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THE COST OF IRRATIONALITY IN SHIP STRUCTURAL DESIGN

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ABSTRACT

The main factors affecting the rationalization of ship structural design are analysed. Particular emphasis is placed on those factors affecting hull steel weight. The loss of income resulting from undue increase in hull steel weight, deficient hull girder stiffness, poor design of local structural connections and complex constructional arrangements is examined and evaluated. It is shown that irrational design of ship's structure may have adverse economical consequences to both shipbuilder and shipowner.

1. INTRODUCTION

The structural design of a ship affects her operation, safety and economical efficiency. The latter is generally influenced by hull steel weight, hull girder stiffness, design of structural connections and the complexity of constructional arrangements. Much work has, therefore, been done to optimize and improve the structural reliability of ship hull girder and its structural components. The optimization of ship hull girder is generally devoted to the minimization of hull steel weight. However, the impact of these rationalization processes on the total economy of transportation has not been fully quantified.

In this paper, the cost of irrationality in ship structural design is investigated and approximate methods for its evaluation is given. Although the emphsis has been placed only on steel ships, similar results could be obtained for other shipbuilding materials, such as G.R.P., concrete, ferrocement,etc.

2. CONSEQUENCES OF IRRATIONAL DESIGN

In order to evaluate the cost of irrationality in ship structural design, it is essential first to recognise the consequences of irrationality in the structural design and then to identify the main parameters affecting these consequences. The latter could be divided into:

- increased hull steel weight,
- increased frequency of structural failures,
- reduced stiffness of hull girder,
- increased building time and cost.

These items affect both initial and running costs of a ship. Therefore, the rationalization process should aim at:

i- reducing hull steel weight,
ii- improving design of hull girder and its structural components,
iii- ensuring adequate hull girder stiffness,
iv- adopting the philosophy of design for production.

In the following analysis, the main factors affecting these desirable objectives are examined.

2.1 Hull Steel Weight

Hull weight depends mainly on main ship dimensions, general arrangement,(number of holds, decks,etc.), distribution of steel over ship section and along her length, geometrical configuration and scantlings of stiffening members, design criteria, corrosion allowance,etc. Reducing hull steel weight could be achieved either by increasing strength/weight ratio, using high strength steels, or by reducing weight/strength ratio, by improving the distribution of steel over ship hull girder. In the majority of cases, however, both approaches are commonly used. In the following analysis, the main factors affecting hull steel weight are examined.

a. Main Ship Dimensions

Significant weight savings could be achieved by using optimum ship dimensions. This is confirmed by the reduction of about 600 tons of steel in a 47 kDWT oil tanker of the "pudgy type" by optimizing ship dimensions only [1]. Ship length is the most effective dimension and if unnecessarily increased, it may produce undue increase in hull steel weight, building costs and operational expenses.

Fisher [2] has studied the effect of incremental variation of main ship design parameters on hull steel weight, machinery weight, among several other items. It is shown that increasing the length of a 253 kDWT oil tanker by 1% increases steel weight by 1.22%. Ship length also affects the quality of steel used. Higher grades of steel or high strength steels may have to be used in certain areas if ship length exceeds certain limits. These types of steel are in general more expensive than ordinary mild steel.

Ship breadth, depth and draught have direct influences on local loading. Undue increase in these dimensions may require corresponding increases in strength, scantlings and weight of primary and secondary transverse stiffening members.

Apart from their direct effects on hull steel weight, ship dimensions and proportions also affect the initial and operational costs of a ship. Length / breadth ratio has a direct effect on operational costs by virtue of its effect on wave-making resistance. Length/depth ratio affects hull girder stiffness. Ship draught may impose limitations on the number of ports of call and the passage through canals, etc.

b. Distribution of Steel

Inefficient distribution of steel along ship length and over her breadth and depth may cause high stresses to be developed in certain areas, reduce hull girder stiffness and generally may increase hull weight. The improper distribution of steel between side shell and longitudinal bulkheads, in oil tankers, may cause high shear stresses to be developed in these members, may impose additional loading on transverse members by virtue of the difference in shear deflections or may lead to increased hull steel weight [3]. It is shown that a saving of up to 15% of the longitudinal material could be achieved by rationalizing the distribution of material carrying shear loading, as shown in table (1). The terms used in the table are shown in fig.(1).

