MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

TOWARDS MINIMUM WEIGHT AND COST-EFFECTIVE DESIGNS OF FLAT AND PITCHED STRUCTURES

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ABSTRACT

The main objective of this paper for weight and cost consideration designs is to give the designer a better tool to compare the relative merits of various design alternatives and to be able to select the corresponding most minimum weight or cost-effective design. An example of a typical problem in shipbuilding is studied in order to explore some general aspects of design. Two different structural forms are considered (flat and pitched). In order to obtain realistic comparisons, the production costs considered in this research are according to the current practice in Egyptian shipyards.

A key finding from the results is that if the optimisation is based on a minimum weight or minimum cost criterion, the pitched structures are superior over the flat ones. In other words, significant savings in weight and cost can be achieved by replacing flat structures by pitched structures.

The labour cost should include the pre-fabrication, sub-assembly, fitting and other relevant activities costs in addition to the welding costs. In addition to the material and labour costs, the total costs should include the overhead costs in order to make a realistic decision for best design.

I. OPTIMUM DESIGN CRITERIA OF SHIP STRUCTURES

In these competitive days, it has become important for the designer to find structural solutions that satisfy design requirements, and at the same time have low weight and low production costs. To obtain reliable results, however, the designer needs accurate tools for analyses which take the complexity and coupling effects of the various structures into account.

In qualitative terms, a structure can be judged by its reliability, cost, and efficiency, which are the main attributes for measuring the quality of a structure. The most convenient definition used for the latter attribute, efficiency, is strength/weight ratio as a criterion, which is more relevant to ships as the weight savings can be translated into improved cargo-carrying capacity. Thus, maximising structureal efficiency is of great

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interest to the designer which must be compromised with the builder's prime objective in the search for 'better' design of minimum construction costs. Regarding ship structures, the interest of the approving authority and the operator is greater reliability or more safety of such structure design, further, the operator's interest is lower maintenance costs.

Details of design, especially with reference to the qualitative aspect of design and construction of structural connections, is the most important factor affecting the structural reliability. To have such a structure design of great reliability, an increased initial cost is required. Therefore, there may be a point at which further increase in reliability becomes uneconomic in terms of its effect on the life-cycle cost of a ship. This means that the life-cycle cost of a structure might be minimised by designing it with an optimum level of reliability which gives the best compromise between initial cost (which increases as reliability increases) and repair cost (which decreases as reliability increases).

For a structure having a specific demand and reliability, either total structural weight or total cost, or a combination of both, may be the prime criterion involved in establishing the superiority of one design over another. Ship structures usually fall between aircraft structures, with their predominant interest in weight saving, and land-based civil engineering structures where their prime objective is cost saving. Although the criterion differs considerably for each type of ship, structure weight and cost acknowledged to the important design considerations in shipbuilding. If either weight or cost was considered independently of the other as the prime objective, different designs would be obtained. Therefore, the true optimum would undoubtedly involve some compromise between the two, depending upon the analysis of the ship's operation. Hence, Caldwell and Hewitt [1] have proposed a generalised objective function in terms of a dimensionless quantity, U, as :

$$U = F(W/W_o) + (1-F)(C/C_o)$$

where W_o and C_o are the weight and initial cost of some basis or standard design. W and C are the weight and cost of a proposed design, and F is a number which varies between zero (where least cost is the objective) and unity (where weight saving is of paramount importance).

II. WEIGHT OPTIMISATION

In the latter reference, it is shown that if the main objective of a designer is minimising the weight of a structure having a specific demand and reliability, there are basically three strategies a designer may investigate, singly or in combination :

1. For a given material, and specified constraints (geometry and behaviour), find the more efficient combination of the free scantling variables,
2. Use different material to suit,
3. Change the constraints for a given material.

It might be possible to consider eliminating the redundant material as one more strategy. This needs to consider adding plates where greater moment of inertia is required in order to resist high stresses; also the judicious use of lightening holes, or by using uniformly varying web- tapered stiffeners (which represent an integral part of many structures). However, most weight saving strategies involving scantlings optimisation or eliminating the redundant material for a given material to be used lead to increased labour cost but decreased material cost.

