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Final Report

for

Development of Integrated Ship Structural Design Technology

VIRGINIA
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Virginia Tech

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Final Report

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Integrated Ship Structural Design Technology

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Owen F. Hughes
Professor of Ship Structures
Department of Aerospace and Ocean Engineering
Virginia Tech

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DR. OWEN F. HUGHES
PROFESSOR OF SHIP STRUCTURES
AEROSPACE & OCEAN ENGINEERING
VIRGINIA TECH

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The report presents the planning and overall strategy for a five-year inter-disciplinary effort to develop a comprehensive reliability-based Ship Structural Design System, involving applied hydro-analysis, non-linear sealoads, improved first principles structural analysis and failure mode evaluations. Although not funded beyond the planning stage, the project produced an improved QUAD4 finite element and an improved method for predicting flexural-torsional buckling.

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1. Introduction

This is the final report for ONR project No. 94-1-0653. The project was intended to be a subset of a multi-year inter-disciplinary effort to develop a comprehensive Integrated Ship Structural Design System. This system was to be developed along with the University of Michigan, separately funded in a coordinated grant, and be reliability-based. Subordinate topics included applied hydro-analysis, non-linear sealoads, improved first principles structural analysis and failure mode evaluations. In October of 1995, more than three years short of the proposed delivery date for the Design System, participants were notified that funds for the upcoming years would not be available. The very nature of such a broad project requires that the early stages have a heavy emphasis on planning and strategy and consequently very few self-contained, short-term results. In addition many of the project participants were forced to seek new positions and relocate with very short notice, thus making it difficult to document their efforts in a final report. Nonetheless several significant advancements were made with regards to the project's overall goals. This report summarizes these accomplishments, grouped into four areas: planning, structural analysis, structural limit states and validation.

2. Planning

2.1 Main Objectives

Early on during the project four main objectives were set for the Integrated Ship Structural Design system:

1. Apply the results of hydro-analysis research to develop realistic design loads.
2. Fundamentally improve ship structural design methodology by utilizing the full capabilities of today's desktop PCs.
3. Implement a reliability-based approach to ship structural design.
4. Produce a definitive solution to the long-standing problem of fatigue.

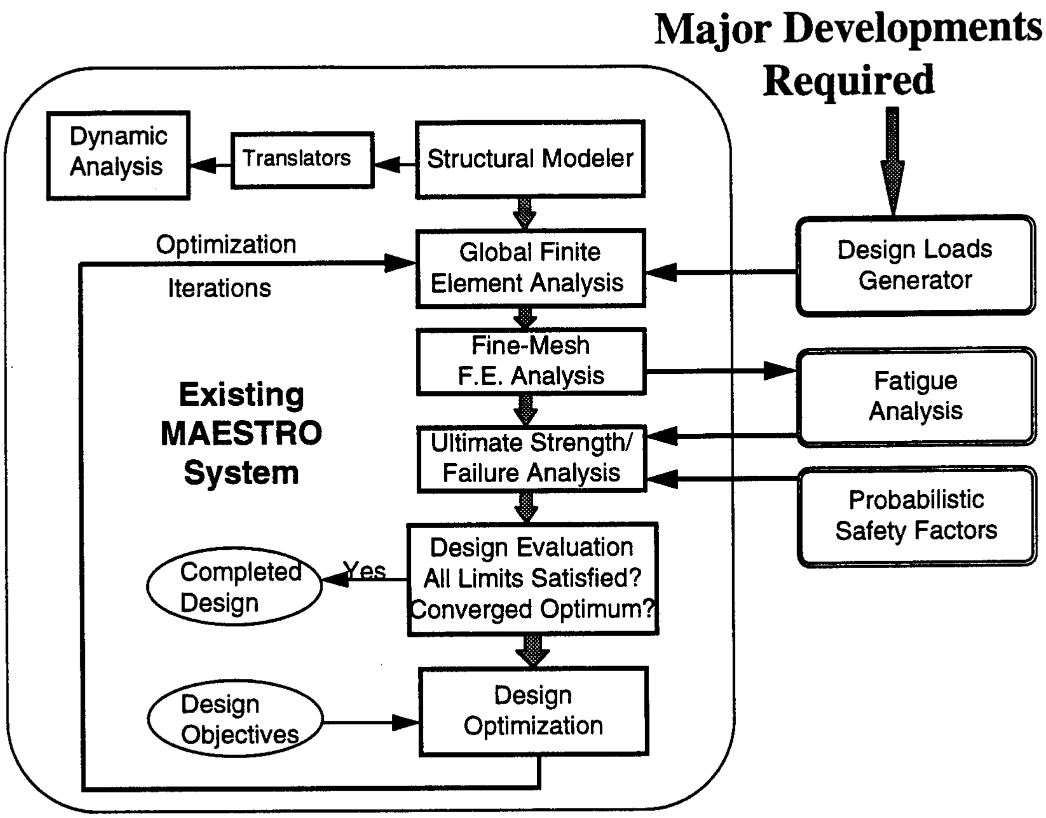
Each of these objectives was chosen because project participants thought they were both achievable and would result in a dramatic improvement in Naval structural design. The attainment of each objective was either necessitated or suggested by recent results. In the case of objective 1, ONR has heavily funded basic research in CFD for many years and it appeared timely to roll that effort into an application for naval structural design. Objective 2, is related to the prior objective in that the continued escalation of computational power on PC's and workstations requires structural designers to rethink the process of structural design. Reliability-based design is far beyond the research stage for most areas of structural design, and the naval field, with its inherently probabilistic lifetime loads, is far behind in the conversion stated in objective 3. Finally, for objective 4, each of the first three objectives builds toward a suitable solution to fatigue design. The Work Plan to achieve these objectives is shown in the schedule on page 10.

