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2- "Optimizing Hull Steel Weight for Overall Economic Transportation", Marine Week, May 2, (UK-1975), Shama, M. A.,

3- "The Cost of Irrationality in Ship Structural Design", PRADS. Int. Conference on Practical Design in Shipbuilding, SNAJ, Tokyo Oct. (Japan-1977), Shama, M. A.,

4- "Computer Design of Ships", Bull. Collage of Engineering, Basra University, (Iraq-1977), Shama, M. A.,

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7- "ON the Economics of Safety Assurance" Dept. of Naval Architecture and Ocean Engineering, Glasgow University, (UK-1979) Shama, M. A.,

8- "CADSUCS, the Creative CASD for the Concept Design of Container Ships", AEJ, Dec. (Egypt-1995), Shama. M. A., Eliraki, A. M. Leheta, H. W. and Hafez, K. A.,

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ECONOMICAL CONSEQUENCES OF IRRATIONAL STRUCTURAL DESIGN OF SHIPS

By

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Summary

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 details and complex constructional arrangements is investigated and evaluated.

It is shown that irrational ship structural design may have adverse economical consequences to both shipbuilder and shipower. It is also shown that significant savings in hull steel weight could be achieved by proper selection of geometry and scantlings of rolled and fabricated sections and also by improving the distribution of steel among the primary structural members.

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INTRODUCTION:

Structural design of ships has a direct influence on their operation, safety and economical efficiency. Therefore, reducing hull steel weight, without affecting the standards of strength, stiffness and safety should represent a major ship design requirement(1).

This paper examines some of the factors affecting ship economical **effeciency**. Special attention is paid to the distribution of steel over a ship section, selection of geometry and scantlings of rolled and fabricated sections, design of local structural details and to the simplification of constructional arrangements. The main factors affecting hull steel weight are examined and numerical examples are given for the sake of illustration. The economical consequences resulting from irrational structural design are then analysed and approximate methods for their evaluation are given.

Consequences of Irrational Structural Design.

Irrational design of ship structures may result from:

a- Irrational selection of main ship dimensions

The main **dimensions** of a ship have direct influences on her inital and operational costs.

Ship length is the most effective dimension and should be kept as low as possible. Increasing ship length increases building costs as well as some operational expenses. Fisher(2) has studied the effect of incremental variation of main ship design parameters on hull steel weight, machinery weight, among other items. It is shown that increasing the length of a 253 KDWT oil tanker by 1% has the effects indicated in table (1).

TABLE (1)

Item	steel weight	construction costs	annual cargo capacity	annual fuel cost
% increase	1.22	0.81	0.98	0.68

Length/depth ratio has a direct influence on hull girder stiffness. Reducing hull stiffness creates additional operational problems, particularly for docking(3), and for oil tankers, the utilization of cargo carrying capacity is adversely affected(4).

Length/breadth ratio has a direct effect on wave-making resistance, thus affecting ship operational costs. Ship draught may impose some limitations on the number of ports of call and the passage through canals.

Main ship dimensions have a direct influence on hull steel weight, and therefore significant savings in steel weight could be achieved by using optimum ship dimensions (5).

Consequently, the selection of main ship dimensions should be based on the total economy of transportation and not on the individual requirments of strength, resistance, capacity......etc.

b- Improper Choice of Material

Although steel is the most commonly used material in shipbuilding, other materials are also used. Concrete, G.R.P., ferrocement,...etc. are the most widely used materials beside steel that may have potential future applications. The selection of the appropriate material should be based not only on technical requirements but also on economical considerations.

For shipbuilding steel, Classification Societies have divided it into five grades: A,B,C,D,and E. As these grades differ in prices, the use of higher grades should be limited to those areas specified by Classification Societies so as not to incur excessive initial cost penalties. The same argument applies also to the use of high tensile steel, which is more expensive than ordinary mild steel. Therefore, the use of high tensile steel should be controlled by economical considerations as well as by the requirements of instability, stiffness fatigue,...etc.

c- Inefficient Distribution of Material

Inefficient distribution of material along ship length and over her breadth and depth may cause high stresses to be developed in certain areas, reduce hull stiffness,...etc. and generally may increase hull steel weight. In oil tankers, the improper distribution of steel between side shell and longitudinal bulkheads may either cause high shear stresses to be developed in these members or may lead to increased hull steel weight(6).

