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Longitudinal Strength Analysis of a Container Ship under Sagging and Hogging Conditions Using the Finite Element Method

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***Abstract*— This study analyzes the longitudinal strength of a container ship under hogging and sagging conditions using the Nonlinear Finite Element Analysis (NLFEA) method. Numerical modeling was performed on a single frame spacing of the container ship to evaluate the stress and deformation distribution due to longitudinal bending loads. A three-dimensional finite element model was developed using SHELL181 elements in ANSYS software, employing large displacement static analysis. The results show that under hogging conditions, the deck experiences a maximum tensile stress of 410.28 N/mm², while the bottom structure undergoes a compressive stress of -405.93 N/mm². Under sagging conditions, the deck experiences a compressive stress of 279.91 N/mm², and the bottom experiences a tensile stress of -387.80 N/mm². The ultimate bending moments were 1.42 × 10^{13} Nmm for hogging and -1.21 × 10^{13} Nmm for sagging, indicating that the ship is more susceptible to structural failure under sagging conditions. These findings highlight the importance of considering both loading conditions in the structural design of container ships to ensure safety and operational efficiency.**

Keywords—Container ship, longitudinal strength, hogging, sagging, finite element method, stress analysis, bending moment, deformation, structural strength.

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I. INTRODUCTION

Container ships are vital to the global economy due to their crucial role in the logistics and transportation chain, based on the principle of economies of scale. This phenomenon states that the unit cost per transported container decreases as the ship's carrying capacity increases, leading to rapid growth in ship size [1]. This increase in capacity is associated with two phenomena: on one hand, an increase in the ship's principal dimensions, and on the other, an increase in the loads and stresses endured by the structure during operation [2].

In this context, container ships have become one of the most essential means of sea transportation to be developed, as they play a key role in handling the volume of goods shipped across the oceans. Container ships facilitate the mass movement of goods, connecting producers and consumers across different regions [3].

To determine the hull girder strength of a ship, it is important to evaluate the most extreme loads that may act upon it. Two main categories are usually considered when assessing a ship's strength: longitudinal and transverse [4]. There are two critical conditions in both directions that must be analyzed — hogging and sagging. The hogging condition is characterized by the deck experiencing tensile stress while the bottom structure experiences compressive stress. Conversely, under sagging, the deck undergoes compression, and the bottom structure experiences tension. In both cases, the deck and bottom are the most critical areas, as they are the first to experience failure. Therefore, it is essential to analyze the magnitude of stress and deformation that occur in these parts.

The behavior or deformation of a ship under hogging and sagging conditions must be analyzed, as it is significantly influenced by the structural elements within the ship. As previously mentioned, stresses act on both the deck and the bottom structures, and the internal elements interact with one another in response to these stresses.

Several studies related to ship strength have been conducted. Li and Kim presented the development of the R–D diagram for Smith-type progressive collapse methods for four classes of double-hull tankers — VLCC, Suezmax, Aframax, and Panamax [5]. Kuvznecos et al. introduced the SHARC methodology for simulating and analyzing damage stability and ultimate limit state (ULS) conditions after collision [6]. Babazadeh and Khedmati investigated cracking effects on the longitudinal strength of ships based on prior research [7]. Chen et al. studied a naval ship model with an integrated composite sandwich superstructure, derived from similarity theory by scaling down an actual naval ship [8]. Jagite et al. proposed a new approach to solve fully coupled hydro-elastoplastic problems [9].

Suci et al. compared ultimate strength with and without hatch openings, considering the ship's longitudinal strength [10]. Muis Alie et al. examined the influence of side girder spacing in the bottom structure of a double-hull tanker on its main strength [11]. Alamsyah et al. calculated the ultimate strength of a 270-foot deck barge under global loads using numerical

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simulation [12]. Suci et al. analyzed longitudinal strength considering cargo load on a Very Large Crude Carrier (VLCC) [13]. Muis Alie et al. investigated the modification of double bottom height and its effect on ultimate ship strength [14]. Suci et al. analyzed stiffened plates under uniaxial loading on an FPSO [15], while Rati et al. studied the influence of extended plates on stiffened plates under uniaxial axial load for FPSO structures [16]. Muis Alie et al. also examined the impact of collision-induced hull damage on the ultimate strength of double-hull tankers [17].

