Application of Scale Finite Element Method for Evaluating Ship Longitudinal Strength

Oludi, Kingsley
Department of Marine Engineering,
Faculty of Engineering,
Rivers State University, Port Harcourt, Rivers State.
kingsley.oludi@ust.edu.ng

&

Nwoka. B.G
Department of Marine Engineering,
Faculty of Engineering,
Rivers State University, Port Harcourt, Rivers State.

Abstract

This research investigates the longitudinal strength of ship hull girders under complex loading conditions using nonlinear finite element method (FEM) analysis. The study employs ABAQUS software to model the MST-3 vessel, focusing on vertical bending moments and the effects of torsion. A comprehensive three-dimensional finite element model spanning three web frame spacings is developed to ensure the validity of the analysis, with boundary conditions and material properties carefully defined. The results highlight critical stress distributions within the hull girder, emphasizing that hull girder stresses due to vertical bending and torsion significantly influence total stress, especially near cargo hold bulkheads and hatch coamings. Torsion-induced warping stresses were found to be predominant in open-deck configurations. The FEM results closely align with experimental findings, demonstrating the model's accuracy in predicting the ultimate longitudinal strength of the hull girder. This study underscores the efficacy of nonlinear FEM analysis in assessing ship structural integrity under various load conditions and contributes valuable insights into hull girder behavior. The findings provide a foundation for improving ship design practices, ensuring structural reliability, and enhancing safety in marine operations.

Keyword*; Design, Hull Girder, Stress, Torsional Effects, Bending Momen*

Introduction

The hull girders of a ship play a major role in the structural system's strength and integrity. It is crucial to assess the most severe loads that can be placed on a hull girder in order to ascertain its strength. When assessing a ship's strength, three factors are often taken into account: longitudinal, transverse, and local. The stability of the ship is significantly impacted by the longitudinal strength of each of its parts (Joynal, *et al.* 2023). Ships with open decks feature larger hatches, which create challenges in maintaining hull strength. These expansive deck openings influence hull stress under both longitudinal and transverse bending. Moreover, wide deck openings in rough seas can diminish hull stiffness against torsional loads (Richardson, 2015). Axial (warping) and shear stresses arise in thin-walled beams under torsion, with warping stresses concentrated around hatch corners. Torsional loading occurs when a ship encounters oblique waves, accompanied by a reduced vertical wave bending moment (Shama, 2010).

Studies on hull strength under combined bending and torsion have provided valuable insights. Elbatouti et al. (2022) utilized finite element methods (FEM) to analyze the SS-7 container ship under vertical, lateral, and torsional moments, identifying that local deformations significantly elevate stress levels in inner bulkhead plates due to structural non-prismatic features and deck openings. Ostapenko (1986) found that torsion in oblique seas reduces a ship's longitudinal hull strength, highlighting the need for robust hull design to enhance safety and performance under various loading conditions.

Similarly, Parunov (2021) examined two general cargo ships and reported sufficient stress levels and compliance with the Croatian Registry of Shipping rules, suggesting the structures could handle intended loads. Vemon and Nadeau (1987) compared St. Venant and warping-based theories for thin-walled beams, concluding that the latter offers a superior representation of prismatic thin-walled sections by incorporating longitudinal deformation. Tang et al. (2019) employed three real-time methods to assess hull longitudinal strength, local yield strength, and fatigue, identifying areas prone to damage under varying wave azimuths. Valsgard et al. (1995) examined the structural impact of torsion, noting diagonal shear deformations, stress concentrations, and fatigue risks at hatch corners.

Research by Paik et al. (2001) explored the ultimate strength of a 4300 TEU container ship's hull under vertical bending and torsion, revealing torsion's limited impact on ultimate strength unless torsional rigidity is low. Iijima and Shigemi (2004) proposed a simplified method to estimate torsional strength by segmenting the hull girder and applying beam theory, emphasizing its importance in container ship design. Senjanovic and Rudan (2008) used 3D FEM to evaluate torsional effects in large container ships, concluding that transverse bulkheads minimally affect bending stiffness but stressing the role of hydroelastic analysis. Chirica et al. (2009) proposed a quick calculation method for torsional analysis using thin-walled beam theory, while Parunov and Uroda (2010) applied FEM to highlight stress-prone areas in general cargo ships, advocating for fine mesh modeling to improve structural safety. Senjanovic and Vladimir (2011) advanced thin-walled girder theories and hydroelastic analysis techniques, employing modified Timoshenko beam theory and FEM tools for ultra-large container ships, validating results through Euler–Bernoulli theory comparisons. Novikov and Antonenko (2015) emphasized the correlation between bending and torsion loads on hull girder stresses, while Vladimir and Senjanovic (2016) examined fatigue and extreme load resilience in conventional container ships. Rorup et al. (2016) utilized complex FEM models for improved design processes.

To accomplish the goal of the study, the following objectives were addressed.

