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Experimental Methods in Ship Structural Evaluation

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ABSTRACT

Experimentation has always been at the core of technological development. Even now, experimental evaluations are needed to validate ship structural design and performance and to lay the foundation for developing and verifying more reliable methods of structural performance prediction. Among the more recent advances in experimental methods are the development of models fabricated of plastics to determine stress distributions and deflections under simulated service loadings, and the application of holography for obtaining response characteristics for complex structural subsystems such as propeller blades. The use of developmental testcraft has improved the technical and economic feasibility of ship structural calibration. The measurement of responses to applied loadings thus allows model and analytical methods to be more readily validated, and the vehicle itself may be employed as a more accurate load sensor. In order to develop fatigue resistant structural details, new methods are being employed to experimentally evaluate large scale structural assemblies under cyclic loading. Improved hardware and techniques are being devised to collect and to reduce experimental data more efficiently and reliably.

INTRODUCTION

Experiments have always served to lay the foundations for the development of the quantitative sciences. Even now, experimental evaluations are needed to

1. Provide the data bases upon which to build and validate analytical tools for predicting the behavior of systems and components,
2. Enable the scale-model checkout of designs in cases where existing empirical approaches are applied beyond their intended limits, or where even sophisticated analytical approaches leave room for doubt,
3. Check out the actual article in its real operational environment.

These reasons for experimentation generally pertain to any system, and to ships in particular.

To be more explicit, in the course of this paper it will be shown how the experimental approach can aid in all stages of ship development, from concept through final design, construction, trials, and even retro-fit if problems should develop after the ship has been completed and is operating. The particular emphasis will be in the area of the ship's hull structure and critical components of other structural subsystems.

Some examples will be given to illustrate how experimental approaches can be and have been employed to

1. Provide a basis for establishing load and structural design criteria for ships with unusual configurations,
2. Assess the degree of applicability of common design practices and sophisticated structural analysis tools such as finite element methods,
3. Provide design support by evaluating the relative cost and fatigue resistance of alternative structural details and material selections,
4. Diagnose problems on existing ships and evaluate possible solutions.

Experimental effort in the area of ship structures encompasses a broad range of activities. A convenient means for discussing this subject is to subdivide the efforts into three major categories which are primarily related to the physical size of the "specimens": small model investigations, large scale structural evaluations and ship trials.

Small structural models are generally evaluated "on the bench" or "in the (wave) tank" to obtain stress distributions or section responses under statically applied loadings or simulated sea environments. These models are used to best advantage when evaluating unusual ship structure configurations. Models for the evaluation of hull structure are generally between ten to twenty feet in length. Components may be close to full size depending on the ship size. Propeller models are usually not more than approximately two feet in diameter.

Large scale structural evaluations employ "specimens" which may vary from a one-quarter scale model of a ship hull to full-scale structural subsystems and components. These large scale models allow laboratory assessment of the static and fatigue behavior of assembled structures and diagnosis and solution of problems in large structural components and sub-assemblies. These evaluations require large laboratory spaces which have the capacity for applying large static and cyclic loads and supporting capabilities for detecting and repairing structural damage.

Little needs to be said about ship trials other than to reiterate their importance. Recent Navy developments in twin-hull ships, including both the conventional catamaran and the Small Waterplane Area Twin Hull (SWATH), and the Surface Effect Ships (SES) have led to new approaches and requirements in the ship trials area. Developmental testcraft are playing an important role in establishing the data base needed to validate or improve new designs. Improvements in shipboard data acquisition and analysis capabilities must keep pace, particularly the onboard measurement of sea waves.

The scope of this paper does not permit an in-depth look at all experimental methods related to ship structural evaluation. Attention will be focused on some of the more recent approaches employed at the Naval Ship Research and Development Center (NSRDC). This should provide a fairly broad picture of general methods and applications. Although the emphasis is on naval ships, the techniques described are readily applicable to all marine structures.

SMALL MODELS

General Considerations

The term "small models" refers to models which are usually less than twenty feet in length and one thousand pounds in weight. These models are used to obtain overall responses and/or detailed stress and deformation patterns in hulls and structural subsystems under statically or dynamically applied loads. Although they may be of metallic composition, they are not used for direct evaluation of fatigue behavior. Small models may be subcategorized into segmented and continuous shell types. It will be convenient to discuss these separately and, finally, to introduce a special variety of the second subcategory, the propeller model.

