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Structures and Materials: Progress and Prospects

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Structures and materials: progress and prospects

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The paper has three main sections. The first reviews recent developments with particular reference to the emergence of a more scientific basis for ship structural design, stimulated by innovations in ship types and sizes, and by increasing scientific and technical knowledge. The latter is discussed in relation to the main stages of the design process.

The second section looks ahead to the 1980s, and to possible factors which might affect decisions about ship structures and materials. These may arise from changes in trading patterns and ship requirements, by the continuing search for economy in both ship operation and in shipbuilding, by sociological and legislative pressures, and by attempts further to improve the efficiency and reliability of ship structures.

The final section draws on the first two to suggest general objectives for contemporary research in this field, and lists about thirty problems whose solution may contribute to those objectives.

1. Progress from the 1960s

When the first International Ship Structures Congress was convened in 1961, structural design – in the sense of applying scientific method to the selection of materials and scantlings – was much less developed for ships than for most other engineering structures. Empiricism and experience had largely controlled the evolution of successful ship structures, and these, together with a modest injection of elementary theory, were the basis of the rules of the classification societies, whose tables of scantlings and accompanying notes provided a ready and dependable means for 'design' of the majority of merchant ship structures.

The pressures that have since brought about substantial changes in this scene were, however, already in evidence at that first I.S.S.C. If the mainspring of change was the demand for new and more efficient modes of marine transport – in which the economies of scale were to play such a major role – change was accelerated by a number of other factors. Foremost among these was the growing recognition (dramatized by some notable structural failures) that experience-based rules might not safely be extrapolated to these new and large ship types; and that if the developing knowledge about the ocean environment and the response of ship structures to this environment could be harnessed with the power of the computer, then a more scientific and flexible method of design could emerge.

The decade saw many innovations, actual and projected, in ship types and structural requirements – articulated ships, open-deck ships, giant tankers, barge carrying ships; and some signs of emerging alternatives to mild steel as the preferred material – reinforced plastics, high tensile steel, even reinforced concrete. Faced with novel design problems of this kind, and unable to draw on relevant service experience, the naval architect needed a design procedure in which the uncertainties of innovation could be countered by the increased power and sophistication of the methods used. The ten years since the first I.S.S.C. have seen – only just in time – the emergence of such methods.

Central to the development of this rational design procedure has been the creation of a supporting scientific framework for:

predicting the load actions on the structure during its life;

predicting the response of a proposed structure to these loads;
defining explicitly the constraints on structural response; and
synthesis and optimization of designs.

Although much remains to be done (see § 3) the decade saw great progress in all these areas, and this is summarized in the following four sub-sections. A brief review of relevant materials research concludes this section.

(*a*) *Load action on ship structures*

Of the great variety of loads sustained by elements of ship structure during its life, those involving significant dynamic components have generally been the least predictable. The quasi-static load actions arising from the still-water loading and self-weight of the ship, or during docking or launching, are easier to estimate, although in some aspects of static loading – such as determination of 'built-in' loads, of thermal loads, and of loads due to granular cargoes – more work needs to be done. So recent research has concentrated mainly on wave, vibratory and impulsive loads on ships. The origin of most of these is the sea itself; and the compilation, on an international scale, of meteorologiccal and oceanographic data along the main trading routes, together with development of statistical and spectral representations of the sea, has opened the way for a logical prediction of the life history of ship motions and sea-way loadings. There are many alternative routes through the problem of relating the *cause* of seaway loads (known from wind, wave or sea-state statistics) to their *effects* (in terms of pressures, bending moments, shear forces etc.) on the hull using various types of cause–effect relation; and figure 1 attempts to portray some of the schemes that have been put forward in the now extensive literature on the subject. The use of sea energy spectra and ship response amplitude operators (from tests or theory) to predict wave loads seems to be the most promising for future use.

With the resulting probability distributions of wave loads in association with an acceptable frequency of occurrence (usually 10^{-8} in one ship life), a 'design' value of wave load can be deduced. A remaining problem is then to combine this with a statistical assessment of still water loads so that the probable simultaneity of extremes is correctly assessed.

Predictions of vibratory and impulsive loads raise problems that are also not yet fully solved. Many of the latter, being mainly local in their effect, can be countered by some local strengthening with no great loss of transport efficiency. But a rigorous determination of wave-excited vibratory loads (which become more acute in large, high-powered ships) awaits a satisfactory analysis of hydrodynamic and structural damping of ships. In short, the problem of dynamic loads, which excite responses around the many possible resonances of a ship structure, promises to be a major concern in future.

(*b*) *Structural responses to load*

Calculation of the behaviour of ship structures under the predicted loads raises problem areas of the kind summarized in figure 2. In the substantial volume of recent research in these areas, two main streams of activity can be distinguished. The first, to which most attention has been devoted (top half of figure 2), is to find the elastic response of the structure; the second (lower half) is to find the limiting conditions under which the structure will fail. Comparison of these two sets of results indicates the degree of safety or reliability, as discussed in (*c*) below.