By considering simple examples, Caldwell and Woodhead [2] have shown that the choice of configuration has the most crucial influence on the quality of the design. The configuration, or overall form, has the most marked effect on the resulting weight and cost of a structure if there are no overall dimensional constraints. For ships, the primary form is largely decided by safety, environmental pollution and operational requirements. Some possible alternative primary forms for transverse structures are suggested to be investigated based on utilising the whole inplane strength of the structure rather than partially.

Full details of a new general theory of anisotropic folded plate structures are studied thoroughly by El-Somokhly [3]. The next stage was to adapt that general theory to pitched structures which are of different form from current practice in order to improve the efficiency of such a structure. He has investigated the structural behaviour, analysis and design of pitched structures, having the kinds of geometric and practical boundary conditions appropriate to ships, as an alternative of flat structures, and also their possible use, see Fig.1.

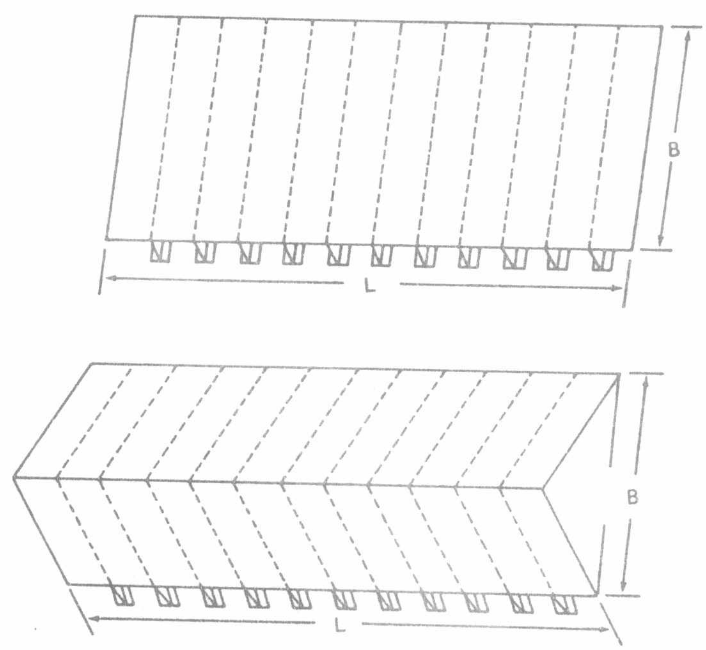

Fig.1. Flat and pitched structures

In a recent paper by Caldwell and El-Somokhly [4], two actual cases have been studied for flat and pitched structures based on weight as an objective function of design.

III. COST OPTIMISATION

The latter reference has been concerned mainly with theoretical and design problems. The authors have suggested that further work on production aspects needs to be carried out if pitched structures are to acquire credibility for general use in ships. Therefore, this paper is the first one as an attempt towards this new area of research.

III.1. Production Factors Influencing Design

The production factors, which should be borne in mind by the designer, in developing designs for production may roughly classed under two board objectives :

i- Minimisation of work content, by for example

a) Reduction of weld joint length, number of 'parts', forming of parts, etc.

b) Standardisation of elements (stiffener sizes and plate thickness) to suit yard ordering policy, and to derive benefits from any price reduction for bulk orders.

c) Reduction of the amount of fairing required, and the number of 'critical' connections which have to be made.

d) Consideration of the requirements for access, etc (the use of girders as staging in large constructions can influence panel configurations).

e) Adaptation of design of structure to suit the outfitting plan for the ship.

ii-Maximisation of effective use of shipyard plant, by

a) Designing blocks, sub-assemblies, etc to be compatible with lifting and turning facilities.

b) Using maximum plate sizes to reduce weld connections.

c) Designing details compatible with NC operation of production processes.

d) Maximising the ratio shop/ship work.

e) Optimising the sequence of fabrication and erection.

