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للأستاذ الدكتور محمد عبد الفتاح شامة

Published Papers (1981-2002)

On Ship Reliability and Safety

by

Prof. Dr. M. A. Shama

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SHEAR STRENGTH OF DAMAGED COASTAL OIL TANKERS UNDER VERTICAL SHEAR LOADING

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ABSTRACT

The main objective of this paper is to examine the shear carrying capacity of a damaged ship section of coastal oil tankers. The effect of damage location on the shear flow distribution and on the ability of the shear carrying material to withstand the resulting higher shear stresses is studied. Only coastal oil tankers having one central longitudinal bulkhead are considered. The redistribution of the shear stresses in the hull section subsequent to the occurrence of damage is obtained and the ship section structure is checked for the buckling mode of failure .In order to achieve an adequate safety level for the ship and to prevent oil pollution after ship damage, which is a major concern of the international marine community, a case study is presented to examine the shear flow distribution for the following cases and compared with the shear flow distribution of the intact ship section . (1) Damage to the side shell plating at the neutral axis of the ship section (2) Damage to the bilge plating, (3) Bulkhead damage at its lower end, and (4) Damage to the keel plating .The damage region is modeled as a crack or separation inducing structural discontinuity. The results of the different damage cases are compared with the results of the intact case . It is concluded that the structural design of coastal oil tankers should be based not only on safety requirements but also on the minimization of environmental impacts.

Keywords: Oil tankers, Shear strength, Damage locations, Shear forces, Shear stresses, Modes of Failure.

NOMENCLATURE

A	Sectional area of the cell under consideration
a	Length of the plate, meters
a_1	Total sectional area of all other longitudinal materials attached to the member
a_j	Area of the path line from the zero shear point to the point j
B	Breadth of the ship, meters
b	Length of the panel, meters
D	Depth of the ship, meters
E	Modulus of Elasticity
F_j	The shear force on any vertical member over the ship section
F_L	Shear force carried by the longitudinal bulkhead plating
F_{s1}	Shear force carried by port side shell plating
F_{s2}	Shear force carried by starboard side shell plating
G	Modulus of rigidity
I	Second moment of area of ship section, m^4
j	Point at any position over the plating
k	Constant depending on the panel end conditions = $5.34 + 4/\alpha^2$, for simply supported ends = $8.98 + 5.6/\alpha^2$, for fixed ends
L	Length of the ship, meters
l	Length of member, meters
l_j	Length of member ' j ', meters
m (s)	First moment of area (as a function of the perimeter of the closed cell)
N	Number of closed cell under consideration
Q	Applied shear force on the ship section obtained from longitudinal strength calculations
Q_1	The maximum shear force which can be carried by the port side shell plating
Q_L	The maximum shear force which can be

	carried by the central longitudinal bulkhead plating
Q_2	The maximum shear force which can be carried by the starboard side shell plating
Q_{max}	The maximum shear force which can be carried by all the vertical members
q_1	The corrective shear flow
q_j	Assumed shear flow for the determinate structure at point j
q_{rj}	Resultant shear flow at point j
s	Frame Spacing, meters
t_b	Thickness of the bottom plating, meters
t_d	Thickness of the deck plating, meters
t_e	Effective thickness of member, meters
t_s	Thickness of the side shell plating, meters
t_j	Thickness of a particular member of the midship section, meters
t_L	Thickness of the central longitudinal bulkhead plating, meters
y_b	The distance of the bottom plating from the neutral axis of the midship section, meters
y_d	The distance of the deck plating from the neutral axis of the midship section, meters
y_j	The distance of point ' j ' from the neutral axis, meters
α	Aspect ratio for the plating panel of the sides or the longitudinal bulkhead
β	Slenderness ratio for the plating under consideration
γ	Factor of Safety
ν	Poisson's Ratio
σ_a	Stress due to hull girder bending stress at section 'i'
σ_{eij}	Equivalent stress at point 'j' in section 'i'
σ_y	Yield stress
τ_{all}	Allowable shear stress
τ_{cr}	Critical shear stress
τ_E	Euler buckling shear stress
τ_{ij}	Shear stress at section 'i' and point 'j'
τ_L	Actual shear stress on the central longitudinal bulkhead plating
τ_y	Yield shear stress
τ_1	Actual shear stress on the port side shell plating
τ_2	Actual shear stress on the starboard side shell plating