Table (1);Effect of Material Distribution

t_C/t_S	1.0	
x	0.2	0.3
t_L/t_S	0.97	1.5
$(t_C + 2t_L + 2t_S)/t_S$	4.94	6.0

For other types of ships, the irrational choice of frame spacing, longitudinal spacing, number of girders, number of transverse bulkheads, etc. may either lead to increased stresses in certain areas or may cause a significant increase in hull steel weight.

c. Geometry and Scantlings of Stiffeners

Stiffening members are either standard rolled sections or fabricated sections. The structural efficiency of these sections are generally affected by : section configuration, presence or lack of symmetry and scantlings, and in general it could be measured by the following non-dimensional quantity [4] :

$$\alpha = Z / \sqrt{A^3}$$

where: Z = section modulus,
A = sectional area,
α = axial unit section modulus.

The structural efficiency increases with α. For a solid square section, α = 0.167 and for an I-section, α = 1.0 - 1.5.

It should be noted that α is not the sole parameter affecting the choice of section configuration. Instability, yielding, fatigue, fabrication, etc. must also be taken into consideration.

The effect of lack of symmetry on the structural efficiency of a member is generally well recognised, particularly for curved regions [5] . Fig.(2) shows the effect of symmetry of section on the stress distribution over the face plate.

The effect on structural efficiency of scantlings of fabricated asymmetrical sections could be indicated by the presence of high stresses in broad thin face plates and lower stresses in narrow thick ones [5], as shown in fig.(3). For fabricated symmetrical sections, the irrational selection of scantlings may lead to a 30% increase over the optimum weight [6]. For standard rolled sections, the irrational selection of scantlings may lead to a 20% increase in their weight, as shown in table (2) for a random sample of an angle section obtained from a Lloyds Register of Shipping publication.

Table (2) ; Effect of Scantlings

Section, mm	Modulus/Area, cm^3/cm^2
a) 70x70x10.5 90x60x8	58.8/13.7 59.5/11.4
b) 130x90x13 150x90x10	191.5/27.05 190/23.2
c) 200x100x13.5 250x90x10	402/38.92 402/33.2

Apart from structural deficiencies, the irrational selection of geometry and scantlings of rolled and fabricated sections may also have an adverse effect on the cargo carrying capacity and tonnage measurements.

d. Corrosion Allowance

Classification societies approve valid methods of hull protection against corrosion and therefore may accept a reduction in cossosion allowance, which may slightly improve the cargo carrying capacity.

e. Design Criteria

Design criteria affect both structural safety and hull weight. Overdesigned ship hull girder may incur initial and operational cost penalties. Underdesigned hulls also have adverse economical effect

2.2 Design of Structural Connections

Major failures of hull girder are rather scarce in comparison with local failures of structural connections. These local failures may result from fatigue, high stress concentration, instability, poor workmanship, poor design,etc. In the majority of cases, poor design represent the main cause of these failures [7]. Fig (4) illustrates some structural connections commonly used in ship construction. In connection "b", the addition of a small bracket on the other side of the transverse bulkhead suppresses the peak stresses induced in this connection. The toes of the bracket shown in "c" introduce hard spots. Increasing the flexibility of these toes, as shown in "d", improves the stress distribution and reduces the frequency of failure of this connection. Using symmetrical face plate, as shown in "f", improves significantly the stress distribution over the section [5]. The direct connection between the longitudinal and transverse member shown in "h" reduces stress concentration and crack initiation. The addition of a small bracket on the other side of the vertical stiffener, as shown in "j", has a marked effect in suppressing the high stresses induced in this connection. Under dynamic loading, a further improvement of this connection could be achieved by increasing the flexibility of the inner lower part of the vertical stiffener.

It is evident from these analyses that connections b,d,f,h and j are more efficient and reliable than connections a,c,e,g, and i.