Furthermore, Shi and Gao conducted collapse experiments on a steel model with a superstructure based on a real cruise ship [18]. Bai et al. applied the Progressive Collapse Method (PCM) for ship structures, simplifying local buckling by adopting an average compressive stress–strain curve for the plate to analyze the ultimate strength of box girders [19]. Shen et al. proposed a probabilistic approach to evaluate uncertainty in ultimate ship strength predictions due to critical characteristics in longitudinal strength capacity (LSC) [20]. Xizhao and Xuekang developed a reliability assessment process for determining the design criteria of Very Large Floating Structures (VLFS), establishing target reliability intervals based on risk assessment methods that consider both failure probability and structural consequence [21].

Containerization the transport of goods using standardized containers has become a dominant part of international trade and maritime transportation. Containers are designed for carrying large quantities of goods efficiently. However, container ships are not exempt from potential hazards during voyages if not built based on precise design calculations.
This study is therefore essential for further analyzing the longitudinal strength of container ships under hogging and sagging conditions. The findings contribute new insights and understanding regarding the structural strength of container ships prior to construction.

II. METHOD

The longitudinal strength of the ship was analyzed using a numerical approach by modeling one frame spacing of the container ship as a representative portion of the structure under study. This numerical approach is widely used and recommended by ship classification societies as the primary method for calculating structural strength, alongside other approaches such as beam theory and stress distribution methods. Therefore, the use of analytical or simplified methods also remains relevant and can serve as an alternative for analyzing a ship's longitudinal strength.

In this study, the longitudinal strength analysis of the container ship was conducted by considering one frame spacing to represent the structural response of the ship under hogging and sagging conditions. The cross-section of this frame spacing was assumed to remain plane during the progressive collapse process. To ensure uniform deformation, a Multiple Point Constraint (MPC) was applied to the cross-section. The MPC position was placed exactly at the neutral axis as a reference point with zero axial force, as illustrated in Figure 1.

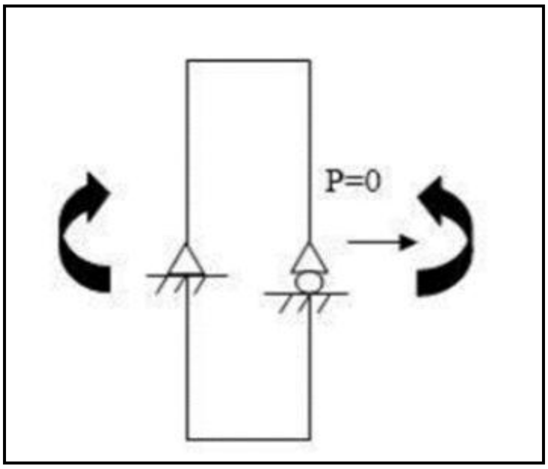

Figure. 1. Boundary Coundition

As shown in Figure 2, the cross-section and material properties of the container ship were defined to represent the structural characteristics of the hull girder in the analysis.