The substantial advances, made in post-war research, in elastic analysis by classical methods of primary structures, sub-structures and local details, has recently been largely overshadowed

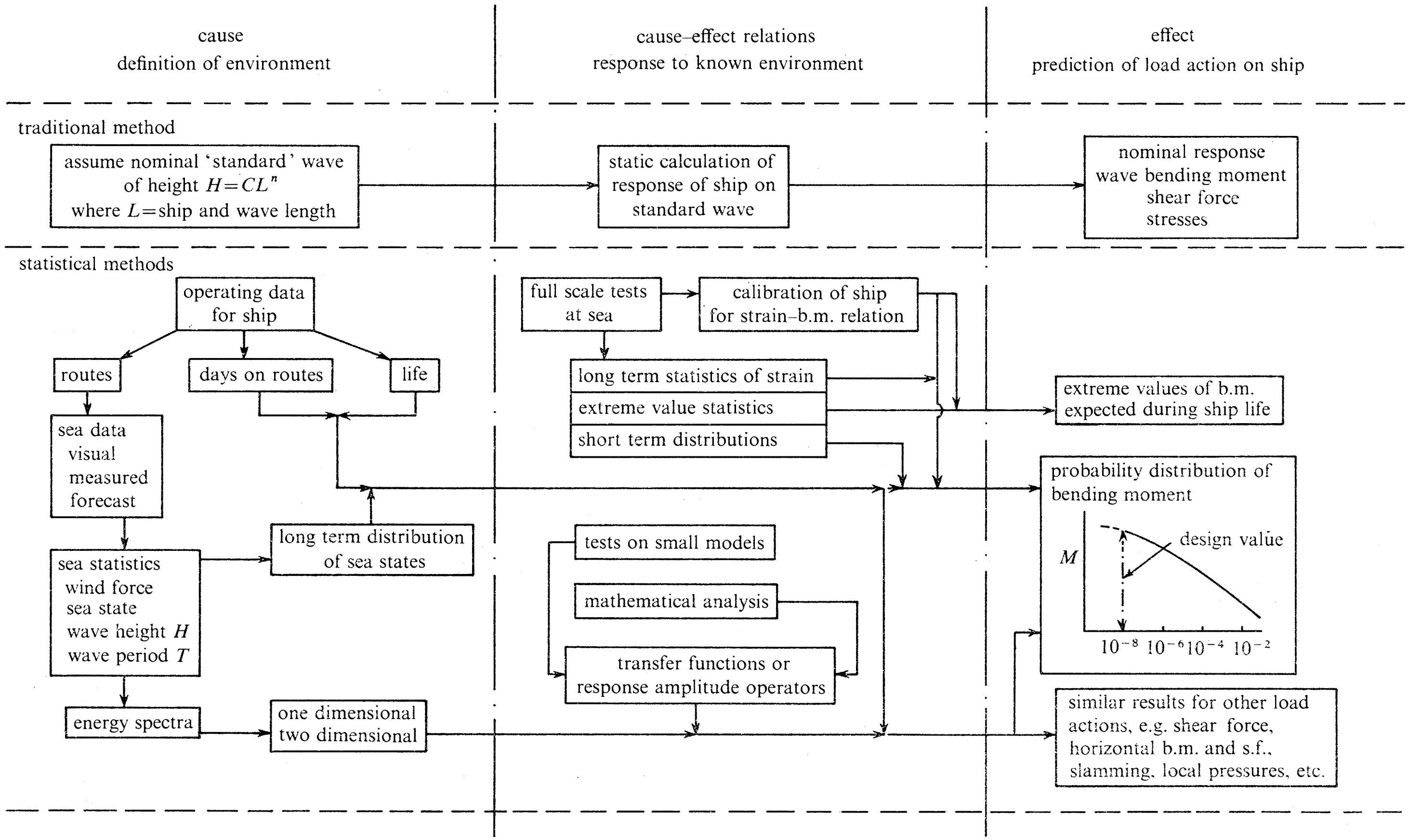

FIGURE 1. Cause–effect relations in predicting load actions on ship structure.

