Structural Design Philosophy

——A Review——

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Introduction

The meeting of the Fourth International Ship Structures Congress here in Tokyo this week marks the completion of nearly ten years of international co-operative effort in ship structural research. During this period we have seen major developments in many branches of this subject, which itself is but one branch of the larger profession of naval architecture. Perhaps there is now a danger of over-specialization, of too much fragmentation of our studies in this field, so that ship design is not deriving as much benefit as it might from the many detailed areas of research. Be this as it may, it is sometimes appropriate to step back from the narrow paths of specialization and to survey the general trend of our efforts in ship structural work. What are our overall objectives ? What practical gains are possible ? How has the practice of ship design advanced ? What are the problems of the future ? Where should our research efforts now be directed ?

Faced with these questions, and because I have had the honour to be invited by your Society to present a paper on "Design Philosophy", I offer no excuses for "philosophizing", which I propose to do for the next hour or so. The subject is the more appropriate since I have this week completed six years as Chairman of the I. S. S. C. Committee on Design Philosophy, and inevitably I shall make some reference to our studies over this period. May I acknowledge the contributions of my colleagues on that Committee, both in the work of the Committee, and indirectly in some of the observations which I shall make in reviewing our subject-"Structural Design Philosophy".

1. Purposes

It is not difficult to state, in a qualitative way, the overall objectives of the designer. He is required to produce the design of a structure which will perform satisfactorily its intended function during the expected lifetime of the ship. More precisely, the "performance objective" (P) can be expressed as a function

$$P=f(E, R) \tag{1}$$

of its efficiency (E) and its reliability (R). Although it may be argued that efficiency and reliability are but two sides of the same coin (since an unreliable structure can hardly be regarded as efficient) it is nevertheless convenient, at this early stage of development of structural reliability concepts, to consider efficiency and reliability as separate (though connected) attributes of a structure. Thus we may regard efficiency as a deterministic (non-probabilistic) measure of functional performance ; while reliability expresses the probability that the structure will achieve that performance during the life of the ship.

It is well-known that the two most meaningful attributes of a ship structure, which determine its merits in the eyes of its builder and user, are weight and cost. Hence we should perhaps express structural performance in some way such as

$$P=f(E^a{}_W,\ E^b{}_C,\ R) \tag{2}$$

in which E_W is the weight efficiency, and E_C the cost efficiency of the structure. a and b are indices which enable the appropriate weighting to be given to weight and cost. Thus, for example, in volume-

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limited ships of high initial cost the index a may be low and b high; whereas in weight-limited ships of low initial cost a would be increased and b reduced.

(1) **Weight and Cost Efficiency**

To quantify such expressions of the performance of a structure, the designer needs explicit ways of defining weight and cost efficiency, so that he can compare the merits of alternative designs. Optimization procedures (of the kind developed by my two fellow-authors today) are becoming available to investigate the effects on weight and cost of quite detailed variations in ship dimensions, structural topology, material properties and so forth. A particularly convenient way of expressing the results of such studies has been developed by Professor Evans. In this, the structure weight W_2 of an alternative design is expressed as a proportion of the weight W_1 of a basis design. Such a whight ratio can be expressed alternatively as a percentage weight saving

$$S_W=100\left(\frac{W_1-W_2}{W_1}\right)=100\left(1-\frac{W_2}{W_1}\right) \tag{3 a}$$

Similarly we may introduce a percentage cost saving

$$S_C=100\left(\frac{C_1-C_2}{C_1}\right)=100\left(1-\frac{C_2}{C_1}\right) \tag{3 b}$$

where the cost ratio of the two designs is obtainable from results of the kind given by Evans. Both S_C and S_W may take positive or negative values. Note that in this context C refers to total cost of ship, not cost of structure alone.

Although these two terms provide useful direct comparisons of the weights and costs of alternative designs, they are not by themselves sufficient to enable a designer to make a decision regarding the choice between designs. It has often been demonstrated that in most (though not all) cases S_W and S_C turn out to be of opposite sign; and to resolve the question as to whether a cost penalty can be accepted for a saving in weight, further information is needed for an overall economic analysis of the alternatives.

