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FACULTY OF ENGINEERING

AN INVESTIGATION INTO SHIP HULL GIRDER DEFLECTION

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SUMMARY

The main causes of ship hull girder deflection are identified and examined. An approximate iterative method is given for calculating the deflection curve resulting from ship loading. The method takes into account the variation in buoyancy distribution along the ship length resulting from the deflected shape of the hull girder. The effect of variation of bending stiffness and shear rigidity along the ship length on ship deflection are studied. The hull girder is idealized by a variable section box girder and the deflection curve is computed firstly with reference to a line joining the two ends of the hull girder and secondly with reference to the still water surface.

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The effects of hull girder deflection on the magnitude and distribution of the shear force and bending moment, along the ship length, are examined. The percentage changes in draughts forward and aft as well as amidships, due to hull deflection, are calculated. Two numerical examples are considered for this purpose; a box-shaped vessel and an oil tanker. The loss in deadweight resulting from a sagging deflection is stressed and the necessary measures to obviate this loss are suggested.

It is concluded that using high strength steels, structural optimisation procedures, increasing ship length/depth ratio, reduction in corrosion allowance and designing to higher working stresses may have an adverse effect on hull flexibility. Excessive hull girder defections may create additional structural, economic and operational unfavourable problems.

INTRODUCTION

The building of the three dimensional complex structure of a ship over a slip-way or in a building dock may cause the hull girder to exhibit a deflected form and also may deform the bottom structures between bulkheads, This built-in deflection, which results basically from welding operations, lack of fit of fabricated units, settlement of building dock or ground during building or due to the flexibility of the hull girder, cannot be easily controlled or even predicted. However, it could be assumed that for large ships (above 100,000 tons deadweight), the built-in deflection over the ship length is of the order of 100 mm, and normally, it is a sagging deflection.

On top of this built-in deflection, a ship also exhibits an additional deflection due to loading. The hull girder could be idealizd by a floating free-free beam of variable cross-section loaded by the various weights of steel hull, outfittings, machinery, cargo ... etc., and supported by buoyancy forces. Under this condition, the hull girder deflects in the longitudinal vertical plane, either in a sagging or a hogging position. The bottom structure also deflects inwards or outwards depending on the local net loading. The megnitude of the hull girder deflection or of the local deflection depends on the distribution of weights and pressures as well as on the variation of shear and bending stiffnesses along the ship length and also along and across the bottom structure. The accuracy of the calculated deflection depends, among other factors, on how the structure is idealized for computation.

Further local and general hull girder deflection result from temperature variations along the ship length and across her breadth and depth. Under certain conditions. this type of deflection may become rather significant and therefore should not be ignored when calculating the total deflection curve of a ship.

In the preliminary design stages, it is not necessary to include the effect of the deformed shape of the hull girder into the subsequent design calcuations, whether for hydrostatic, hydrodynamic, structural or operational purposes. However, the importance of calculating the correct deflection curve is realised in the operational problems for ships having wide hatch openings, for large ships working in shallow water zones or passing through shallow water canals, and for long ships having large length/depth ratio. For these types of ships, the structural and operational problems, which may result from excessive hull girder deflection, should be taken into consideration. The calculation of the true deflection curve of a ship is also very useful when designing the Block arrangement for docking. Here, the problem is very complicated as the true deflection surface depends not only on the load distribution and the flexibility of the hull girder, but also on the flexibility of the building dock or floating dock as well as the docking blocks (1). The basic solution of a beam on an elastic foundation is given in detail in reference (2).

This paper gives an approximate method for calculating the deflection curve of a ship, using the distribution of weights and buoyancy as well as the variation of shear and bending stiffnesses along the ship length. The shear deflection is taken into occount and the total deflection curve is computed with reference to a line joining the two ends of the hull girder as well as to the still water surface. In this analysis, it is assumed that the deflection of the bottom structure between bulkheads, although may reach values higher than 30 mm (3), is relatively small in comparison with the longitudinal vertical deflection of the hull girder which may reach 400 mm for large ships. The effect of hull girder deflection on the distribution of shear force and bending moment along the ship length, is examined. Two numerical examples are considered for this purpose: a box-shaped vessel and an oil tanker. For the tanker, the distribution of shear force and bending moment along the ship length, for one loading condition, is given before and after being corrected for ship deflection.

Apart from the structural strength consideration, the deflection curve of a ship may also have a significant effect on the load carrying capacity of large ships (4). The load-line marks for a ship in a sagging condition touches the still water surface only at the midship region and not at the ends. The lost buoyancy is in fact equivalent to the reduction in the load carrying capacity of the ship. This reduction in deadweight may reach, in some cases, over 1000 tons.

No attempt is made here to investigate the effect of hull deflection on the calculation of hydrostatic, hydrodynamic characteristics or on ship performance and ship operation. Problems regarding shaft alignment and deflection of engine room double bottom (5) is of local nature and is outside the scope of this paper. The effect of hull flexibility on the dynamic response of ships, with particular reference to slamming has been studied in detail elsewhere (6). Whipping stresses resulting from hull flexibility has been examined in reference (7). The effect on transverse strength of soil tankers of longitudinal vertical deflections of side shell and longitudinal bulkheads has been studied in reference (8).