III.2. Determination of Production Cost 'C_p'

The production cost of a structural unit is defined as the sum of the labour and overhead costs incurred by the production processes involved. As material passes through the production processes it accumulates cost as a sequence of the work done on it by various work stations. Both labour and overhead costs may be initially calculated on a work station basis and then observed from the work station directly to the product on the basis of time required to complete the productin unit at the work station.

The labour cost is defined as the cost of the direct labour force associated with any particular work station, expressed as cost per unit of work content. This cost is directly related to the man-hours expressed at the

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work station by the factor of the wage rate. Hence, if these man-hours can be related to the work which takes place within the work station, it is possible to predict the labour cost incurred in carrying out only particular tasks of known work content. The relationship between man-hours and work content is defined es the 'performance index'. Thus, given a level of work content in a production unit, expressed in terms of a parameter such as joint length, or number of piece parts, the time required to process that unit, and hence the labour cost, is given by the product of the work station performance index, expressed in man-hours per unit work content. Caldwell and Hewitt [5] evaluated designs on the basis of construction cost, comprising material cost 'C_M', labour and overhead component 'C_P' with the labour cost being based on the welded length in the structure 'C_W'.

In shipbuilding, overhead costs are normally allocated on a basis of a labour cost. Such practice is clearly undesirable where the ratio of man to machines varies considerably within any one shipyard. Since, as the level of investment in the work area increses, the labour cost associated with that area usually decreases and so, under the conventional costing system, the overhead allocated to that area would also decrease. Overheads are generally divided into those which are fixed and those which are varible. The fixed overheads have to be paid for whether men work in the yard or not, while the variable overheads vary in relation to the number of direct workers and/or the level of production. In fact, the determination of overhead cost is more difficult and certainly more controversial. However, any study involving total production cost cann't be realistic unless overhead cost is included as is previously well established and re-recommended by Kuo and others [6]. Booz-Allen [7] indicated that in 1971 the breakdown of total costs in shipbuilding was 55%, 25% and 20% for material, labour and overhead costs, respectively. The majority of production cost in a panel shop consists mainly of overhead costs; this is due to high capital investment in machinery such as gantries, welding equipment and cranes etc.

IV. CASE STUDY

A comparison of flat and pitched structures is illustrated by using a mild steel deep tank bulkhead 5m deep and 8m in breadth. The maximum head of fresh water in the tank is 8m above its base, see Fig.2.

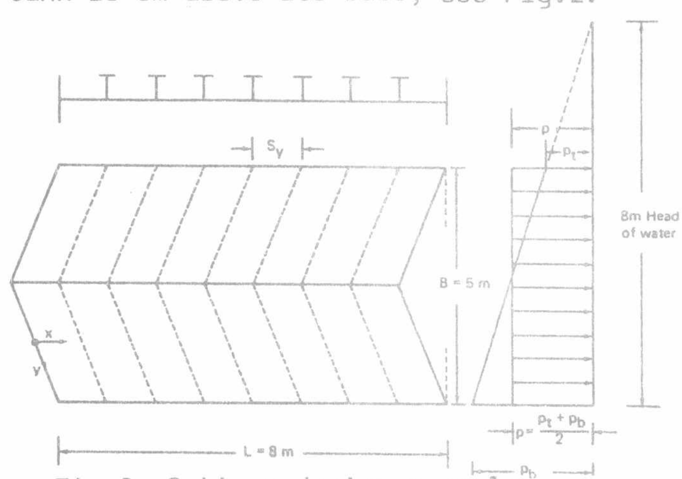

Fig.2. Optimum design example

It is required to calculate the total weights and costs of flat as well as pitched structures under similar design constraints, and with similar system of stiffening, see Fig.1, in order to compare 'like with like'. The boundaries are assumed in all cases to be simply-supported (i.e. rotationally unconstrained).

