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Modeling and Simulation of Ship Structures Using Finite Element Method

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Abstract**—**The development in the construction of unconventional ships and the implementation of lightweight materials have shown a large impulse towards finite element (FE) method, making it a general tool for ship design. This paper briefly presents the modeling and analysis techniques of ship structures using FE method for complex boundary conditions which are difficult to analyze by existing Ship Classification Societies rules. During operation, all ships experience complex loading conditions. These loads are general categories into thermal loads, linear static, dynamic and non-linear loads. General strength of the ship structure is analyzed using static FE analysis. FE method is also suitable to consider the local loads generated by ballast tanks and cargo in addition to hydrostatic and hydrodynamic loads. Vibration analysis of a ship structure and its components can be performed using FE method which helps in obtaining the dynamic stability of the ship. FE method has developed better techniques for calculation of natural frequencies and different mode shapes of ship structure to avoid resonance both globally and locally. There is a lot of development towards the ideal design in ship industry over the past few years for solving complex engineering problems by employing the data stored in the FE model. This paper provides an overview of ship modeling methodology for FE analysis and its general application. Historical background, the basic concept of FE, advantages, and disadvantages of FE analysis are also reported along with examples related to hull strength and structural components.

Keywords**—**Dynamic analysis, finite element methods, ship structure, vibration analysis.

I. Introduction

PROVIDING sufficient strength in a ship at a reasonable cost has always been one of the most challenging tasks for ship designers and the ship industry. Classification societies are providing the required standards for certifying the ship strength against all necessary conditions encountered during service life of the ship.

The conventional techniques of ship structural design have been using the past design experience of same size ships. Generally, this kind of experience is found in classification society rules and specifications in the form of formulae. Design skill has shown that levels of failure can be evaluated by using suitable margins for strength against predictable loads. But this design approach is not the exact technique when the degree of structural strength is considered.

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Previously, the ship design formulations were principally dependent on practices and experience of existing ships already in service and the scantling requisites were specified in tabular data forms precisely based on main particulars of the ship. With the advancement of new ship designs, it has become a core issue to develop new and advance scientific approach for ship analysis. Although these analytical formulae were scientific, designers were unable to identify the safety limitations and characteristic assumptions, and hence, difficult to construct an innovative design. Numerous researches in the ship design community have implemented probabilistic analysis techniques in various design problems related to mechanical and marine engineering fields. Ship structural design procedures are closely linked with ship efficiency, speed, weight and cost. The commercial success of design depends greatly on rational design that can be optimized with newly developed materials, fabrication procedures and environmental issues. This shows that recent computing techniques and rational analysis procedures are necessary for an efficient structural design process.

Since hydrodynamics and structural analysis are emerging from the last few decades, the newly developed methods provide an improved application of environmental loads to ship strength. These analyses are becoming technically more advanced, and are integrated in the ship classification society rules for design and analysis.

Several attempts and solutions have been developed specifically by Dumez, et al. [1], then by von Selle et al. [2] and Doig et al. [3] during the past few decades to incorporate FE mesh in ship design. During the concept design phase, it is convenient to have a global FE model which helps in reducing the overall design cost. If a concepts design is effectively predictable by using finite element analysis (FEA), then these results can be utilized during the detail design process. Currently, the general tendency in both ship design offices and shipyards is to develop the methods for the unified design process, where the three-dimensional ship model is created in one system only, and that information is used for numerous purposes.

The exact date of the invention of the FE method cannot be mentioned; however, the method was first used in solving structural and complex elasticity analysis problems in aeronautical and civil engineering. During the early 1940's its advancement can be found in [4] and [5]. During the period of 1950s and 1960s, a numerical method was proposed by Feng [49]. His method was based on the computations analysis which was performed in construction of a dam. It can be predicted that all these methods and solution approaches have a common characteristic of converting the continuous mesh domain into a set of separate small sub-domains, which are generally called as mesh elements.