1. INTRODUCTION

The environmental disaster of the Exxon Valdez in 1989 followed by several other oil tanker spills caused by grounding, collision, structural failures, fire and explosion, has spurned the marine community to undergo detailed studies to help prevent marine accidental pollution caused by tankers. Part of these studies are concerned with the reserve strength subsequent to the various modes of structural failures.

In oil tankers, hull girder shear stresses represent an important design consideration when determining the thickness of the shear carrying material such as the side shell and longitudinal bulkhead plating. A series of studies were carried out to investigate the shear stress distribution and the shear carrying capacity of the intact structure of oil tankers and bulk carriers [1,2,3,4,5] . These studies have presented in detail methods for calculating the shear flow distribution over the intact ship sections as well as the corresponding shear carrying capacity of the ship section . The aim of this paper is to examine one major cause of tanker oil spills, that due to minor structural damages leading to the inability of the structure to further carry the loads imposed on the damaged structure . Therefore, the effect of the presence of a minor structural damage and its location on the shear flow distribution and the shear carrying capacity of small oil tankers having one central longitudinal bulkhead is studied. It is an important design requirement that the failure or damage of any part of the ship structure will not propagate or cause further damage or failure leading to the release of the oil to the sea and causing oil pollution . It is important, therefore, to determine the impact of local structural damage on the shear carrying capacity of the ship section of coastal oil tankers .

A case study is presented and the following cases of damage location are assumed:

1- Damage of side shell plating at the neutral axis of the ship section .
2- Damage of the bilge plating .
3- Damage of the longitudinal bulkhead plating at its lower end.
4- Damage of the keel plating .

2. CALCULATION OF SHEAR FLOW DISTRIBUTION

The procedure for calculating the shear flow distribution over the ship section of a coastal oil tanker is based on the method presented in [1].

The calculation of shear flow distribution around a ship section of a coastal oil tanker is based on the idea that the structure is allowed to distort under an assumed shear flow distribution. A correcting shear flow is then introduced to satisfy the existing conditions of geometry. The resultant shear flow distribution must satisfy the following conditions of equilibrium :-

1- the sum of horizontal shear forces must be equal to zero
2- the sum of the vertical shear forces must be equal to the applied shear force
3- the angle of twist must be equal to zero for each closed cell, and for the whole structure. It is assumed that no torsional moments are applied.

In order to satisfy this condition for each closed cell, an opposite uniform shear flow (correcting shear flow) is applied ,so that the angle of twist θ, resulting from the assumed shear flow distribution, vanishes. The angle of twist θ, is given by:

$$\theta = \frac{1}{2AG} \oint \frac{q}{t} \, ds \qquad (1)$$

The thickness used in calculating the shear flow distribution is the effective thickness, t_e, given by:

$t_e = t + a_1 / l$

A brief summary of the method is given in Appendix (1).

3. PLATE FAILURE MODES

In general, plate elements have a measure of post buckling reserve. Thiss study specifies both plate buckling and plate collapse modes of failure under pure edge shear loading.

3.1. *Shear Buckling of Side Shell and Longitudinal Bulkhead Plating*

The presence of an in-plane shear stress τ in a plate tends to lower the resistance of the plate to the applied compressive stresses. It is given in [6] that:

- For $\tau < 0.175\ \sigma_y$, the effect of shear stress should be ignored
- For $\tau > 0.175\ \sigma_y$, a reduction factor for the yield stress should be used.