The effect of longitudinal material distribution between side shell and longitudinal bulkheads on hull steel weight could be illustrated by table(2). The terms given in the table are shown in fig.(1).

TABLE (2)

t_C / t_S	1.0		1.4	
α	0.2	0.3	0.2	0.3
t_L/t_S	0.97	1.5	0.85	1.07
$(t_C+2t_L+2t_S)/ t_S$	4.94	6.0	5.1	5.54

The inefficient distribution of longitudinal material imposes additional loading on transverse members by virtue of the difference in shear deflections between side shell and longitudinal bulkheads (6). This additonal loading requires a corresponding increase in the scantlings of transverse members. Therefore, the irrational choice of t_C/t_S, t_L/t_S and α, see Fig.(1), may either cause high stresses to be developed in certain areas or may cause a significant increase in hull steel weight.

The irrational selection of frame, longitudinal and transverse spacing as well as the spacing between girders, transverse bulkheads,....etc. may also cause a significant increase in hull steel weight.

d- Irrational Selection of Geometry and Scantlings of Rolled and Fabricated Sections.

The improper selection of geometry and scantlings of rolled and fabricated sections may lead to higher weight/strength ratio and may also cause unfavourable stresses to be developed in these members. This could be easily illustrated by the higher structural efficiency of symmetrical sections in comparison with asymmetrical sections (7), particularly in curved regions, see fig.(2).

The effeciency of structural members could be evaluated by the following nondimensional quantity (8):

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

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

The higher the value of "w" the more efficient is the section. Table (3) gives numerical values for "w" for five different sections.

TABLE (3)

section	circle	square	ring	channel	I-section
w	0.14	0.167	0.73- 0.84	0.57- 1.35	1.02-1.51

From table (3), it is obvious that significant weight saving could be achieved by proper selection of section configuration. However, this table is given here only for the sake of illustration, as "w" is not the only parameter affecting the choice of section configuration. Instability, yielding, fatigue, fabrication,...etc. are also important parameters affecting the choice of section.

The improper selection of scantlings may be illustrated by the use of broad thin face plates for asymmetrical sections instead of narrow thick ones. The former scantlings create high stresses at the inner edge of the face plate (7), see fig.(3).

The irrational choice of scantlings could be also illustrated by the selection of a rolled angle section for a given section modulus, as shown in table (4). The figures given in table (4) represent a random sample and are obtained from reference (9).

From table (4), it is obvious that a significant increase in steel **weight** may result from irrational **selection of rolled sections.**

For fabricated symmetrical sections, the irrational choice of scantlings may increase the weight of member by 30% over the optimum weight (10).

It should be realized that the irrational selection of rolled and fabricated sections may also

TABLE (4)

scantlings, mm	section modulus, cm^3	section area, cm^2
a-70 X 70 X 10.5	58.8	13.7
b-90 X 60 X 8	59.5	11.4
a-130 X 90 X 13	191.5	27.05
b-150 X 90 X 10	190.0	23.2
a-200 X 90 X 12	343.0	33.6
b-225 X 90 X 10	343.0	30.7
a-200 X 100 X 13.5	402.0	38.92
b-250 X 90 X 10	402.0	33.20

affect the bale capacity of holds as well as the Gross and Net tonnages. However, the emphasis in this paper is placed only on weight rather than volume requirements.

e – Irrational Choice of Design Criteria.

The irrational choice of design criteria may produce either a heavier or a lighter structure than is actually required. The former incurs **initial** and operational cost penalties whereas the latter may have initial cost advantages and operational cost penalties due to probable failures and breakdowns. Therefore, the choice of design criteria should be based not only on realistic estimates of loading but also on proper assessment of structural capability (11). The latter depends on several factors, among them are the standards of strength established by Classification Societies. These standards **are** based on the estimation of the maximum values of bending moment, shear force,... etc., likely to occur over the service life of a ship. Since the estimated life of a ship varies between 20 and 30 years, depending on ship type , the standard of strength is based on a probability of occurance of 10^{-8} (11). This low value of probability might have been economically satisfactory in the past decade, where international trade and economy were relatively stable. Presently, the situation is different, and a fresh look at the standards of strength is necessary. These standards should be based on the total economy of transportation as they have a direct influence on hull steel weight as well as ship's service life.

f- Improper Hull Maintenance.