The real stimulus in the FE method was started during the 1960s to 1970s by Argyris, Clough, Irons, Zienkiewicz with his fellow members, and Gallagher. Availability of open source FE software programs provided further advances [6]. NASA sponsored the initial version of NASTRAN, whereas UC Berkeley developed AP IV [7] a widely available FE program. In 1969, DNV GL (Det Norske Veritas) a classification society of ship design in Norway developed Sesam for analysis [8]. In 1973, mathematical-based FE methods was provided by Fix and Strang [9]. This method helps in developing numerical models of various physical systems in different engineering disciplines, like fluid dynamics, heat transfer and electromagnetism [10], [11].

Over the past 25 years, the theory and methods of ship structural modeling analysis have been technologically advanced with the passage of time, resulting in a gradual change in the philosophy of designing complex ship structures. The conventional methods of selecting scantlings according to the classification society rules is being improved and, in many cases, replaced by rational stress analysis, considering the variable loads during the expected service time of a vessel in a most realistic way. This approach is a prerequisite for the extremely competent design of modern ships, allowing the maximum number of containers to be put in and on the vessel by minimizing the space taken up by the structural components. A design based on rational analysis can accommodate innovative design aspects and mechanisms to facilitate the stowage and handling of containers. It is a fact that modern container ships as well as large liquefied natural gas (LNG) carriers and other gas tankers rely on detailed strength and vibration analysis.

The demands for efficient, faster in speed, light weight and reasonable cost ships are intensely linked to the philosophy of ship design procedures [12]. The adoption of light and advanced materials and development of unconventional vessels displayed the limitations of existing rules and making FE method as a comprehensive tool in ship designing [13].

The analysis process today combines the overall strength considering static as well as dynamic loads with fatigue life of all critical structural details. This leads to a well-designed and more evenly utilized structure with a high degree of reliability [14].

In the late 1950s, FEA was started to use in the shipbuilding industry when a curved grillage analysis was first performed for between bulkhead section of the ship and then experimentally verified. After the successful completion of this analysis, static and dynamic analysis of ship decks and bulkheads started. Some comparable computer programs were developed called BOSOR IV and ASSSAI [15], for buckling and axisymmetric stress analysis respectively for submarine pressure hulls.

Classical methods like beam theory and grid analysis by Timoshenko, Goodier [16], and Clarkson et al. [17] resulted in a slow advancement in ship design industry [14]. Shear lag by Schnadel [18], Schade [19] and orthotropic plate theory by Schade [20] based on numerical methods, assisted the naval architect in the analysis of new designs. Detailed design charts and empirical formulae were prepared to cover the most common structural configurations. The size of the ships increased in small steps, the deck openings were carefully examined by applying the classification society's rules.

A significant change occurred with the introduction of the FE method to the analysis of ship structures. Since the material is defined with the same Young's modulus for the whole structure, the average normal stress distributions are compared about the usability of selected plate thicknesses. This kind of approach has also been studied by Paulling and Payer [21]. Based on the evolution of the computers, extensive numerical calculations were suddenly possible for analysis of individual structural designs. At that time, a sudden rapid development in shipbuilding took place.

The torsion bar method used exclusively for the analysis of ships with large deck openings by de Wilde [22], Meek et al. [23], and Pedersen [24], was gradually improved by the FE method allowing a refined consideration of the discontinuities between open and closed deck areas. As the FE method became universally available, the detailed three-dimensional analysis was started as an integral tool in the design of new ship types and forms requiring no prior skills. Many ship types in operation today, are fully based on detailed FE calculations presented by Abrahamsen [25] and Fricke [26]. The interaction between the ship hull structure and other independent substructures such as hatch covers of multi-purpose cargo ships and tanks of liquefied petroleum gas (LPG) and LNG carriers is very complex, and it could not be analyzed with sufficient accuracy and in satisfactory detail by classical methods. The FE technique has been proven to be a most valuable tool also for the prediction of the vibration behavior of ships exposed to excitation by the propeller and main engine, as shown by Carlsen [27], Payer and Asmussen [28] and Asmussen and Mumm [29].