Such an analysis can be carried out at various levels of complexity. It detailed information regarding costs of construction and operation, fiscal policies, projected revenues etc., is available, then a full DCF analysis enables design alternatives to be compared on some rational economic basis, such as Nett Present Value. A comprehensive attack on this method is being made by workers in the United Kingdom, and seems likely, when further developed, to provide a most valuable tool for decision-making at the design stage, and for establishing those areas of design and research which are most likely to influence profitability.

Where detailed information is not available, or where (as now) only broad trends are being investigated, some simpler economic criterion may be used. It must, however, account reasonable accurately for the separate effects of structure weight and cost in the overall profitability of the ship. This requires absolute, rather than comparative, data regarding the contribution of the structure to the weight and cost of the ship. For our purposes here it is convenient to introduce the ratios

$$R_W=\frac{\text{weight of structure}}{\text{payload}}=\frac{W}{W_p} \tag{4 a}$$

$$R_C=\frac{\text{annual costs dependent on initial ship cost}}{\text{average annual cost}}=\frac{\phi C}{A} \tag{4 b}$$

Payload denotes the revenue-earning portion of the deadweight. ϕC accounts for those costs (interest, depreciation etc.) which are directly related to the initial capital cost (C) of the ship.

Of the various economic criteria which have been proposed, the Ship Merit Factor (M), introduced by Cheng, is useful in the present context:

$$M=\left(8760\frac{f_S f_W f_V}{1+f_p}\right)\left(\frac{\Delta}{R}\right)\left(\frac{R_V}{P_B}\right)(P_B)\left(\frac{1}{A}\right)\left(\frac{W_p}{\Delta}\right)=\frac{1}{\text{RFR}} \tag{5}$$

where f_S = ship utilization factor
f_W = ship load factor
f_V = speed factor
f_p = port time factor
Δ/R = displacement/drag ratio
$\frac{R_V}{P_B}$ = propulsive efficiency
P_B = power delivered by prime-mover
A = average annual cost
W_P/Δ = payload/displacement ratio
RFR = required freight rate

To examine the effect of structural design on M, we note that the first four brackets on the right-hand side are practically independent of structural design, weight and cost, provided that a difference in structural weight between alternative designs results in a corresponding change (of opposite sign) in payload, thus keeping displacement constant.

Two objections to the above may be raised. First, in capacity ships the payload is volume, rather than weight dependent. Hence the following is intended to apply primarily to designs which are weight sensitive; it is such designs which in any case are primarily of interest in structural optimization. Secondly, it may be argued that the utilization factor f_S may be influenced by the need to repair structural damage, which in turn is related to the quality of the design. This interaction however, is assumed to be negligibly weak; and this aspect of design is more a question of structural reliability, to which we return later,

With these assumptions we may group those terms (K) which are independent of structural design, to write the Ship Merit Factor

$$M=\frac{K}{A}\left(\frac{W_p}{\Delta}\right) \tag{6}$$

We may now use equation (6) to compare the merit factors M_1 and M_2 of two designs having structure weights W_1 and W_2 and costs C_1 and C_2 respectively. It can be shown from equation (6) that

$$M_2 \gtrless M_1 \quad \text{if} \quad S_W+S_C\left(\frac{R_{C1}}{R_{W1}}\right) \gtrless 0 \tag{7}$$

where R_{W1} and R_{C1} are the weight and cost ratios (equation 4) for design 1.

As an example, suppose a proposed design of ship structure resulted in a structure weight of one quarter of the payload. Then if a weight-optimized re-design effected a weight-saving of, say 5% of the original structure weight, the merit factor would only be increased provided the initial cost of the ship did not increase by more than 6.25% for $R_C=0.2$, or by more than 3.12% for $R_C=0.4$. The corresponding values for a ship having a smaller structure weight to payload ratio are reduced in proportion.

There is at present rather little precise information on values of R_W and R_C for a range of ship types and sizes. For bulk carriers, R_W is around 0.2 and for tankers slightly less; in both cases the value appears to decrease slightly with ship size. On the other hand R_C, which reflects the effect of initial capital costs on annual outgoings, increases significantly with size. For such ships the attractiveness of weight-efficient, but more expensive, designs is thereby reduced.

The foregoing elementary considerations serve to show that the overall performance of a structure, as affected by its weight and cost can be assessed, and the effect of design variations estimated, for preliminary design purposes. With rapid development of sophisticated techno-economic design programmes a more detailed study of weight-cost performance trade-off is becoming practicable.

There seems little doubt that the continuing search for improved efficiency of ships will lead to