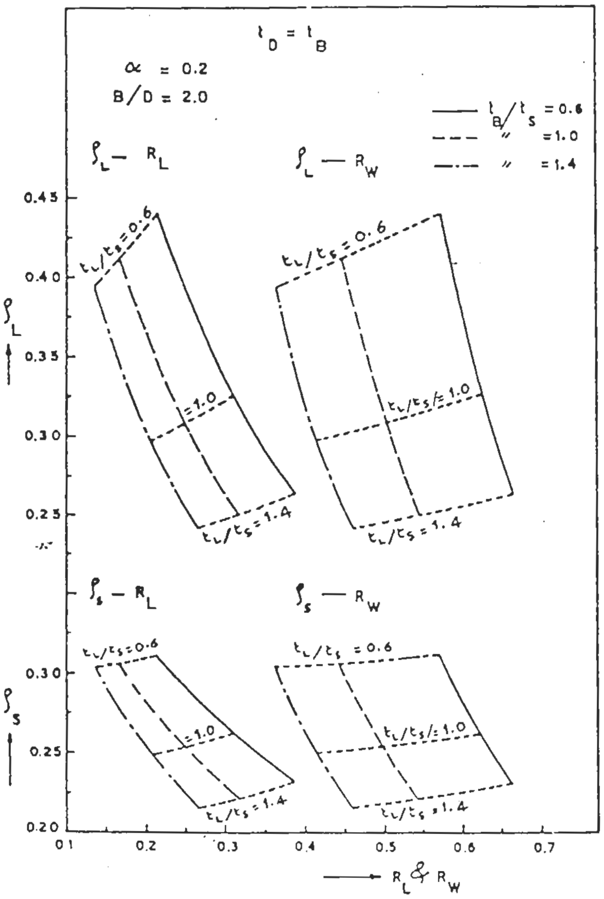


Figure 8.

3. Effect of t_B/t_S

Increasing t_B/t_S ratio has the following effects:

1. q_S, q_L, τ_S, τ_L, F_L are reduced
2. F_S is increased for low values of t_L/t_S and is slightly affected for higher values of t_L/t_S.

4. Effect of t_L/t_S.

Increasing t_L/t_S ratio has the following effects:

1. q_L, F_L are increased
2. q_S, τ_S, τ_L, F_S are reduced.

5. Effect of α.

Increasing α has the following effects:

1. q_L, τ_L, F_L are increased
2. q_S, τ_S, F_S are reduced.

From the above analysis, it is shown that in order to keep down the shear stresses in the side shell and longitudinal bulkheads, the following conditions should be maintained:

a. t_B/t_S, t_L/t_S ratios should be high

b. α should be chosen such that neither τ_S nor τ_L reaches the maximum allowable value.

It should be mentioned that it is shown in reference [4] that the transverse position of side longitudinal bulkheads not only affects its own weight but also it affects the weight of transverses and transverse bulkheads. It is shown that for minimum weight of transverse bulkheads α = 0.1667 and for minimum weight of transverses α = 0.25. Consequently, the optimum value of α should be obtained not only from the point of view of maximum shear stress in the longitudinal bulkheads but also from the minimum total steel weight point of view.

B. Calculation of the maximum allowable shear force.

The above results could be used to calculate the maximum shear force which will not induce shear stresses, in side shell plating or in longitudinal bulkheads, greater than a maximum allowable value.
It is shown that the maximum shear stress in the side shell plating and side longitudinal bulkheads are given by:

$$\tau_s = \varsigma_s \cdot \frac{F}{D\bar{t}_s} \qquad (24)$$

$$\tau_L = \varsigma_L \cdot \frac{F}{D\bar{t}_s} \qquad (25)$$

If the shear stress in side shell plating or longitudinal bulkhead plating reaches the maximum allowable value:

i.e. $\tau_s = \tau_a$

or $\tau_L = \tau_a$

then from (24) and/or (25), the maximum allowable shear force could be calculated as follows:

$$F_{max} \leqslant \frac{\tau_a \cdot D\bar{t}_s}{\varsigma_s} \qquad (26)$$

or

$$\leqslant \frac{\tau_a \cdot D\bar{t}_s}{\varsigma_L} \qquad (27)$$

where: τ_a = maximum allowable shear stress and varies between 6.0 - 7.0 kg/sq. mm. (for shipbuilding steel).