Classification Societies approve valid methods of hull protection against corrosion and therefore may accept a reduction in corrosion allowance. This reduction in hull steel weight may improve the earning capacity of the ship in addition to reducing her initial cost. Therefore, the initial as well as the running costs of the various methods of hull protection against corrosion should determine the most economic method to be used and at the same time should give the acceptable reduction in corrosion allowance. Any appreciable saving in hull maintence and any reduction in corrosion allowance will certainly improve the total economy of transportation. Therefore, the current corrosion allowance as well as the available methods of hull protection should be reviewed and examined in the light of the economic life of the ship and the total economy of transportation.

g- Poor Design of Local Structural Details.

Major failures of hull girder are rather scarce in comparison with local failures of structural members and connections. These local failures may result from fatigue,high stresses, instability, bad workmanship, poor design,...etc. In the majority of cases, poor design of local structural connections is responsible for most of the failures (12).

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 has a significant effect in reducing the high stresses developed in this connection.

The toes of the bracket shown in "c" introduce hard spots and therefore are responsible for crack initiation. Increasing the flexibility of these toes as shown in "d", improves the stress distribution and reduces the frequency of failure of this connection.

The symmetrical face plate shown in "f" is more efficient than the asymmetrical arrangement shown in "e" (7).

The direct connection between a longitudinal and the transverse member shown in "h" is certainly more efficient than the indirect connection using a lug, as shown in "g". Arrangement "g" promotes crack initiation.

In connection "i", very high stresses may be induced at the lower inner edge of the vertical stiffener. The high stresses induced in section MN are responsible for the frequent failures of this connection (12). The addition of a small bracket on the other side of the web, as shown in "j", has a marked effect in suppressing the high stresses developed in this connection. Under dynamic loading, a further improvement of this connection could be achieved by slotting the inner edge of the vertical stiffener at its lower end, as shown in "k". This design increases the flexibility of the inner lower part of the stiffener and therefore improves the stress distribution.

From the foregoing analysis, it is obvious that the frequency of failure of local structural connections depends mainly on the magnitude and distribution of stresses induced by static as well as dynamic loading. Therefore, improving the design of these local details not only improves stress distribution but will also reduce the frequency of local structural failures.

h- Improper selection of Edge Preparation for Welding.

In a welded **assembly**, the amount of weld metal deposited and the number of runs are both dependent on the type of edge preparation, plate thickness, type of welding machine,...etc.Weld **deficiencies** and residual stresses are also affected by the type of edge preparation, among several other factors. Therefore, improper selection of edge preparation, particularly for thick plates, may increase production time and costs, induce residual stresses, promote weld defects,...etc. In automatic welding of thick plates, significant savings in welding and assembly times and costs could be achieved by using proper edge preparation (13).

i- Inefficient Constructional Arrangements.

Reducing building time of a ship has direct economical advantages and could be achieved by the widespread use of mechanization and automation, increasing resources, optimizing the sequence of operations, working overtime and also by using simple constructional arrangements. Fig.(5) shows three different structural connections. Each connection has two alternative constructional arrangement. In connection "A", frame bending is required in arrangement "a" while arrangement "b" requires a bracket connection. As frame bending is more expensive and time consuming than welding, arrangement "b" is much cheaper to fabricate and assemble than arrangement "a".

In item "B", automatic welding could be used in arrangement "d" for both sides simultaneously (14). In arrangement "c", welding of both sides has to be carried out successively.

In item "C", arrangement "e" requires only one forming operation whereas arrangement "f" requires cutting, edge preparation and welding.

It is obvious that constructional arrangements b, d and e are more economical to produce than arrangements a, c and f. Consequently, significant savings in building time and cost could be achieved through design for production.

Economical Consequences of Irrational Structural Design.

From the foregoing analysis, it is evident that the main consequences of irrational structural design could be summarised as follows:

i. Increased hull steel weight,
ii. Inefficient constructional arrangements,
iii. Increased frequency of failure of local structural connections,
iv. Reduced hull girder stiffness.