2.2 Build Strategy

Once the project objectives were clearly defined, participants were able to generate a strategy for accomplishing those objectives in a manner which maximized the useful results delivered to the Navy. In essence a modular design system, to which components would be added as they were developed, was necessary. Such a system would provide the following application-oriented benefits:

1. Produce practical and timely engineering tools.
2. Improve structural design by using more accurate engineering methods.
3. Deliver computer software proven in the ship engineering environment.

The logical basis or framework for this modular design system is MAESTRO. MAESTRO is an existing structural design program that is already in use by the US Navy. Using it as the basis has the advantage that the project developments are immediately usable and are inherently integrated. The envisioned design system, including MAESTRO and the additional project generated components, is shown on page 4. By following this "build strategy", the project developments would have been produced within the time frame of the project, as shown in the work plan. Note that only the improved QUAD4 element was scheduled to be completed by the time project participants were notified the project was canceled. As shown in Section 3.1, this objective was achieved. Other achievements are described in sections 4.1 and 4.2.



2.3 Required Features

The project participants translated the objectives into a series of requirements for an Integrated Ship Structural Design system:

1. Realistic sea loads.
2. Full ship finite element modeling and analysis.
3. Unified overall analysis and local stress analysis.
4. Comprehensive failure analysis.
5. Fatigue analysis.
6. Reliability-based, using the LRFD format of probability based safety factors.

7. Optimization capabilities to achieve reduced weight and cost while retaining a consistent level of safety.

Such a transition from empirical rulebooks and design data sheets to a first principles structural design system is in keeping with the work being performed in the commercial ship world by classification societies such as ABS (Safehull), Lloyd's Register (ShipRight), DNV (Nauticus)and Bureau Veritas (Veristar).

2.4 Design Loads Generator

One of the critical planning issues early on was the transfer of loads information from the complex hydro-analysis common in the research world to a form sufficiently accurate and efficient for structural design. In cooperation with Dr. Armin Troesch at the University of Michigan, the concept of a design loads generator (DLG) was developed. In essence the DLG was to be a linear loads predictor augmented by various nonlinear routines and a database of parameters. Initially the nonlinear components were to be existing empirical and semi-empirical methods calibrated and improved through computational fluid dynamics (CFD). In tune with the intended design system, the DLG was to include the probabilistic, or statistical, nature of the loads as an integral part. The DLG was to be modular, with parts readily upgradable (by replacement) as technology or opportunities allowed. In essence the DLG was to be a comprehensive interface between the often disjoint fields of Naval CFD and ship structural design.

3. Structural Analysis

3.1 Improvements to the QUAD4 Element

In the area of structural analysis, the Virginia Tech project team made a significant improvement to the NASTRAN QUAD4 shell panel element. In-plane rotational stiffness was added to each node of the element. This corrected a problem (present in many FE codes) which can cause a displacement error (and in turn an error in the resulting stress level) of 20% for elements with trapezoidal shape. The project also tested and validated another improvement to the QUAD4 element made by Dr. John Adamchak, who incorporated the stiffness of panel stiffeners into the element. In combination, these two developments create an element that has no equal for the vital task of coarse mesh finite element analysis of a complete ship structure.