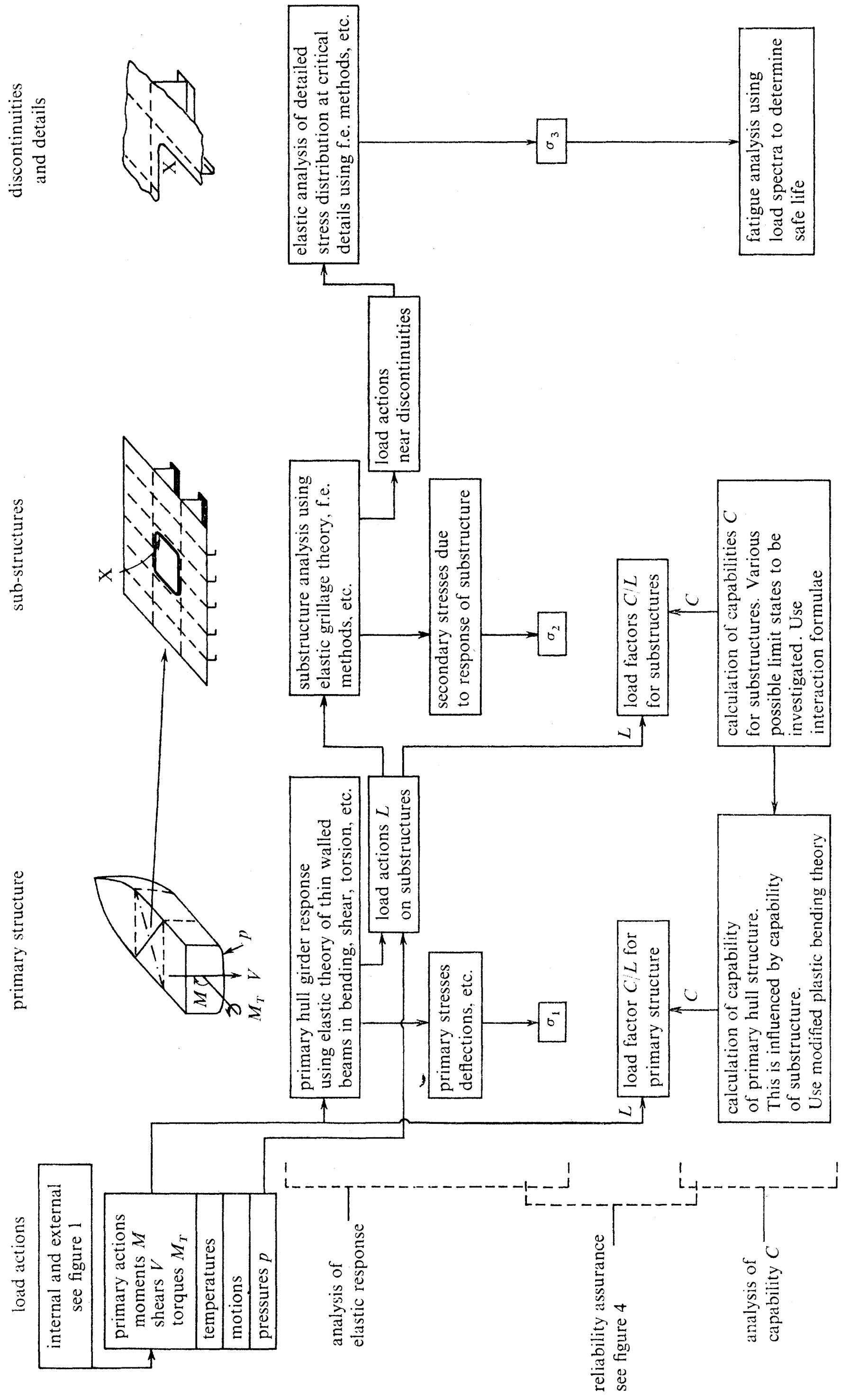

FIGURE 2. Response analysis for ship structures.

by the remarkable progress in 'finite element' (f.e.) treatment of these problems, though the former methods and the resulting data are still valuable for many purposes. The 'zooming' process, whereby the analysis of major structure provides the boundary actions for the analysis of sub-structures, can now be automatically carried out by f.e. methods, which by also enabling longitudinal and transverse stress analysis properly to be combined in a three dimensional treatment, have shown some important defects in traditional methods. Large tankers, bulk carriers, open-deck and other new ship types have now been successfully stress-analysed by these methods. Automated print-out of the results (e.g. figure 3) is a valuable by-product of these computer-based stress analysis procedures.

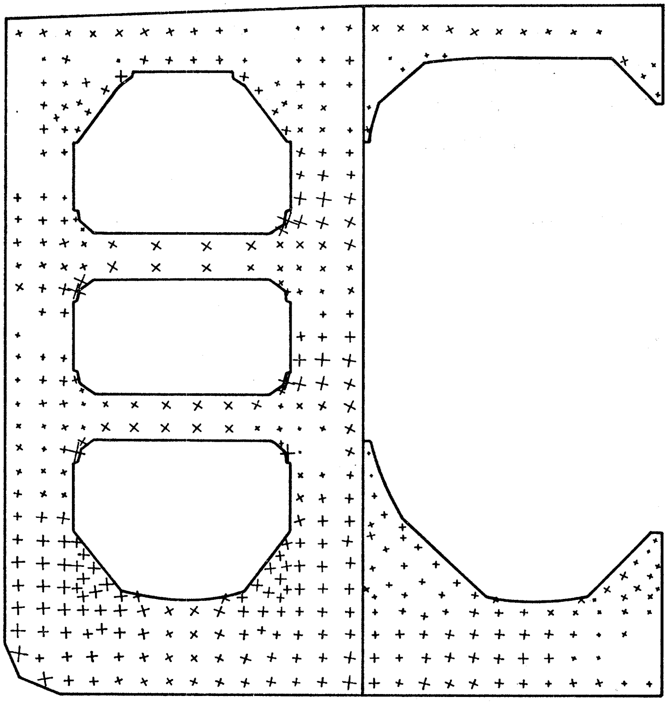

FIGURE 3. Principal shear stress diagram for a transverse of a 250000 ton tanker. Load: wing tank full, centre tank empty and 0.25 load draft.