These consequences have direct effects on the total economy of transportation, and could be separately evaluated as follows:

i. Effect of undue increase in hull steel weight

Let: w = unnecessary increase in hull steel weight,
C = cost of steel/ton, $
f = mean freight rate/ton of cargo/return trip, $,
n = number of return trips/year,
N = ship's life in years,
i = rate of interest.

Assuming that ship displacement is constant, then any increase in hull steel weight will be on the expense of cargo deadweight. Therefore, the loss of income, from the shipowner's point of view, could be evaluated as follows:

material cost of unnecessary steel = R_{s1} = $C.w$ \$

lost income/year due to the reduction in cargo carrying capacity = R_L = $w.n.f$ \$

Penalty paid by shipbuilder to shipowner due to deficient DWT = $R_p = p.w$ \$

where: p = penalty/ton of DWT \$

Hence, present worth of lost income = $P_1 = \eta\, .C.w.$ \$

where: $\eta = 1.0 + (UPWF)^i_N \cdot \frac{n.f}{C} - \frac{p}{C}$

$(UPWF)^i_N$ = uniform present worth factor based on N years and rate of interest i (15).

It is evident that a shipowner should try to make P_1 as low as possible. This could be achieved by reducing either w or η. The latter could be reduced by increasing the magnitude of the penalty p.

If the penalty term is not present, the variation of η with $\frac{n.f}{C}$ and i is as shown in fig.(6).

On the other hand, the loss of income, from the shipbuilder's point of view, could be evaluated as follows.

$$P_1' = R_p + R_{s2}$$

where: R_{s2} = shipyard cost of unnecessary fabricated steel.

Therefore, shipyards should aim at reducing both p and w.

Similarly, if the cargo DWT is assumed to be satisfied, any unnecessary increase in hull steel weight will require a corresponding increase in ship displacement. The increase in ship displacement depends mainly on ship type and could be evaluated as follows:

Let: Δ = ship displacement, ($\Delta = W_H + W_M + DWT$),

W_H = hull weight,

a = W_H / Δ ,

W_M = weight of main engines,

w_m = weight of main engines/power = $\frac{W_M}{HP}$,

A = Admiralty coefficient.

The required power to drive a ship at a speed V knots could be approximately calculated as follows:

$$\text{Power} = V^3 \cdot \Delta^{2/3} / A$$

$$\text{Thus. } W_M = w_m \cdot V^3 \cdot \Delta^{2/3} / A$$

Therefore, change in Δ due to an unnecessary increase in hull steel weight, w, is given by:

$$\delta \Delta = a . \delta\Delta + \frac{2}{3} . \frac{W_M}{\Delta} . \delta\Delta + w$$

i.e. $\delta\Delta = w/\beta$

Where: $\beta = 1 - a - \frac{2}{3} . \frac{W_M}{\Delta}$

For certain types of ships, such as trawlers, β may reach 0.5, giving $\delta\Delta \cong 2w$.

For oil tankers, $\beta \cong 0.75$, giving $\delta\Delta \cong 1.33\ w$

This increase in displacement is obtained by increasing ship dimensions, as C_B, (block coefficient), is controlled by ship speed. However, increasing ship dimensions leads to increased hull steel weight, power, fuel requirements, ...etc. Therefore, the penalties of unnecessary increase in hull steel weight, when the cargo DWT is statisfied, is the same as the penalties of increasing ship dimensions.

ii. Effect of inefficient constructional arrangements

The cost of fabrication of hull assemblies depends on several parameters, among them are steel weight, thicknesses of plating, complexity of local structural connections, suitability for mechanization ,...etc., and in general could be evaluated as follows:

$$C = a_o + a_1 .W + a_2 .T$$

where: a_i, $(i=0,1,2)$ = cost rates, which depend on the degree of skill of labours, types of resources used, degree of mechanization and planning,...etc. Their values vary from yard to yard and require a separate investigation for their evaluation,

C = cost of fabrication and assembly,
W = weight of assembly,
T = fabrication and assembly time.

Therefore, any unnecessary increase in production time, weight of assembly or complexity of design will be reflected directly on the fabrication and assembly costs C as follows:

$$\delta C = a1 \,.\, \delta W + a2 \,.\, \delta T$$

where: δW = unnecessary increase in steel weight,
δT = increase in fabrication and assembly times resulting from increased steel weight, complexity of construction, ...etc.