Deflection Curve of a Free-Free Beam

The general deflection theory of beams is given in detail in several text books (9). Only a brief summary of this theory, as applied to the case of a floating free-free beam of variable cross-section, is given here :

The total deflection curve of a floating free-free beam, of varible cross-section, under the action of any aribtrary loading system is composed of two parts, bending deflection and shear deflection.

The bending deflection is calculated from the following general differential equation :

$$\frac{d^2}{d x^2} \left(E I_x \cdot \frac{d^2 w}{dx^2} \right) = q_x \qquad (1)$$

The shear deflection is calculated from the following equation :

$$w_s = \int_0^x \frac{\lambda F}{GA} \, dx \qquad (2)$$

where $q_x = f(x) - p(x)$, see fig. (1)

$f(x)$ = downward forces

$p(x)$ = upward supporting forces

λ = a constant depending on the geometry of the cross-section and is given by :

$$\lambda = \frac{1}{AF^2} \int_0^A \tau^2 dA$$

The curvature of the elastic line due to shear action is determined from equation (2) as follows :

$$\left(\frac{dw^2}{dx^2}\right)_s = F \frac{d\alpha}{dx} + \alpha\, q_x \qquad (3)$$

where : $\alpha = \lambda / AG$

For ship type structures, although the hull girder is of variable cross-section, the variation in A and λ may not be very significant and therefore equation (3) reduces to :

$$\left(\frac{d^2w}{dx^2}\right)_s \cong \alpha\, q_x \qquad (4)$$

The total curvature of the elastic line at any position x along the ship length is therefore given by :

$$\left(\frac{d^2w}{dx^2}\right)_t = \left(\frac{d^2w}{dx^2}\right)_b + \left(\frac{d^2w}{dx^2}\right)_s \qquad (5)$$

where $\left(\frac{d^2w}{dx^2}\right)_b$ and $\left(\frac{d^2w}{dx^2}\right)_s$ are obtained from equations (1) and (4) respectively. Substituting for their values in equation (5) we get :

$$\left(\frac{d^2w}{dx^2}\right)_t = \frac{M'_x}{E\,I_x} + F_o \cdot x + M_o \qquad (6)$$

where : M'_x = bending moment corrected for shear effect

$$= M_x + \alpha\, E\, I_x\, q_x \qquad (7)$$

$$M_x = \int_o^x \int_o^x q_x \, dx^2 \qquad (8)$$

F_o and M_o are arbitrary constants and could be determined from the end conditions.

For ship type structures, the end conditions are :

at $x = 0$ and $x = L$,

$$\left(\frac{d^2 w}{d x^2}\right)_t = \left(\frac{d^3 w}{d x^3}\right)_t = 0$$

Substituting these conditions in equation (6), we get:

$$M_o = F_o = 0$$

Hence, the curvature of the elastic line is given by:

$$\left(\frac{d^2 w}{dx^2}\right)_t = \frac{M'x}{EIx} \qquad (9)$$

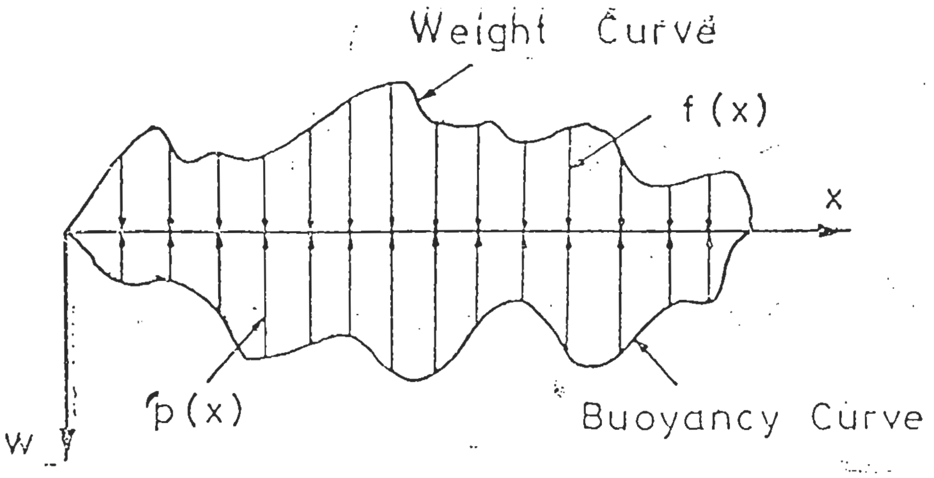
From equation (9), the equation to the elastic line is given by :

$$(w_t)_x = \int_0^x \int_0^x \frac{M'_x}{EI_x} dx^2 + \theta_o \cdot x + w_o \qquad (10)$$

where θ_o and w_o are arbitrary constants dependent on the chosen reference line and the end conditions, see Fig. (2).