Stif. No.	dimensions	type	σ_Y (MPa)	Stif. No.	dimensions	type	σ_Y (MPa)
1	300 × 38	at-bar	352.8	9	230 × 10	at-bar	313.6
2	300 × 28	at-bar	313.6	10	300 × 90 × 13/17 IA	angle-bar	313.6
3	250 × 90 × 10/15 IA	angle-bar	313.6	11	150 × 90 × 12/12 IA	angle-bar	313.6
4	250 × 90 × 12/16 IA	angle-bar	313.6	12	250 × 90 × 12/15 IA	angle-bar	313.6
5	300 × 90 × 11/16 IA	angle-bar	313.6	13	150 × 12	at-bar	313.6
6	300 × 90 × 13/17 IA	angle-bar	313.6	14	150 × 90 × 9/9 IA	angle-bar	313.6
7	350 × 100 × 12/17 IA	angle-bar	313.6	15	150 × 10	at-bar	313.6
8	400 × 100 × 11.5/16 IA	angle-bar	313.6	16	300 × 90 × 11/16 IA	angle-bar	313.6

(dimensions in mm)

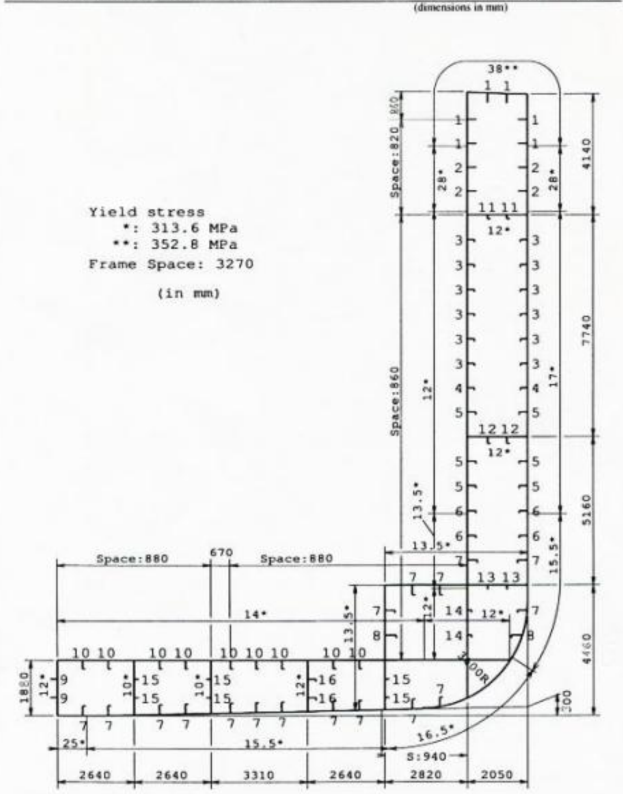

Figure. 2. Container Ship Cross Section

A three-dimensional finite element model was developed using SHELL181 elements, taking into account the configuration and material specifications of each component, as shown in Figure 3. A uniform mesh size of 300 mm was applied throughout the entire model.

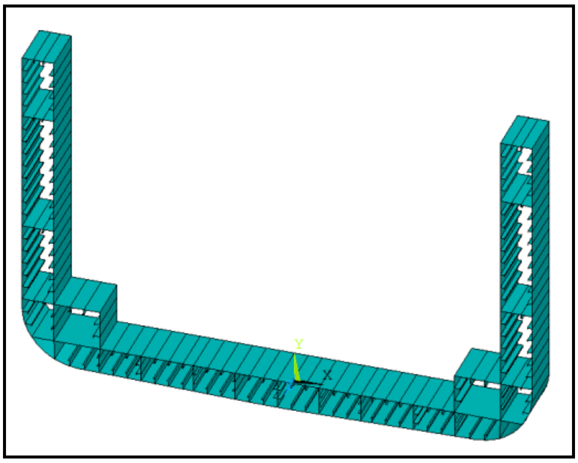

Figure. 3. Container Ship Cross Section in ANSYS

The position of the neutral axis was first calculated to determine the location of the Multiple Point Constraint (MPC) to be used. The MPC was then placed on one side of the container ship's cross-section and connected to the bending moment load. This step was carried out to illustrate the stress distribution pattern and structural deformation of the container ship's cargo hold during progressive collapse under longitudinal bending loads in both hogging and sagging conditions, as shown in Figure 4. The numerical analysis was performed using the ANSYS Student Version, with the analysis process divided into 100 substeps using a large displacement static analysis type.