Therefore, the total increase in building cost is given by:

$$P_2 = \sum_{i=1}^{n} \delta C_i \quad , \quad n = \text{number of hull assemblies.}$$

The evaluation of P_2 for any specified case is beyond the scope of this paper.

iii. Effect of frequent structural failures.

Frequent failures of local structural connections increase repair costs and reduce ship earning time. The evaluation of these two effects could be carried out as follows (1):

$$P_3 = \sum_{j=1}^{N} (SPWF)_j^i \cdot R_{Fj}$$

where: P_3 = present worth of lost income over N years,

$SPWF$ = series present worth factor (15),

R_F = loss of income/year, ($R_F = n.e + C_R$),

n = number of days lost for repair work/year,

e = earning capacity/day \$,

C_R = total cost of repair work/year \$,

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

iv. Effect of Deficient Hull Stiffness

A ship hull girder having sufficient longitudinal strength does not necessarily have sufficient longitudinal stiffness. This condition may result from the widespread use of high strength steels, increased length/depth ratio, reduced corrosion allowance, using irrational design criteria,...etc. For certain types of ships, such as oil tankers, increasing hull flexibility has an adverse effect on the cargo carrying capacity (4). The loss of income in this case, could be evaluated as follows:

$$P_4 = (UPWF)^{i}_{N} \cdot R_D$$

where: P_4 = present worth of lost income over N years,

R_D = loss of income/year, ($R_D = w.n.f$)

w = loss in DWT due to a sagging deflection, and could be estimated as follows (4):

$$w = \rho . \delta . A_w \left(1 - \frac{0.24}{C_w}\right)$$

where: δ = sagging deflection amidships,

C_w = waterplane area coefficient,

A_w = waterplane area,

ρ = density of sea water.

Concluding Remarks.

From the foregoing analyses, it is evident that:

i. The rationalization of ship structural design could be achieved by reducing hull steel weight, improving design of local structural details and adopting the concept of design for production.

ii. Hull steel weight optimization could be achieved by rationalizing the selection process of ship dimensions, geometry and scantlings of rolled and fabricated sections and also by improving the distribution of material along ship length and over her breadth and depth. However, the optimized hull steel weight should not have adverse effects on hull stiffness and its structural reliability.

iii. One of the objectives of the rationalization process could be stated as follows:

$$\sum_{i=1}^{4} P_i \longrightarrow \text{min.}$$

However, as there is no common factor among the different "P" values, it would be necessary to carry out the minimization process in steps such as:

a – minimization of hull steel weight,
b – checking hull stiffness and redistribute material if necessary,
c – improve design of local details,
d – improve design to simplify production.

iv. From the shipowner's point of view, the adverse effects of irrational ship design may be covered by an appropriate design penalty.

v. From the shipyard's point of view, the economical consequences of irrational ship design are always harmful. Therefore, all feasible measures should be taken to rationalize the design process.

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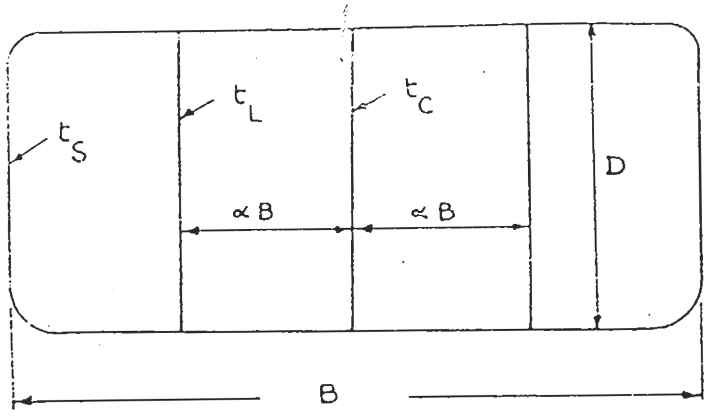