Strength analysis, by contrast, has not developed to the same extent, although classical plastic analysis is being applied to certain design problems. Contributory reasons are the inherent non-linearities of plasticity and instability; the uncertain effects of imperfections and welding stresses; the complex loading actions on most structural elements; and the multiplicity of their possible failure modes, including fatigue and fracture. For these reasons controversy still persists as to whether calculation of failing loads is indeed feasible or realistic; and whether elastic stress criteria must therefore suffice. Another difficulty, which seems likely to become more acute in relation to possible fatigue, is that of dynamic stressing. Here again f.e. analysis appears promising, especially with the recent development of fluid elements whereby the important added mass and damping effects of adjacent fluid may eventually be included. Thus while elastic static linear stress analysis has probably now reached sufficient levels of sophistication, more work on limit-state and dynamic response seems necessary.

(*c*) *Reliability assurance*

The assurance of safety and reliability of ship structures is a primary concern of the classification societies. The methods they have evolved include:

initial quality control, both of materials and construction; quality maintenance, by regular survey and provision of margins for deterioration;

loading control, by specifying limits; and

specification of procedures and constraints in design.

It is in the last of these that the most significant changes have occurred in this review period. Through a transition phase in which the old 'scantling tables' were transformed into simple formulae, we are now close to a situation in which, as an alternative to these established forms, the design 'rules' may well involve only:

(i) specification of load actions to be considered;

(ii) recommendations regarding response analysis methods to be used;

(iii) specification of margins of safety (or limiting stresses); and

(iv) a few constraints on topology or scantlings (e.g. minimum plate thicknesses, design of details, etc.).

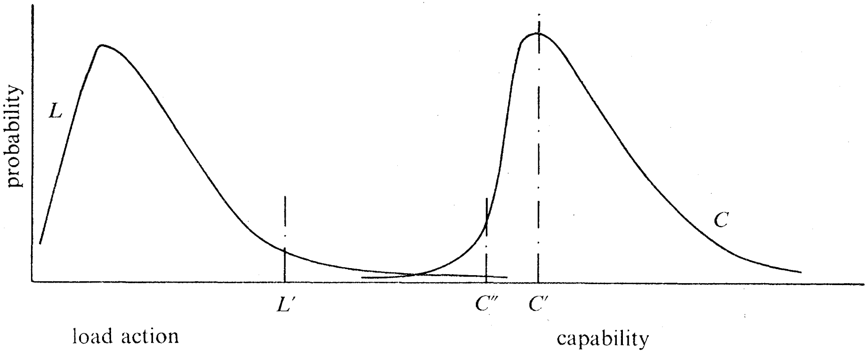

FIGURE 4. Reliability assurance procedures in the design of merchant ship structures.

Stage 1 (*traditional method*). Safety margins implicit in tables of required scantlings, or in empirical formulae representing tabular requirements.

Stage 2 (*limiting stress method*). Limiting stresses specified for each structural element, $\sigma \ngtr \sigma_r/n$, as a fraction of material yield stress. Stability controlled by specifying maximum slenderness ratios.

Stage 3 (*load factor method*). Use of load factors relating nominal design load L' to limiting load C', i.e. calculated load at which a limit state of structure is reached. Required load factor C'/L' assessed by considering uncertainties in L and C, and consequences of failure.

Stage 4 (*semi-statistical method*). Probability distribution of load actions L obtained from environmental data. Hence probability of L exceeding a calculated 'design' value of capability C'' within expected life of ship.

Stage 5 (*full-statistical method*). Variations in capability also allowed for by considering variabilities of constituent properties of structure. Risk of failure, $P(L-C) > 0$, obtained from statistics of L and C distributions. Acceptable risks determined from past experience.

(i) and (ii) were discussed in §§ 1 (*a*) and (*b*) above. Recognition of the crucial importance, in these direct design procedures, of explicit specification of safety margins (iii), has stimulated useful work on design criteria. Figure 4 attempts a summary of the main stages of development towards logical procedures for reliability assurance.

At present, the 'limiting stress' method (stage 2, figure 4) predominates; permissible stresses, previously unknown to the designer, are being specified. But two main shortcomings of the simple stress factor point the way to further research. Firstly, it may not properly express the safety margins against failure where this might involve fatigue, fracture, plasticity or instability.

Second, the essentially statistical nature of both loading and strength characteristics (see curves L and C in figure 4) shows that reliability assurance should ultimately involve an assessment of the probability that $L > C$. A start has been made on statistical assessment of C, and this together with increasing knowledge of the load actions, L, may enable reasonable estimates of failure risks to be made. Acceptable levels of these risks must then be deduced from past experience and social and commercial acceptability.

(*d*) *Design synthesis and optimization*

This eventual more explicit presentation of design codes of practice for merchant ship structures, made possible by the more scientific determination of loads, responses and safety margins, has now generated a real interest in methods of synthesizing this growing knowledge into practical design and optimization procedures. Other papers in this Discussion report will describe such procedures more fully; here only some pertinent scientific difficulties will be mentioned.

Structural design, regarded as an optimization problem, seeks that set of design variables y_n such that its 'utility' $U = F(y_n)$ is maximized, and that it fulfils its functional requirements without violating prescribed constraints on geometry and response σ_n, that is $G(y_n, \sigma_n) \geqslant 0$. The response of the system is known from the relations $H(y_n, \sigma_n) = 0$. But in most ship applications:

(i) n is very large, if topological, material and dimensional variables are included. Most studies have limited y_n to a few free dimensions, with results showing rather limited gains in efficiency.

