UNIFIED FIRST-PRINCIPLES SHIP STRUCTURAL DESIGN BASED ON THE MAESTRO METHODOLOGY

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INTRODUCTION
The demands of the shipping industry for more efficient, higher speed, lighter weight, and lower cost ships are strongly linked to the issue of ship structural design. The economic success and safety of shipping rely heavily on intelligent structural design that optimizes the use of new materials, improved fabrication procedures, and efficient life-cycle maintenance to address the current and future trade requirements. Environmental issues have never been more distinctly involved in the criteria for successful and safe ship operation. All of these demands place increasing emphasis on the structural design process. This paper summarizes the value of unifying ship structural design through combining rapid structural modeling, global as well as local finite element analysis, comprehensive failure and limit state analysis, and the use of mathematical optimization to meet these increasing demands. The unification and continued development and extension of this methodology based on the MAESTRO computer program is presented: implementation of improved structural limit state evaluations; automation of detailed finite element meshing and analysis; implementation of composite structural modeling, analysis, and failure evaluation; improved support for fatigue design; connectivity to preliminary design tools for hull form and other naval architectural design tools, such as GODDESS; integration with 3D CAD-based ship product models; and, integration with cost estimating and production planning resources. These developments represent significant progress toward unifying first-principles structural design with the total ship design and construction planning process. Plans are presented for implementing Multidisciplinary Design Optimization (MDO) within these integrated ship design technologies. For structurally intensive ships, such as heavy cargo vessels, high-speed ferries, and naval combatants, these developments offer improved designs, and lower construction and life-cycle maintenance costs. Examples of designs and applications are presented to illustrate all of these developments.
UNIFIED, RATIONALLY BASED SHIP STRUCTURAL DESIGN

*MAESTRO* is a computer program for rationally based optimum design of large, complex thin-walled structures. In essence, *MAESTRO* is a synthesis of finite element analysis, failure (or limit state) analysis and mathematical optimization, all of which is smoothly integrated under a user-friendly graphical interface. *MAESTRO* accommodates non-linear failure modes and large complex structural geometries. It can therefore be used for virtually all large structures including cargo ships (tankers, bulk carriers, and containerships), high speed multi-hull and monohull vessels, surface combatants, aircraft carriers, submarines, and floating offshore facilities. The theoretical basis for *MAESTRO* is provided in *Ship Structural Design* (Hughes [1]). The *MAESTRO* system incorporates interfaces with hull and arrangements surface models and CAD models in formats routinely used in concept and preliminary design. For this reason, *MAESTRO* provides a structural design facility that can be applied as early as concept design and used to support decisions regarding light ship weight objectives and overall naval architecture impacts of the structural design.

**Basic Capabilities**

The basic capabilities of the *MAESTRO* structural design system are summarized below. These capabilities and the software system are illustrated in Figures 1 and 2.

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**6 Basic Aspects of Rationally Based Design**

1. **MODELING OF LOADS**
2. **STRUCTURAL RESPONSE ANALYSIS**
   - Calculate load effects, $Q$
3. **LIMIT STATE ANALYSIS**
   - Calculate limit values of load effects, $Q_L$
4. **EVALUATION**
   - A) Formulate constraints
   - $\gamma_1 \gamma_2 \gamma_3 Q \leq Q_L$
   - B) Evaluate adequacy
   - Constraints satisfied? Objective achieved?
5. **OPTIMIZATION**
6. **OBJECTIVE**

- All 6 are necessary
- All 6 must be balanced and integrated

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Figure 1. Rationally Based Ship Structural Design
**Rapid Structural Modeling** - The *MAESTRO* Modeler is an interactive graphics tool that enables the rapid creation (typically in days, rather than weeks or months) of a full ship finite element model. The same model is used in failure analysis, evaluation of structural adequacy, and structural optimization. Figure 3 presents a representative full ship *MAESTRO* structural model of a high speed ferry.

**Finite Element Analysis** - *MAESTRO*’s FEA, normally completed for the entire structure, determines the stresses (symbolized by Q - “Load Effects” in Figure 1) in all structural members and for all load cases. *MAESTRO* offers flexible, ship-oriented and highly automated specification of loads.