4. Limit State (Structural Failure) Analysis

Limit state analysis is the process of calculating the levels of stress that would cause failure of the various structural members, and comparing these with the actual stresses to determine if a structural failure (due to yield, buckling or fatigue) has occurred. Work on limit states was pursued in two areas: flexural torsional buckling of stiffened panels, and fatigue design of ship structures.

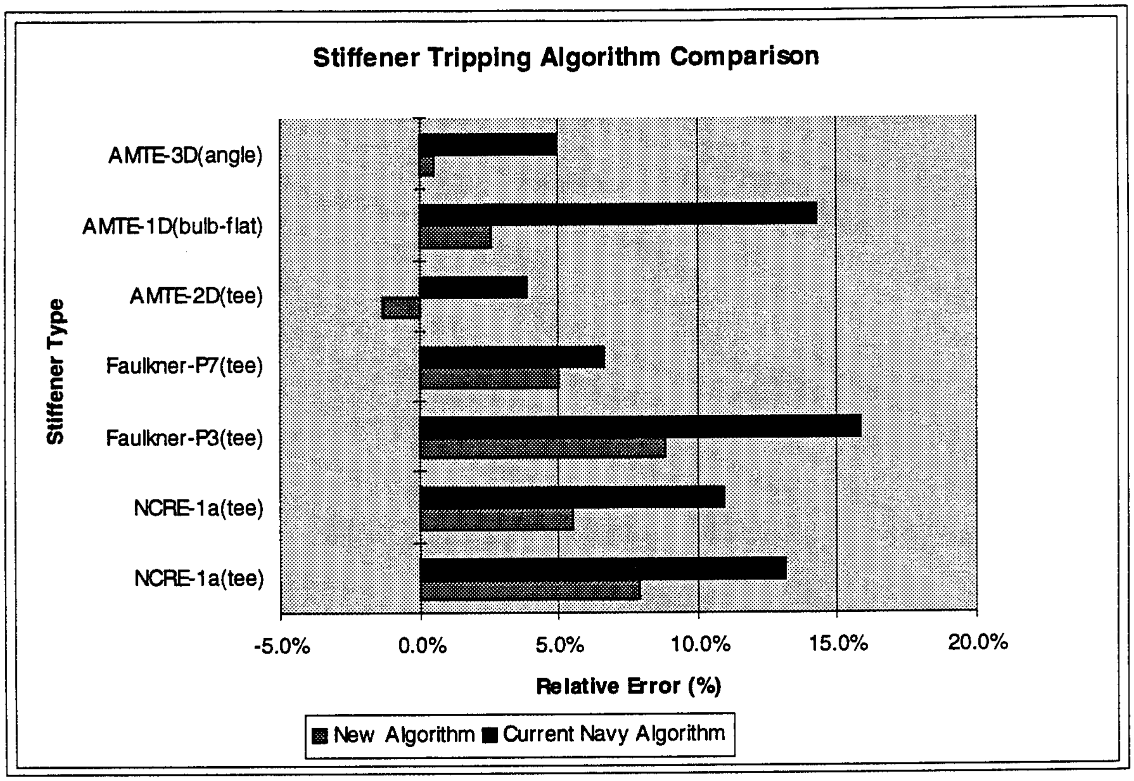
4.1 Flexural Torsional Buckling

Significant progress was made with regards to the collapse of stiffened panels due to flexural/torsional buckling ("tripping") of the stiffeners. Project personnel developed a new algorithm which agrees well with both experimental and non-linear finite element results. This algorithm has a strong advantage over non-linear FE in that it is far more efficient, even to the extent that it can be included within the evaluation loop of an overall ship structural optimization method.

The new stiffener tripping algorithm addresses several topics that have long been troublesome for naval designers:

1. Applicable to unsymmetric stiffeners such as angles and bulb flats.
2. Can account for the effect of web deformations for the case of lateral loading.
3. Can account for unequal end moments.
4. Can accommodate any combination of axial, end bending and lateral loads.
5. Provides an improved representation of plate rotational restraint.
6. Provides an improved representation of plate effective width.

The chart below compares the relative error in predicted buckling load for both the current Navy algorithm and the newly devised method versus experimental results for various stiffener cross sections.



During 1995 the algorithm was completed, validated and installed in MAESTRO's stiffened panel strength analysis, and is now available to the Navy's ship structural designers.