The evolution of ships is particularly connected with FE calculations of ever increasing complexity. As a result of optimization studies based on such calculations, a modern ship truly is a thin structural shell designed strong enough to carry a maximum number of containers in the hold or on deck. Every element of the structure serves a purpose. The conventional methods of ship structural design are using previously built ships experience [30]. Classification societies are providing the required standards to certify the suitability of strength against all circumstances that can be experienced by ship during service life. Several researchers used different optimization techniques for ship design problem. Harlander [31] made the first optimization in marine structure by hand. Subsequently, Evans and Khoushy [32] and Nowacki et al. [33] developed an optimization algorithms and computer-assisted designs. Hughes et al. [34] and Hughes [35] then presented important progress in ship structural optimization. The optimization tools were used for a single aspect like; shape, scantlings, propeller, ultimate strength and a single objective like; weight, resistance or cavitation [36].

Developments in CAE/CAD systems introduce various contact algorithms used in FEA codes as in LS-DYNA. Later, ship collision problems were analyzed by using these FEA codes. Similarly, PISCES and DYTRAN codes are being considered for ship slamming analysis. MARC and ABACUS have the FEA codes for fracture mechanics both for linear and non-linear analysis, ZENCRACK, used these codes to predict propagation rates fatigue crack. The latest ABAQUS software has an Euler module which can be employed for modelling water and air. This Euler module can readily be coupled with Lagrangian structural module. Recently, LS-DYNA has turned into the leading code for whipping and shock predictions. Now, Classifications Societies are also offering FEA codes in CADMID systems [12]. Most shipbuilders, marine and offshore fabricators are using virtual product development (VPD), which can be seen in the most recent ISSC [37], PRADS [38] and OMEA [39] conference. Recently, VPD process also considered computational fluid mechanics, computational structural mechanics and multi physics as part of its domain and it is practiced throughout Europe.

FE calculation methods today have reached a certain state of maturity, at least regarding linear analysis. Currently, pre- and post-processing programs are developed to make the complex analyses less cumbersome and less time consuming and to minimize the risk of errors. Even with the achievements already reached in this respect, further development, particularly concerning data generation is needed. It is, however, helpful when complete automation of FE model generation, for instance, from CAD-data banks will be achieved. Relevant expert systems need to be developed, there is still a lot of decision work required for engineering judgments which could not be done completely by the computer [14].

Optimization tools are now becoming more and more generic and reliable. References [40]-[47] used various design and optimization techniques in different models for optimization. They checked the structural response by varying the design variables and constraints for different analysis methods; analytical linear and non-linear, 2D and 3D FE analysis. They also investigated structural weight and production costs. However, all researchers approved that in marine structures it is not appropriate to accurately model the relevant features for only one specific objective [36]. However, FEA has the capability to update the mesh with minimum effort at any time during the design process when design attributes changes [48].

II. Modeling Procedure

Generally, ship structure and components are evaluated for vibration and structural strength under normal and critical loading condition. Now, a day strength assessment is based on 'Direct Strength Analysis' which removes errors during interaction between different structural members. This method incorporates the effect of axial and torsional deformations, and bending and shear, all together at the same time. Therefore, it is especially helpful for large ships having complicated structural arrangements and various loading conditions for ballast and cargo.

A. Modeling

The FEA Pre-processor is used to completely model the ship structures varying in length from 100 meters to 300 meters, breadth between 7 meters to 30 meters and from depth 5 meters to 30 meters.

1. Shell elements used for modeling of hull plates are

   Shell 63
   Shell 43
   Shell 181

2. Whereas beam elements used for modeling of hull stiffeners are

   Beam 4
   Beam 44
   Beam 188

Line elements are used to develop all the pipes, while mass elements are used to develop all remaining structures of the ship. Complete ship structure modeling with all details is time consuming and difficult. ANSYS APDL and macros decreases a lot of modeling manual errors and time consumption during ship modeling. After the completion of complete ship model, each of the plates, stiffeners, pipes and other structures can be independently selected. Then, real constants are attached in the tabular form. This process can also be automated with the help of APDL and ANSYS macros.

B. Global Structure Model

This structural model is used to check the strength of ship hull and its primary members against still water loads and wave induced loads. The global model is usually the full length complete ship model. Half symmetry conditions can reduce the cost and computational time. In this model, we can incorporate all primary transverse members; bulkheads, decks, transverse webs and longitudinal members that contribute in ship strength. Commonly, a coarse mesh is adopted covering the entire ship hull. Primary strength components of the hull are developed by using quadrilateral and triangular shell elements. Supporting members without deep web are created by using beam elements, whereas, the stiffened panels and frame structures are created as a complete assembly by using shell and beam.