The magnitude of F_{max} depends on the magnitude of τ_a, ς_s or ς_L, depth D and thickness of side shell plating $\bar{t}_s$. Using L.R. Rules, for 1968, the minimum thickness of side shell plating is given by:

$$\bar{t}_s = \frac{s + 150}{640} \sqrt{\frac{dL}{D}} \quad \text{mm.} \qquad (28)$$

where d, D, L are draft, depth and length of ship
s = spacing of side framing or side longitudinals in mm and is given by:

$s \nless 559 + 1.11\ L$ mm.

Equation (28) could be simplified by:

$$D\bar{t}_s = RD \cdot \sqrt{fD} \qquad (29)$$

where $R = \dfrac{(559 + 1.11\ L) + 150}{640}$

$f = \dfrac{L}{D} \times \dfrac{d}{D}$

Therefore, for any ship having main dimensions, L, B, D, d, the maximum allowable shear force could be calculated using equation (29), and the smaller value of ς_s or ς_L. However, expressions (26) and (27) could be represented graphically for different values of B/D, t_B/t_s, t_L/t_s, α and using several values of τ_α.

A sample of these curves is shown in Figure 9 for the special case when B/D = 2.0, $t_D = t_B$, $\alpha = 0.2$, $t_B/t_s = 1.4$, $\tau_a = 6.0$ kg/sq. mm., f = 10.0 and for three values of t_L/t_s.

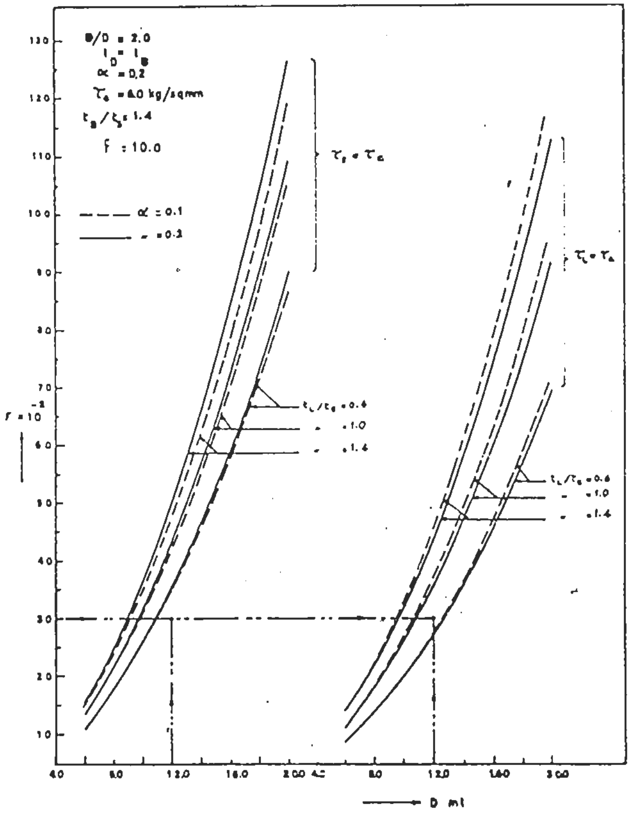


Figure 9.

If $f \neq 10$, the maximum shear force is given by:

$$F_1 = F\sqrt{\frac{f}{10.0}}$$

These curves will be most useful to check that the maximum shear stress in either side shell plating or longitudinal bulkheads, due to a maximum shear force is less than the maximum allowable value. It should be emphasized that this is a requirement of L.R. Rules (D. 4105) when the load is not uniformly distributed over the cargo tank length [6]. Alternatively, the maximum allowable shear force, which will not induce shear stresses in side shell plating or longitudinal bulkheads, greater than the maximum allowable value, could be determined.

In order to show the use of Figure 9, an example for a tanker is considered.

a. Tanker main dimensions:

$L = 175.0$ m $B = 24.0$ m $c_b = 0.8$
$D = 12.0$ m $d = 9.2$ m

$$f = \frac{175}{12} \times \frac{9.2}{12} = 11.17$$

Assume that: $\alpha = 0.2$

i.e. the side longitudinal bulkhead is at a distance 4.8 m from the ship centre line. Using L.R. Rules, we get:

$\bar{t}_s = 16.5$ mm for $s = 760$ mm
and $\bar{t}_L = 10.9$ mm for $s = 800$ mm
$= 12.25$ mm for $s = 900$ mm
$= 13.6$ mm for $s = 1000$ mm

Minimum thickness = 11.0 mm

Assuming the maximum shear force to be:

$$F = 2840.0 \text{ tons}$$

$$F_1 = 2840 \sqrt{\frac{11.17}{10.0}} \cong 3000.0 \text{ tons.}$$

b. For a depth $D = 12.0$ m and maximum shear force $F = 3000$ tons, the ratio of t_L/t_s which will not induce shear stresses $\geqslant 6.0$ kg/mm^2 in either side shell plating or longitudinal bulkheads is obtained from Figure 9, as follows:

1. $t_L/t_s = 0.3$
   in order that $\tau_s \leqslant \tau_a$
2. $t_L/t_s = 0.75$
   in order that $\tau_L \leqslant \tau_a$
   Assuming that $t_L/t_s = \bar{t}_L/\bar{t}_s$

   Hence: the minimum thickness of longitudinal bulkhead plating which will not induce shear stresses in side shell or longitudinal bulkheads greater than τ_a is given by:

   $$\bar{t}_L = 0.75\, \bar{t}_s$$

   i.e. $\bar{t}_L = 12.35$ mm.

   Consequently, the choice of longitudinal bulkhead plating thickness and stiffener spacings should be based not only on minimum weight basis [7] and constructional arrangements, but also on shear stress calculations as the latter may be the dominating factor in some cases.

Conclusions.

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

1. The ratio of effective thickness of longitudinal bulkhead plating to effective thickness of side shell plating has a great effect on the shear flow distribution, maximum shear stress and participation of longitudinal bulkheads to the shear carrying capacity of the main hull girder.
   On the other hand, the effective thickness of deck and bottom platings, as well as breadth to depth ratio have a smaller effect on the magnitude of the maximum shear stress .
2. The effect of the transverse position of side longitudinal bulkheads on maximum shear stress and participation of the longitudinal bulkheads to the shear carrying capacity of main hull girder is of the order of 10%. Consequently, the longitudinal bulkhead position should be chosen not only from the minimum weight and constructional points of view, but also from the maximum shear stress and shear carrying capacity points of view.
3. The results of this investigation could be used to check graphically, the shear strength of tankers under the action of a maximum shear force. Alternatively, the condition of the ship section which will not induce, under the action of a maximum shear force, shear stresses greater than a maximum allowable value, could also be determined.

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List of symbols.

t = thickness
t_B = effective thickness of bottom plating
t_D = effective thickness of deck plating
t_L = effective thickness of side longitudinal bulkhead
t_s = effective thickness of side shell plating
$\bar{t}_L$ and $\bar{t}_s$ = actual thickness of side longitudinal bulkhead and side shell plating, respectively
B = breadth
D = depth
d = draft
γ = B/D
α = normalized distance of side longitudinal bulkhead from ship centre line
x = t_D/t_B
y = t_L/t_s
z = t_B/t_s
γ, α, x, y and z are independent parameters
I = second moment of area of ship section about its own neutral axis
= $\psi \cdot D^3 t_s$
ψ = non-dimensional coefficient of second moment of area
R_w, R_L = ratios of web sectional area and of side longitudinal bulkheads/ total sectional area of longitudinal material, respectively
R_w and R_L = dependent parameters
Q = first moment of area
$\bar{y}$ = height of centroid of area above neutral axis
φ_s and φ_L = non-dimensional coefficients of first moment of area for side shell plating and side longitudinal bulkhead, respectively
w = φ/ψ
q = shear flow in tons/cm
$\bar{q}$ = mean shear flow
q_{ij} = shear flow at point 'i' in direction ij
$(q)_c$ = correcting shear flow
q_i = shear flow at point 'i'
$(q_i)_r$ = resultant shear flow at point 'i'
$(q_L)_y$ and $(q_s)_y$ = shear flow at a depth y from the neutral axis for side longitudinal bulkhead and side shell plating, respectively
τ_s and τ_L = maximum shear stress at neutral axis for side shell and side longitudinal bulkhead, respectively
ς_L and ς_s = non-dimensional coefficients of the maximum shear stress
F = longitudinal vertical shear force
F_L, F_s = shear force carried by one side longitudinal bulkhead and one side shell plating, respectively
K_L and K_s = coefficients of the shear forces carried by side longitudinal bulkhead and side shell, respectively
G = modulus of rigidity.

Appendix I.

a. Independent parameters.

1. $t_D/t_B = x$
2. $t_B/t_s = z$
3. $t_L/t_s = y$
4. $B/D = \gamma$
5. Distance of side longitudinal bulkhead from ship centre line/B = α .

b. Dependent parameters.

1. $R_W = A_W/A_T$

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

2. $R_L = A_L/A_T$

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

where: A_T = effective sectional area of (deck + bottom + longitudinal bulkheads + side shell plating).

A_W = sectional area of longitudinal bulkheads and side shell plating;

A_L = sectional area of side longitudinal bulkheads.