For a reference line passing through the two ends of the hull girder, at the still water surface, the two constants θ_o and w_o are determined from the following conditions :

$$(w_t)_o = (w_t)_L = 0$$



$$q_x = f(x) - p(x)$$

FIG. (1) LOAD DIAGRAM

The equation to the elastic line is therefore given by :

$$(w_t)_x = \frac{1}{E}\left[\int_0^x \int_0^x \frac{M'_x}{I_x} dx^2 - \frac{x}{L} \int_0^L \int_0^L \frac{M'_x}{I_x} dx^2 \right] \quad (11)$$

On the other hand, if the still water surface is assamed to be the reference plane, see Fig. (2), the two constants θ_o and w_o are determined from the following equilibrium conditions :

$$\text{i)} \quad \int_0^L (\Delta q)\, dx = o \qquad \text{(a)}$$

$$\text{ii)} \quad \int_0^L (\Delta q)\, x . dx = o \qquad \text{(b)}$$

where Δq = change in load due to hull girder deflection

$$= \gamma y_x (w_t)_x$$

y_x = breadth of the ship at the water-line and is assumed to be constant over the ship deflection range

Substituting $(w_t)_x$ from equation (10) into (a) and (b), we get ;

$$\int_0^L \gamma y_x \left[\frac{1}{E} \int_0^x \int_0^x \frac{M'_x}{I_x} dx^2 + \theta_o x + w_o \right] dx = o \quad (12)$$

$$\int_0^L \gamma y_x \left[\frac{1}{E} \int_0^x \int_0^x \frac{M'_x}{I_x} dx^2 + \theta_o x + w_o \right] . x . dx = o \quad (13)$$

Solving equations (12) and (13) for θ_o and w_o and then substituting in equation (10), the deflection curve of the elastic line of the hull girder could be determined with reference to the still water surface.

It should be realised that for ship type structures, these calculations can be easily carried out numerically, once the distribution of loading and stiffness along the ship length are known.

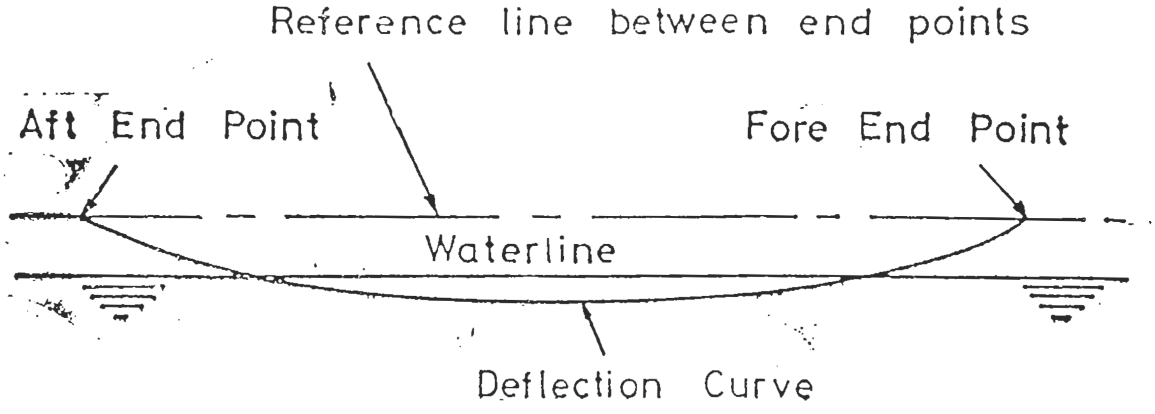


FIG (2) SHAPE OF DEFLECTION CURVE

Effect of flexibility of ship hull girder on the magnitude and distribution of shear force and bending moment along the ship length.

The complicated structural configuration of a ship could be approximately idealized by a box girder of variable cross-section. Full scale tests (10) have shown that the observed hull deflections check reasonably well with the theoretical values. The calculation of the "true" deflection curve of the idealized hull girder and the subsequent calculation of the shear force and bending moment distribution along the ship length could be determined by an iterative process. The first trial is based on an assumed distribution of weight and buoyancy along the ship length. The subsequent iterations modify the calculated distribution of the shear force and bending moment along the ship length as well as the shape of the deflection curve. These calculations are iterated a few times until the change in the magnitude of the highest value of bending moment or deflection is within acceptable pre-determined limits. The mathematical procedure is carried out as follows :

1. Change in load,

$$\Delta q_i = \gamma y_x . ({w_t})_x \qquad (14)$$

2. Change in shear forces

$$\Delta F_i = \int_0^x \Delta q_i dx \qquad (15)$$

3. Change in bending moment,

$$\Delta M_i = \int_0^x \int_0^x \Delta q_i \, dx^2 \qquad (16)$$

4. Change in deflection,

$$\Delta ({w_t})_{xi} = \int_0^x \int_0^x \frac{\Delta M_i}{EI_x} dx^2 + \theta_{oi} X + w_{oi} \qquad (17)$$

where : $i = 1, 2, 3, \ldots n$, and n is the number of iterations

and x identifies the position along the ship length.

The two constants θ_{oi} and w_{oi} are also determined using the two equilibrium conditions given by the pre-mentioned expressions (a) and (b).