C. Hold Model

Hold model is used to inspect the reaction of the primary strength members under the action of internal loads and external water pressure in a specific portion of the hull girder. This model depends on the loading conditions, ship type and ratio of symmetry in transverse and longitudinal directions. Single hold, two cargos hold lengths (+1/2 +1+1/2) or three hold lengths (1+1+1) may be used [26]. A half breadth model may also be used in analysis.

Generally, a coarse mesh is generated for the FE hold model. Girder webs with reduced equivalent thickness are modeled in place of webs having cut-outs. Cargo holds modeling is completed using a four-node plate-shell or membrane elements. Shell elements are used to model longitudinal bulkhead, decks and inner bottom portion of a ship to account for the lateral pressure.

D. Grillage Model

Grillage model is used to examine the strength of a structure which is supported by transverse frames and longitudinal girders. The structures are under lateral pressure and normal loads. An idealized grillage model in ship structural modeling is developed from a flat plate having stiffeners and transverse frames with girders. Beams are used for developing grillage model are flanged ones contributing in effective breadth. Bulkheads of ship structure, double bottoms hull, and deck structure are some of the examples. This model is created with the help of conventional 3D beam elements.

E. Frame Model

Frame model is associated with 2D or 3D frame structures. These frame structures are longitudinal girder, transverse webs and flange connected plates. This model is used to analyze the frame structures for investigating bending and shearing of the web structure, and torsion, for which fine meshing of a model is required. Different plates between stiffeners are typically modeled by using shell elements. Some extra position of web frames and girders are created to examine the stresses without using interpolation.

F. Local Structure Model

Local Structure model is created to examine the local structure and special components. The examples of local members are the plate stiffeners, which are laterally loaded and subjected to relative distortions between end supports. The modeling of local structures under large deformation requires fine mesh with good aspect ratio. Three 4-node shell elements are used to model the stiffeners with flange. Modeling of plates between stiffeners requires a minimum of three shell elements.

III. FEA Procedures

A. Meshing

When the complete structure model is prepared, the pipes, plates, stiffeners and other structures are then meshed individually. Selection of element size, shape and element divisions are the final steps before meshing. A complete FE mesh model is generated by selecting and repeating the mesh process for every part of the model separately. The plates having sharp corners and curvature are critical portions in meshing. "Smart element sizing" is used to re-mesh these. The number of element and degrees of freedoms associated with the structure should be properly controlled. This step is most important to control the solution time. However, accuracy of the results cannot be compromised.

A ship's structure is assumed as a thin wall box which is stiffened by beams and subjected to shear and torsion loads. Plate shell element is the ideal FE technique for modeling such a structure. The elements type selected for a ship's structural analysis must be tested for convergence and consistency. One dimensional truss elements having axial stiffness can be used to model stiffeners in ship analysis, whereas 1D beam elements having axial, shear, bending and torsional stiffness are used for modeling beam structures. Stiffeners and eccentric beams with offset neutral axis cannot be modeled from beam elements. Equivalent concentric beams are selected to allocate the right beam elements properties. The neutral axis is supposed to be positioned at the central layer of the connected plate. This process also utilities the effective plate width in the calculation of moment of inertia. During calculation of sectional areas of beam elements, all the attached plates are omitted.

Deck structures are subjected to in-plane loads rather than transverse loads, and therefore, membrane elements are used for their modeling. Two dimensional shell elements with out-of-plane bending and torsional stiffness are used for modeling of side shell structures. However, when transverse loads are applied to a deck structure, 3D solid elements are required for analysis. The selection of solid elements with reasonable thickness is important to calculate the stress. Supports connected by stiffeners are modeled by using boundary and spring. In dynamic analysis, point or mass elements are used. Since computer technology has developed and computing time is reduced for FE analysis, the combination of beam elements with bending plates is therefore preferable. Plate elements are the best option for stiffeners modeling except for rolled sections like full bulb profile and Holland profile. The combination of bending and membrane plate elements is not commonly used in FE modeling. However, rod elements (face plates) and bending plates (web plates) can be combined for supporting structures.