(ii) The utility U is difficult to define. Most studies equate U with weight-saving, but (as further discussed in § 2*b*) a cost criterion may be a more appropriate measure of merit.

(iii) The behavioural functions H are generally complex and non-linear. Good approximations need to be developed.

(iv) The constraints G need to be formulated very carefully in view of their important effects on optima. This applies to constraints set by production requirements no less than those due to prescribed safety margins.

Although there has been very rapid recent development of the mathematics of optimization, and some notable applications to ships, the impact of these studies on design has not yet been very great. Perhaps merchant ship structures had evolved already to a high level of efficiency. But as new options in materials and in structural topologies become available, and as cost-sensitivity increases, then the optimization work of recent years may come to have a more direct effect on design.

(*e*) *Materials research*

The good cost–strength–weight characteristics of mild and medium strength steels for major merchant ship structures, and the lack of any emerging competitor, has resulted in a comparatively modest civil effort on materials research in this period. With the steep fall in demand for passenger ships, aluminium alloy requirements fell likewise, and marine interest in it was maintained largely through its use as a containment material in chemical carriers, and other rather specialized applications. Although no other homogeneous materials attracted much interest for ship structures during the period, the potential of various composites began to be realized. Glass-reinforced plastics displaced wood as the principal materials of pleasure boat construction; but large-scale applications have been few, a notable exception being the minehunter for the Royal Navy. Nevertheless useful data on material properties and production problems has been accumulated against the time when reduced material and production costs invite use in larger ships.

Concrete composites, in various forms, have had a growing number of protagonists, and feasibility studies of large tankers have been carried out. The material seems to have most promise for mass production of simple hull forms in 'green-field' shipyards where steel and steelworking labour is scarce.

Civil research on conventional structural steels has centred on three main aspects: fatigue and fracture properties of welded structures, optimum utilization of higher strength steels, and surface protection. Research on brittle fracture, which had declined as better material specifications were evolved, was stimulated (in Japan particularly) by a recent rapid sequence of major ship failures. Likewise fatigue, for long regarded as a rather minor hazard, has latterly received increasing attention as reports increase of damage, particularly in large tankers and fast container ships. Another recent and growing source of trouble has been 'through-the-thickness' failures in some critical areas of thick plating. It may well be that in the search for higher structural efficiency, and increased utilization of large, high-powered ships of monolithic structure, a period of renewed activity in materials research is at hand.

(*f*) *Summary*

The 1960s, then, saw change and progress on a number of important aspects. There has been in this subject a good level of technology transfer in matters such as statistical method, oceanology, computing science, optimization methods, and stress analysis; but at rather lower levels in materials science, production technology, reliability analysis and limit design. The emergence, late in the period, of a rational methodology of design has helped the naval architect to respond to the economic needs for innovation and extrapolation in ship design. The technological problems, and the resources to meet them, have thus remained roughly in balance.

2. Prospects for the 1980s

The design of ship structures, and the materials used, in the 1980s, will no doubt be determined, as now, by a concern for maximum efficiency and acceptable reliability. But before discussing in § 2*f* below some ways in which these objectives might be achieved, we consider briefly in §§ 2 (*a*) to (*e*) some more general features of the marine transport scene which might directly or indirectly affect decisions about ship structures and materials, and thereby influence research priorities.

(*a*) *Trades, routes and ship types*

Trade matrices in the 1980s are likely to show significant differences from those of today, because of the changing patterns of supply of primary and manufactured commodities, and of demand stemming from increase and redistribution of wealth. Some major influences affecting ship design may be:

(i) Commodities. Growing demand for bulk transport, particularly of specialized chemicals as well as foodstuffs and minerals.
Extension of containerization to other commodities and larger size of units.

(ii) Routes. Development of new routes (e.g. in the Southern Hemisphere).
Need for ships to meet special route requirements (e.g. draught limitations for large ships; ice hazards for polar routes).

(iii) Transport systems. Trend towards integration of land/sea, sea/coast, or deep sea/short sea systems. Greater efficiency of cargo transfer, requiring less vertical movement, or utilizing 'phase-change' of cargo (e.g. slurries, pellets).

(iv) Non-cargo ships. Growth of sea-leisure; hotel and cruise ships, marinas, air/sea holidays. Need for stable work-boats and platforms to support sea exploitation, in increasingly hostile seas.

Some broad consequences for ship structures and materials of such trends might be:

(i) Emergence of the multi-hull structure as a generic type. These may be in the 'end-on' mode (rigidly or flexibly coupled) in separable ship systems for sea/coast or short sea transport systems; or in the 'side by side' mode (catamarans or trimarans) where low motions and/or large deck areas are required, as in (iv) above.

(ii) Increasing use of structures with large perforations. Exemplified by present open-deck and 'ro-ro' ships, this trend towards operational efficiency would focus attention on stress diffusion and discontinuity problems, and on structural response to load actions other than those conventionally considered in design.

(iii) Route requirements will increase interest in hulls of unusual dimensional ratios, e.g. high breadth/depth ships for draught limitations. Because of this, and of size increases, *transverse* strength and stiffness of ships will assume growing importance.

(iv) Need for oceanological data for new routes.

(v) Development of materials combining both suitable containment and structural properties for chemical carriers.