The fixed design parameters (e.g. web depth/thickness ratio, minimum plate thickness, minimum thickness of stiffeners, flange breadth/thickness ratio etc), are typical to those commonly used in shipbuilding. The structure was assumed to be made up from identical general T-section stiffeners. Two design cases for tee-section stiffeners are considered, which are: the ratio of stiffener flange area to web area (A_f/A_w) is equal to 0.67, and that ratio is equal to zero, i.e. flat-bar stiffeners. For an efficient one-pitch structure the aspect ratio L/B should prferably not be less than unity [4], and therefore the depth (the shorter dimension) of the tank is considered as the transverse span B. Tt is assumed that the effective breadth of the plating is equal to the stiffener spacing.

For the purpose of optimisation studies, it may be assumed, without loosing much generality, that the material cost can be calculated on the basis of cost per tonne mass of material irrespective of whether the material forms plating or stiffening members.

The production cost of welding for cross-stiffened panels may generally be divided into four categories depending on the production processes:

- plate butt welding
- stiffeners welding
- heavy deep section welding
- intersection joint welding

Also for the purpose of the present cost optimisation study and to maintain generality and simplicity, the cost parameters are obtained as the current practice of Egyptian shipyards.

Although the plate butt welding cost is not significant in the overall production cost and design considerations butt welding, using manual arc welding, is included by considering weld metal deposition rates 0.82 and 1.04 kg/hr and required weld metals 0.64 and 1.14 kg/m for plate thicknesses 5-10 and 10-15mm, respectively.

In the case of fillet welding of stiffeners, various classification societies specify the fillet sizes. The most common practice in stiffener welding is double continuous fillet welding. With this welding process, DNV and LR specify a minimum required throat thickness of 3.5 mm for plate or web thickness up to 24mm. To satisfy the above requirement for throat thickness, some amount of margin should be added (e.g. 2mm) due to the fairness of the plating and the gab between two members to be welded. Therefore the actual minimum throat thickness considered in this research is 5.5mm. With throat thickness 5.5mm, the weld metal weight including flux is about 0.7 kg per unit metre of joint length for double continuous welding.

A possible way to produce such a pitched structure, which is considered in the case study of this paper, is that to have two separate stiffened panels, then chamfer them at one edge making an angle 'α'. Then weld both sides together with a vertical flat bar making a pitch angle 'α', see Fig.3.

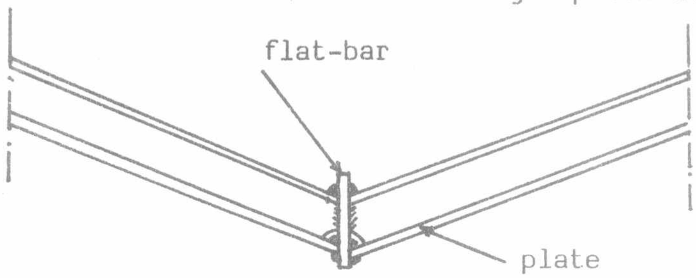

Fig.3. Two stiffened flat panels connected through flat bar

Rates used for labour and overhead categories are given in the following table:

category / rate	prefabrication	sub-assembly Plater	sub-assembly Assistant	Welders	consumables manual m/c	consumables semi-aut. m/c
hr/tonne	10	10.5/13	10.5/13	--	--	--
L.E./hr	3.836	3.836	1.872	3.836	0.18	0.43

The following important notes and data are considered in calculating the overall costs:

- For the third and fourth columns of the above table, the upper value refers to flat structures while the lower one refers to pitched structures.
- For material, rate of L.E. 320 per tonne mass, is used.
- The prefabrication cost includes the costs of straightening, marking, cutting, and bending.
- The cost of welding metal is L.E. 1.85/kg; and for pitched structures, rates of 0.385 and 0.23 hr/joint are used for welding the joints at the apex for A_f/A_w equal to 0.67 and 0, respectively.

V. RESULTS AND DISCUSSIONS

It has been found [4] that the optimum pitch angle 'α' for the same case of study is of 22^o. Fig.4 shows the variation of panel weight with number of stiffeners N for A_f/A_w equal to 0.67 and 0. For flat structures, the optimum numbers of stiffeners are 25 and 17 for A_f/A_w equal to 2/3 and 0, respectively. For $\alpha = 22°$, the optimum values of N are not apparent from the curves, this is because of the minimum plate thickness constraint. The percentages of weight saved by replacing flat by pitched structures are 31.6 and 45.9 for A_f/A_w equal to 2/3 and 0, respectively.