B. Loading

Generally, all the necessary loads are calculated by direct hydrodynamic calculations method. The loads acting on a ship can be divided into:

1. Static Loads – These loads consist of loads which remain stable with time, or even if they vary, their effect with respect to time could be ignored. Some static loads are ship components weights, hydrostatic pressure, cargo and ballast loads. These loads also include moments and forces produced by waves.
2. Dynamic Load – Dynamic analysis is required to be performed when applied loads vary with time, and this variation becomes significantly large with time. Hydrodynamic pressure produced by waves, operational loads of machinery, underwater explosion and wind loads are also considered as dynamic loads.

Therefore, it is important to apply the correct loads and analyze the structure accordingly. ANSYS makes the application of load practicable with fewer errors while combining the loads.

C. Boundary Conditions

In FE methods, boundary conditions are applied at different supports by selecting the relevant nodes to constrain their translational and rotations movement. For the global analysis, it is necessary to avoid the rigid body motion of the model which is normally controlled by 6-DOF. The translational supports are placed away from the areas of interest. A balance load is generated at translational supports to eliminate the forces of constrained node. In some analyses, symmetric boundary conditions are helpful and are related to load application and structural arrangements.

Symmetric boundary conditions for the half breadth model are applied with respect to center line. In case of uniform lateral loads, symmetric boundary conditions are applied at the ends of the model and stresses generated by the global hull are overlapped into the results. On the contrary, stress and displacement generated due to hull girder bending and shearing forces can be set at the end cross sections. Alternatively, if a hull model is supported by vertical springs, then spring constants are equally distributed at relevant interactions between the transverse bulkhead and hull inner sides and between the transverse and longitudinal bulkhead. Vertical forces can also be applied along the intersections in place of vertical springs, while nodal points at each intersection are required to be fixed in the vertical direction to remove the rigid body motion.

Different boundary conditions are required for a hull module under hull girder loads. For hull girder vertical bending, these are applied at transverse bulkhead. Whereas, in the case of vertical shearing forces, symmetric boundary conditions are placed at the ends of the cargo hold model. When a ship is assumed under vertical shearing forces and only half breadth of the ship is considered, then symmetric boundary conditions can be applied along the center line of ship.

D. Analysis

Different types of analyses can be performed according to requirements. Analysis results are checked for buckling, yielding and ultimate strength at selected positions. The various FE analyses that are generally performed are:

1. Stress analysis of complete ship,
2. Ultimate strength analysis,
3. Vibration analysis,
4. Thermal analysis,
5. Transient dynamic analysis due to impact.

Before performing these analyses on the complete model, they are always carried out on simple structures such as plates and plates with stiffeners. Appropriate FE models are prepared, and proper loads and constraints are applied to thoroughly check the model for non-linear and transient dynamic analysis by using fine mesh size, different element types, and various time steps. Then, analysis results are compared with either published or experimental results. After the satisfactory results, these analyses are performed for the ships having intricate structures and components.

In FE analysis, all the loads and constraints are thoroughly examined, and therefore, there are less chances of errors in the selection of analysis methods. Also, the analysis performed for intricate ship structures can also be verified by measuring the results on real ship structures. After the verification of results, the FE method is concluded for consequent analyses.

IV. Finite Elements Analysis

FEA has been used in the marine industry for many years. Lloyds, along with other ship classification societies, were earlier adopters of this technique. Today this method has been used in the design and verification of all vessels and large commercial ships. The FE method supports different types of analysis, the main types of FEA and their applications are:

A. Linear Elastic Analysis

In Linear Elastic analysis, stress is assumed in the elastic limits and linear relationship between stress and strain is considered. Generally, initial design and scantlings are checked by using stress and deflection results obtained from the linear elastic analysis. Commonly, classification societies emphasize on elastic region during ship design, with the maximum stress ranging between 75% to 80% of the yield strength and shear stress approximately 50% of the shear yield strength. As the stress and strain is directly proportional in linear analysis, the displacement and rotation are therefore assumed very small at the supports as the structure starts deforming.

B. Nonlinear Analysis

A ship hull is considered as a thin-walled box structure organized with open or closed stiffened panels according ship characteristics. All structures constructed from thin walls are subjected to buckling. In general, the two categories of nonlinear analysis have significant applications in ship structural analysis:

1. Material nonlinear analysis
2. Geometric nonlinear analysis

Large deflections and large strains are the main cause of geometric nonlinearity, and in general, this phenomenon occurs in thin walled structures. The steel material of shipbuilding has a nonlinear stress strain pattern.