(*b*) *Shipping economics*

In a similar manner, the shipowner's continuing concern to find the most profitable way of meeting the changing demands for marine transport may have some indentifiable implications for our subject. In seeking maximum transport efficiency, design decisions at two levels are relevant; first, the choice of the best overall ship characteristics; secondly, the optimization of the design within those specified characteristics.

Relevant overall ship technical characteristics are: ship type, size, dimensional ratios and form, speed, and ship life. Some consequences of the first three items are noted in (*a*) above. Other structural consequences of increasing ship size *per se* are:

(i) For very large ships, still water loading conditions assume greater importance *vis-à-vis* primary wave loads. Horizontal shear and bending actions also appear to become more significant.

(ii) Large spans of secondary structure call for closer attention to local loading. Shear strength of stiffening members, particularly at support points and joints, assumes increasing importance *vis-à-vis* bending strength.

(iii) Natural frequencies, varying approximately inversely with scale, make stiffness considerations more critical.

(iv) Loads arising during conventional launching become more acute.

(v) As plate thicknesses increase, the 'through the thickness' strength becomes more critical.

The interactions of ship speed and structural design are not very strong; but some structural consequences of any trend towards higher sustained sea speed are:

(vi) Increased dynamic loads, particularly at the fore end, raise problems of local structural design, and increase the resulting overall 'whipping' stress levels.

(viii) Increasing wave encounter frequencies raises the probability of wave-excited vibrations.

(viii) Higher power concentrations at the after end may accentuate vibration problems there.

Ship life seems likely to enter more strongly as a design parameter. Its economic consequences are important, although the evidence is not yet clearly in favour of deliberate reduction or increase in 'design life'. But the emergence of life as an explicit parameter would:

(ix) require statistical estimates of time-dependent strength aspects, especially fatigue;

(x) call for better knowledge of corrosion rates and of the efficacy and economics of protective systems.

At the second level of design, the owner's need to maximize the utility of his ship requires that its structure and materials are chosen for maximum 'efficiency' with acceptable reliability. Efficiency of the structure affects economic performance through the following characteristics of design:

Cost initial capital cost and 'operating' costs, e.g. maintenance and repair.
Weight more critical in weight-limited designs.
Volume occupied by structure.

The relative importance of minimizing these three (generally conflicting) requirements varies considerably with ship type. In the present context, our interest is in possible changes in their relative importance which may affect decisions regarding structures and materials in the 1980s.

The interactions of structural design and initial ship cost are discussed more fully in § 2*c*; but for weight-limited designs the choice between weight-saving and cost-saving can be judged by noting that, very approximately, of two competitive designs (A and B) having different values of structure weight and initial cost, the profitability of design B will exceed that of design A if:

$$S_w + S_c(R_c/R_w) > 0$$

in which S_w and S_c are the percentage savings in cost and weight of design B over design A, and

$$R_w = \frac{\text{weight of structure}}{\text{payload}} \quad \text{for design A}$$

$$R_c = \frac{\text{annual costs dependent on initial ship costs}}{\text{average annual costs}} \quad \text{for design A}$$

Thus the decision as to whether weight saving (through sophisticated design, high strength materials, etc) should be adopted at the expense of higher initial cost depends principally on the weight and cost ratios R_w and R_c. Typical values for a large modern bulk carrier might be 0.2 and 0.4 respectively. Hence the percentage saving in weight would need to be at least twice the percentage increase in cost if the profitability of the ship is to be improved. Moreover the trends are towards increasing R_c/R_w, as initial costs (and thereby depreciation charges) assume a larger proportion of annual outgoings, and as structural efficiency increases. Hence design to minimize initial cost of structure seems likely to assume greater importance than weight minimization.

Little systematic work appears to have been done on ways of increasing the volume efficiency of structures. If economic studies indicate potential benefits then we may see a trend towards designs with shallower stiffening members, possibly involving greater use of cross-stiffened structures, broad flanged stiffeners of double-skin construction.

The economic virtues of reliability, as distinct from efficiency, of structures, are likely to be increasingly apparent for a number of reasons. Although at present the proportion of annual shipowner's costs due to repair and maintenance appears to be small (5–10 %), the loss of earnings due to time out of service makes reliability increasingly desirable as ship size and cost increase. This is amplified by any trend towards crew reduction, whereby regular maintenance is reduced so that a crack or excessive corrosion might go unnoticed for longer periods. Add to this the growing concern of the regulatory and environmental agencies at the possible effects of marine accidents (see § 2*e*), and it is clear that design, both of structure and equipment of ships, must be increasingly committed to ensurance of reliability.

(*c*) *Shipbuilding economy*

The common concern of both owners and builders to minimize construction costs is likely to have important repercussions on ship structural design. In the U.K. at present very roughly one third of the initial cost of a ship is accounted for by the structure, this being divided about 60:40 between material cost and labour. The continuing trend towards capital-labour substitution will bring with it increasing applications of automated production procedures, and a reduction in structural features having high work content. Some likely consequences are:

(i) Reduction of number of structural parts and joints.
(ii) Standardization of stiffener sizes and plate thicknesses to take advantage of steel ordering policies and standard working procedures.
(iii) Increasing use of flat panel construction, both for internal and hull elements.
(iv) Progessive elimination of expensive structural connexions (e.g. requiring close tolerances, curved flanges, etc.) in favour of simple joints.
(v) Possible use of 'standard grillages', mass-produced and adaptable to a wide range of ship designs.
(vi) Growing importance of design-production links in the shipyard.
(vii) As the ratio of labour/material costs increases, decisions regarding materials may be affected.