Segmented Models

Segmented models represent the mass and elastic properties of the structure in a discrete manner, much as mathematical "lumped-mass" models are used in vibrational analysis. Usually these models are employed to measure the structural response of the hull girder, including elastic-dynamic response of the ship model operating in a wave-tank simulation of the ocean environment. Figure 1 illustrates a segmented model. A metal bar in the model, extending along the longitudinal axis, is scaled to simulate the bending rigidity of the hull girder at discrete locations. The rigidity may be constant between these discrete points, or it may vary continuously by tapering the bar. The hull shell is segmented, and each segment is attached independently to the bar. The slots between segments are made watertight by applying strips of rubber across the slots leaving slack for small relative deformations between the segments. Ballasting is in the form of lumped masses, installed in the model so the scaled total weight of each seg-

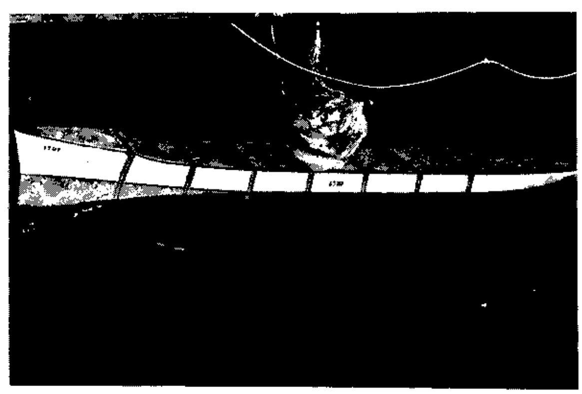

Fig. 1 Segmented Model

ment is simulated. Experience has shown that reliable measurements of responses, including elastic dynamic shears and moments, can be obtained when operating these models in simulated wave conditions (1). This modeling technique has been applied to various ship types.

In the case of a Navy Catamaran Auxilliary Submarine Rescue Ship, a segmented model was used to define expected wave induced primary loads in the cross-structure (2). Here the segmentation was merely a pair of beams, one forward and one aft, bridging the port and starboard hulls. This technique has also been used for obtaining data for load criteria development for small waterplane area twin-hull (SWATH) ships.

Continuous Shell Models

As opposed to the segmented variety, these models have a continuous structural skin. Rigid vinyl (polyvinyl chloride) is a material which is often used for these models because of its low elastic modulus which is approximately a half million pounds per square inch. This often allows for convenient modeling of structural dynamic response in the wave environment where time scaling is required. This is generally not the case for metallic models. Furthermore, fabrication in rigid vinyl is simpler and more economical than with metallic materials. The technique of modeling an entire ship structure in rigid vinyl has been described by Austin (3).

For hulls, an attempt is made to scale at least the most important hull-girder elastic properties. The primary structural bending, shear, and torsional rigidities may usually be scaled without undue effort. Scaling of secondary structural properties, such as stiffened plate local bending rigidity, is usually feasible. Representation of local plating properties is often a practical impossibility. If the structural geometry is linearly scaled in the same way as the overall geometry, model plating thickness may become exceedingly small. For example, at a scale ratio of 40, quarter inch plating becomes 0.006 inches thick. Then, model fabrication and handling problems result. Also, rigid vinyl is commercially available only in increments of .005 inches from .010 to .030 inches thick, and in increments of .010 inches from .030 to 0.100 inches. Fortunately, in many cases it is possible to allow all plating and member thicknesses to be oversized by a constant distortion factor without affecting the distribution of primary stresses. Critical buckling stresses are then increased, and plating stresses induced by normal loads applied in handling are reduced.

A dissertation on the hydro-elastic aspects of structural modeling is beyond the scope of this paper. It will suffice to say that rigid vinyl modeling generally allows the overall hull girder to be scaled in a way that permits the determination of elastic-dynamic response under wave impact loads. The determination of responses of secondary and tertiary structures to wave impact loads is possible in some cases. In addition to employing continuous shell models for obtaining stresses in simulated wave environments, this technique allows the determination of strain sensitivity to statically applied loads (calibration). Then, the model may be employed as a direct sensor for measuring wave induced section responses (shears, moments, torques). Relating wave induced section responses to the wave and operating conditions then permits the establishment of load criteria.