Figs. 5 & 6 show the variation of total cost with number of stiffeners N for A_f/A_w equal to 2/3 and 0, respectively. From those two figures, the total production costs 'C_p' cann't be based only on the welding cost 'C_W', since total welding costs represent about 50% and 60% of total production costs of flat and pitched structures, respectively. Material cost 'C_m' represents about 55-65% of the total costs for flat and pitched structures.

For flat structures, optimum cost design leads to number of stiffeners of 22 and 14 for A_f/A_w equal to 2/3 and 0, respectively; while for pitched structures those values of N are 22 and 20 for A_f/A_w equal to 2/3 and 0, respectively. The percentages of cost saved by replacing flat by pitched structures are 15 and 31.5 for A_f/A_w equal to 2/3 and 0, respectively.

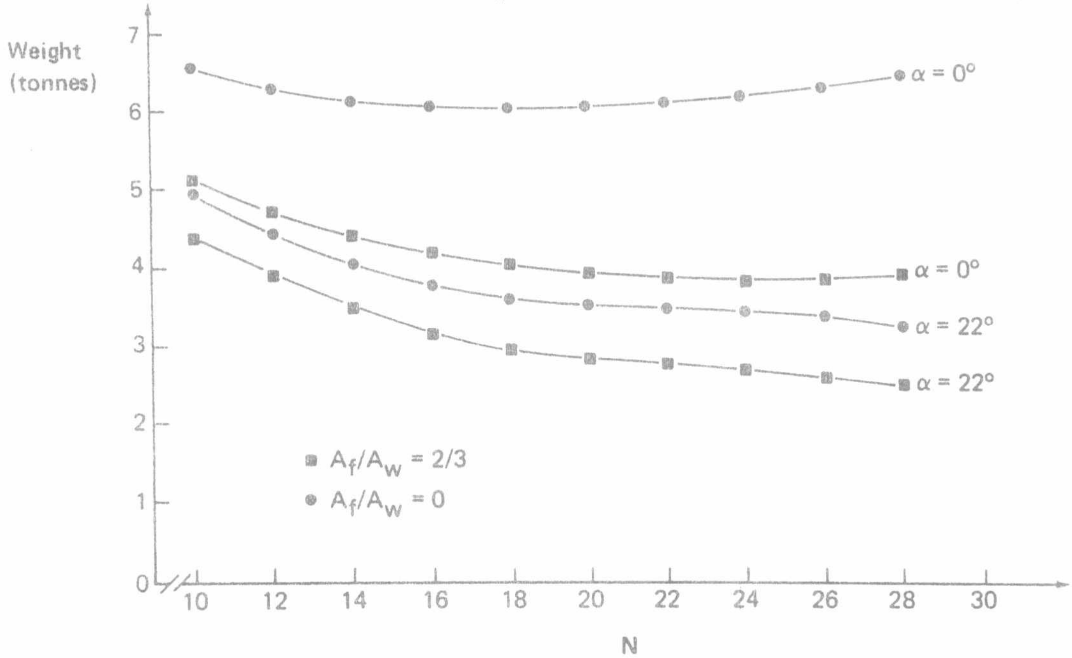

Fig.4. Variation of weight with number of stiffeners N

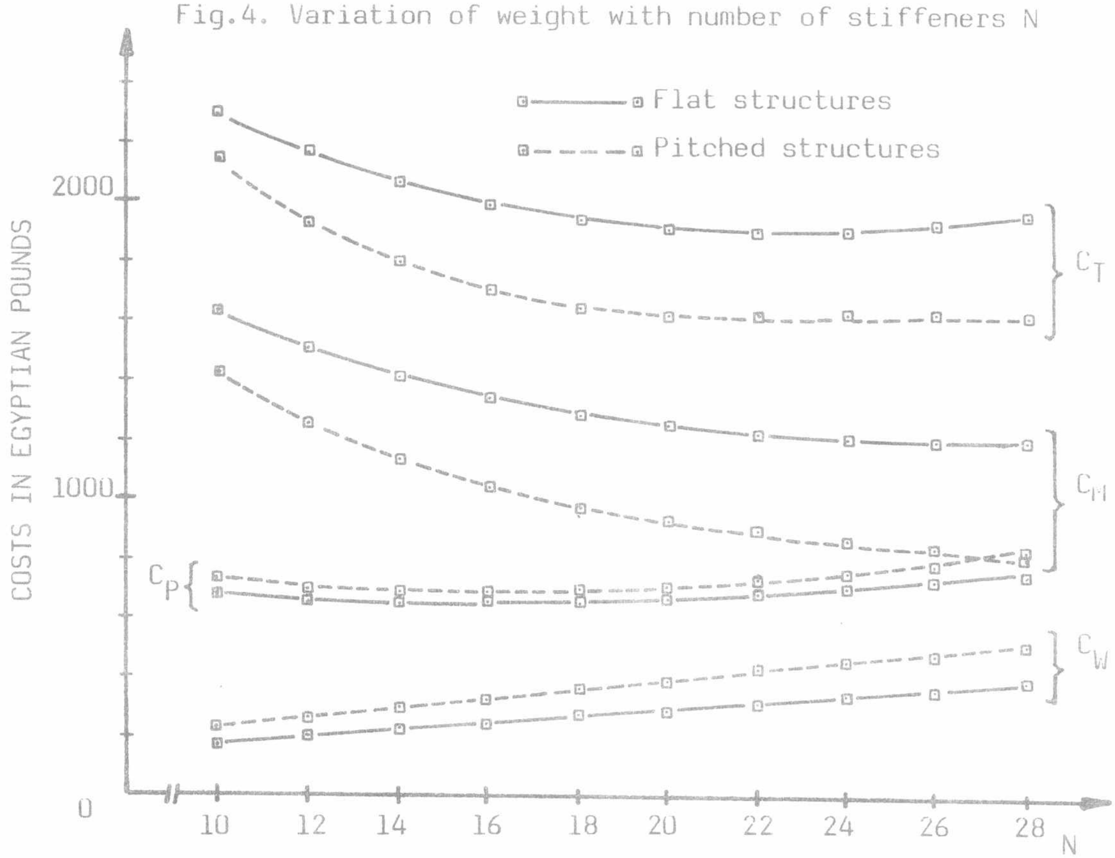

Fig.5. Variation of cost with number of stiffeners N for A_f/A_w=2/3

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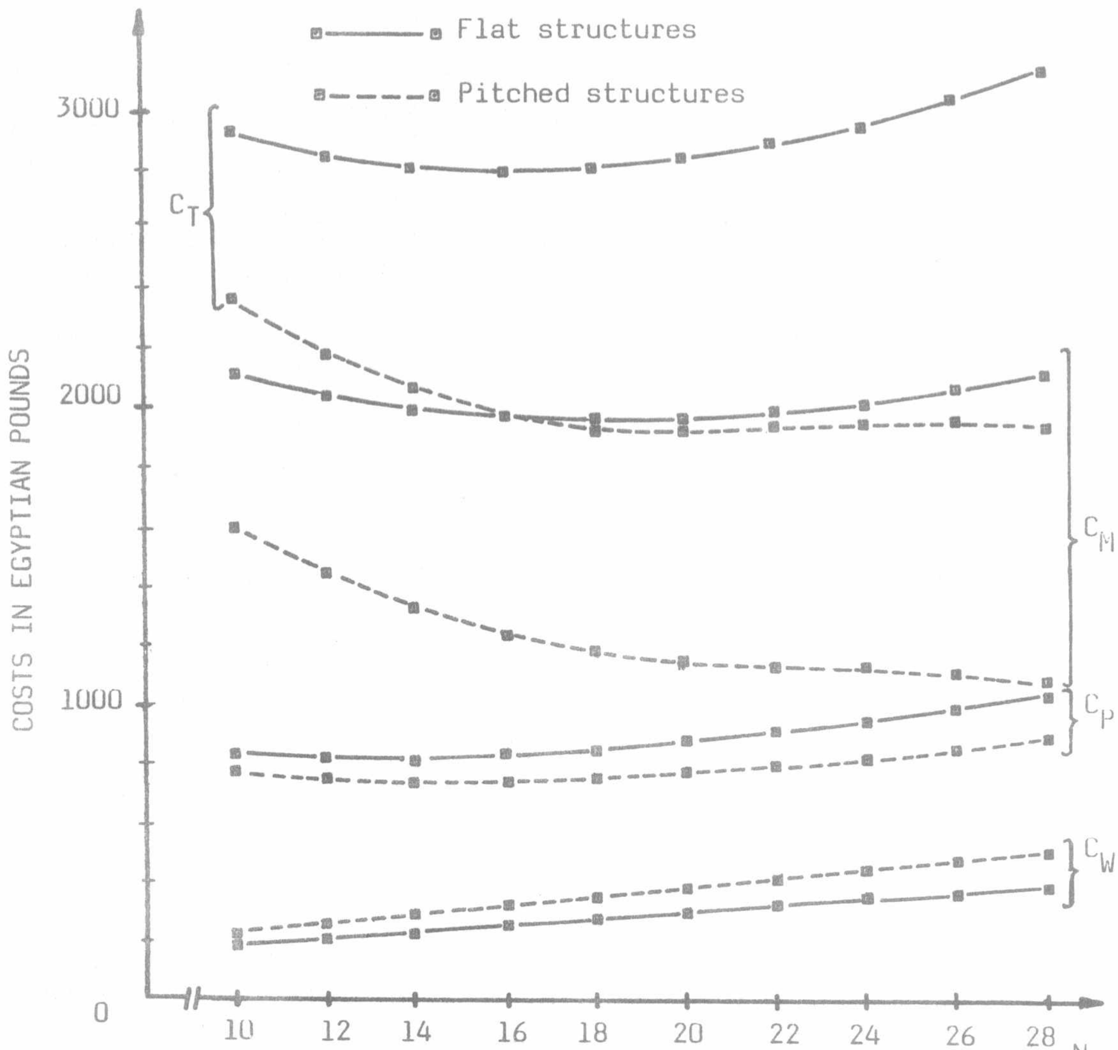

