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Analysis and Design Requirements

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ABSTRACT

Major changes in the size, shape and performance of ships will create a severe challenge to the technical skills of ship structural designer. Fortunately, the groundwork has already been laid for the technology required to support him. The nature and quality of this technical base is discussed and gaps are identified. The serious need for closing the interface between researcher and designer is noted. References were selected to give a broad background in progress to date, and an easy initiation into all facets of the topic.

INTRODUCTION - THE DESIGN PROCESS

The practicing structural naval architect is at once blessed and cursed by the thousands of years of experience garnered by his precursors -- blessed, because few professions enjoy the benefits of so many thousands of full-scale experiments which led to today's empirical design methods, and cursed, because in the face of such soundly-based tradition, it is very difficult to promote innovation. However, innovation is required, and must be promoted, to meet tomorrow's design challenge. Empiricism, which served us well for millenia, has been stretched to the breaking point by our recent exponential increases in the speed and size of ships. Further, empiricism based on experience cannot safely deal with new concepts in hull form, propulsion technology and dynamic lift. Development of completely rational structural design methods is essential to insure that structural efficiency and reliability will keep pace with other performance parameters in the rapidly-developing field of marine technology.

Since the 1920's, major improvements have been made in the structure of ships, including the introduction and refinement of welding and the development of many excellent high-strength steels and marine aluminums. Even more important, the theoretical ground-work has been laid for a totally rational process of ship structural design, with the potential for optimization and lifetime reliability prediction. Between the development of a theoretical concept and its practical application in a design office, however, there is a great gulf which can be spanned only by hard work. The nature and scope of this work, and the new design methods which will hopefully result, will be the principal subjects of this paper.

Before discussing the future of the ship structural design process, it is necessary to outline briefly the present nature of the process, and the environment in which it operates.

The process of overall ship design is an iterative one, proceeding cyclically to resolve the conflicts among the many systems which comprise the ship, each of which has its own separate objective and constraints, but with each contributing to the overall goals of ship performance. These conflicts are often serious, and difficult to resolve, and the compromises which must be made sometimes produce marked changes in the objectives of individual systems. The system designer may find that he has developed two or three completely different systems for the same ship, with only the last representing a totally acceptable compromise in itself, and with other systems. The key words in the ship design process are "time" and "cost", and the usual demand for speed and productivity leaves little opportunity for any system designer to advance the state of his art.

The structural design process itself is also an iterative one, since direct structural synthesis has been achieved only for very simple structural systems. The core of this iterative cycle contains these steps: postulation of a geometry; analysis of the response under applied loads; comparison of calculated response against an established standard; and return to the geometry, revising it for an improvement in response. Other peripheral steps are required to support the cycle, including the calculation of loads, the carrying-out of trade-off studies leading to material selection, and optimization studies for certain geometric parameters, and the establishment of performance criteria for materials and structural elements. Once the general geometry is fixed, fabrication studies will locate butts and seams, and establish the nature of joints; protection studies will locate sacrificial anodes and develop coating systems; and a periodic maintenance plan will be developed.

The entire structural design process is normally conducted within the state-of-the-art, or at best with very minor extrapolation. The normal customer has no interest in supporting tool-sharpening, or in advancing the status of marine technology. He wants as much ship as his money can buy. Thus, the principal advances in the state-of-the-art have come through government or government-funded research programs, such as those of the Ship Structure Committee, the Navy, the Coast Guard and the Maritime Administration, or through the efforts of a few enlightened owners, operators and builders who can see the eventual profit accruing from a carefully-directed research task, or through the continuing work of the world's regulatory agencies, who clearly have a vital interest in the structural adequacy of ships. All these efforts may be sparked by questions raised, or preliminary investigations conducted, by technical or trade associations. The SNAME Technical and Research Program makes significant contributions to this end.

It's appropriate next to look at the design techniques now developing, to assess their potentials, and to determine what's left undone. There is a vast wealth of research applicable to the structural design of ships, much of it published in the professional journals of the civil and mechanical engineering societies and the foreign marine societies, and in the foreign and U.S. trade and technical journals, but this paper will merely identify the salient features of developing technology, using the publications of the Ship Structure Committee and the Society of Naval Architects and Marine Engineers as the principal sources.

A major concern throughout the design community is for the lack of follow-through among researchers. The bulk of all research projects culminates in reports which are not directly useable by the designer, and which require further translation and verification to become practical design tools. This translation of research results into design tools is an overhead task, and a time-consuming one, and only the largest and wealthiest of engineering activities can afford the luxury of pursuing it. It is vital that the translation be accomplished.