Recently, a continuous shell model of a 190 ton small waterplane area twin hull (SWATH) type craft was evaluated at NSRDC (Figure 2). The prototype was constructed of aluminum above the intersection of the struts and the upper boxlike hull, and of steel below this intersection. Because the elastic moduli of aluminum and steel are so dissimiliar, the model was constructed of two materials having the same ratio of moduli, rigid vinyl and glass reinforced plastic (GRP). This model is being used to explore the structural strength and vibratory characteristics of the vehicle. Results are being compared with full scale trials data and analytical predictions.

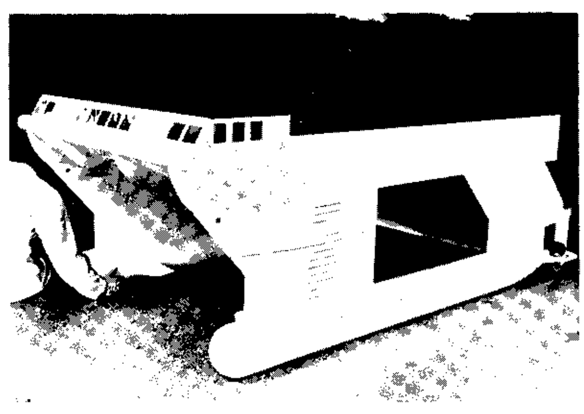

Fig. 2 Continuous Shell Model

Rigid vinyl models have also been employed in evaluating the structural behavior of the SL-7 containership, under Ship Structure Committee Sponsorship, and for assessing the effects of side openings in an aircraft carrier sheer strake.

Continuous shell models are also used to evaluate ship structural subsystems and components. In one case, rigid vinyl modeling was used to solve a strength problem in the foundation of the mechanism used to retract the foils on a hydrofoil ship. A model of the subsystem was built and evaluated to diagnose the problem. Then a proposed fix was incorporated into the model and re-evaluated. The fix was determined to be suitable and was successfully implemented on the prototype. This effort was accomplished in a few man weeks, with negligible material costs.

At present, the application of continuous models is restricted somewhat by the lack of variety in the elastic properties of available materials. Efforts are being made to search out new materials or combination of materials, so that small scale modeling techniques may be expanded to easily and reliably include investigations into areas such as buckling, elasto-plastic behavior, and local response to wave impact.

Propellers

Although propellers are a subcategory of the continuous shell models, they will be discussed separately because of the unique nature of their structural geometry and the specialized techniques being developed for evaluating their structural behavior. The prediction of stresses and deflections for a propeller operating in its normal environment is no simple matter. Even if the propeller is modeled, how does one determine where the maximum stresses will occur so that they may be measured; how are the stresses to be measured; and how should the loading be simulated?

Strain gages are of limited utility in evaluating propellers. Even if the model is operated in its normal environment, water, so that the loading may be reliably simulated, only a few gages may be employed because of the practical difficulties in transferring the gage-sensed signals from the propeller to a recording medium. Furthermore, the presence of the gages themselves may disturb the flow and thus the loading, or, if they are recessed and faired over, the structure is changed. Finally, one is left with the problem of where to mount the few gages that can be used. Fortunately, the use of photoelastic and holographic techniques promises to overcome many of these problems.