**Failure Analysis** - *MAESTRO*’s failure analysis begins with the calculation of stresses ($Q_L$) in Step 3 of Figure 1 that would cause failure of each member, for all possible failure modes (yielding, buckling, plastic hinge, etc.) and other design limits (e.g., deflections). Table 1 lists the 25 failure modes treated at the individual structural member level. Additional failure modes or limit states are computed at the overall structural level, typically using the full hull cross section.

**Evaluation of Structural Adequacy** - This is done automatically by *MAESTRO*. It applies safety factors (symbolized in Figure 1 by $\gamma_1$, $\gamma_2$, $\gamma_3$) and then, for every member (stiffened panels, girder and frame segments), for each failure mode (all 25 modes, see Table 1) and every load case, it checks the requirement that the factored stresses ($\gamma_1 Q$, $\gamma_2 Q$, $\gamma_3 Q$) must not exceed the failure values, $Q_L$. Expressed mathematically, the requirement is $\gamma$
\[1, \gamma_2, \gamma_3 Q \leq Q_L.\]  \textit{MAESTRO} uses a non-dimensional “adequacy parameter” to quantify the degree of adequacy or inadequacy of each member. The adequacy parameters are normalized in the range of -1.0 to +1.0, where “0” signifies that the structural member just satisfies the strength required to prevent failure, including safety factors.  

\textit{Structural Optimization}-Based on a designer-specified optimization objective of either least weight, or least cost, or any weighted combination of these, \textit{MAESTRO} interactively revises the structural design to achieve the optimum solution. Using the structural adequacy evaluations as constraints, the optimized design provides the required safety margins against all structural failure modes and also satisfies any number of other user-specified constraints (e.g., minimum/maximum sizes, standard sizes, fabrication requirements, etc.).

\textbf{Detailed Stress Analysis} - \textit{MAESTRO}’s Detailed Stress Analysis (DSA) capability consists of fine mesh modeling and stress analysis of any portion of structure using a library of 24 finite element types. This allows the modeling of complex details such as corrugated plating, openings, and brackets. The fine mesh model can remain within the global model as a true (statically condensed) superelement. This avoids the laborious and error-prone process of transferring data and boundary conditions from the global model to the fine mesh model. Detailed meshes are easily generated using \textit{MAESTRO}’s powerful interactive graphics tools. An example of a \textit{MAESTRO} DSA model is shown in Figure 4.

\textbf{Translation to Other Analysis Formats} - Other types of analysis are possible because the \textit{MAESTRO} Modeler can automatically create files for other programs, such as NASTRAN, VAST, and/or dynamics programs as noted in Figure 2.
Figure 3. Fast Ferry Full Ship *MAESTRO* Model

Figure 4. *MAESTRO* Detailed Stress Analysis (DSA) Model - SWATH Structure
Table 1. *MAESTRO* Structural Member Limit States

<table>
<thead>
<tr>
<th>INDIVIDUAL MEMBER FAILURE MODES</th>
<th>GIRDER</th>
<th>FRAME</th>
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<td><strong>PANELS</strong></td>
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<tr>
<td>Collapse</td>
<td>Collapse</td>
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<td>compression, plate &amp; flange</td>
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<td>Stiffener yield</td>
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<td>tension, plate &amp; flange</td>
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<tr>
<td>Plate unserviceability</td>
<td>Yield</td>
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**STRUCTURAL FAILURE EVALUATIONS**