2.3 Hull Girder Stiffness

Hull girder stiffness may be adversely affected by the widespread use of high strength steels, increased length/depth ratio, reduced corrosion allowance,etc. [8]. Deficient hull girder stiffness may create several operational problems, among them docking [9], shaft alignment [10],[11] , reduction in DWT carrying capacity [12], etc. Therefore, strength and stiffness of ship hull girder should be examined simultaneously.

2.4 Design For Production

It is evident that reducing building time and cost of a ship will have direct economical advantages. These reductions could be achieved by the widespread use of mechanisation and automation, production planning, simplification of constructional arrangements, etc. The importance of the latter approach could be illustrated by fig.(5). In construction (A), frame bending is required in (a) while (b) requires a bracket connection. As frame bending is more costly and time consuming than welding, connection (b) is more economical to fabricate and assemble than connection (a). In construction (B), automatic welding could be used simultaneously for both sides of (d) [13], and successively for (c). In construction (C), arrangement (e) requires one forming operation only whereas (f) requires cutting ,edge preparation and welding. It is evident, therefore, that arrangements b,d and e are cheaper to fabricate than arrangements a, c and f.

Edge preparation for welding affects the amount of weld metal deposited, number of welding runs, weld deficiencies, residual stresses, etc. In automatic welding of thick plates, significant savings of weld metal and assembly times and cost could be achieved by using proper edge preparation [14].

3. EVALUATION OF THE COST OF IRRATIONALITY

The economical consequences of irrationality in ship structural design could be evaluated in terms of the following main parameters [15]:

3.1 Effect Of Undue Increase In Weight

a. Constant Ship Displacement

For constant ship displacement, any increase in hull steel weight will reduce her cargo carrying capacity. Therefore, the annual loss of income to shipowners results from both reduction in cargo carrying capacity and increase in cost of steel hull. The present worth of this loss in income may be evaluated as follows :

$$P_1 = c.w.\eta$$

where: $\eta = 1.0 + (UPWF)^{i}_{N}.\frac{n.f}{c} - p/c$ $

i = rate of interest,
c = cost of steel/ton , $
n = number of return trips/year,
N = ship's life in years,
w = unnecessary increase in hull steel weight,
$(UPWF)^{i}_{N}$ = uniform present worth factor[16]
p = penalty/ton DWT, $

Therefore, shipowners should try to minimise P_1 by selecting an appropriate value for p. However, if the penalty term does not exist, the variation of η with n.f/c and 'i' is shown in fig.(6).

Similarly, the present worth of the loss of income for shipbuilders may be evaluated as follows :

$$P_1' = w(p + c')$$

where: c'= shipyard cost of steel/ton, \$

b. Constant Deadweight

When a specified value of the DWT is required, any increase in hull steel weight requires a corresponding increase in ship displacement. The latter is given by:

$$\Delta = W_H + W_M + DWT$$

where: $W_H = a\Delta$ = hull steel weight,
$W_M = bP_s$ = weight of main engines,
P_s = shaft power, ($P_s \propto V^3 . \Delta^{2/3}$),
a and b = coefficients,
V = ship speed.

Therefore, if the unnecessary increase in hull steel weight is 'w', the corresponding increase in ship displacement is given by :

$$\delta\Delta = w / \beta$$

where: $\beta = 1.0 - a - 2W_M/3\Delta$

The magnitude of β depends on ship type ; for oil tankers, $\beta \leqq 0.75$ and $\delta\Delta \cong 1.33w$. For trawlers, $\beta \leqq 0.5$ and $\delta\Delta \leqq 2w$.

It is evident that the required increase in ship displacement could be provided by increasing ship dimensions, as the block coefficient is generally related to ship speed. Therefore, the penalties of unnecessary increase in hull steel weight, at a specified value of DWT, are the same as the penalties of increasing ship dimensions.

3.2 Effect Of Frequent Structural Failure

Frequent failures of structural connections not only increase repair costs but they also reduce ship earning time. The present worth of the loss of income resulting from these two effects may be evaluated, over ship's service life, as follows :

$$P_2 = \sum_{j=1}^{N} (SPWF)^i_j . (C_R + n.e)$$

where: (SPWF) = series present worth factor,
n = number of days lost for repair work/year,
e = earning capacity/day, \$
C_R = total cost of repair work/year, \$.