Photoelasticity. Photoelasticity is a common experimental technique for determining stresses in models made of a birefringent material. A birefringent material is one which, when stressed, refracts light into planes parallel to the two principal stress planes. The velocity of the light travelling in each of these planes depends upon the magnitude of the corresponding principal stress. For evaluation, the model is stressed by external loading, and polarized light is passed through the model and a polarizer. The resulting fringe pattern can be interpreted to give stress levels in the model material. Photoelasticity lends itself directly to the analysis of two-dimensional models. Three-dimensional models, such as propellers are more difficult but can be analyzed photoelastically by the use of a stress freezing technique. The model is heated in an oven, loads are applied, and while still loaded, the model is slowly cooled, thus retaining the stress pattern imposed at the higher temperature. Analysis is then performed by cutting slices from the model and examining them under polarized light. This technique, together with strain gaging, has recently been employed at NSRDC in analyzing stresses in various parts of controllable pitch propellers. This method has advantages over strain gaging in that stresses can be determined at any location on or in the model. However, except for inertial body forces, the loads must be externally and statically applied. In the case of propellers, this means that the loading must be known and representable by the application of a finite number of discrete loads. Photoelastic techniques can also be applied to non-birefringent objects by cementing films or thin sheets of birefringent material to them. Figure 3

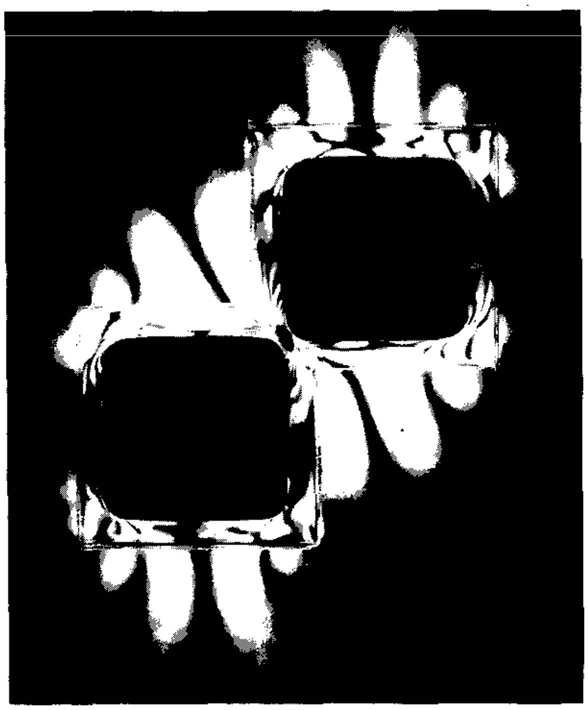

Fig. 3 Photoelastic Stress Pattern

shows a photoelastic representation of the stress pattern around a pair of openings in a plate under inplane loading.

Holography. Holography is a full-field, optical technique which employs laser light, generally to measure displacements as small as ten micro-inches. Holographic methods are directly applicable for measuring distortions, and for determining vibratory mode shapes. Stresses may be derived from displacement patterns and can be determined directly in certain transparent models. Advances are being made in the experimental evaluation of propeller strength and loading by employing holography to measure deflection, stress, vibration, and pressure loading on propeller models operating in a fluid medium (4). These methods are applicable to rotating objects in general, and therefore to such things as marine or aircraft propellers, helicopter rotors, turbine and generator blades.

LARGE SCALE EVALUATIONS

General Considerations

The term "large scale evaluations" means the experimental evaluation of large scale models of full or partial hulls, or prototype structural subsystems or components. Although such evaluations include the determination of buckling and ultimate strength, emphasis will be placed on the assessment of stress distribution and fatigue evaluation.

Obviously, these kinds of evaluations require large laboratory spaces and high capacity loading devices. For fatigue work, capability for high magnitude cyclic loading is required. This entails sophisticated electro-hydraulic loading equipment and electronic control systems. Fatigue evaluations of complete systems and subsystems require equipment and expertise for detecting and repairing fatigue damage. Furthermore, the determination of the loading spectrum to be applied in a given case is an art in itself.

The prediction of the fatigue performance of the primary structure or structural subsystems of a ship is becoming increasingly important. The development of new ship types and the application of new materials is taking the ship designer far beyond the point where traditional design approaches are readily and safely applicable. New ship geometries result in loadings and stress distributions not found in the existing handbooks. The use of materials such as aluminum in the primary structure raises questions as to the definition of good details, and expected frequency, cost and techniques of repair of fatigue damage. These questions may be best answered by controlled laboratory evaluations of large scale representations of ship sections wherein the behavior of detail connections can be determined, and repair methods evaluated.