The reduction factor is given by:

$$r_\tau = 1.05 \sqrt{1 - 3\left(\frac{\tau}{\sigma y}\right)^2}$$

In order to ensure adequate strength against plate shear buckling, the maximum shear force which the side shell and longitudinal bulkhead plating can sustain, can be determined from the condition that the maximum expected shear stress should not exceed the critical value, i.e.

$$\tau \leq \tau_{cr}$$

The critical shear buckling stress of a panel of plating shown in Figure (1), subjected to pure shear loading[7], is given by:

$$\tau_E = \frac{E\pi^2}{12(1-\nu^2)} K \left(\frac{t}{S}\right)^2$$

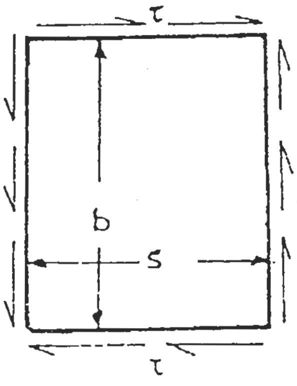

Figure 1. Panel of plating subjected to pure shear.

If $\tau_E < 0.5\ \tau_y$

then $\tau_{cr} = \tau_E$

If $\tau_E \geq 0.5\ \tau_y$

then $\frac{\tau_{cr}}{\tau_y} = [1 - 0.25\ (\frac{\tau_y}{\tau_E})]$

$$\tau_y = \sigma_y/\sqrt{3}$$

$$\left(\frac{\tau_E}{\tau_y}\right) = 1.56\,\frac{K}{\beta^2}$$

$$B = \frac{b}{t}\sqrt{\frac{\sigma y}{E}}$$

Assuming a factor of safety, γ, then,

$$\tau_{all} = \tau_{cr}/\gamma$$

let

$$\phi = \frac{\sum a_j y_j}{I\, t_j}$$

$$Q = \tau/\Phi$$

The maximum allowable shear force is, therefore given by:

$$Q_{all} = \tau_{all}/\Phi$$

3.2. *Collapse Mode of Failures of Side Shell and Longitudinal Bulkhead Plating Under Vertical Shear Loading*

The collapse strength of all plate elements under vertical shear loading is to be identical to the shear buckling mode of failure as obtained in section (3.1) [7].

4. CASE STUDY

The calculations of shear flow, stresses, forces, and critical buckling stresses are applied to a coastal oil tanker having the following main particulars, L.B.P = 65.00 meters, B = 12.85 meters, D = 5.80 meters. The geometrical and other characteristics of the ship section are given in Appendix (2).

The method of calculation is applied to the following cases of structural damage :

1- Damage of side shell plating at the neutral axis of the ship section .
2- Damage of the bilge plating .
3- Damage of the longitudinal bulkhead plating at its lower end .
4- Damage of the keel plating .

The shear flow distributions over the shear carrying materials of the ship section are obtained for each assumed damage location on the ship section .

4.1 *Effect on shear flow distribution of structural damages at the specified locations on the midship section*

It is shown from Figures (3,4,5,6) that the shear flow distribution over the ship section after the assumed local structural damages have changed drastically from the original distribution of the intact ship section shown in Figure (2).

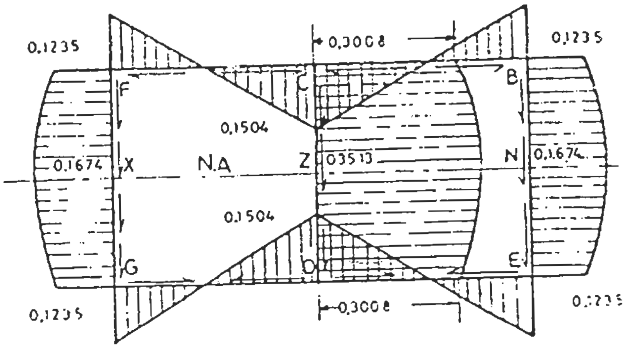

Figure 2. Shear flow distribution for intact ship case.

From Figure (3), where the assumed damage occurs in the side shell plating near the position of the neutral axis of the ship section, it is shown that there are significant increases in the maximum shear flow values in the deck, bottom, side shell, and central longitudinal bulkhead plating.