The *MAESTRO* approach to rationally based structural design includes a comprehensive treatment of structural failure evaluations. This treatment is based on the technical approach that displacements and stresses generated by finite element analysis should not only be used for assessing stress conditions in materials, but should also be used to quantitatively evaluate the structure’s condition relative to all of its principal modes of failure. *MAESTRO*’s treatment of this “limit state evaluation” includes 25 failure modes at the structural level of the individual stiffened panel and its adjoining girder and frame beam elements. For each such stiffened panel and its adjoining beam elements in the entire structure, *MAESTRO* conducts a quantified evaluation of the 25 failure modes listed in Table 1. As discussed above, *MAESTRO* computes the critical stress value for each failure mode for each element of the structure, and then compares these critical values to the working values obtained from each load case analysis to quantify and normalize these evaluations, again, for the entire structure, all of the limit states and for every load case. These calculations are conducted as a routine part of a *MAESTRO* analysis run. The results of these evaluations are immediately available to the user in a highly accessible graphical format. The *MAESTRO* limit states also include a user-specified factor of safety, which can be indexed to the requirements of specific safety authorities such as national naval organizations and ship classification societies. Such an indexing has been implemented in *MAESTRO* for the DNV Rules for Ships, and for High Speed Light Craft (HSLC) for both steel and aluminum.
SHIP DESIGN PROCESS AND STRUCTURES
Structural design is an essential consideration in the overall ship design process from the earliest stages. Traditionally, early stage design emphasizes hullform, arrangements, stability calculations, resistance and powering, and operational issues such as cargo capacity, operational performance, and life cycle costs. With the increasing emphasis on higher performance structural designs, initiation of actual scantlings has migrated to progressively earlier stages of design. For this reason, a structural design capability is needed which interfaces with the design tools used to support the other elements of early stage design, and which will furthermore support the transition of the design into preliminary and contract levels. An example of this methodology is the system in use and being further developed by the British Navy described in the next two sections.

UK MOD Concept Design Phase
Initial ship design studies frequently give rise to more than one concept that may satisfy requirements. These concepts are normally subjected to naval architecture and engineering analysis (with relatively few details). This concept phase is normally completed using CONDES, the UK MOD concept design suite. The CONDES suite of programs allows the user to translate a set of payload demands and mission requirements into a balanced concept ship design. While CONDES is primarily intended to develop new concept designs, the programs can also be used to assess the balance of concepts developed by industry in response to design and build contracts. CONDES has a dedicated database which contains information on: type ships, default demands and algorithms, ship descriptions, library models, scaling laws, towed body and engine data. The CONDES system is limited to use on monohull surface vessels in a displacements range of approximately 500 to 20,000 tons. A limited capacity exists for vessels outside this displacement range and for multi-hulled vessels such as SWATH and trimaran, but the accuracy is restricted because of the limited databases.

UK MOD Feasibility Design Phase
Once the concepts have been reduced to a manageable number, the feasibility stage of design begins. Here the UK MOD employs the GODDESS ship design system developed for the design of surface warships and submarines. GODDESS consists of an integrated/interactive suite of computer programs supported by an extensive database of geometrical and numerical information. GODDESS enables feasibility studies of surface warships to be carried out quickly and economically. A feasibility study establishes that a concept is technically viable and can be built without any costly major modifications. GODDESS can also be used to carry out preliminary design studies to validate the stability and performance of the ship.

SHIPSTRUCT, a software package developed by the UK Ministry of Defence, complements the GODDESS software suite, utilizing a ship structural synthesis process. SHIPSTRUCT enables early evaluation of important structural options without the advance assembly of substantial amounts of data. It also enables rapid evaluation of existing structures to be carried out. SHIPSTRUCT provides naval architects with a means of rapidly developing a preliminary structural design and weight distribution starting with
little more than a basic requirement. The SHIPSTRUCT philosophy and its relationship with GODDESS is shown within the box outline in Figure 5. Feasibility design involves trying to optimize the ship design by subjecting the possible variants to the following calculations and assessments:

- Hull Design
- Layout Requirements
- Weight Estimates (structure, equipment etc.)
- Weight/Space Balance of Design
- Stability Assessment
- Structural Design/Strength Assessments
- Seakeeping Assessments
- Resistance/Fuel/Propulsion Requirements.