4.2 Fatigue Design of Ship Structures

The project also examined the complex limit state of fatigue failure. Most of the work on fatigue consisted of long term planning and establishing the requirements to be met by the DLG. The long range planning identified two major subdivisions of fatigue analysis that need to be addressed: linear and non-linear. The bulk of a ship's fatigue life may be identified in terms of linear events. In this case it is possible to use a frequency response fatigue analysis method based on: (a) short term spectra of wave loading, (b) S-N curves to calculate cumulative damage, and (c) fine mesh FE for hot-spot stress evaluation.

Linear fatigue analysis, while not yet a common component of ship structural design, is nevertheless a well posed engineering problem for which suitable technologies are available.

Non-linear ship response to extreme conditions and the resulting fatigue damage is not readily analyzed with the above techniques. In this case a time domain solution for specific time periods (such as a slamming event) must be performed. Such a time domain solution within the Integrated Design System requires the efficient calculation of loads, the transfer of such loads from the CFD code to the structures code, coarse mesh FE analysis of the entire ship, fine mesh FE analysis of the required connection details and a fatigue damage calculation. All these tasks must be repeated for every time step during the non-linear event.

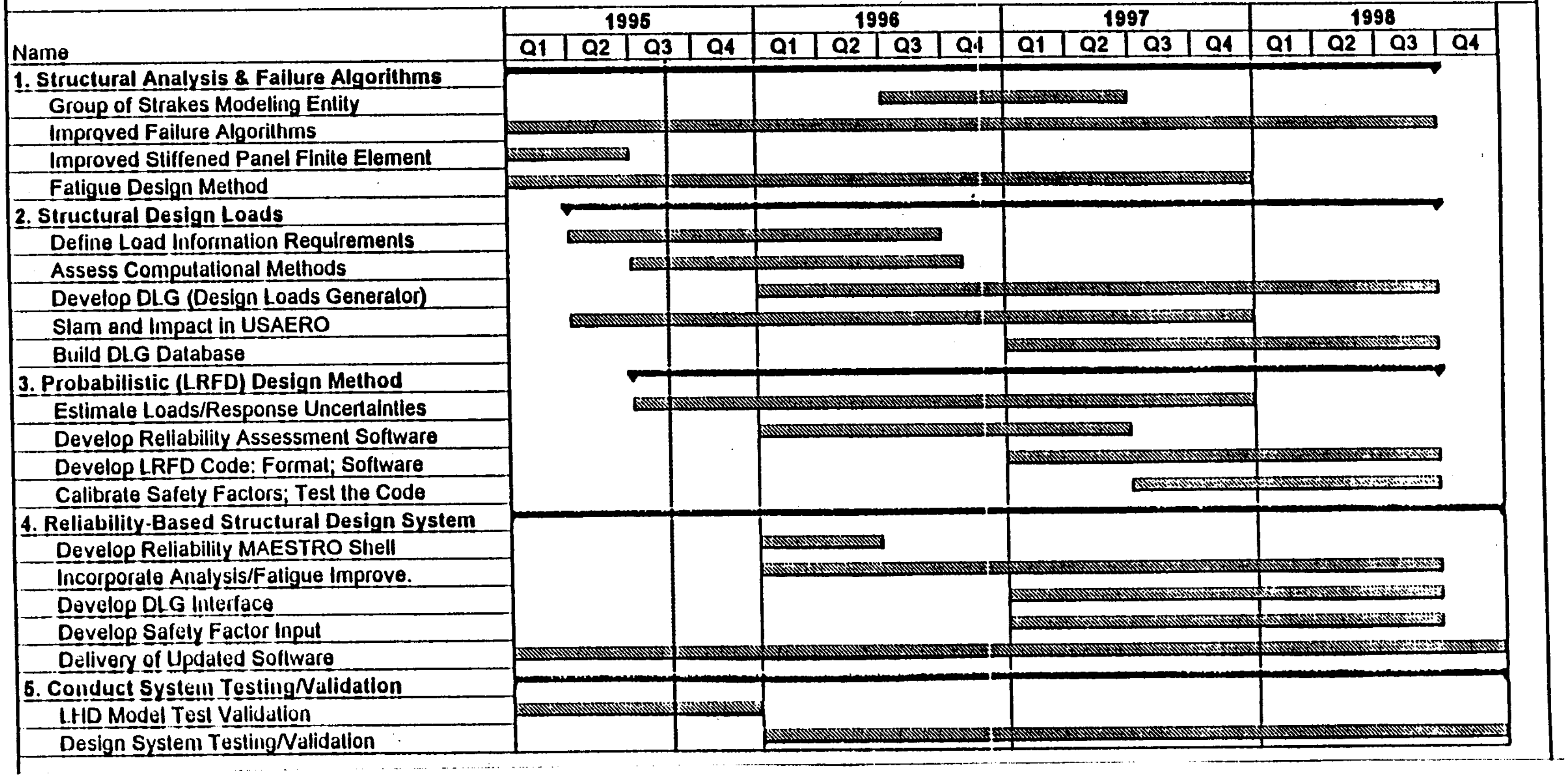
Major progress was made towards a practical and efficient fatigue analysis by adding a fine mesh capability to MAESTRO. It is now possible to quickly refine a coarse mesh, whole ship MAESTRO model in the vicinity of fatigue susceptible joints. The great advantage to this method over similar modeling in a general purpose FE program is that MAESTRO uses the coarse mesh model to directly impose boundary conditions and loads on the fine mesh. Thus one of the major challenges to linear fatigue analysis of full ship structures, the estimation of hot-spot stresses, has been greatly simplified.