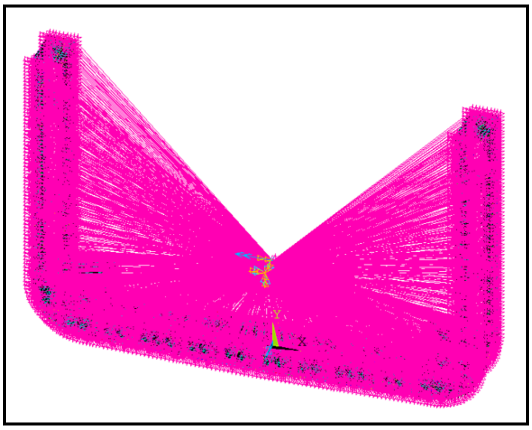

Figure. 4. Boundary Conditions for NLFEA Method

To simplify the modeling process, several factors such as strain, initial geometric imperfections, residual stresses from the welding process, and damages such as impacts or cracks were neglected in this analysis.

III. Results and Discussion

The analysis was carried out to determine the ultimate strength of the container ship under hogging and sagging conditions. The structural behavior characteristics of the container ship's cross-section under hogging conditions for this configuration are shown in Figure 5. This stage represents the ultimate strength phase, where the container ship is subjected to longitudinal bending (hogging). The upper part of the structure experiences tensile stress (tension), illustrated in red, while the lower part experiences compressive stress (compression), shown in blue. The presence of hatch openings causes a reduction in stiffness in the upper region, resulting in the red-colored area extending toward the side shell.

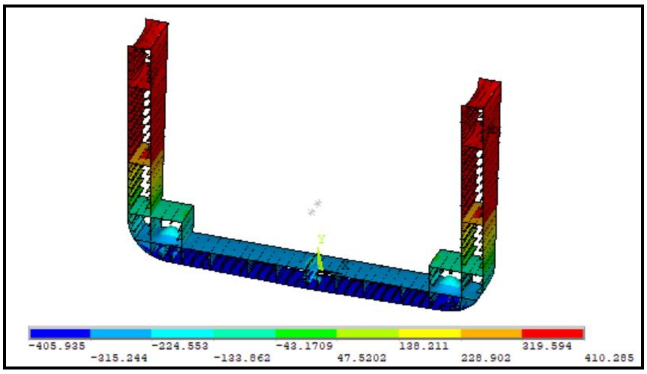

Figure 5. Deformation of the hull girder limit strength due to hogging

In the figure above, the working stress values occurring in the container ship structure under hogging conditions are -405.93 N/mm² at the bottom of the ship, while the maximum stress occurs on the deck with a value of 410.28 N/mm². Figure 6 shows the characteristics of the container ship's cross-section under sagging conditions at the ultimate strength stage. It can be observed that when the cross-section of the container ship is in the sagging condition, the upper part experiences compression, while the lower part experiences tension. The sagging condition can be seen in the following figure.

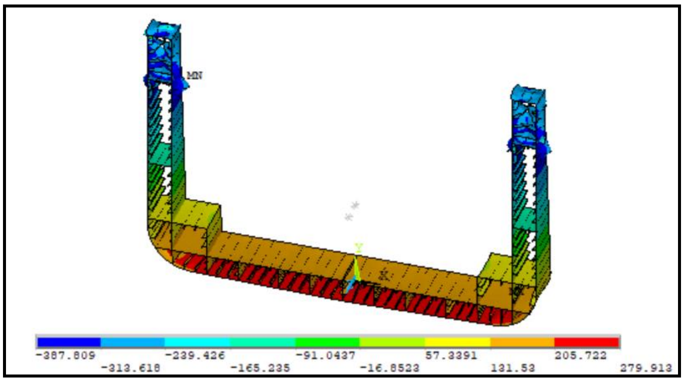

Figure 6. Deformation of the hull girder limit strength due to sagging

In the figure above, the working stress values occurring in the container ship structure under sagging conditions are -387.80 N/mm² at the bottom of the ship, and a stress of 279.91 N/mm² is observed on the deck. Table 1 presents the results of the ultimate strength calculated under sagging and hogging conditions using Nonlinear Finite Element Analysis (NLFEA).