It is during this feasibility design stage and the subsequent detailed design stage that the MAESTRO suite of programs can be utilized as a powerful tool in the design of both commercial and military ships. To this end, the UK’s Defence Evaluation and Research Agency (DERA) has been incorporating the MAESTRO system into an integrated structural design package, shown in Figure 6, for the structural design of ships. To fully integrate the MAESTRO suite of programs into the UK MOD’s ship design suite of programs, considerable work has been carried out to develop the linkages between GODDESS/SHIPSTRUCT and the MAESTRO Modeler code, to enable geometric and structural data to be transferred.
Figure 5. Functional Breakdown of Proposed Ship Structures Design Software Suite
Further work has been carried out on the MAESTRO Analysis code to implement the UK Warship Design Limit States, detailed in NES 154/SSCP23 (Dow [2,3]), covering buckling, yielding and failure of structural components. This work essentially provides an alternative set of limit state evaluations to the 25 failure modes used by MAESTRO to assess the individual structural members. Making use of these failure modes, structural optimization can be carried out using MAESTRO to develop a ship structural design based on the MOD’s warship design criteria. A major application of this software in the UK has been to investigate the effect of degradation of material properties on the adequacy of large composite ship hulls. To enable this type of analysis to be carried out efficiently, a set of failure criteria for composite structural components are being developed by DERA. These will be implemented in MAESTRO as another alternative set of limit states. Some work in modifying existing failure criteria has already been carried out, which enabled hull life assessment of existing composite warships to be accomplished.

Further development work has been carried out on the MAESTRO code to incorporate the DERA Ultimate Strength Procedure (Smith and Dow [4]) into the MAESTRO software as an additional Adequacy Parameter to be considered when developing the ship structural design. These developments represent a significant step towards the integration of the MAESTRO software package into the MOD design procedure for UK warships.

DETAILED FINITE ELEMENT MODELING AND ANALYSIS
Applying global, realistic loads to the full ship structural model is key to establishing accurate boundary conditions for conducting local structural analysis. Local analysis, using detailed fine mesh finite element models is an essential element of the structural design process. Fine mesh modeling and analysis supports design of local structures, structural details, fatigue analysis, and other specialized structural requirements. Having an efficient modeling and boundary condition application approach is essential to the accuracy and efficiency of conducting fine mesh, local structural analysis.

The MAESTRO system, refer to Figure 2, includes a Detailed Stress Analysis (DSA) module which facilitates fine meshing local portions of the global structural model. The DSA Modeler also supports adding structural details and/or modification of global structure to reflect local details. Boundary conditions are automatically applied using either a top down or a superelement approach. The top down approach applies displacements from the global analysis as boundary conditions for the local finite element analysis. The superelement approach condenses the fine mesh finite element model to the master nodes of the global model, and conducts the global analysis incorporating the structural stiffness of the local fine mesh model. An example of a DSA model is provided in Figure 4, presented previously.

COMPOSITE STRUCTURAL DESIGN
Current trends in ship design and construction require the capability to model, analyze, and design large-scale ship structures in composite materials, as well as in steel and aluminum. The objective of the composite modeling and analysis capability is to utilize an identical modeling approach for the large scale global ship structural model in which the structural materials can be specified as composite structures instead of, or as alternatives to, the metal structures. The MAESTRO system is being extended to incorporate such a capability
(Hughes[5]). This composite modeling resource enables an existing MAESTRO model or a new model to reflect composite structures either in a monolithic multi-ply or in a sandwich composite configuration. The analysis of composite structures is conducted with all of the same load application resources as the traditional MAESTRO finite element analysis for metal structures, and the composite elements are post-processed to compute stresses in each ply of the composite structures. This data is made available to the user through the MAESTRO graphics post-processing system.

Composite structures pose unique requirements with respect to failure or limit state evaluation. MAESTRO uses the Tsai-Wu interaction formula for first ply failure and last ply failure of orthotropic panels, as in paragraph 1B202 of Part 3, Chapter 4 of the HSLC Rules. The formula uses the strength values $X_t$, $X_c$, $Y_t$, $Y_c$, and $S$ which are part of the input data. These must always be verified by material testing. In the finite element analysis, the stresses are calculated in every ply of every panel. A check is then made of each ply for first ply failure and last ply failure by substituting the stresses into the Tsai-Wu formula and using the factors of safety $R$ given in the Rules. Core shear stresses and maximum deflections are checked against the maximum permissible values given in the Rules. The program also checks for panel buckling. For sandwich panels, this includes local buckling of the skins. These failure capabilities are currently under development.