5. Validation of Loads Transfer

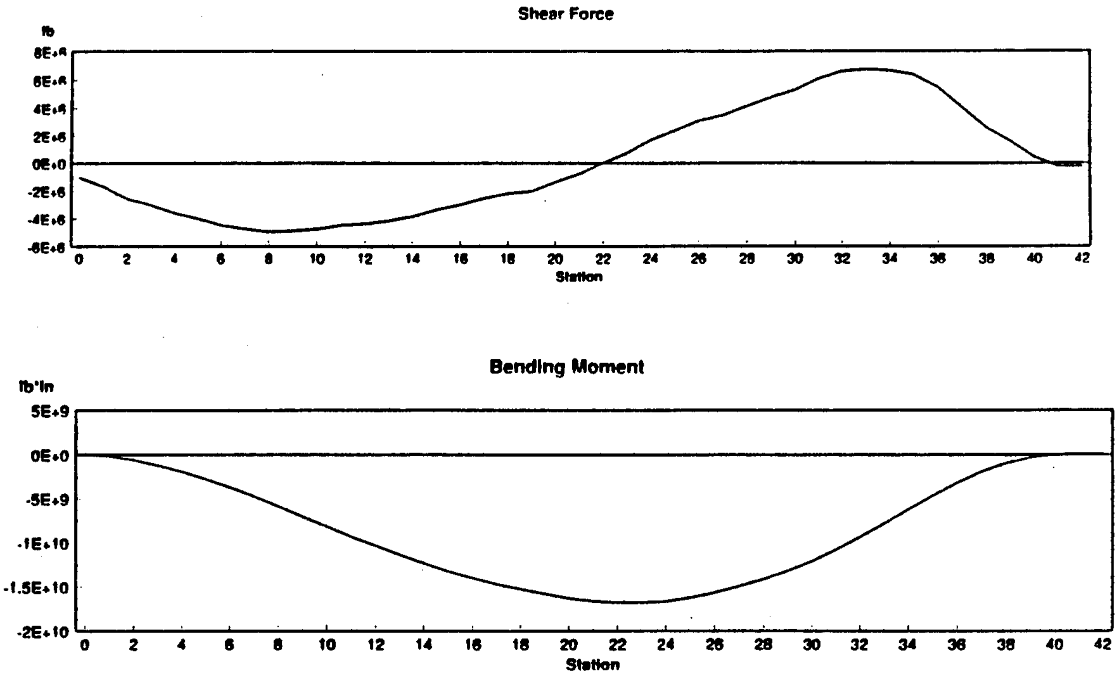
An intermediate phase in the project was to be a full validation of USAERO and MAESTRO versus tow tank results. This validation required a full working MAESTRO model of the LHD, an interface between USAERO and MAESTRO and hull girder stress results from MAESTRO. A first cut at calculating hull girder forces can be made internally within MAESTRO. This internal evaluation required extensive updating of an existing MAESTRO model of the LHD and resulted in the hull girder forces shown on page 11.

For the final validation, the internal MAESTRO hydrostatic loads were to be removed and panel pressures from USAERO were to be applied to the MAESTRO model. MAESTRO would then be used to predict the resulting hull girder forces and a comparison would be made with results from a tow tank experiment. The two way transfer of data from MAESTRO to USAERO and back was accomplished, but the termination of the project and subsequent departure of key project personnel prevented any further progress on the validation.

ONR STRUCTURAL DESIGN TECHNOLOGY DEVELOPMENT



LHD : Weight + Hogging Wave



LHD : Weight + Sagging Wave