The "correct" distribution of load, shear force and bending moment along the ship length, as well as the "correct" shape of the deflection curve are given by :

$$(q)_x = q_x + \sum_{i=1}^{n} \Delta q^*_{xi} \qquad (18)$$

$$(F)_x = F_x + \sum_{i=1}^{n} \Delta F^*_{xi} \qquad (19)$$

$$(M)_x = M_x + \sum_{i=1}^{n} \Delta M_{x_i} \qquad (20)$$

$$(w)_x = (w_t)_x + \sum_{i=1}^{n} \Delta (w_t)_{x_i} \qquad (21)$$

where $(q)_x$, $(F)_x$, $(M)_x$ and $(w)_x$ are the corrected load, shear force, bending moment and deflection at any position x along the ship length,

and $$F_x = \int_0^x q_x \, dx \qquad (22)$$

$$M_x = \int_0^x \int_0^x q_x \, d^2 x \qquad (23)$$

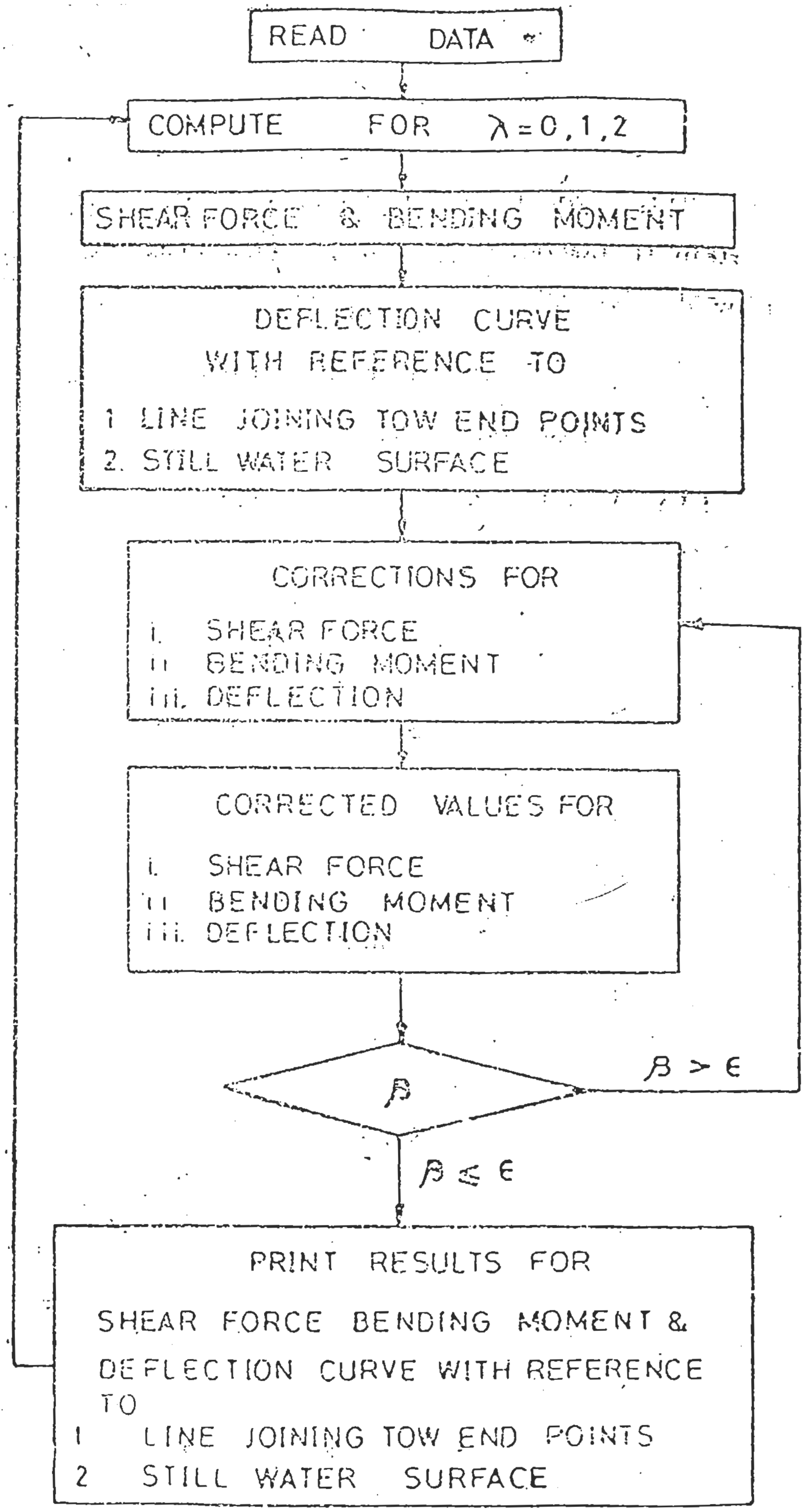


FIG.(3). FLOW CHART OF COMPUTER PROGRAM.

This method of calculation has been programmed in Fortran II for the University of Alexandria computer and a flow diagram is shown in Fig. (3).

The following two cases have been considered :

I) A box—shaped vessel, see Fig. (4).