It is evident that small cracks that may not immediately threaten the safety of a ship may subsequently have deleterious effects on her economy.

3.3 Effect Of Deficient Hull Stiffness

For certain types of ships, such as oil tankers, the unnecessary increase in the flexibility of ship hull girder have an adverse effect on the cargo carrying capacity [12]. The cost of this deficiency in stiffness could be evaluated in terms of the present worth of the loss in income, as follows:

$$P_3 = (UPWF)^i_N . (w.n.f)$$

where: w = loss in cargo deadweight due to a sagging deflection δ and could be evaluated as follows:

$$w = \rho . A_w . \delta (1 - 0.24/C_w)$$

where: A_w = waterplane area,
C_w = waterplane area coefficient,
ρ_w = water density.

For an oil tanker of length 300 m, C_W = 0.85 and a sagging deflection of 300 mm, w may reach 2700 tons.

3.4 Effect Of Complexity Of Connections

The cost of fabrication of hull assemblies depends on several factors, among them steel weight, thicknesses of plating, suitability for mechanization, complexity of connections, etc. Therefore, any unnecessary increase in production time, weight of assembly or complexity of design may have adverse effects on fabrication costs, Q. These adverse economical effects may be evaluated by estimating the present worth of the unnecessary increase in building costs, P_4, as follows :

$$P_4 = \sum_{i=1}^{r} \delta Q_i$$

where: r = number of hull assemblies,
Q = unnecessary increase in building costs.

4. TOTAL COST OF IRRATIONALITY

The present worth of the total cost of irrationality in ship structural design, C_i may be evaluated as follows:

$$C_i = \sum_{r=1}^{4} P_r$$

It is evident, therefore, that the minimization of C_i represents a major ship design requirement. However, as there is no common factor among the different 'P' values, it would be necessary first to minimise hull steel weight and then check stiffness of hull girder, design of local details and the complexity of structural connections. However, this problem is beyond the scope of this paper.

5. CONCLUSIONS

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

a- In order to reduce the cost of irrationality in ship structural design, the rationalization process may be based on :
  i- minimization of hull steel weight without impairing hull girder stiffness and structural reliability. This could be achieved by using optimum ship dimensions, proper selection of geometry and scantlings of rolled and fabricated sections and improving the distribution of steel over ship hull girder.

ii- improving design of structural connections.
iii- adopting the philosophy of design for production.

b- All feasible measures should be taken by shipbuilders to rationalize the design process so as to reduce the adverse economical consequences of irrationality in ship structural design.

c- The cost of irrationality could be significantly reduced for ship owners by the proper selection of a design penalty.

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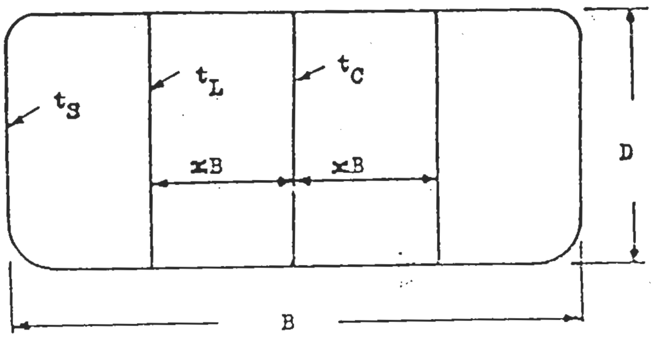