**STRUCTURAL FATIGUE ANALYSIS**

MAESTRO offers a unique Unit Load Analysis Method, which is an efficient method for calculating the local (hot spot) unit wave stresses that are needed for a first principles lifetime fatigue analysis of ship structural details. This method significantly reduces the size of the analysis process while preserving accuracy. For example, for a typical bulk carrier the number of load cases is reduced from about 9000 to about 1200, with no loss of accuracy. This new capability fits very well into overall fatigue analysis methods and provides major benefits in speed, unification, and ease of use.

Fatigue analysis typically requires using a ship motions and loads program (usually strip theory) to calculate the wave-induced pressures on the ship, the displacements and rotations at the C.G. of the ship, and the vertical and horizontal bending moments at selected positions along the ship length. The analysis then uses a large (usually three cargo hold) finite element model, and involves all three types of cyclic loads:

- external pressures due to waves and ship motions
- internal pressures due to the accelerations of cargo and ballast
- vertical and horizontal bending moments at the ends of the model

The number of load cases is very large, even with a linear, spectral-based unit wave approach. The number of load combinations is roughly:

- 18 ship-to-wave headings
- 25 wave frequencies
- 5 ship speeds
- 2 or 4 loading conditions (2 for a tanker; 4 for a bulk carrier)

This gives a total of either 4500 or 9000 load cases. Three principal features of MAESTRO provide major benefits in making this fatigue analysis process more efficient.
Rapid Global Structural Modeling - The MAESTRO Modeler allows the construction of a three hold finite element model in from five to seven days, depending on the geometry (e.g. corrugated bulkheads take longer because of the intersections at the upper and lower stools). It is the same Global Modeler that is used to build whole ship finite element models for strength and vibration analysis. Thus in many cases the global fatigue model will already be available (a MAESTRO model is inherently modular, such that a three cargo hold model can be extracted from a larger model in a few minutes).

Rapid Local Structural Modeling and Analysis - The MAESTRO Detailed Stress Analysis (DSA) Modeler performs fine mesh modeling and stress analysis of any portion of structure, using a library of 24 element types and powerful interactive graphics meshing tools. Templates allow the rapid modeling of complex details such as corrugated plating, cutouts and brackets. The DSA Modeler has a smooth interface with the Global Modeler. It automatically begins with and uses all relevant information from the Global Modeler (geometry, master nodes, etc.). Likewise it automatically uses the boundary node displacements from all the unit loads (wave pressures, cargo/ballast pressures and bending moments) and, if relevant, any cyclic pressures that act directly on the local model. This smooth interface avoids the laborious and error-prone process of transferring data from a global model to a separate local model, and it thus improves both the modeling speed and the integrity of the local model. In a MAESTRO fatigue analysis, the stresses from the local model are actually Stress Influence Coefficients, and the next point explains how they allow a much more rapid and efficient fatigue analysis than would otherwise be possible.

Automated Unit Load Analysis Method - This method dramatically reduces the number of load cases, with no loss of accuracy. For example, for a bulk carrier the number of load cases is reduced from 9000 to about 1200. The result is that MAESTRO's global analysis takes only five hours on a standard 133 MHz PC (one time only, regardless of the number of structural details to be analyzed) and the local analysis takes about eight hours per structural detail, assuming about 30,000 degrees of freedom per detail. The results from these MAESTRO analyses (the Stress Influence Coefficients) are the unit wave stresses, which are needed in a first principles fatigue analysis. The MAESTRO Stress Influence Coefficients are used to obtain these stresses. At this point, ship motions analyses, such as strip theory results, must be interfaced with the MAESTRO results. This requires that the pressures from the strip theory analysis must be allocated or mapped to the MAESTRO patches. Based on this mapping, the actual stress responses at the structural details can be generated and used to complete the fatigue analysis.

COST ESTIMATING AND PRODUCTION PLANNING
At every stage of ship design, including early design, it is necessary to generate accurate cost estimates that reflect the current stage of the design. The MAESTRO structural model defines the principal structural members of the ship, and provides an excellent data source for accurate estimates of structural weight, centers and cost. An automated interface has been developed between MAESTRO and the ship cost-estimating program ESTI-MATE, developed by SPAR Associates, Inc. This interface collects the quantities of structural plates and shapes from a MAESTRO structural module and transfers this data as input to ESTI-MATE, where costing can be developed using the shipyard’s cost estimating
relationships for the particular structures and their associated fabrication processes. Structural data in ESTI-MATE can be further transferred to the production planning modules of the PERCEPTION integrated shipbuilding production management system. PERCEPTION provides build strategy and work package planning and scheduling, materials purchasing and inventory management, and labor planning, as well as real-time feedback against schedules and budgets during the construction process.