II) An oil tanker having the following particulars :

$$LOA = 194.0 \text{ m}$$

$$LBP = 184.5 \text{ m}$$

$$B_m = 25.6 \text{ m}$$

$$D_m = 14.0 \text{ m}$$

However, if the shape of the deflection curve could be approximately represented by a second degree parabola of the form :

$$(w_t)_x = a x^2 + bx + c \tag{24}$$

the shear force and bending moment components resulting from hull girder deflection are given in detail in Appendix (1). For a uniform box girder floating in still water, the shear force and bending moment components at any position x along the girder length are approximately given by .

$$F_x = \gamma B \Delta \left\{ \frac{4 x^3}{3 L^2} - \frac{2 x^2}{L} + \frac{2 x}{3} \right\} \tag{25}$$

$$M_x = \gamma B \Delta \left\{ \frac{x^4}{3 L^2} - \frac{2 x^3}{3L} + \frac{x^2}{3} \right\} \tag{26}$$

The maximum value of the bending moment component amidships is given by :

$$M_{max} = \frac{\gamma B L^2 \Delta}{4800} \text{ t.m.} \qquad (27).$$

where L and B are the length and breadth of the box girder, in meters.

and, Δ is the maximum deflection amidships relative to a line joining the two ends of the idealized hull girder, in cm

It is evident from this analysis that the conventional term of the still water bending moment (SWBM) should be corrected to take into account the effect of hull deflection, i.e.

$$(SWBM)_C = SWBM + (SWBM)_F$$

$$= (1 + \eta) \cdot SWBM$$

where $(SWBM)_C$ = still water bending moment corrected for hull deflection

SWBM = still water bending moment for a rigid body i.e. uncorrected for hull deflection

$(SWBM)_F$ = the additional bending moment component resulting from hull flexibility

η = a factor depending on hull flexibility.

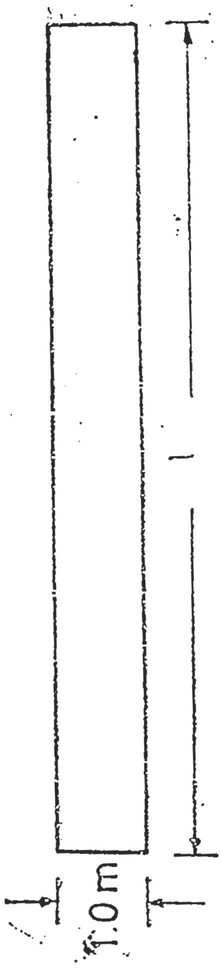
The effect of variation of buoyancy distribution along the ship length due to hull deflection has also been emphasised in reference (11). The difference between the calculated and measured stillwater stress, given in reference (11), may be partly due to η.

Loss of Deadweight due to Ship Deflection

The deflection shape of a ship in a sagging condition allows the load-line marks to touch the still water surface only in the midship region, see Fig. (5). As a result, the ship will not carry its full load. The reduction in deadweight is in fact equivalent to the loss of buoyancy, which is shown in Fig. (5)- For the oil tanker under consideration, this loss of buoyancy is of the order of 700 tons and for larger ships it could easily exceed 1000 tons. In order to avoid this loss of deadweight the ship could be built originally with a hogging deflection such that when loaded, the sagging deflection will approximately straighten the ship out. Alternatively, a correction should be given to the load-line marks amidships such that due account is taken of ship deflection. The former solution may impose some difficulties during ship construction and may increase the building cost, but an additional 1000 tons of cargo is worth considering. This is particularly important for ships normally running full loaded. On the other hand, the second solution require an International agreement on the scope and limitations of the free-board correction. This requires a separate investigation and is beyond the scope of this paper.

Results and Analysis of Calculations

Various conditions of loading and several distributions, along ship length, of shear area and sectional moment of intertia, for both cases of the box-shaped vessel and the oil tanker, are studied. It is assumed, in these calculations,

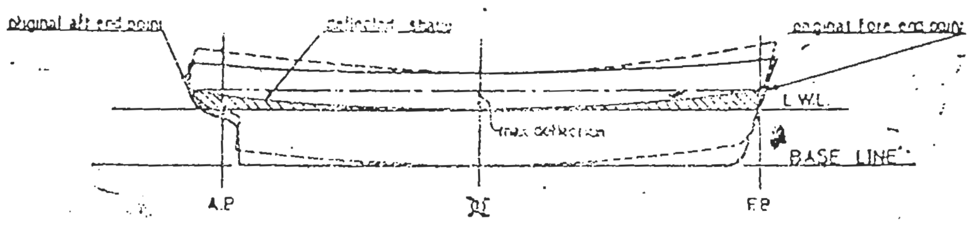


Shear area = 6000 mm^2

Section moment of inertia = 30 $cm^2 m^2$

l = 10, 20, 30 mt

FIG. (4) BOX SHAPED VESSEL



FIG(5). LOST BUOYANCY DUE TO SHIP DEFLECTION.

that $\lambda = 1.2$. The results of one particular loading condition for the oil tanker are given in Tables 1, 2.

The main conclusions drawn up from the results of these calculations are as follows :

1. The deflection curve is calculated with reference to a line joining the two ends of the idealized hull girder and also with reference to the still water surface, see Fig (2).

2. The ratio of shear deflection/bending deflection depends upon the raito of shear area / sectional moment of inertia and the length/depth ratio. For certain cases, the shear deflection may exceed 15% of the total deflection amidships. This result is in good agreement with the results given in reference (6).

3. Changing the length/depth ratio has a remarkable influence on the magnitude of maximum deflection. Long shallow ships may experience excessive deflections. Classification Societies control hull girder flexibility by setting an upper limit to the L/D ratio, (L/D = 16).