3. Position of neutral axis from base line. This is defined by the normalized distance β, see Figure 1, and is given by:

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

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

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

where ψ is a non-dimensional coefficient and is given by:

$$\psi = (1+y)\left[\tfrac{1}{6} + 2(0.5-\beta)^2\right] + \gamma z\left[(1-\beta)^2 + \beta^2\right]$$

APPENDIX (II)

SHEAR FLOW DISTRIBUTION (q)

MEMBER OR POINT	$A\bar{y}/D^2t_s$	$\sum A\bar{y}/\frac{F}{I}.D^2t_s$	$\bar{q}/\frac{F}{I}.D^2t_s$	$\frac{\Delta s}{t}/\frac{D}{t_s}$	$\bar{q}\frac{\Delta s}{t}/\frac{F}{I}.D^3$
A					
HA	$\alpha\gamma xz(1-\beta)$	$\alpha\gamma xz(1-\beta)$			
L					
HL	$y(1-\beta)^2/2$	$y(1-\beta)^2/2$	$y(1-\beta)^2/6$	$(1-\beta)/y$	$(1-\beta)^3/6$
HB		$\alpha\gamma xz(1-\beta) + y(1-\beta)^2/2$	$y(1-\beta)^2/2 + \gamma xz(\frac{1}{2}+\alpha)(1-\beta)/2$	$\frac{\gamma(\frac{1}{2}-\alpha)}{xz}$	$\frac{\gamma y}{2xz}(\frac{1}{2}-\alpha)(1-\beta)^2 + \frac{\gamma^2}{2}(1-\beta)(\frac{1}{4}-\alpha^2)$
BH	$\gamma xz(\frac{1}{2}-\alpha)(1-\beta)$	$y(1-\beta)^2/2 + \gamma xz(1-\beta)/2$			
BS	$(1-\beta)^2/2$		$(\frac{y}{2}+\frac{1}{3})(1-\beta)^2 + \gamma xz(1-\beta)/2$	$1-\beta$	$(\frac{y}{2}+\frac{1}{3})(1-\beta)^3 + \gamma xz(1-\beta)^2/2$
S		$(1+y)(1-\beta)^2/2 + \gamma xz(1-\beta)/2$			
EI	$\alpha\gamma z\beta$	$\alpha\gamma z\beta$			
IL	$y\beta^2/2$	$y\beta^2/2$	$y\beta^3/6$	β/y	$\beta^3/6$
ID		$\alpha\gamma z\beta + y\beta^2/2$	$y\beta^2/2 + \gamma z\beta(\frac{1}{2}+\alpha)/2$	$\frac{\gamma(\frac{1}{2}-\alpha)}{z}$	$\frac{\gamma y}{2z}(\frac{1}{2}-\alpha)\beta^2 + \gamma\beta(\frac{1}{4}-\alpha^2)/2$
DI	$\gamma z\beta(\frac{1}{2}-\alpha)$	$y\beta^2/2 + \gamma z\beta/2$			
DS	$\beta^2/2$		$(\frac{y}{2}+\frac{1}{3})\beta^2 + \gamma z\beta/2$	β	$(\frac{y}{2}+\frac{1}{3})\beta^3 + \gamma z\beta^2/2$
S		$(y+1)\beta^2/2 + \gamma z\beta/2$			

$$(q)_c = \frac{\sum \bar{q}\,\frac{\Delta s}{t}}{\sum \frac{\Delta s}{t}} = \varphi_L \cdot D^2 t_s \cdot \frac{F}{I} = (w)_c \cdot \frac{F}{D} \qquad \text{where} \quad (w)_c = \varphi_L/\psi$$

$$\text{where} \quad \varphi_L = \frac{0.5(1+y)[\beta^3 + (1-\beta)^3] + \frac{0.5\gamma y}{z}(0.5-\alpha)[\beta^2 + (1-\beta)^2/x] + \frac{\gamma^2}{2}(\frac{1}{4}-\alpha^2) + \frac{\gamma z}{x}[x(1-\beta)^2 + \beta^2]}{\frac{y+1}{y} + \gamma(0.5-\alpha)(1+x)/xz}$$

$$q_L = w_L \cdot \frac{F}{D} \qquad \text{where} \quad w_L = (w)_c$$

$$q_S = w_S \cdot \frac{F}{D} \qquad \text{where} \quad w_S = \varphi_S/\psi \quad \text{and} \quad \varphi_S = (y+1)\beta^2/2 + \gamma z\beta/2 - \varphi_L$$