LOADS

Our present skills in analysis and materials technology far outweigh our accuracy in load prediction -- so much so that the practical structural designer has been reluctant to employ some of the more sophisticated tools of analysis available to him, knowing that inaccuracies inherent in his load criteria would wipe out any merit the analysis process might have to offer. One reason for this mismatch is the probabilistic nature of seaway loads, which prevents the clean, deterministic statement of load criteria with which the analyst is most comfortable. The procedures for predicting wave loading on a statictical basis are still under development. The other reason is the weight of tradition and a century of satisfactory experience with empirical methods. The time available to the designer for development of load criteria is seldom adequate for investigation of new prediction techniques. The inadequacy of empiricism in dealing with new hull forms, or even in coping with recent major increases in ship size and speed, has been the driving force toward improvement in load prediction techniques.

For most ships, the controlling load forms are consequences of operating in waves, and the probabilistic approach to prediction of wave effects, pioneered by Pierson and St. Denis (1) over twenty years ago, clearly represents both a marked improvement in prediction capability and a welcome transition from empiricism to a theoretically-supportable procedure. An excellent first exposure to the basic method has been developed by Michel (2), and is recommended for anyone interested in understanding the principles involved. The concept is completely rational, and readily understandable, and it is not surprising that Gerard and Lewis (3), in recommending a proposed course of action for the Ship Structure Committee in 1959, set forth the verification and development of the statistical approach to wave loading as one of the keystones to the Committee's long-range program. Work in this area has been continuously funded by the Ship Structure Committee since that time. Prediction of load response to waves of unit height and varying length, an important step in this procedure, was initially based on model tests. The strip-theory work of Korvin-Kroukovsky and Jacobs, supported by several sponsors and summarized in a SNAME monograph (4), provided the basis for a completely analytic replacement for model testing, thereby offering a significant saving in time and cost. Computerization of the strip approach has been supported by the Ship Structure Committee (5, 6, 7), and the SCORES program which resulted (8) has since been extended and adapted for a wide range of marine vehicles, including surface effect ships and semi-submersible drill rigs.

Prediction techniques must be verified experimentally, to give confidence in their outcome, and the techniques developed to date for unit response to waves leaves something to be desired in this regard. The SCORES program was verified initially against model tests in head seas, and correlation was good. Later tests, however, run for Ship Structure Committee in seas from varying directions (9) have shown that strip theory, as presently applied, runs into trouble in cases where wave encounter frequencies and ship motion frequencies approach coincidence, as in roll or in following seas (10). The Ship Structure Committee is supporting further investigation to tie down the cause of this problem and achieve correction. In addition, the assumption of linearity of response with wave height underlies the entire process, and recent work (11) indicates that non-linearities, which we recognize to exist, may have important bearing on predictive accuracy.

A serious defect in all strip theory approaches, from the designer's standpoint, lies in the format of their output. Since they were conceived as replacements for the static-balance bending moment calculation, and are based on a concept which divides the ship lengthwise into discrete elements, they give us gross hull girder shears, moments and torques on the planes dividing these elements. Where the ship hull is treated as a simple beam, this is an admirable presentation. However, for a finite-element hull representation, it requires a very tedious conversion to modify these section forces into sets of forces acting at the element nodes. An entirely different approach has been proposed (12), which provides a set of pressures on the surface nodes, and inertia forces on these and the internal nodes, to provide the same result in an output compatible with a finite-element representation.

As ships go faster, impulsive bending, or whipping, and impact, or slamming, became more important. For example, Heller and Kammerer (13) identified whipping as responsible for almost half the maximum total bending moment experienced in an aircraft carrier, operating at high speed in bad weather. Slamming pressures have been an important cause of structural damage for years (14), and a SNAME bibliography, "Notes on Slamming", is presently being readied for publishing. Since both of these phenomena are dependent on ship motion, it seems reasonable to consider whether the strip-theory approach can be expanded to include them. Kaplan (15) has made a first attempt to consider whipping, with some success, but the feature is not yet included in his SCORES program. An NSRDC program, IPRESS (16) generates design slamming pressures, using specific geometries of ship and wave, and predetermined closing rate, as inputs. Mating of this program to a good ship-motion program seems to be a possible way to relate slamming pressures to sea-state, which will solve the response-amplitude operator portion of the problem (17).

The above procedures relate ship geometry, speed and direction to response in a given regular sea. This is then expanded, by superposition, to give the response to a specific random sea. The last phase in the total procedure is to consider the effect of operating the ship, for a normal liftime, on its intended service route, exposed to a historically-supported distribution of possible sea states. We are interested in two outputs from this procedure -- a life-cycle history of loading, for fatigue analysis; and a lifetime maximum loading, for comparison against hull girder strength. For the first, the bulk of the area under the distribution curve, figure 1, is of interest. For the latter, interest is concentrated on the outer leg of the curve. Statistically, this has no limit, and can only be bounded by accepting some risk of failure. Outlines of appropriate calculating procedures have been developed by Lewis et al (18) and Mansour (19). Ochi has developed a separate process (20) for predicting maximum slamming pressures, incidence of slamming, and deck wetness.