At the time of this writing, static and fatigue evaluations are being performed at NSRDC on a prototype controllable pitch propeller assembly. Work is underway in conducting fatigue evaluations of hydrofoil foil structure models and a large scale aluminum hull structure. These evaluations will now be discussed in some detail.

Hydrofoil Box Beams

Fatigue and ultimate strength evaluations are being performed on box beams that are representative of hydrofoil foil strength sections. These evaluations are being done to develop information for including fatigue considerations in foil design. The primary objectives are threefold: First, to determine experimentally the fatigue characteristics and life of several materials in a representative structure under simulated life-cycle loading and environment. Second, to determine relative construction costs, fabrication difficulties, and achievable dimensional tolerances for the selected materials and configurations. Third, to assess the degree of agreement between fatigue lives predicted analytically from "coupon" specimens, and for the "as fabricated" box beams. The materials undergoing investigation include high strength steels, stainless steel, titanium alloys and fiber reinforced plastic. This evaluation program was begun about three years ago. To date, over half a dozen foil models have been evaluated to equivalent operational lives of fifteen years. Although the program is not yet completed, information of practical value for design consideration has been gathered in the following areas: relative fabrication costs of candidate materials, weld configuration for least distortion, relative fatigue life for material selection and fabrication scheme, best methods for making repair welds, ultimate strength prediction, degree of applicability of cumulative damage theory and fracture mechanics techniques.

Aluminum Ship Evaluation Model.

Recently, NSRDC began preparations to conduct fatigue evaluations of an 85 foot long, 40,000 pound, aluminum hull (Figure 4). These evaluations will provide useful information for developing improvements in several areas relative to the use of aluminum in ocean going ships. The reliability, efficiency, and cost of particular details will be examined. For example, the performance of fillet welds smaller than required in existing Military Standards will be explored to determine whether these smaller welds, which produce less distortion, will perform reliably. Also, the relative performance of continuous and butt welded longitudinal members will be assessed. Structural details incorporated in this model are typical of those currently being used today in high performance ships. The particular aluminum alloys incorporated in the model are 5456-H116 and 5086-H111.

Fig. 4 Aluminum Ship Evaluation Model

In order to develop techniques for assessing the initial and progressive "health" of a structure subjected to fatigue loading, methods of non-destructive testing for shipyard use will be evaluated. Visual, dye penetrant, radiographic, eddy current and ultrasonic methods will be compared to establish relative merits of time and reliability for accomplishing inspections.

The determination of time or service increments at which inspection should be performed will be explored. Maintenance and repair methods will be evaluated to compare relative costs and effectiveness. Evaluation will be made of existing methods for predicting stress distributions as well as fatigue and ultimate strength. This effort will also further develop our capability for validating ship structures before fleet deployment.

The development of loading spectra to be employed is nearly complete. Data from model and full scale trials have been used. The method of loading will be through a series of 13 load frames, one at each transverse bulkhead. Resultant applied bending moments will be on the order of ten million foot-pounds. An operational life of fifteen to twenty years for the prototype will be simulated in about two and a half years of laboratory time.

SHIP TRIALS

The area of ship trials is one in which it may readily be presumed that little technology is emerging. However, there are some new developments to report. Significant advances are being made in instrumentation for measuring and recording the structural behavior of ships at sea. Before discussing these, an approach to ship development which is not entirely new but which is becoming more prevalent bears some discussion.

Developmental Testcraft

The idea of employing manned models to evaluate new ship concepts is not entirely new. However, technological progress continually brings previously unfeasible concepts closer to the realm of practicality. These new ship concepts are frequently so dissimilar to existing vehicles that little basis exists for designing them. In many cases, analytical and model predictive methods are not adequate to fully assess the performance potential of the vehicle. Therefore, the decision is often made to build and evaluate developmental testcraft. This approach has been taken in the case of hydrofoils, surface effect ships (SES), and ships having both a small waterplane area and twin hulls (SWATH).

Generally, these testcraft provide an excellent opportunity for measuring structural responses and evaluating structural behavior so that prototype structural performance can be more accurately predicted. In particular, testcraft provide improved technical and economic means for conducting structural calibrations (relating strains to applied static loads). This then allows the vehicle to be employed as an accurate sensor of total section responses (shears, bending moments, torque) so that more reliable prototype load criteria may be developed. Furthermore, the measurement of responses to known static and wave environmental loads provides baseline data for the development and validation of model and analytical predictive tools.