FIG.(1). MIDSHIP SECTION CONFIGURATION

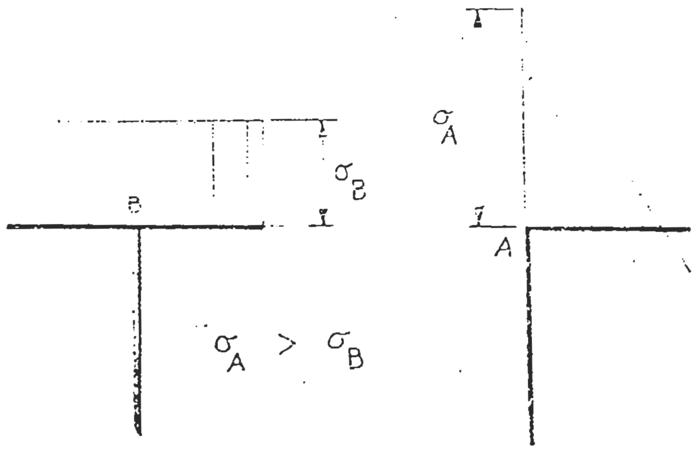
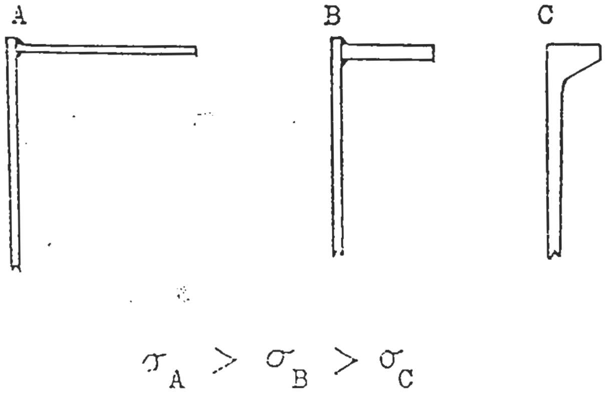