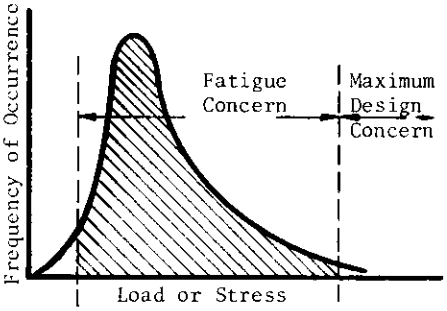

Figure 1 Areas of interest in the distribution of load or stress for the service life of a structural element.

Considering the working cost of all of the above procedures, and the intricacy of the input data they require, they can scarcely be considered practical for early phases of design, where major changes are frequent, and the ancient ways still give "ball park" figures which are adequate for this early work. These recent statistical approaches can prove indispensable, however, for new and novel hull forms, or for any other design problem which is outside the range of reliable extrapolation from present practice. They do require one important decision -- the acceptance of a specific risk of failure. The concept of failure as a design goal may be unpalatable to many old-time structural designers who control our destinies, but it is inherent in the statistical design process. It's an unspoken element in any design process which contains a random function. Even the underwriter's rules which govern ship design today make no promise to avoid failure, and now that we must define, in numbers, the risks we can afford to take, the results of years of ship operation under these rules can give us some clue as to what an acceptable number might be. Some early cuts at this number have been taken (21), but a definitive study is overdue.

Slamming and hull-girder bending are not the only loads needing consideration -- in fact, for some smaller, faster ships, normal surface forces may be responsible for more than half the structural weight. The present approach to these surface forces involves the arbitrary establishment of lines of design pressure head, based on estimated effects of roll and pitch in waves, tempered by experience. Strip-theory deals basically with regular waves, not with the ultimate, superposed combination of waves which provides the maximum pressure head. Something new is needed to develop a response prediction procedure for surface hydrostatic pressure over the entire envelope.

There are many load forms which the ship's structure must survive. Fortunately, they don't all reach their peak at the same instant. Some can be assigned to a specific part of the operational cycle, but others occur randomly. It's necessary, particularly for finite-element analyses, to establish a load envelope which includes all the load forms active at a given moment. This, too, can be done on a statistical basis, using combined probabilities of occurrence, as proposed by Lewis, et al. (22). At present, it's done by judicious but empirical selection of combinations of load maxima (23), but a formalized procedure is needed to produce load envelopes of design maxima for all structure. Abrahamsen (24) has proposed a deterministic approach to the superposition of hull girder loads, and Mansour, in work supported by SNAME and yet to be released, provides a statistical summation of secondary vertical hull girder stresses, for combination with similarly expressed primary stresses. The relative merits of all these approaches require careful comparison.

ANALYSIS

The function of analysis is simple. It predicts the response, in terms of stress or deflection, of a structure or structural element under a given load condition. Based on this prediction, the designer either modifies his structural geometry to produce a more desirable response, or he defines the predicted response as acceptable, and proceeds to the next problem.

There is a continuous spectrum of analysis complexity and sophistication available, ranging from the MC/I approach used in first-pass design to the full-hull finite-element analysis, typified by the American Bureau of Shipping DAISY program (25). All the elements in this spectrum may be invoked, at some time, in the ship design process. The choice of an analysis method for a specific problem must be based on a reasonable trade-off among the considerations of accuracy and detail required, the time and skills available, and the cost of the procedure.

In another dimension, the solution of the differential equations of element response, pioneered by such revered titans as Timoshenko, Flugge and Bleich, have long since progressed to the simultaneous solution of sets of equations for multi-element structures. To deal with structures of awkward shape, which produce unsolvable differential equations, or which even defy development of an equation, techniques have been developed which break these complex structures into simpler elements, which can now be solved simultaneously or progressively to give a close approximation to the true response. Both finite-difference and finite-element methods fit in this latter category, and these methods form the bases for most of the powerful computerized structural analysis methods now available.

Despite the publicity given to finite-element methods in the technical press, the classical differential-equation procedure is far from obsolete. For example, the line-solution procedure, widely used by European analysts, has been summarized in handbook form by Pilkey (26) under the joint sponsorship of the Ship Structure Committee, the Office of Naval Research, and others. Orthotropic-plate solutions, which are essentially differential-equation solutions to a much-simplified model of a cross-stiffened plate, are still being developed. A recent investigation by Mansour (27) into the response of the orthotropic stiffened-plate model beyond the elastic limit is being extended under SNAME sponsorship (28), to include the post buckling response of stiffened plate under combined loading. This problem of ultimate strength of stiffened plate grillages is under attack from several other directions, following the approaches used by Ostapenko (29), Chang (30), and Faulkner (31). The latter approach is one of the end-products of a year's effort by a select group of investigators coordinated by Prof. J. H. Evans of M.I.T. and jointly supported by the U.S. and Royal Navies and the Ship Structure Committee. The summation of results of this year of work has been published by the Ship Structure Committee (32), and provides an excellent guide to the design of hull girder structure, using the most up-to-date working methods in load prediction, analysis and material selection, including considerations of fatigue and fracture, corrosion, thermal effects and optimization. This document should be in every ship design office.