The technical problems associated with such developments are self-evident, and decisions resulting from them will depend on optimization studies in which the trade-off between cost and weight (or other attributes such as surface area) are examined. For (iii), despite the limited success of the *Pioneer* design, straight-line forms will be increasingly attractive (but loss of the strengthening effect of curvature must be properly allowed for). Of crucial importance if these constructional trends develop, is the strength and design of joints. As stress levels increase in response to improved knowledge and efficiency, as dynamic stressing increases, and as higher strength and thicker materials are more widely used, so the fatigue and fracture strength of welded joints must become a subject for increasing concern. It is in the design of joints that the requirements of production and of structural efficiency are often most directly opposed, and the reliability of the structure most affected.

With regard to (vi), we may expect to see shipyard design offices very much more involved with the direct design of the ship structure than is the case today. Structural analysts at present being trained and recruited to design teams, will by then be concerned to know the effects on the reliability and efficiency of their structures of the production processes in the shipyard. Thus the interactions of design and production seems likely to be a major area of research and development for the future.

With reference to (vii) above, increasing ratios of labour/material costs will encourage the use of materials having high strength/weight ratios. Thus in the U.S. the economic case for using aluminium alloys for major ship structure has recently been re-examined. Any material with appropriate mechanical properties, and a rapidly declining specific cost, must have potential application for the 1980s. Fibre-reinforced composites, though still prohibitively expensive for large ships, may have found more extensive use by then. Changing cost ratios should also increase the use of higher tensile steels, provided the fatigue strength of details is better understood.

(*d*) *Sociological aspects*

Although apparently somewhat remote from the concern of this paper, there are certain sociological trends which seem likely to have some impact on ship structures and materials within the time-span of our enquiry.

The increasing expectation of higher living standards, will bring with it changing ratios of labour costs, and demands for better working environment. Thus will mariners (male and female), port and shipyard workers become both more expensive and more concerned to have good working conditions, in the physical and psychological senses. Some possible consequences for structural design are:

(i) Structures adapted to more mechanized cargo-transfer will be required.

(ii) High port costs will encourage the trend towards separable ship systems and articulated structures.

(iii) Low levels of structure-borne noise and vibration may increasingly be demanded, and may lead to the special use of materials and joints with good damping and transmission properties.

(*e*) *Legislation and regulation*

Environmental concern can be expected to be acute by the 1980s, and measures to ensure safety and to minimize pollution hazards are likely to impinge increasingly on design and operation of ships, either directly through legislation or indirectly through the insurance market. Of the two principal facets of control regulations:

(i) reduction to acceptable levels of the risk of accident;

and (ii) minimization of the adverse consequences of an accident;

the latter has most effect on structural design, as in existing subdivision regulations which affect the topology of ship structures in a very important way. Limitation of tank size is another such control; and in the case of ultra-hazardous cargoes, as with radioactive hazards, we may expect to see more stringent requirements for containment or for structural collision barriers. Although some useful work was done on this in relation to nuclear powered vessels in the late fifties, such regulations would necessitate further research on the gross damage and energy absorption of barriers, and would stimulate interest in materials and structures having high ratios of energy absorption to weight.

Codes of practice for ship structural design are likely to be increasingly standardized through international agreements of the classification societies. But their most important impact will be in their changed nature, which if present trends continue (see § 1*d*), will place a premium on good design, and raise the standard of design skill to meet the varied and novel demands of the decade.

(*f*) *Towards efficiency and reliability*

Aspects such as (*a*) to (*e*) above will affect the design problems posed in the 1980s. The ability to provide efficient solutions to these problems will then depend on the resources of available knowledge and skills. It can be expected that the kind of scientific design procedure outlined in § 1 will by then be well established; that oceanological data will be more plentiful; predictions of static and dynamic loadings more precise; and response analysis (especially in relation to structural dynamics and failure) more reliable.

Given this improved background to design, in what specific ways, if at all, will the designer then seek to improve the weight or cost efficiency of the structure without detriment to its reliability?

The interplay between structure weight, cost and efficiency was discussed briefly in § 2*b* above, and some approaches to initial cost reduction in § 2*c*. Weight reduction, provided it does not unduly increase cost, generally remains a desirable objective and can be effected in the following ways:

(i) By optimizing the overall topology of the structure. However, the positioning of the principal elements of structure is largely dictated by operational, functional and safety requirements; and the scope for radically improved layouts seems small.

(ii) Optimization of free scantling variables (stiffener sizes, spacings, plate thicknesses) for a prescribed topology and material. Recent studies suggest only small gains are practicable.

(iii) Use of material with improved strength/weight ratios. Apart from cost disadvantages, the use of such materials generally accentuates stability problems, so that their efficient use will call for lower slenderness ratios in plates and stiffeners, leading to new types of structural layout.