4. The factor K = 0.09 suggested in reference (6), to be used in the approximate deflection formula :

$$w_b = KML^2/EI \qquad (28)$$

is in good agreement with both results of the box girder and the oil tanker.

5. A small change in the shear area or the sectional moment of inertia does not have any significant effect on the magnitude of the maximum deflection.

6. For both the box shaped vessel and oil tanker, it is shown that the maximum shear force, maximum bending moment and maximum deflection, corrected for ship hull deflection may be less than the corresponding uncorrected values by about 3 %.

7. Hull girder deflection may change the fore and aft draughts by more than 2% and the midship draught by more than 1%

8. Deflection curves for the box-shaped vessel are shown in Fig. (6) for two loading cases and two different values of sectional moment of inertia. Fig. (7) shows the deflection curve for the oil tanker for two different values of the sectional moment of inertia.

9. An approximate estimate of the effect of hull deflection on the magnitude and distribution of the shear force and bending moment along a floating box-shaped vessel could be achieved by assuming the deflection curve to be a simple polynomial.

Concluding Remarks

The main conclusions drawn up from this investigation are summarised as follows :

1. Because of the increased knowledge on local, dynamic and wave induced loading on ships, Classification Societies may

raise their allowable stresses with a subsequent reduction in ship sectional modulus and moment of inertia. Also, when effective measures against corrosion are considered, Classification Societies may allow a reduction in corrosion allowance with a consequent reduction in ship sectional moment of inertia. This increased hull flexibility may be further increased by using high L/D ratio. Also, increasing strength/weight ratio by using high strength steels or reducing weight/strength ratio by using structural optimization procedures may cause an appreciable reduction in the stiffness of hull girder. Effective measures should therefore be taken to control all these factors so as not to impair hull girder stiffness.

2. The deflection of a hull girder changes the assumed distribution of load, shear force, bending moment as well as the mode of deformation. Excessive static deflection affects still water shear force and bending moment as well as ship response to sea waves, particularly slamming (6) and whipping (7).

3. Ship deflection may reduce the maximum values of still water shear force, bending moment and hull deflection by more than 3·0%.

4. In order to satisfy the deadweight requirements, the current load-line marks should be immersed by about 30% of the total deflection.

5. A built-in hogging deflection could obviate the loss in the load carrying capacity due to hull girder deflection. Alternatively, the draughts and loadline marks of a ship should be

corrected to take into account the deflection curve experienced in its normal loading condition.

6. Increased ship hull girder deflections may impose limitations on the use of high strength steels as well as on the degree of optimization of the steel weight in ship structures.

7. Excessive hull girder deflections may increase the operational problems resulting from the sinkage and trim associated with ships passing through shallow water zones.

From the above concluding remarks, it should be realised that using high strength steels, structural optimisation limitations on ship dimensions, reduction in corrosion allowance ... etc., should not be on the expence of excessive hull girder flexibility.

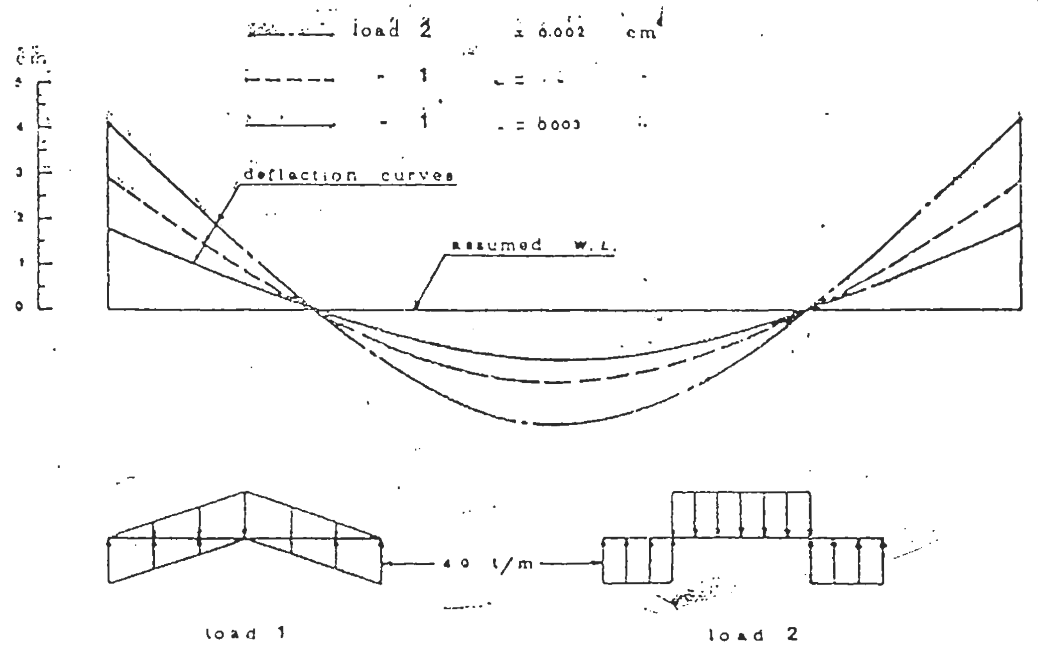
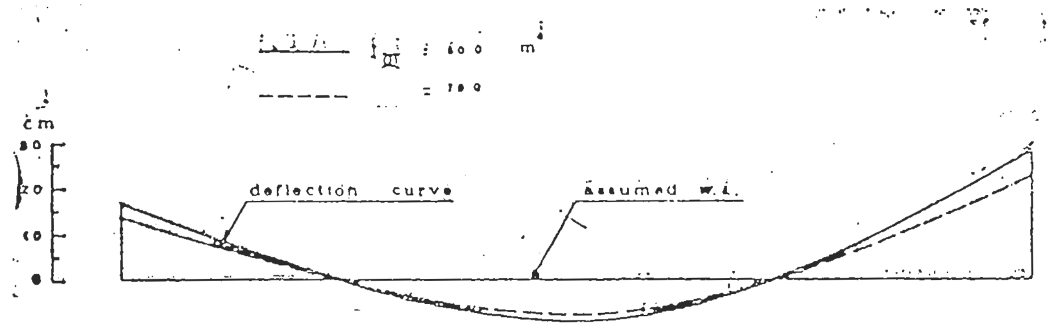