MULTI-DISCIPLINARY DESIGN OPTIMIZATION
The MAESTRO structural design system integrates optimization of the structure using a user specified mix of objectives that include least weight, lowest cost and lowest vertical center of gravity. As further progress is made in developing interfaces between MAESTRO and other software based elements of the design and production planning process, a significant technology opportunity exists: to use the coupled information systems within a multidisciplinary design optimization (MDO) environment to realize full coupling between the design and ship construction processes. MDO is an R&D technology that has been under development at Virginia Tech for many years. These efforts are concentrating on applying optimization mathematics to design and production processes associated with aerospace vehicles and ships. MDO offers the opportunity to automate the interaction of the diverse components of an integrated ship design and production planning system, using the design and process-specific software components as the discipline-specific engines of the MDO process. Just as MAESTRO already implements such a “first principles” optimization methodology, addressing thousands of structural performance constraints simultaneously in developing an optimum combination of practical structural scantlings that realize the user-specified objectives of lowest cost and least weight, an integrated design system equipped with MDO will automate the interaction of basic ship design analyses with manufacturing processes, such as steel fabrication alternatives, to achieve optimums of total ship cost, shortest construction time, improved use of existing inventories and available fabrication facilities, etc.

DESIGN EXAMPLE
Currently, the UK Ministry of Defence is carrying out design studies on a novel, advanced trimaran hull for use as a frigate. This design has a long slender main hull fitted with smaller outriggers to provide stability for the platform. The principal motivator for a slender hull form for a large warship is reduced resistance, other advantages of the trimaran hull form are increased deck area and internal volume provided by the wide cross-deck structure. The three hulled design introduces a range of unknowns for the structural designer. The main areas of structural risk are:

- Quantification of structural loads, both longitudinal and transverse;
- Structural Adequacy; is the design strong enough to cope with the loads?;
- Structural Weight Fraction, although the resistance for a given displacement is lower, the large cross-section adds to the structural weight fraction without contributing to the buoyancy.

A concept design of a trimaran warship was produced using CONDES and GODDESS. A preliminary structural design was then produced using SHIPSTRUCT, and a MAESTRO
model, shown in Figure 7, was developed. *MAESTRO* was then used to assess the adequacy of the preliminary structural design and to develop improved structural capability. The *MAESTRO* model of a bulkhead showing the course mesh modeling using additional beams and panels is shown in Figure 8. Subsequent to the *MAESTRO* model being created, analysis was carried out on deck, shell and bulkhead structures to investigate structural effectiveness, load paths and fatigue stresses using the *MAESTRO* DSA Solver in conjunction with NASTRAN. Figure 9 shows a fine mesh model of the bulkhead created using *MAESTRO* DSA. This approach enabled fairly detailed design studies to be carried out at a very early stage in the design/assessment process.

Figure 7. Trimaran *MAESTRO* Model

Figure 8. Trimaran Transverse Bulkhead: *MAESTRO* Coarse Mesh Model
CONCLUSION
This paper summarizes the increasing role that ship structural design is playing in the overall ship design process, with particular emphasis on defining structure earlier in the process than has been traditional. Structural design is also incorporating the use of limit states or failure modes in a more comprehensive way by automating these calculations, which in the past have required time consuming manual modeling and calculations. The MAESTRO structural design methodology employs this first-principles approach to unify rapid structural modeling, finite element analysis at both global and local levels, limit state evaluation, and structural optimization. Specific aspects of structural design continue to receive development attention, including structural fatigue analysis and composite structure design. The unified approach offered by the MAESTRO system is shown to be an effective design tool with which to implement design criteria for a specific class of ships or for a specific safety or regulatory/design approval authority’s requirements. In general, the unified approach to ship structural design improves the quality and efficiency of the design and the integration of structural design with the overall ship design process.
REFERENCES