The biggest change in the analyst's capabilities has been wrought by the computer. While it can do only what the analyst himself can do, its speed and patience permit the tackling of the tremendous bookkeeping problems inherent in iterative or simultaneous solutions, on a time scale approaching compatibility with the design cycle. The computer readily solves complex differential equations, using iterative methods of proven validity, but its most valuable application for the ship structures analyst has been in the field of finite-element analysis. Conceived in the computer's own infancy, developed by Argyris (33), Clough (34), and a host of followers, this procedure can now provide bar, beam, shell and solid elements from which a representation can be built up for any ship structural component. These elements have been used to build up a variety of programs aimed at solution of specific ship problems. Typical of recent programs in current use, are those developed for Ship Structure Committee by St. Denis (35, 36) and Nielsen and Chang (37, 38, 39) for solving the three-dimensional problem of stress distribution in transversely and longitudinally framed structures. The advent of the latest generation of computers has made possible the development of super-programs such as DAISY (25), which can analyze an entire ship's hull structure at one pass.

The application of the finite-element process requires that the real structure be modeled as a complex of beams, shell and solid elements having mechanical properties equivalent to the real thing. The modeling process is the most critical step in the procedure. It is the last stronghold of true engineering judgment in the procedure, and deserves the most experienced talent that can be made available.

The newer, better finite-element programs ask only for the measurable physical properties of the elements, and save the analyst from the onerous chore of calculating stiffnesses in all directions. This is excellent, as long as the analyst can affort to run a fully-realistic model of the real structure, complete in every detail. Use of a coarser grid, which will save in computer dollars, requires considerable analytic work to combine the properties of all the members within a chosen element. The mathematical model is the engineer's statement to the computer of the problem he wants solved. It must possess those features of the prototype which the engineer wants analyzed, and in the proportions which will produce a comparable response, but it must be restricted in size and complexity to a level commensurate with the worth of the expected solution. Despite the critical nature of the modeling process, it is singularly ignored in the literature. The only way to learn the art today is through painful, expensive experience, although the NASTRAN system does run a user-oriented exchange which provides users with the benefits of the mistakes of their precursors. A useable text or course on the subject of structural mathematical modeling is long overdue.

The problem of mathematical modeling is worsened by the length of the painful process required to set up the usual analysis program. In addition to the decisions involved in selecting the model's gridwork, and the characteristics of the specific elements to be used, a tremendous volume of work is involved in locating the coordinates of nodal points, and calculating the characteristics of the individual elements. Preprocessors are available for some programs, which take over some of this odious chore, and for some of the simpler programs, interactive subroutines help the engineer to deal directly with the computer. The effectiveness of graphical interaction is now being investigated (40), following its apparent success in the aircraft industry. The GIFTS system (41), developed by the University of Arizona for ONR, is specifically designed for use in ship structural work, and is being tried out by Coast Guard and others.

The programs themselves are currently the least of our problems. The important finite-element programs presently in use are briefed by Pilkey and others (42), and the most useful to the ship design industry are discussed further by the contributors to the ONR symposium summarized in reference (43). They are being improved, in efficiency and capability, by such additions as reduced substructuring, isoparametric elements, varied "zooming" techniques for inspecting highly-stressed locations, and more economical matrixinversion techniques. They have, in general, more power than we can wisely use, and discretion is required to avoid overkill, with resulting cost ineffectiveness. They will continue to be improved, because of the glamor surrounding the programming game, and these improvements will not be wasted; but they are not our most urgent need.

Solution of the usual medium-to-large sized structural problem usually involves only about 10% of the total cost in the computer operation itself. The other 90% is spent in getting data ready for the computer, and in translating its output into useful conclusions. The activity in process in input generation has already been discussed. The output problem is of equal magnitude.