FIG.(8) DEFLECTION CURVE OF BOX-GIRDER



I_{III} : sectional moment of inertia amidships

FIG.(7) DEFLECTION CURVE OF THE OIL TANKER

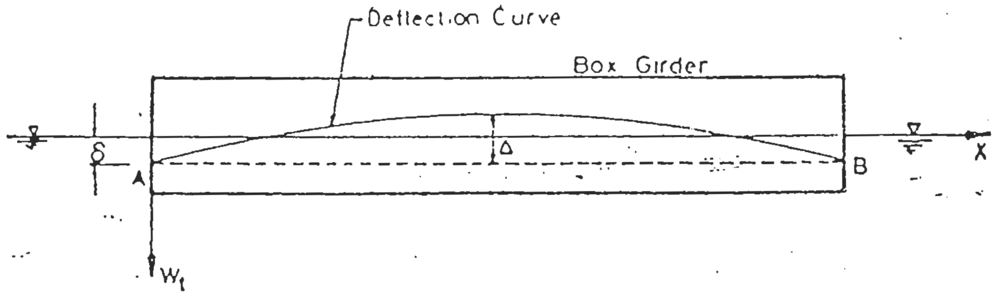


FIG.(8). ASSUMED DEFLECTION CURVE.

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List of Notation

A = Shear area

B = breadth at waterline

E = modulus of elasticity

F_o = constant depending on the refrence line

F_x = shear force at a distance x

G = modulus of rigidity

I_x = second moment of area of the longitudinal material for a floating free-free beam, or ship section, at a distance x

L = ship length

M_x = bending moment at a distance x

M_x' = bending moment corrected for shear action

M_o = constant depending on the reference line

q_x = load at any position x along the ship length (or a floating free-free beam)

= $(\text{weight})_x - (\text{buoyancy})_x$

x = distance along the ship length from the aft end

y_x = breadth of the ship at the water-line and at a distance x from the origin

w_s = shear deflection

w_b = bending deflection

w_o = a constant of integration

w_t = total deflection ($w_t = w_s + w_b$)

α = a factor associated with shear stiffness, ($\alpha = \lambda/AG$)

β = computed difference for either delfection or bending moment during the iteration process

γ = density of water

θ_o = a constant of integration

λ = a constant depending on the geometry of the cross-section

τ = shear stress

ϵ = a pre-determined value representing the acceptable margin to be used in the iteration process

Δ = maximum deflection amidships relative to a line joining the two ends of the idealized hull girder.

Table 1.

Shear Force and Bending Moment Distribution

STN	Shear Force (tons)		Bending Moment (t.m)	
	corrected	uncorrected	corrected	uncorrected
1	0.00	0 00	0.00	0 00
2	−32.75	−47.36	− 2404 3	− 2343.6
3	294.00	−327.64	− 3448.3	−3170.6
4	− 1307.55	−1358.63	− 1392.0	2055.9
5	− 2163.54	− 2226.69	14859.8	10047.2
6	−2691.39	−2759.34	34714 9	36504.4
7	− 2864.92	−2929.88	57809.3	60210.4
8	−2822.20	−2877.10	81511.3	84464.9
9	− 2481.34	− 2520.49	103448 3	106836.3
10	−1856.25	−1875.79	120934.2	124594.6
11	− 1013.37	− 1011.62	131653.2	135398.4
12	−33 67	−10.81	133969 9	137605.4
13	863.92	906.39	127631 8	130970.8
14	1595.46	1654.09	113783.6	116662.2
15	2090.85	2159.84	94280.4	96577.4
16	2241.67	2313.19	71800.9	73457.4
17	2338.08	2402.82	48185.2	49222.7
18	1741.68	1790.63	26880.1	27403.3
19	1039.29	1067.01	11569.9	11750.6
20	197.60	206 09	3385.9	3411.8
21	0.00	0.00	0,0	0.0