Recently, NSRDC has performed static load calibrations of the primary structure of three developmental testcraft: a 100-ton SES, a 190-ton SWATH (referred to earlier), and a 3.5-ton SES with a high length to beam ratio. In the case of the 100-ton SES, each loading condition was obtained by jacking the craft to fully support it at a particular pair of transverse bulkheads. Changes in applied hull girder shears, moments, and torque were then related to changes in strain levels. By this method, a matrix was constructed by which hull girder bending moment and torque could be obtained from strains measured during sea trials.

In the case of the SWATH type vehicle, the significant primary loads occur in beam seas and tend to differentially move the hulls toward or away from each other. Therefore, static loads were applied by a jack and pipe-column placed in series between the hulls. Again, strains were related to side load magnitude. Comparison of these results with similar data obtained from a continuous shell model (Figure 2) show fair agreement.

For the 3.5-ton manned model of the high length to beam SES, the hull girder was calibrated by changing the still-water moment. This was accomplished by repositioning moving weights (people, actually), and simultaneously measuring strain changes. Transverse trusses were calibrated in a similar manner so that these may be employed as relatively large-area impact response sensors from which impact load criteria may be derived.

These types of static load evaluations are providing the basis for validating sophisticated experimental and analytical stress determination tools such as rigid vinyl models and finite element methods. Thereafter, it may be possible to calibrate ship structures either in the laboratory or analytically thus reducing the cost and complexity of developmental testcraft trials evaluations.

Instrumentation

Instrumentation refers to the equipment used in measuring and recording responses. A discussion of this area in depth would be somewhat beyond the intended scope of this paper and would add very little to the main point: experimental evaluation is often the best method of checking out a ship structure before the ship is built. However, the instrumentation employed does bear on the economy, effectiveness and reliability of experimental evaluation. Advances in the instrumentation area continue to be made thus expanding the quantity and quality of data measurement and analysis. Improvements in strain gages, accelerometers, and other sensors continue to expand the range of applicability of experimental methods. Sensing devices based on radar and sonic principles are gradually providing better on-board wave measuring capability, but more emphasis is needed here. Application of the laser promises to greatly improve the capability for measuring the deflection and distortion of ship structures at sea. Data recording devices are improving rapidly. Magnetic tape recorders and associated electronic equipment now permit the recording of signals from over a hundred transducers on one reel of tape. Also, miniaturization and other electronic advances are bringing the capability for shipboard data analysis closer to practical and economic feasibility. For example, devices already exist which can generate various kinds of statistical analyses of data as fast as it is being collected. Evolutionary improvements in instrumentation are expected to continue to increase the effectiveness and economy of ship trial evaluations.

SUMMARY

Small models, large scale evaluations, and ship trials each have their own particular areas of application for contributing to the development of improved ship structural systems and components. Small models are particularly useful for determining sea loadings and responses for ships still in the early stages of design or concept development, as in the case of twin-hull ships. Stress distributions and vibratory characteristics can be defined using these methods, as has been done for aircraft carrier side openings and a SWATH type vehicle, respectively. These modeling approaches have also proven useful for diagnosing and solving problems related to ship structural components such as propellers and a hydrofoil retraction mechanism. Optical techniques such as photoelasticity and holography promise to vastly expand the utility of small model evaluations, especially in the area of propellers.

Large scale evaluations are being employed to predict the fatigue performance of ship structures and components. Data of practical use in tradeoff studies and detail design are being generated. Relative fabrication costs for different materials, expected frequency of fatigue damage, improved details and repair methods are being developed for hydrofoil foils. A large scale evaluation of a complete hull will provide similar data for aluminum ship hull structures.

Ship trials are being performed on developmental testcraft. Hull structural calibrations and rough-water trials data are being employed to more accurately predict the behavior of prototypes at reduced risk and cost. Additionally, these data are valuable in improving and validating design and analysis methods.

Instrumentation improvements promise to expand the utility and range of application of experimental methods for developing more efficient, reliable, and economic ship structural systems, subsystems and components.

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