The volume of data developed by today's standard programs is truly and depressingly huge. As W. J. Roberts notes (44), the solution to one ship girder problem has produced a printout 4½ times the length of the ship. Reduction of this volume of data to useful knowledge can be a tedious chore. For structural data, offline sub-programs which prepare graphical plots of stress distribution or deflection can be very useful. It's even possible to apply dynamic loads progressively, plotting responses at regular time intervals, to generate a "cartoon" which, with the aid of a movie projector, gives a semblance of the real motion under load. This technique is particularly useful for developing an understanding of vibration problems. Other time-saving techniques can be invoked, if some foreknowledge of the probable outcome is available: output can be limited to critical areas; or it can be reduced by asking for stresses only above a certain level. Regardless of the available method used, however, the total time required to encode, calculate, and decode, is presently longer than is permissible in the normal ship design cycle, and the consequence is that the ship is designed by simpler, cruder methods, and checked, on a not-to-delay basis, by the computer. Techniques are under investigation which involve catalogs of elements, any of which can be plugged into a pre-established geometric skeleton by interactive graphic techniques, permitting a computerized version of the iterative procedure common to the slide-rule engineer. Within the narrow range of geometries and elements used in the aircraft design business, this process is working. The superposed load combinations, the complex and redundant structure, and the short design schedules imposed on the ship design community, make this a much more difficult problem for the programmer and the computer system designer. Interaction between a graphic console controlled by a mini-computer, and a data bank stored in a large computer, may make this approach practical.

Despite its awesome power, the computer is a mindless beast, doing only what it is told to do, but doing it faithfully and with great precision and speed. Its user must know what it has been told, in order to assess the validity of results. The limits of usefulness of the algorithms it employs, the ranges of its applied constraints, the quality of data in its catalog and other similar programmer-controlled limitations, all affect the quality of its response, particularly in the outer fringes of its applicability, and seemingly reasonable but inaccurate answers may result. Inclusion of logical and understandable error-messages in the program is essential. It is also the duty of the programmer to include, in his documentation, the assumptions and constraints that went into the program, to insure that it won't be applied outside its range. However, accuracy of an analysis will always rest with the engineer doing the analysis, and he must always view computer results with suspicion, and have at hand quick methods to insure that the answers the computer gives him are in the right ball-park. This is an area wherein the universities owe the technical world a service. Too many recent graduates believe that the computer is the only solution tool now needed. Slide rule sales have dropped to zero, and with this trend, interest in the classical methods has also dwindled. The computer must be fed and interpreted by reasoning and mistrusting individuals who understand the algorithm with which the computer is working, who are acquainted with the engineering principles behind the computer method, and who know -- or can easily calculate -- the range wherein the answer should be, and who are ready to investigate if something looks wrong.

Both management and engineer need to be well aware of the practical limitations of the computer. For example, it solves only the problem that was given it -- the engineer's mathematical model -- not the real, nuts-and-bolts problem. It will do only what it's told, and the engineer must take the responsibility to convert the computer's analysis of his model into an accurate analysis of the real structure. Also, it often speaks in average terms, particularly for plate elements. This is fine for a uniform or slowly-varying stress field, but in the vicinity of a stress concentration, it doesn't tell the worst. Computer approaches to stress-concentration solutions usually involve "zooming", or fining down the mesh in the critical spots. This is useful, once the critical spot is located -- but consider the plight of the analyst concerned with fatigue. He has to get a picture of all the highly-stressed locations, under each critical loading condition, with a quantitative measure of the stress for each. To do this fully, by computer, may cost more than the structure's safety is worth. Short-cuts to this process must be found.

Structural optimization has been with us for years. It is common practice, in trade-off studies, to investigate the effect on weight of modifying frame spacing (45), or of using other materials (46, 47). Our principal interest in optimization, however, is not necessarily weight. For most ship designs, optimization should probably be pursued on a basis of life-cycle cost, and this objective has too many variables to permit the classic minimization procedure to succeed. Even overall ship weight optimization has too many variables to permit a one-pass approach. Fortunately, weight optimization can be effectively pursued, on different segments of the hull girder, by individual actions, without too much error. Before it is employed, however, it must be clear that weight optimization has the potential for improving the ship.

The possibility of a total probabilistic approach to ship design was mentioned earlier. This concept has proven successful in estimating reliability in electronic components, and has been suggested as a possible approach to predicting the useful life of ships, or the risk of possible loss, or any other statistical measure of integrity or reliability. Many of the joint probabilities which go into such a determination are already being worked out -- for example, the prediction of maximum wave loading, and the normal distribution of yield strength. Techniques have also been suggested (48) whereby these probabilities can be combined to predict a cumulative probability of failure (or survival). This is an appealing prospect. However, Freudenthal (49) warns that, for large structures, failure statistics can't be developed experimentally, for economic reasons, and must be tentatively estimated from a combination of small-element testing and analysis. This is generally the approach followed in the aircraft industry, except that they often have production runs large enough to support fatigue-testing of one or two full-scale vehicles to provide experimental demonstration of the validity of the reliability prediction. This will seldom be the case for ship design and construction. However, we do have thousands of ships in service, and it may be possible to tap this large reservoir of operational experience to supply a statistical base for reliability projections, following the lead of reference (14).