FIG.(2). EFFECT OF SYMMETRY ON STRESS DISTRIBUTION



FIG(3).EFFECT OF WIDTH OF FACE PLATE

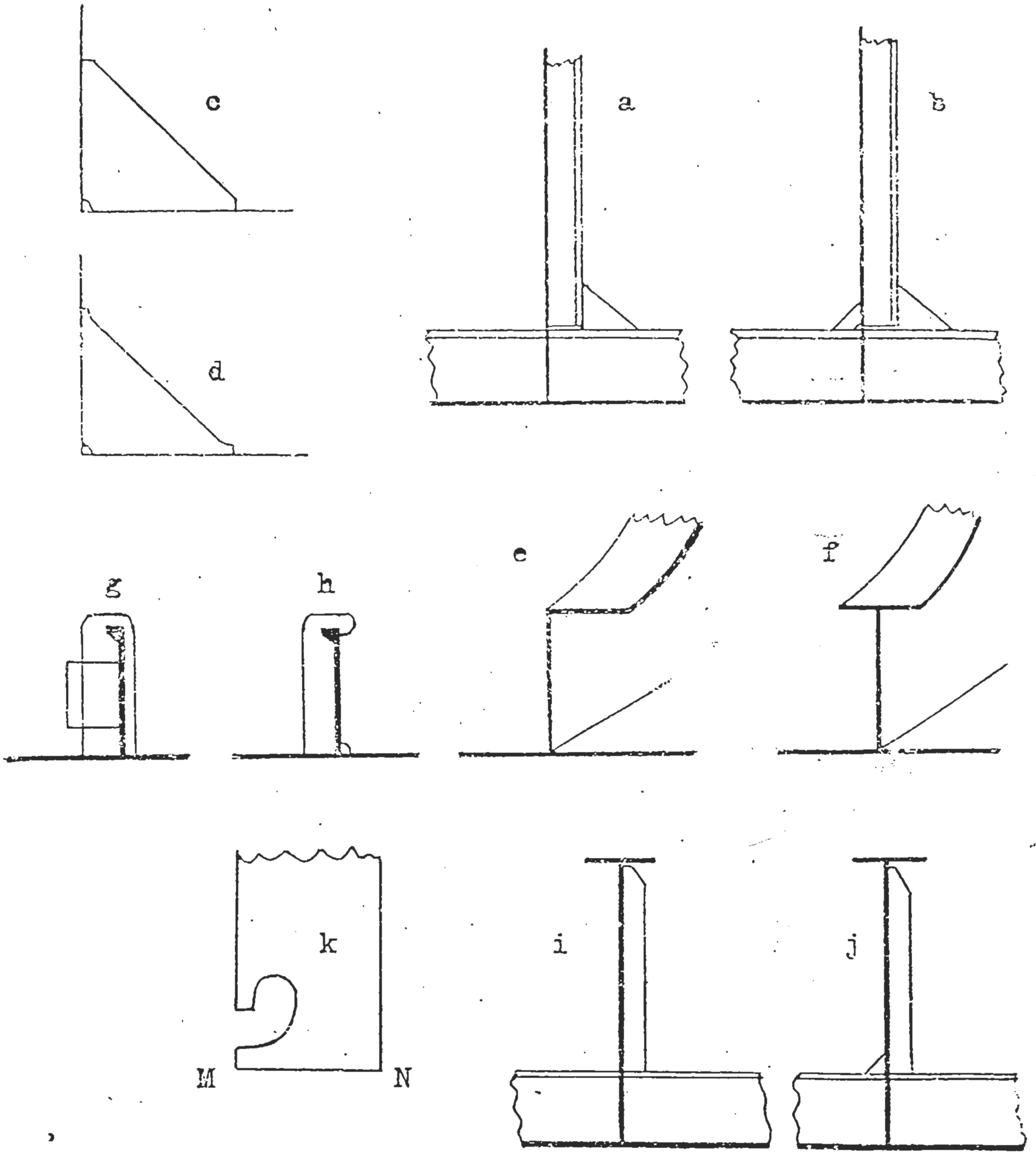


FIG.(4). SOME COMMONLY USED SHIP STRUCTURAL CONNECTIONS