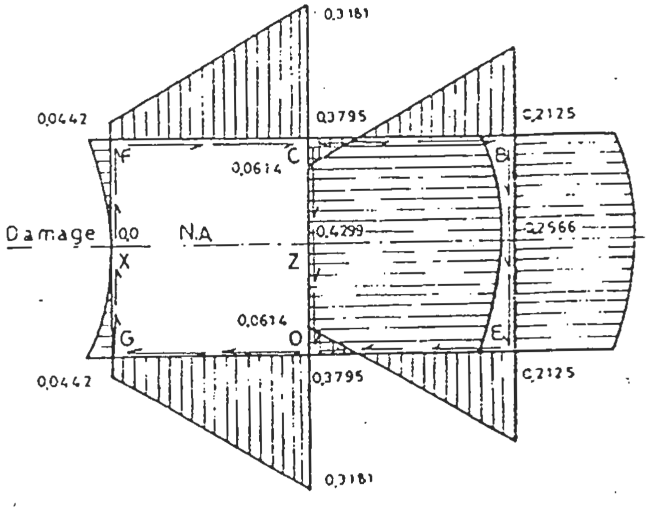

Figure 3. Shear flow distribution for the neutral axis damages case.

From Table (1), it is evident that the deck and bottom plating have the largest percentage of increases in the maximum values of the shear flow. This additional shear loading on the deck, and bottom plating should not be ignored so as to avoid indirect subsequent failure of the ship section .

Table 1. Comparison between the shear flow values of case (1) and original case.

Case	Location on ship section				
	2	4	5	6	7
0	0.1504	0.3008	0.1234	0.1674	0.3513
1	0.3180	0.3794	0.2126	0.2566	0.4299
%	211	126	172	153	122

From Figure (4), where the assumed damage occurs at the bilge plating, it is shown that there are significant increases in the maximum shear flow values in the deck, bottom, and central longitudinal bulkhead plating as listed in Table (2). From Table (2), it is evident that the deck, bottom, and side shell plating have the largest percentages of increases of the maximum shear flow values .The deck, bottom, and side shell plating should be designed to sustain the additional loading resulting from an assumed damage at the bilge plate.

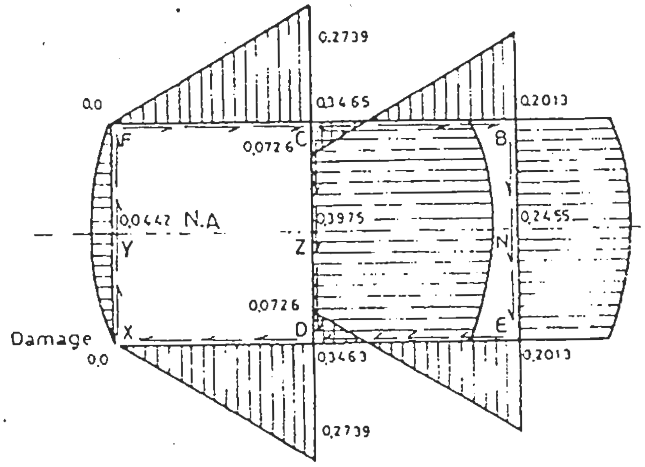

Figure 4. Shear flow distribution for bilge damage case.

Table 2. Comparison between the shear flow values of case (2) and original case

Case	Location on ship section				
	2	4	5	6	7
0	0.1504	0.3008	0.1234	0.1674	0.3513
2	0.274	0.3470	0.2010	0.2450	0.3975
%	182	115	163	146	113

From Figure (5), where the assumed damage occurs at the lower end of the central longitudinal bulkhead, it is evident that there are significant increases in the maximum values of the shear flow in the side shell and deck plating as listed in Table (3). These increases in the shear flow values should be taken into account in the design of the side shell plating.

Table 3. Comparison between the shear flow values of case (3) and original case.