MATERIAL SELECTION - THE FATIGUE AND FRACTURE PROBLEMS

Material selection is the structural designer's prerogative and responsibility. For commercial ships, this selection is normally based on a series of trade-off studies leading to cost optimization, which must consider lifetime profitability. For military ships, where profit is not a consideration, the goal is a combination of life-cycle cost and performance optimization.

The basic tools of the process are already available, in the form of economic models (50, 51), and simplified ship design models (52), and these tools have been used already for the Ship Structure Committee in evaluating the future potential of aluminum (46) and glass-reinforced plastic (47) for specific functions.

The conventional static properties of the available shipbuilding materials are readily obtainable - often from the material suppliers, and the designer will seldom have difficulties resolving the problems associated with strength and stiffness. The properties of toughness, creep and fatigue resistance are not as well as defined, and their application in the design process is far from being adequately described.

Creep - the long-term deflection response of a material under load - has not been recognized as an important problem for the shipbuilding profession, since creep in carbon steels is a negligible quantity at normal working temperatures. However, as we make wider use of fiber-reinforced plastics, aluminums and titaniums, creep will become an operating consideration and we must prepare to design for it.

The mechanisms of fatigue and of brittle fracture have been researched exhaustively, and are fairly well understood. Both require some form of material defect for initiation; fatigue can begin from a molecular defect, but fracture requires a more substantial flaw, sometimes as much as several inches in size. In fact, fatigue is often the cause of the flaw which ultimately produces fracture. Both can take place at average stresses well below yield, since the stress concentration at the flaw produces the stress levels required for damage. The propensity for fracture has been determined (53) to be largely dependent on material toughness, a temperature-dependent quality which is measurable by simple testing (54). Fatigue sensitivity, however, is more difficult to detect, and is usually measured by subjecting the material to accelerated cyclic loading, using many specimens at many stress levels.

While the theoretical explanation for the phenomena of both fatigue and fracture may be fairly well established, the approach to considering them in design is not nearly as clear. The approach in the past was simply to avoid all materials which proved to be sensitive to either fatigue or fracture. Following the epidemic of brittle fractures in ships during and immediately after World War II, material standards were established for ship steels which insured that, even at expected sub-freezing temperatures, any failure would occur plastically. Also, design and production standards were improved to avoid sharp corners, weld undercuts, and other stress concentrations where either fatigue cracks or brittle fracture could start. This pragmatic approach has been quite successful in reducing the number of hull girder failures. However, if it were to continue in force, it would place a serious restriction on ship structural efficiency, since it rejects most of the higher-strength steels.

The greatly increased competition in the marine field in recent years has placed much emphasis on efficiency in all ship systems, and the efficiency of the hull structure system can be measured by the ratio of strength to weight. The mild steel which has been in use for several decades is a reliable, forgiving, easily-worked material, but its yield strength is only 33,000 psi. This yield strength is readily increased by either alloying or heat treatment, and the resulting improved strength-to-weight ratio is attractive to a designer or owner seeking to improve his transport efficiency. Navy has successfully used a 45,000 psi alloy (55) to reduce weight in combatant hull structure for years, and commercial designers and owners have cautiously been experimenting with higher-strength steels. A guide for the use of high-strength steels in shipbuilding has recently been revised by the Society of Naval Architects and Marine Engineers (56), and will be republished shortly. Aluminum, also, has been used in superstructure and in some high-speed hulls, but seldom at its full strength capability. This concern for unrestricted use of these weight-saving materials is well founded. In general, as the yield strength of a metal is raised, either by heat treatment, cold working or alloying, its toughness decreases, its propensity toward fatigue damage grows, and the plastic range between yield and rupture shrinks. The designer who proposes to use a higher-strength metal must consider what effects these changes will have on his design. Since fatigue is a time-dependent phenomenon, he can no longer close his mind to the life of the ship after launching, but must become involved in such matters as overhaul cycles, minimum flaw sizes, crack growth rates, and non-destructive test capabilities.

The designer has two paths to follow (57). He can produce a "safe-life" structure in which, by judicious selection of materials and working stresses, he can insure that, for the specified operating life, fatigue cracks will not grow to critical size, or a "fail-safe" structure, in which a potential flaw and its resulting crack can be contained within a limited area. The first will put severe constraints on the materials which can be used, and will not permit achieving a particularly efficient structure. The second sounds risky, but is actually a very common practice. It can result in useful weight reduction, since higher-strength materials can be employed.

It is possible to categorize materials, through their toughness, by the size of the flaw which can propagate into a brittle fracture. HY 80 steel can operate in the vicinity of yield with a flaw several inches long, whereas some of the steels used in aircraft landing gear components must spend their life polished and oiled, since a scratch barely visible to the naked eye can cause fracture under load. This relationship between toughness and flaw size is one key to the designer's approach to material selection. He cannot tolerate the possibility of an undetectable flaw generating a catastrophic fracture, so he must limit his selection to materials in which the critical flaw size is readily detectable by the inspection procedure which is expected to be available.