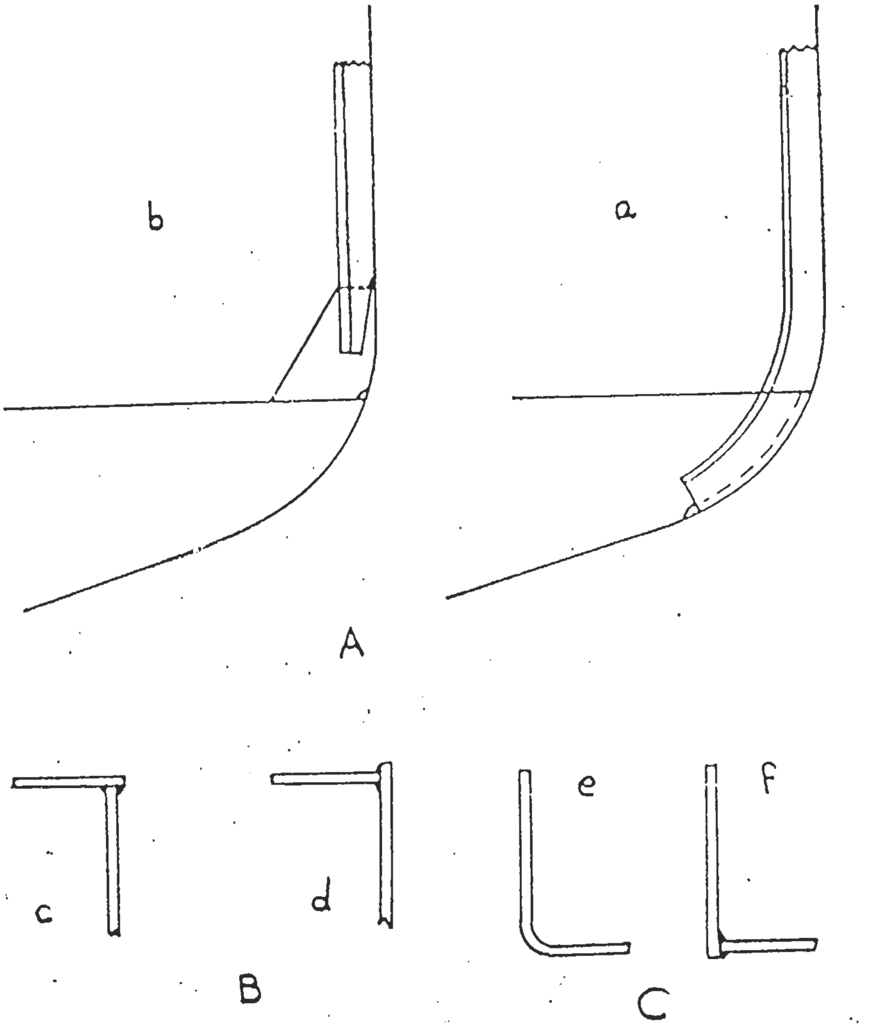


FIG.(5). ALTERNATIVE CONSTRUCTIONAL DETAILS

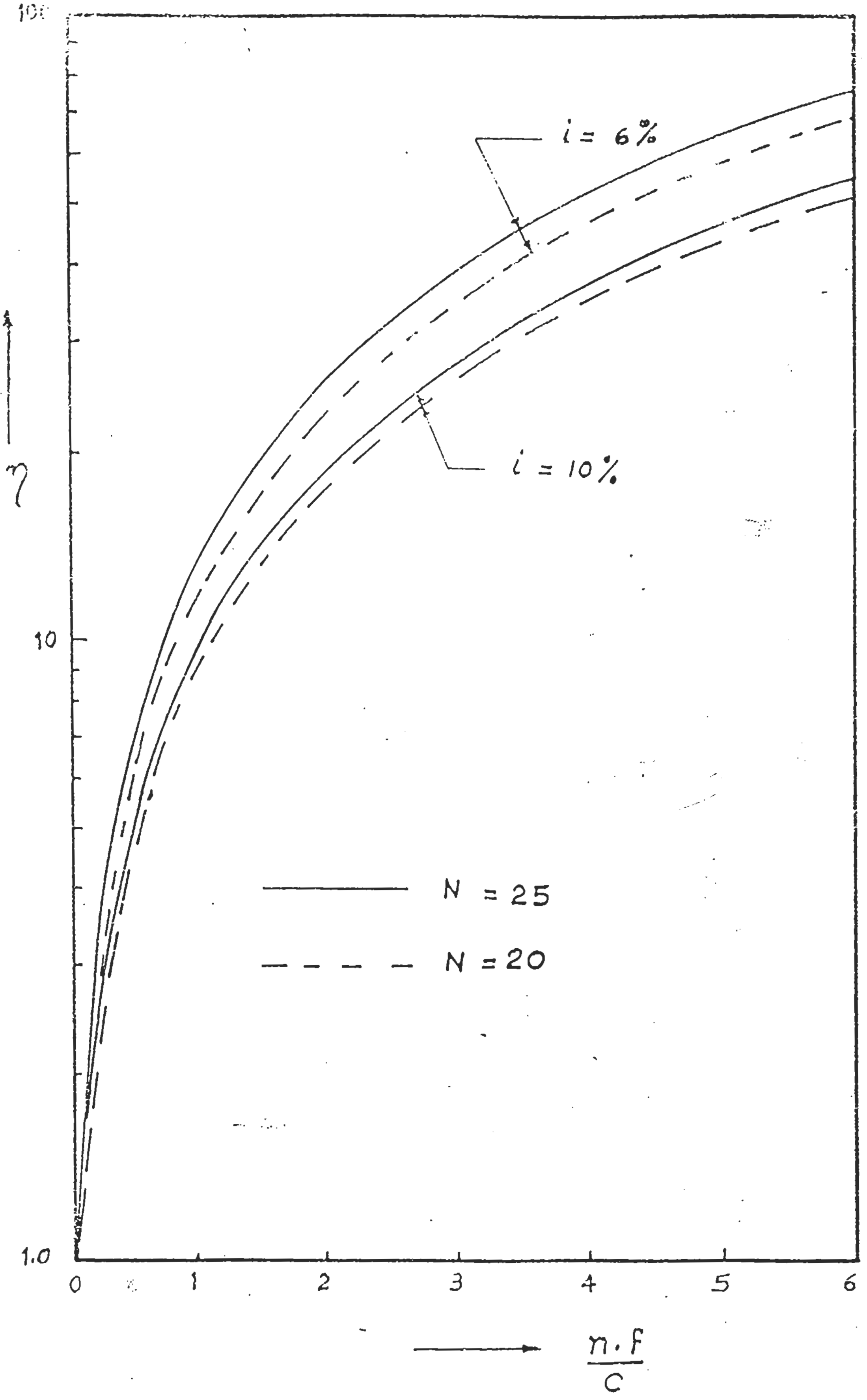


FIG.(6). VARIATION OF η WITH $\frac{n.f}{C}$, i AND N