− ve downward shear force and hogging moment

+ ve upward shear force and sagging moment

Table 2

Deflection Curve

STN,	Deflection Curve (mm)			
	with reference to W.L.		with reference to end points	
	Corrected	Uncorrected	Corrected	Uncorrected
1	− 181.6	− 161.3	0.0	0.0
2	—146.0	—127.1	38.9	40.3
3	− 110.1	− 92.6	78.0	80.8
4	—74.0	—57.9	117.4	121.5
5	—38.3	− 23.6	156.5	161.9
6	− 3.8	9,3	194 2	200.8
7	27.7	39.1	229.0	236.7
8	54.5	64.0	.59.1	267.6
9	74.7	82.0	282.6	291.6
10	86·4	91.3	297.6	307.0
11	88.5	90.6	302.9	312.3
12	85.0	84.3	302.8	312.0
13	76.0	72.1	297.0	306.0
14	56.6	49.4	281.0	289.3
15	28.1	17.3	255.7	263.2
16	− 8.1	—22.7	222.8	229.3
17	50.2	− 68.6	184.0	189.4
18	—96.3	—118.8	141.1	145.3
19	- 145.2	− 171.7	95.6	98.4
20	−195.8	−226.4	48.3	49.7
21	−247.4	−282.2	0.0	0.0

(— ve) above water surface

(+ ve) below water surface

APPENDIX I

Calculation of the shear force and bending moment distribution for an assumed shape of the deflection curve

Assuming that the deflection curve is a second degree parabola given by :

$$(w_t)_x = ax^2 + bx + c \qquad \text{(A1)}$$

The constants a, b and c are determined from the following conditions, see Fig. (8).

$$\text{at } x = 0 \qquad w_t = \delta \qquad \text{(i)}$$

$$\text{at } x = \frac{L}{2} \qquad w_t = -(\Delta - \delta) \qquad \text{(ii)}$$

$$w'_t = 0 \qquad \text{(iii)}$$

where δ = end ordinate of the deflection curve relative to the still water surface

Δ = maximum ordinate (assumed amidships) relative to the chord A B.

Substituting conditions (i), (ii) and (iii) into equation (A1), we get :

$$a = \frac{4\Delta}{L^2}, \quad b = -\frac{4\Delta}{L}, \quad c = \delta$$

Hence, the equation to the deflection curve, see Fig (8), is given by :

$$(w_t)_x = 4\Delta \left[\left(\frac{x}{L}\right)^2 - \left(\frac{x}{L}\right) \right] + \delta \qquad \text{(A2)}$$

The load intensity per unit length is given by :

$$q_x = Y_x \cdot (w_t)_x \cdot \gamma$$

$$= \gamma Y_x \left\{ 4 \Delta \left[\left(\frac{x}{L}\right)^2 - \frac{x}{L} \right] + \delta \right\} \qquad (A3)$$

where : γ = water density

Y_x = width of waterplane at a distance x from the origin.

$(w_t)_x$ = deflection ordinate at a distance x.

The shear force and bending moment at any distance x are given by :

$$F_x = \int_0^x q_x \, dx$$

$$= \gamma \int_0^x Y_x \left\{ 4 \Delta \left[\left(\frac{x}{L}\right)^2 - \frac{x}{L} \right] + \delta \right\} dx + C_1 \qquad (A4)$$

$$M_x = \int_0^x F_x \, dx = \int_0^x \int_0^x q_x \, dx^2$$

$$= \gamma \int_0^x \int_0^x Y_x \left\{ 4 \Delta \left[\left(\frac{x}{L}\right)^2 - \frac{x}{L} \right] + \delta \right\} dx + C_1 x + C_2 \qquad (A5)$$

The constants C_1 and C_2 are determined from the end conditions :

at $x = 0$ $F_x = M_x = 0$

For a uniform box girder floating in still water, Y_x becomes invariable and equals the breadth B. Hence, equations (A4) and (A5) become, after substituting conditions (iv) :

$$F_x = \gamma B \left\{ 4 \Delta \left[\frac{x^3}{3 L^2} - \frac{x^2}{2 L} \right] + \delta x \right\} \qquad (A6)$$

$$M_x = \gamma B \left\{ 4 \Delta \left[\frac{x^4}{12 L^2} - \frac{x^3}{6 L} \right] + \delta \frac{x^2}{2} \right\} \qquad (A7)$$

The relationship between δ and Δ is obtained by satisfying the condition :

$$F_x = 0 \quad \text{at} \quad x = L$$

Hence $\delta = \frac{2}{3} \Delta$

Equations (A6) and (A7) are reduced to :

$$F_x = \gamma B \Delta \left\{ \frac{4 x^3}{3 L^2} - \frac{2 x^2}{L} + \frac{2 x}{3} \right\} \qquad (A8)$$

$$M_x = \gamma B \Delta \left\{ \frac{x^4}{3L^2} - \frac{2 x^3}{3 L} + \frac{x^2}{3} \right\} \qquad (A9)$$

Therefore, given the maximum deflection amidships i.e. Δ the distribution of shear force and bending moment along the length of a floating uniform box girder are given by equations (A8) and (A9).

The maximum bending moment occurs at $x = \frac{L}{2}$.

Hence, $M_{max} = \frac{\gamma BL^2 \Delta}{4800}$ t.m.

where B, L are in meters and Δ is in cm.

For the box girder under consideration i.e. L = 15 m, B = 2.0 m, $\gamma = 1.0$

$$M_{max} = \frac{3}{32} \Delta \text{ t.m.}$$