Case	Location on ship section				
	2	4	5	6	7
0	0.1504	0.3008	0.1234	0.1674	0.3513
3	0	0	0.2740	0.3180	0.0505
%	0	0	222	190	14

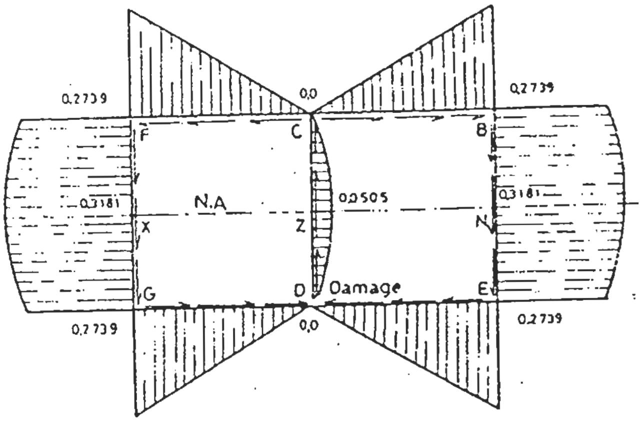

Figure 5. Shear flow distribution for bulkhead damage case.

From Figure (6), where the assumed damage occurs at the keel plating, there are obvious increases in the maximum values of the shear flow in the side shell and deck plating as listed in Table. (4). The additional loading on side shell and deck plating resulting from the redistribution of shear flow, should not be ignored when designing the side shell plating .

Table 4. Comparison between the shear flow values of case (4) and original case.

Case	Location on ship section						
	1	2	4	5	6	7	8
0	0.1234	0.1504	0.3008	0.1234	0.1674	0.3513	0.1674
4	0.2740	0	0.1419	0.1321	0.1762	0.1924	0.3180
%	222	0	47	107	105	55	190

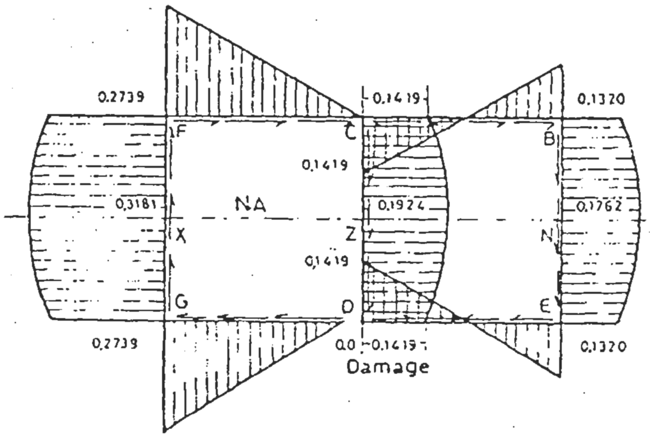

Figure 6. Shear flow distribution for keel damage case.

It is evident from these calculations and analysis that, when a coastal oil tanker is assumed to be damaged at specific locations, the shear flow will be redistributed over the ship section .The redistribution will result in significant increases in the maximum values of the shear flow on the side shell, deck, bottom, and central longitudinal bulkhead .

The members seriously affected by the redistribution of shear flow subsequent to the assumed damage locations of the midship section of a coastal oil tanker are given in Table (5).

The importance of taking these high increases in the shear flow subsequent to minor structural damages results from the fact that the actual flexural stress at any point over the ship section should tak into account the shear stress at that point . Th could be achieved by using the equivalent stres formula as follows:

$$\sigma_{eij} = \sqrt{\sigma_{ij}^2 + 3\,\tau_{ij}^2}$$

Table 5. Members seriously affected by the redistribution of the shear flow

Case	Side shell	Deck	Bottom	Long. Bulkhead
1	Y	Y	Y	
2	Y	Y	Y	
3	Y	Y	Y	
4	Y	Y	Y	

Therefore very high values of equivalent stresse may be induced in sections other than thos subjected to the highest bending stress or thos subjected to high shear stresses.

4.2. *Calculation of shear forces carried by t vertical members of the ship section*

The shear force on any vertical member over th ship section, can be calculated by integrating th shear flow distribution over that particular membe as follows:

$$F_j = \int_0^{l_i} q\, ds$$

The calculated shear force should satisfy th condition that the sum of the vertical shear forc must equal the applied vertical shear force obtained from the longitudinal strength calculation i.e.

$$Q = F_L + F_{s1} + F_{s2}$$

The vertical shear forces F_L, F_{s1} and F_{s2} for eac case of damage, are given in Table.(6), together wi the corresponding values obtained for the [illegible] condition .The percentage increase of the she forces for each vertical member over the corresponding value of the original case is also listed in Table (6)

Table 6. Shear forces on vertical members.