(iv) Relaxation of limitations on stress or deflexion, by reducing nominal 'safety margins'. A 10% increase in permissible stress for example, would save 7–8% of the structural weight of a large tanker (perhaps 2000 tons for a 250000 ton dwt tanker).

The last method (iv) thus offers substantial gains in efficiency and cost reduction. But can it be achieved without increasing risks of failure?

Reference to figure 4 suggests alternative ways of reducing the nominal safety margin (i.e. increasing stress levels) without loss of reliability:

(i) by reducing the uncertainties in prediction of loads L and strengths C through research on these aspects;

(ii) by reducing possible deficiencies in strength by raising the level of production quality control, inspection or testing; and

(iii) by deliberately reducing possible extremes of loading through the use of shipboard stress monitoring devices, by weather routing, or by more rigorous control of operating conditions.

Most of these strategies will tend to increase costs of production or operation, but these may be more than offset by the resulting weight reductions leading to greater operational efficiency.

3. PRIORITIES FOR THE 1970s

To what extent is the rate and direction of our recent progress in ship structures and materials technology (as outlined in § 1) properly adapted to the needs of the 1980s envisaged in § 2? Some observations regarding general objectives, and then more specific research needs, are offered below.

(*a*) *General objectives*

Basic and applied research and development in this field should:

(i) help to maintain and improve the efficiency and reliability of marine structures;

(ii) anticipate future structural problems; and

(iii) raise the general level of design competence to meet the more exacting demands of the future.

Of central importance in achieving all these objectives is:

(iv) The continuing evolution of more scientific and versatile procedures for design synthesis and optimization of marine structures. The need for such methods (as outlined in § 1) will be further emphasized by future developments as outlined in § 2.

(*b*) *Requirements of the design procedure*

Such a design procedure should ideally:

(i) be readily adapted to new methods and knowledge as they become available;
(ii) be applicable equally to novel or conventional structures or materials;
(iii) involve a logical assessment of load actions on the structure, taking account of routes, operating conditions, etc.;
(iv) incorporate analyses of structural response which correctly account for all significant modes of damage or failure;
(v) utilize stress criteria or safety margins which are based on assessment of reliability rather than empirical factors;
(vi) take proper account of ship life and associated acceptable risks of failure;
(vii) permit optimization of topology, material and scantlings;
(viii) enable different objective functions (cost, weight, etc.) to be investigated; and
(ix) be strongly linked with production, both in providing production-oriented information, and in allowing for the effect of production processes on structural efficiency and reliability.

Of course it is not expected that a sophisticated procedure of this kind would be used for every new design of ship. In many cases, especially where ruggedness and reliability are more important than transport efficiency, or where conventional designs are adequate, simpler empirical design procedures will suffice.

But where, as envisaged in §2, the demand for greater transport efficiency leads to novel structures or materials, or when shipyards wish to develop new production procedures affecting structural reliability, or when it is desired to optimize the design of a new 'standard ship', or perhaps when more stringent requirements for safety and habitability have to be met, then a design capability as outlined above will be a real asset. Some topics for the necessary supporting research are outlined below, based on the preceding discussion.

(*c*) *Detailed research topics in support of structural design*

Among many areas where significant uncertainty still exists, but which appear important in the light of future developments, the following are suggested as appropriate research topics for the 1970s:

(i) Load actions.

Improved prediction methods for wave loading (particularly along newly developing routes) and including horizontal shear, bending and torsion.

Estimation of probability of whipping loads.

Statistical combining of still water and wave loads, and of lateral and in-plane loads.

Local pressure loading on large ships.

(ii) Analysis of structural response.

Improved methods for three dimensional analysis of multi-hull, perforated or discontinuous structures.

Transverse strength of large ships and ships with high breadth/depth ratios.

Dynamic response, vibration and noise transmission in primary and secondary hull structure.

Dynamic response to wave or other excitation in large ships. Evaluation of damping characteristics.

Strength of elements under complex or combined loads.

Effects of imperfections and production processes.

Analysis of energy-absorbing protective structures.

(iii) Fatigue and fracture.

Dynamic strength of large welded joints in thick plates.

Fatigue in higher strength steels.

Development of safe-life or fail-safe design methods.

Through-the-thickness failure in large welded joints.

Effects of corrosion on fatigue and fracture.

(iv) Reliability.

Development of structural reliability analysis, particularly where fatigue and fracture may occur.

Assessment of existing levels of reliability.

Effects of production processes on reliability.

Evaluation of safety margins from reliability studies.

Effects of deliberate load control on reliability and operational efficiency.

Effects of quality control on initial cost and reliability.

(v) Design for production.

Effects of standardization on structural efficiency.

Development of standard grillages.

The efficiency of inexpensive joints.

Effects of production processes and sequences on structural strength.

(vi) Design synthesis and optimization.

Evaluation of alternative topologies.

Efficient optimization procedures for large numbers of variables.

Development of objective functions based on initial or life-cycle costs.

Optimization studies for alternative materials.

(*d*) *Conclusion*

A period of quite vigorous development in the 1960s has brought the science of ship structural design to a level which is now at least comparable with other heavy engineering industries. With some further research of subjects suggested in (*c*) above, and the concurrent development of logical and practical design procedures as outlined in (*b*), the industry should be well capable of meeting the demands of the 1980s in this area of naval architecture.