Table 1.
Ultimate Torsion Strength Results

Kondisi	NLFEA
Mu Hogging x 10^{13}	1,42
Mu Sagging x 10^{13}	-1,21

Based on the table above, the ultimate strength of the container ship under hogging conditions is 1.42 × 10^{13} Nmm, while under sagging conditions it is -1.21 × 10^{13} Nmm. The relationship between the moment of curvature and the bending moment of the container ship obtained using the NLFEA method in ANSYS is shown in Figure 7 below.

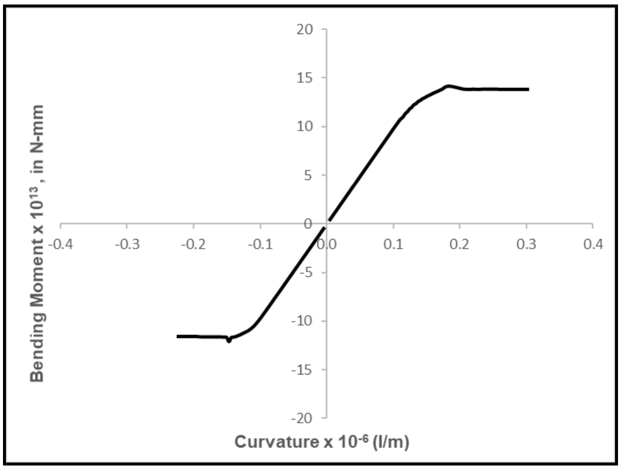

Figure 7. Moment-curvature relationship

The figure shows that when the container ship is in the sagging condition, the structural ultimate strength is reached more quickly, making the ship more vulnerable to damage compared to the hogging condition. This is indicated by the smaller value of the vertical ultimate bending moment under sagging compared to hogging.

The influence of bending moment characteristics on the container ship structure is highly significant in determining the ship's longitudinal strength. The bending moment, which arises from the combination of wave loads and cargo distribution, causes alternating tensile and compressive stresses on the upper and lower parts of the ship's cross-section. Under hogging conditions, the deck experiences tensile stress, while the keel is under compression. Conversely, in sagging conditions, the deck is under compression, and the keel experiences tension.

These differences in bending moment characteristics affect the distribution of longitudinal stresses and structural deformations along the ship's hull. As the bending moment increases, the structure undergoes greater deformation, requiring additional stiffness through the optimization of plate dimensions, stiffeners, and frame spacing. Finite Element Method (FEM) analysis shows that variations in the bending moment determine the structural strength limits, particularly in critical areas such as the deck, side shell, and bottom structure, which are most susceptible to failure due to bending loads.

Thus, the characteristics of the bending moment serve not only as an indicator of the ship's global loading condition but also as a fundamental basis in the design of safe and efficient container ship structures under both hogging and sagging conditions.

IV. Conclusion

Conditions The longitudinal strength analysis of the container ship using the finite element method shows that hogging and sagging conditions have a significant influence on the stress distribution and deformation of the ship's structure. The maximum stress occurs on the deck under hogging conditions and on the bottom structure under sagging conditions. Based on the NLFEA results, the ultimate bending moment under hogging is 1.42 × 10^{13} Nmm, which is greater than that under sagging, -1.21 × 10^{13} Nmm. This indicates that the ship reaches its failure limit more quickly under sagging conditions. Therefore, increasing stiffness and structural reinforcement in the bottom and deck areas is necessary to maintain stability against extreme bending moments. This study provides an important contribution as a reference for designing safer and more reliable container ship structures capable of withstanding hogging and sagging load conditions.

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