Case	F_{sl}	%	F_{s2}	%	F_L	%
0	0.8869	100	0.8869	100	1.9399	100
1	-0.0854	10	1.4032	158	2.3959	123
2	0.1707	19	1.3383	151	2.2047	114
3	1.7593	198	1.7593	198	0.1915	10
4	1.7593	198	0.9363	105	1.0181	52

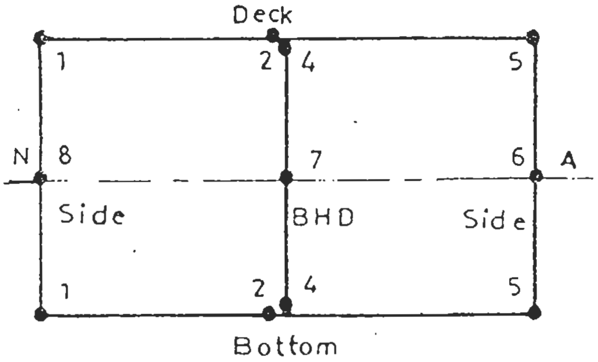

Figure 7. Numbering of points on the midship section of a coastal oil tanker.

From Table (6), it is shown that the side shell plating will be subjected to an additional shear force of 98 % of the original value, when the central bulkhead is damaged at its lower edge .
From Table (6), the vertical members of the midship section of the coastal oil tanker subjected to the high shear force subsequent to each assumed case of damage are shown in Table (7).

Table 7. Members subjected to highest shear forces subsequent to each damage case.

Force Case	F_{s1}	F_L	F_{s2}
1	-	123	158
2	-	-	151
3	198	-	198
4	198	-	-

It is evident from Table (7) that, the damage cases that have a pronounced effect on the:

i- port side shell plating, are cases No. (3) and (4)
ii- longitudinal bulkhead, are cases No.(1)
iii- starboard side shell plating, are cases No.(1), No.(2) and No. (3)

4.3. *Shear buckling of side shell and longitudinal bulkhead plating*

Following the procedure given in section (3) of the text, the maximum allowable shear force that the ship section could sustain after the assumed damage could be estimated as follows :

i- Side Shell Plating

Assume the following data for the side shell plating:

t_s = 10.5 mm

s,b = 0.76 m, 2.7 m

$\alpha = b / s = 3.55$

$\tau_y = 13950$ tons / m^2

$E = 2.2 * 10^7$ tons / m^2

$\nu = 0.3$

$K = 5.675$

Then,

$$\beta = 2.40$$

The elastic critical buckling shear stress for side shell plating is given by :

$$\tau_E / \tau_y = 1.536 > 0.5 \text{ then}$$
$$\tau_{cr} = 11676.11 \text{ tons / m}^2$$

Assume a factor of safety for shear buckling γ=1.7
The maximum allowable shear stress is given by:

$$\tau_{all} = 6868.3 \text{ tons/m}^2$$

The maximum allowable shear force carried by the side shell plating is given by :

$$Q_{s1} = \tau_{all} / \Phi_{s1}$$

Table (8) gives the maximum allowable shear force carried by the vertical members for the assumed damage conditions .

Table 8. Maximum shear force obtained from buckling criteria.

Case	ϕ_1	Q_1	ϕ_L	Q_L	ϕ_2	Q_2	Q_{max}
0	4.3	1598	7.88	871	4.3	1598	871
1	0	0	9.65	712	6.58	1044	712
2	1.133	6066	8.91	771	6.29	1091	771
3	8.16	842	1.13	6066	8.16	842	842
4	8.16	842	4.32	1591	4.52	1520	842

It is shown in Table (8) that the maximum allowable shear force for all the assumed damage cases is 712 tones . This figure gives the strength capability of the ship section of the coastal oil tanker for the assumed scenarios of the damage cases .This value is less by 11.5 % than the allowable shear force of the original intact case .