Fig.6. Variation of cost with number of stiffeners N for $A_f/A_w=0$

VI. CONCLUSIONS

This investigation has shown the feasibility of designing the basic elements of welded ship structures against a criterion of minimum weight or minimum cost. The optimum design of stiffened flat and pitched structures can readily be found if quantifying production cost enables the cost of unit operations to be determined. The following main conclusions may be mentioned :

- The costs and constraints of production influence the forms and layout of ship structures.
- Designing to minimise weight leads to flat structure of a relatively thinner plating and more closely spaced stiffeners, while pitched structure is of a more thinner plating and smaller stiffener spacings.
- Designing to minimise total cost leads to simpler flat and pitched structures with fewer parts, thicker plating, more widely spaced stiffeners compared with those based on minimum weight as objective function.
- Differences between minimum cost and minimum weight designs are not substantial, this is mainly due the high ratio of material cost to production cost. However, that difference can be expected to increase as the ratio

of production cost to material cost increases.

- The percentages of weight saved by replacing flat by pitched structures are higher than those of cost saved.
- If the optimisation is based on a minimum weight or minimum cost criterion, the pitched structures are superior over the flat ones.
- Higher costs in production of pitched structures don't offset the savings in weight, and the production cost of pitched structures may not greatly differ from that of flat structures.
- The labour cost should not be based only on the welded length in the structure, but pre-fabrication activities , which include straightening, marking, cutting, fairing, cleaning the floor area, transporting material and moving the whole panel should be included in the labour cost.
- In the case of welding activities, the causes of variation are the type of welding (whether manual or automatic), edge preparation of plates, choice of electrodes and the welding position.

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