Fig.(1). Midship Section Configuration

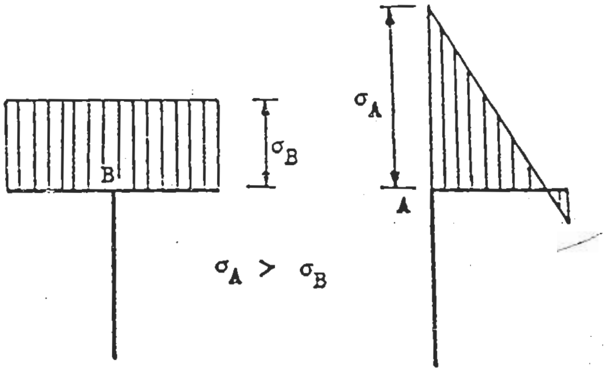

Fig.(2). Effect of Symmetry

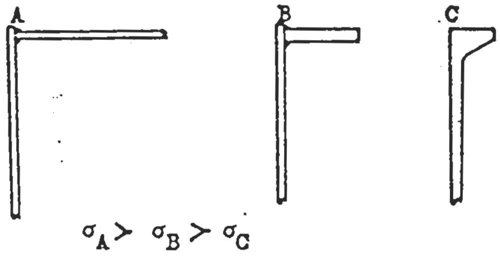

Fig.(3). Effect of Width of Face Plate

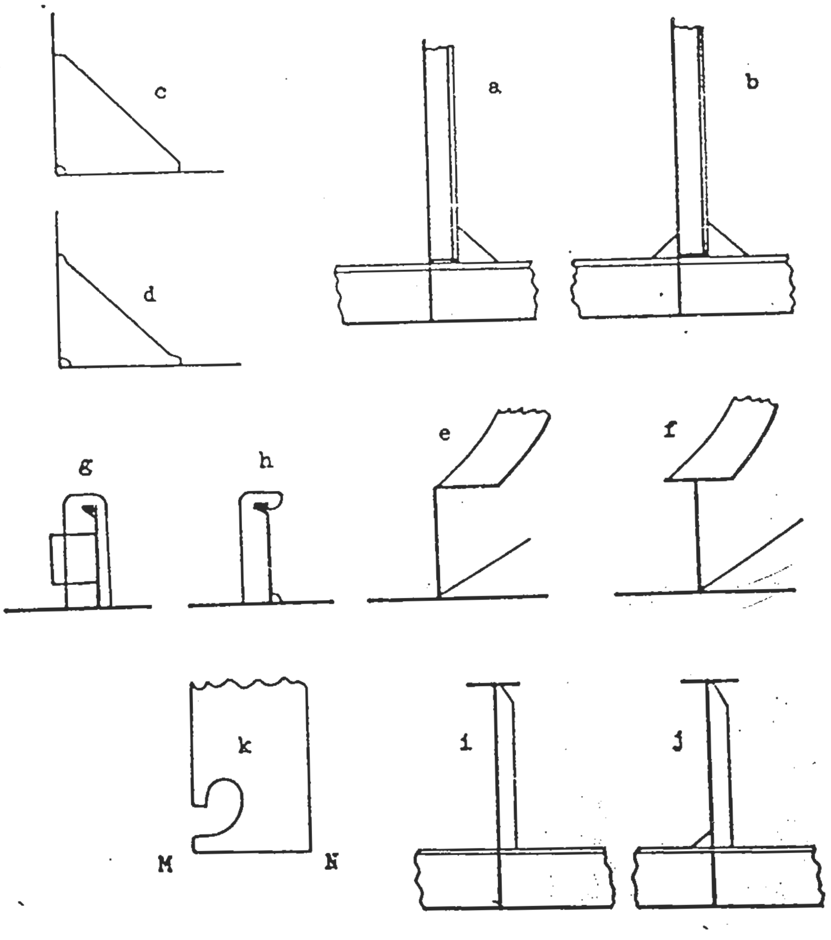