5. CONCLUSIONS

The main conclusions drawn up from this investigation are :

1- Very high shear stress values could be induced in the deck, bottom ,side shell, and the central longitudinal bulkhead of coastal oil tankers subsequent to minor damages, in certain locations over the ship section .

2- Very high equivalent stresses could be induced in the deck and bottom plating subsequent to minor damages, in other locations of the ship section .

3- Minor structural damages in certain locations over the ship section of coastal oil tankers could cause major structural collapse of the ship section due to shear buckling of side shell or longitudinal bulkhead .

4- The procedures commonly adopted for the structural design of coastal oil tankers should take into account possible modes of failure subsequent to assumed minor damages in certain critical areas of the ship section .

5- In order to reduce oil spills as a result of structural failures of coastal oil tankers, the philosophy of ship structural design of these tankers should be based not only on the safety aspect of the intact structure but should also take account of the reserve strength given possible scenarios of the damaged structure .

Appendix 1.

A brief summary of the method is as follows :

i-) Assume a shear flow distribution over the ship section after introducing a longitudinal cut for each closed cell as shown in Figure (8).

The assumed shear flow distribution will cause the ship section to distort by an angle, as given by equation (1) .

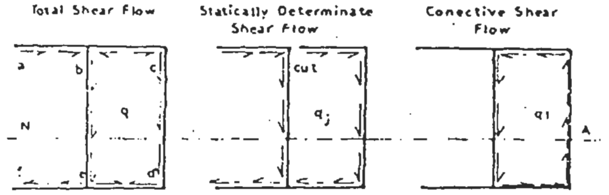

Figure 8. Calculation of shear flow in a multi-cell ship sections.

The shear flow at any point, j is given by :

$$q_j = \frac{Q}{I} \sum a_j y_j$$

ii-) A correcting shear flow is assumed for each cel so as to cancel the torsional deformatio induced by the assumed shear flow . Th correcting shear flow is then given by :

$$q_1 = -\frac{\oint \frac{q_a}{t} ds}{\oint \frac{1}{t} ds} \text{ for closed cell 'BCDEB'}$$

Note that, the negative sign means that the correcting shear flow is counter clockwise

iii-) The resultant shear flow at any point is given by:

$$q_{rj} = q_j + q_1$$

Appendix 2.

The examination of the shear carrying capacity a damaged ship section of a coastal oil tanker is carried out for the following given data:

i-) Main Dimensions

L.B.P = 65 m
B = 12.85 m
D = 5.8 m

where :
L.B.P Length between perpendiculars
B Breadth of the ship, meters
D Depth of the ship, meters

ii-) Effective Thicknesses

The effective thickness of deck, bottom, longitudinal bulkhead, and side shell plating are given by:

$t_s = 10.5$ mm
$t_L = 12.0$ mm
$t_b = 14.7$ mm
$t_d = 14.7$ mm

where :
t_b Effective thickness of the bottom plating, meters
t_L Effective thickness of the central longitudinal bulkhead plating, meters
t_d Effective thickness of the deck plating, meters
t_s Effective thickness of the side shell plating, meters

iii-) Material Properties

E Modulus of elasticity = $2.2 * 10^7$ tons / m^2
ν Poisson's ratio = 0.3
τ_y Yielding shear stress = 13950 tons / m^2

iv-) Geometrical Calculations of the Ship Section

$y_b = 2.9$ m
$y_d = 2.9$ m
$A = 0.5692$ m^2
$I = 3.7137$ m^4

where:
y_b The distance of the neutral axis of the midship section from bottom plating, m
y_d The distance of the neutral axis of the midship section from the deck plating, m
A Area of the midship section of a coastal oil tanker, m^2
I Second moment of area of ship section, m^4

iv-) Plate Geometry

$$\alpha = b / s = 3.55$$

where :
α Aspect ratio for the plating of the sides or the longitudinal bulkhead panel
b, s Length and width of the plate

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