C. Static and Dynamic

The loads resulted due to high speed and slamming pressure and lightweight structures are simulated using static and free vibration analysis. Most ships are fabricated with aluminum and steel, it is necessary to check the ship strength against slamming loads. The free vibration analysis of the complete ship and superstructure are performed to calculate the natural frequency and the mode shapes to avoid resonance. When dynamic loads vary with time, they have a direct impact on the mass and stiffness of the structure. For example, we need greater support when a heavy cell phone drops because of its greater mass.

D. Mast Static and Dynamic Analysis for Ships

Mast structure is analyzed against ship motion and wind loads. The base of the radar antenna is attached to the mast structure and for the precise functioning of the radar the mast deflection must be small against radar operational frequency. Transient dynamic analysis is used in this situation and the mast structure is modified to limit the deflection within an allowable range.

E. Comparative and Absolute

By using comparative analysis, it may be possible to see whether changes in geometry are going to improve or reduce the performance of the unit without knowing spring loads. For example, it might be a coil spring from a car suspension.

F. Vibration and Impact

It is necessary to perform a free vibration analysis during the early design stage of a vessel to estimate the natural frequencies and various mode shapes. These analyses are usually done for different loading conditions:

1. Light ship condition
2. Fully loaded condition
3. Ballast conditions

Added mass effects are also integrated in the simulation to check the behavior of vibration elements in contact with water.

G. Buckling

Buckling occurs in relatively thin and narrow objects like beams and sheet-metal parts. As an example, a length of wire supports less load as compared to the tension in wire due to the buckling phenomenon. FEA is used to estimate, fully or partially, buckle objects, against the applied loads. In ship structure design, buckling analysis is done to test the strength of ship structures against local and global loads. For different pressures, different force and moment are applied at the same time for the analysis. The hatch coaming requires special investigation for buckling against different axial loads.

H. Fatigue

The effects of cyclic loading acting on different components are easily predicted by using FEA. Estimated product life span, crack initiation and propagation area can also be highlighted through fatigue analysis.

I. Heat Transfer and Thermal Deflections

FE analysis techniques are used to calculate temperature distribution at different areas of objects and effect of heat on a component's strength.

J. Creep and Relaxation

Creep is a process in which engineering materials tend to steadily extend over time and ultimately rupture. It is a major consideration for most plastic designs and is highly influenced by temperature. FEA have the capabilities to predict this behavior during the analysis.

V. Results and Discussion

THE use of FEA for ship structure has increased greatly over recent years. This increase is due to advances in research in computational methods together with the advancement in performance. Different loadings conditions can be applied on the ship; nodal load (point loads), element load (pressure, thermal, inertial forces) and time or frequency dependent loads.

It is now possible to characteristically investigate many issues related to a specific kind of ship. It is wise to have a global FE model during the early design stage efficiently evaluated with FEA, which yields an optimum situation, where the results of the FE study can be utilized during the later design process. APDL and ANSYS macro played a major role in expanding the scope of FEA for various operating conditions, specifically at the design stage, to construct advance ship structures which are 'fit for purpose', more than ever before. The use of these methods is still dependent on keen knowledge of structural behavior against different boundary conditions for actual results. At the same time, FE analysis is only the approximation of the mathematical model of a system and only one specific numerical result having a finite number of significant digits is obtained for any specific problem. FEA may have inherent errors during the formulation and mistakes done by users during the input of analysis properties and parameters can be fatal. Certain effects are not automatically induced in the model such as complex buckling, hybrid composites, nanomaterial modeling, as well as multiple simultaneous causes. Therefore, more attention is required in cost reduction, structural optimization, reliability, probabilistic design and application of sensitivity and parametric studies in linear and non-linear analysis, when the effects of initial imperfections and residual stresses are also considered during analysis. There is great scope in investigating the multi physics applications to ship seaway response against wave loading including fore and aft slamming. More extensive research in FEA is required to consider the life extension of ageing ships and fatigue due to vibration.

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