In determining critical flaw size for the materials under consideration, the designer, with a tight schedule to meet, has no time for theoretical or experimental developments. He will normally use readily available data, such as the Ratio Analysis Diagrams developed by Naval Research Lab (58). These diagrams represent a generalization of available fracture mechanics knowledge regarding the relationships that tie yield strength and measured toughness to critical flaw size and probable failure mode. To enter them, it's necessary that toughness test data be available for the material in question, and that an assessment be made of probable operating stress and section thickness. The conclusions to which the RAD leads are by no means specific -- they can't cover the pecularities of the existing stress field, its modification by the crack's progress or the geometry of the crack tip. On the other hand, the designer is concerned with several hundred or several thousand tons of ship structure, and he normally can't investigate the stress state in the vicinity of all flaws-some of which will not develop for months. He has to be satisfied with generalities, and must make a quick decision, without benefit of any detailed analysis. If the material he's considering hasn't yet been characterized for toughness, he must drop it from further consideration, unless there's time for laboratory testing in the design schedule.

The other half of this flaw-size comparison is the detectability limit, and this is the point where the ship designer gets into the maintenance business, and also into time-dependent phenomena. Much of the flaw-critical area of a ship's structure is painted, or insulated, or otherwise uninspectable during normal operations, so inspection for flaw or crack development must be planned for overhaul, when coverings can be removed. The combination of detectable crack size and crack growth rate must be such that the crack can't grow to critical size before the succeeding overhaul period. Cracks for surface ships are presently detected by visual inspection alone. While this is quite positive and requires negligible instrumentation, it's quite restrictive to material selection, since the minimum detectable size is rather large, and the flaw must be at the surface. Acoustic and x-ray methods have been used for flaw detection in submarines and some high-performance patrol craft, with considerable success, but they are time-consuming and expensive, and their cost must be factored into the trade-off study which considers any material requiring such instrumentation. Obviously, development of an inexpensive, high-resolution flaw detection system will enhance the practicality of using higher-strength materials.

The factor of crack-growth involves the designer with fatigue, since cyclic loading is the cause of crack growth. For this specific part of the problem, the designer is not interested in the crack-initiation phase of fatigue, but only in the time it takes to grow a crack from just under detectable size to critical size. The traditional stress-frequency (S-N) diagram doesn't do a good job of this, since it's based on tests which include the crack-initiation phase, as well as a definition of failure based on decrease in strength, rather than fracture or a specific flaw size. The da/dN or crack-growth diagram, however, is just what is needed -- if it's available for the material under consideration. If not, there are some general expressions, (59), which apply to broad categories of steel, and are adequate for this purpose. They require calculation of the stress-intensity factor from the initial flaw size and stress range (yield to yield is the safest assumption). Integration of the process from initial flaw size to critical flaw size, to obtain number of cycles, is then required. This number of cycles is compared against an equivalent, estimated number of cycles which could occur between overhauls, to determine whether the possibility of catastrophic failure exists.

There is a pragmatic alternative to this, somewhat more expensive in construction costs, but less demanding of the designer. This is the use of crack arresters, of tougher material, strategically located throughout the hull girder to intercept running cracks before they become fatal. The concept dates back to the early days of welded ships, and its effectiveness is well-proven. Some suggested geometries are given in reference (59). This is one way of achieving a "fail-safe" structure, and does so without requiring alternate (and heavy), redundant load paths.

Fatigue can have three unpleasant conclusions -- either a through-thickness crack which leaks, a reduction in effective area to the point where maximum load can no longer be carried, or a crack which grows to the critical crack length in a brittle material. For a "safe-life" structure, the last two must be avoided for the ship's operating life. For a "fail-safe" structure, crack growth to critical size, between inspections, is the major concern, and will usually occur well before loss or effective area becomes a problem. The matter of crack growth between inspections has been discussed earlier. This leaves the problems involving the "safe-life" ship as the major concerns.

Fatigue damage is a function of two principal variables, cyclic strain history, and material properties. Since both of these vary from location to location, some way must be found of limiting the size of the problem to avoid having to look at every piece of the ship. The ideal structural design is the "one-hoss shay", in which every molecule gives out at the same instant. In a random-load, random-strength environment, this ideal is unachievable, and there will be many areas of the ship's structure which will endure more severe cyclic loading than the rest. In some of these areas, a fatigue crack will initiate, grow, and die out, due to lack of a supporting stress-cycle field. In other areas, however, the crack can continue to grow until failure through criticality or through loss of area occurs. The designer must use his stress analysis skill to detect the areas in which fatigue cracks will probably arise and grow to cause failure. He must then make some attempt to predict the process of crack initiation and development, with time in service.