Fig.(4). SOME COMMONLY USED SHIP STRUCTURAL CONNECTIONS

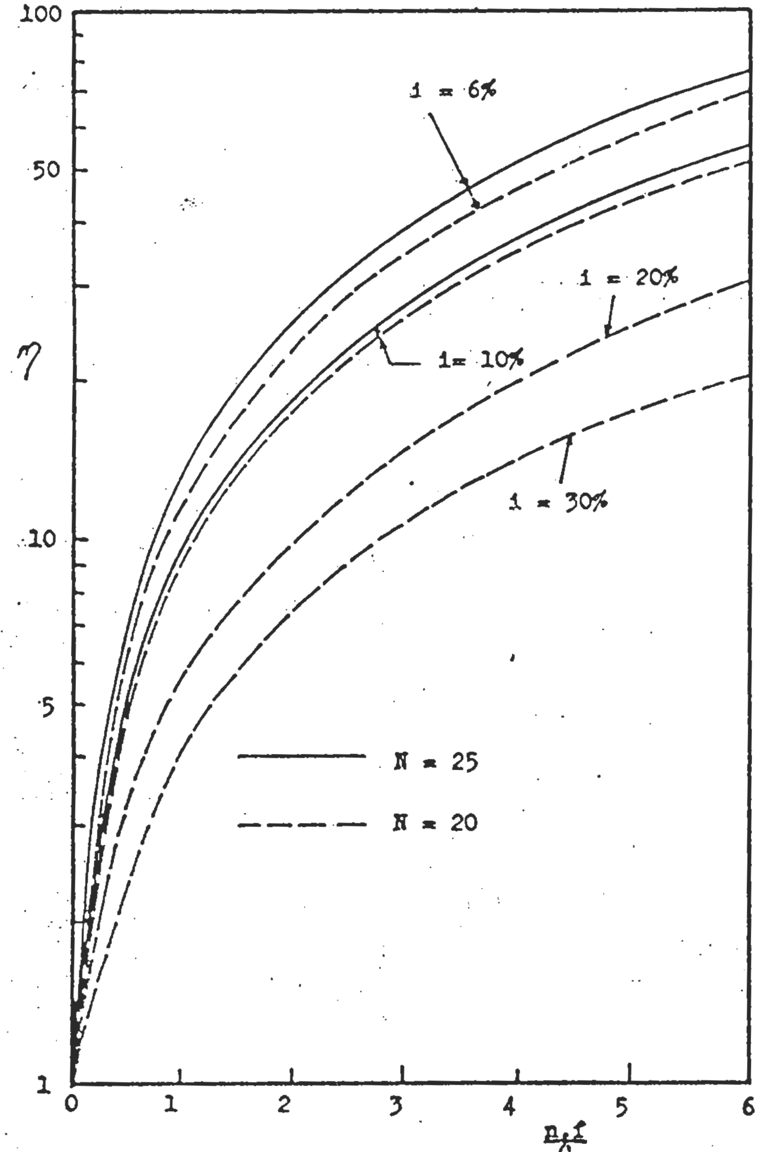

Fig.(6) Effect of $\frac{n.f}{C}$ and i on η

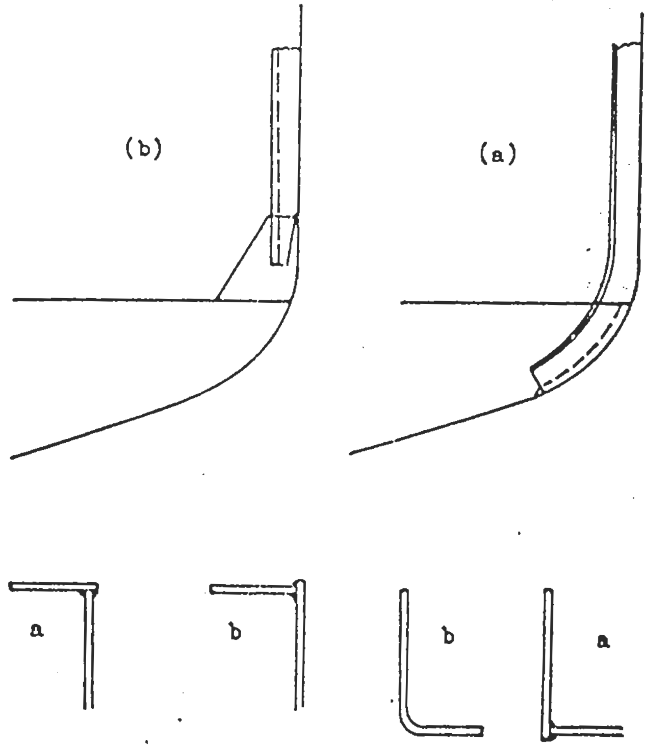

Fig.(5) Alternative Constructions