An approach to prediction of fatigue damage requires three elements: prediction of strain history; characterization of fatigue response of the material involved, based on standardization tests; and a cumulative-damage theory. The usual S-N curve is fine for predicting the expected demise of a machinery component, under constant cyclic loading, but fails to do the job under the sort of random loading to which a ship is exposed. Here, the cumulative effect of distinctly-different levels of loading must be assessed. An early entry in this field was the Palmgren-Miner Rule (60), which makes no differentiation between varying sequences of loading, and is inexact, at best. Other cumulative-damage theories have been developed or are under development, some of which have sound probabilistic basis, some of which separate crack initiation from crack growth, but all of which have one basic fault - to date, they can boast no better accuracy than the Palmgren-Miner procedure. This, then, is today's procedure, hopefully to be replaced soon by something better.

The strain history must be a joint product of stress analysis of the structure, and a load history projection based on some form of operational scenario. If simple fatigue is the only concern, this can be expressed in terms involving only strain intensity and frequency of occurrence. If stress-corrosion is important to the material involved, then time, also, becomes important.

To use any cumulative-damage theory, it is necessary to have experimental data on the fatigue response of the material in question, over a complete range of strain amplitudes and ratios. For most of the common shipbuilding materials, this is available, in the form of S-N plots, for amplitudes, and Goodman Diagrams, for stress ratio effects. The available data is usually taken from machined-specimen tests in controlled environments. Real structure is often replete with flaws, fabrication notches, residual stress, and other stress raisers which can't be assessed for stress levels using normal analytic techniques. It would be most useful, therefore, if the testing process could include some of these fabrication-geometry characteristics to close the gap between calculation and reality. Unfortunately, this adds several new dimensions to the design of test specimens, and greatly magnifies the volume of desirable testing. Some excellent work has been done in this direction by Nibbering (61), concentrating on specific design features which have given frequent trouble with fatigue. Future work may well follow his lead.

Since fatigue prediction combines both theory and experience, at this stage, it's necessary that feedback be used to improve predictive accuracy, and thus reduce the need for large factors of safety in design. Navy is trending in this direction for design of high-performance ships (62). Their approach, however, appears to follow that of the aircraft industry, which makes extensive use of full-scale fatigue-test models to guide their maintenance and repair procedures and to reinforce theory for later application. Such a procedure is not economically practical, in the general marine field, and alternatives are needed.

CONCLUSIONS AND RECOMMENDATIONS

The mushrooming demands being made of water transportation have placed comparable requirements on the shoulders of the structural designer and the structural researcher. Over the past decade, the researcher has opened up great possibilities in design technology, giving promise that this challenge can be met. The results have not, however, been completely available for application. Not only must the designer learn the mechanism of this new technology, but the technology itself must be carried beyond the mere proof of capability, into the status of a verified, working tool, useable within the constraints of a tight design schedule. Of all the efforts presently needed in the field of ship structures, this translation of research results into design tools is the most urgent and most potentially profitable.

The adoption of probabilistic, rather than deterministic, definitions of design parameters, and the extension of probabilistic approaches into all facets of structural design, may be the most important single achievement of the past two decades. To be fully useful, it requires more than just the development of technology - it also needs a broad base of large-and full-scale experimental data, and an industry which understands the basis and application of the procedure.

The computer has overshadowed all other calculating tools, and has added tremendous depth to the designer's analytic capability. It makes severe demands, however, on the designer's resources of time and money, and its output is only as reliable as its input. Future engineers must be taught not only how to use the computer, but how to understand and live with its limitations, and a major challenge to the programming industry lies in the need for improving the techniques of getting onto and off the computer.

The improvements in operating efficiency realized through use of materials with higher ratios of strength to weight are also purchased at considerable pain to the designer and some added risk to the operator. The problems of fatigue and fracture are still in need of solutions, useable in the design cycle, which will take fullest advantage of the strength capabilities of newly-developed materials.

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Any trained and thinking structural designer must recognize that his achievements rest on the cumulative accomplishments of hundreds of men, working over thousands of years. Even in our own generation, it is impossible to sort out just a few great minds, since so many intellects have brought us to this stage in technology. Two major repositories of talent have achieved much, in the past few decades, to get the problem-owners and the problem-solvers together, and to lay complete, prioritized plans for the systematic acquisition of knowledge. These are the Society of Naval Architects and Marine Engineers, working through its Technical and Research groups, and the interagency Ship Structures Committee, through the Advisory Groups of its Ship Structure Subcommittee. They, in turn, derive their support from agencies of the government, from the American Bureau of Shipping, and from the private members and commercial enterprises which support SNAME. It is this support, in the long run, which makes progress possible.

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