1. Derive finite element formulae for calculating ship longitudinal strength.

2. Determine the hull girder strength of a vessel, as well as studying the strength of a vessel and find possible reason for deformation.
3. Analyzing stress distribution throughout the hull, as well as identifying areas of high stress concentration.
4. To determine the longitudinal strength of a vessel by making use of MATLAB software

Materials and Methods

Material

The material for this research work involves the use of ABAQUS software to conduct a finite element analysis on the MST-3 vessel. MST-3 vessel is used as a case study for this research work. When a ship's hull is intact, it can withstand applied loads that are less than the design load and won't experience any structural damage under typical seagoing and authorized cargo loading conditions. However, because of the nature of strong waves and the potential for irregular cargo loading and unloading, the loads acting on the ship hull are unpredictable. In exceptional instances, the ship hull may collapse both locally and globally due to exerted loads exceeding design loads. The ship hull's structural components will yield in tension and buckle in compression as exerted loads rise over the design loads. Buckling and collapse of more structural elements will gradually develop as loads climb further, until the hull girder as a whole reaches the ultimate limit condition.(Jeom & Alaa. 1995).

HOW TO USE FEM TO DETERMINE THE MST-3 SHIP'S LONGITUDINAL STRENGTH

A variety of models with finite element lengths were proposed by various researchers, ranging from full-scale ship models to 1+1/2 holds models, 1+1/4 holds models, 1/2+1/2 transverse frame spacing, 1/2+1+1/2 hold tanks, three cargo hold models, and 1+1+1 web-frame spacing.

Since the neutral axis shifting in this study depends on the model's curvature during the progressive collapse analysis, it is required to expand the model sufficiently to remove the boundary condition's influence on the analysis. According to the analysis, it makes sense to at least extend the finite element model to three web frame spacing (see Figure .1). The study is valid in the center part of the finite element model. A full breadth model should be used in the transverse plane, and a full depth model in the vertical direction.

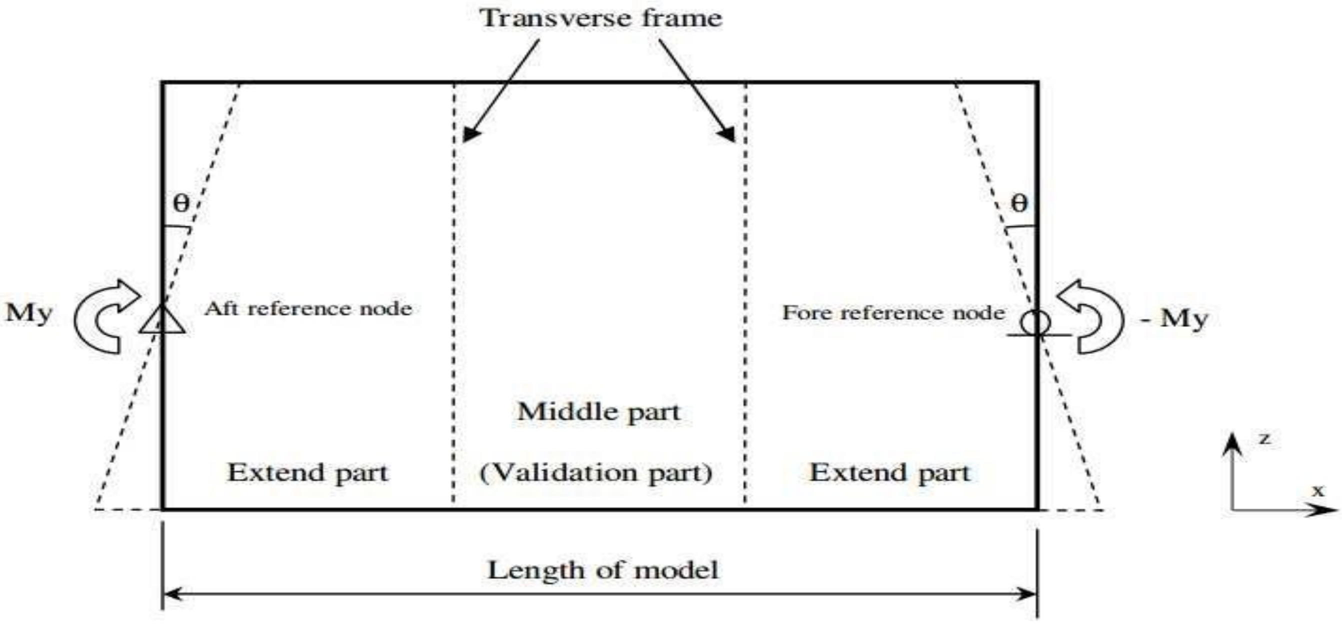

Figure 1: The finite element model's foundation in this investigation.

Boundary Conditions

The displacement at the two ends of the model (in Figure 1) can be simulated by means of multiple points constraints, it so called MPC. The independent point (reference point) is located at aft and fore end of model, there are the intersection between centerline and either centroid of the cross section or an arbitrary height of a cross section of ship hull girder. The simply supported will be applied at two independent points as Table 1.

Table 1 Boundary Conditions of the Independent Points

Location of independent point	translational			rotational		
	Dx	Dy	Dz	Rx	Ry	Rz
Aft end of the model	fixed	fixed	fixed	fixed	-	fixed
Fore end of the model	-	fixed	fixed	fixed	-	fixed

TYPE OF ELEMENT

To simulate ship structures, a variety of shell elements are provided. The majority of finite element algorithms incorporate general purpose shell elements, which are utilized for thick and thin shell issues and offer precise solutions in those situations. The small-strain shell elements S4R5 (Each node has five degrees of freedom., hourglass control, reduced integration, and a four-node thin shell with a double curvature.*)* in ABAQUS are employed in this investigation.

INITIAL DEFLECTIONS

Elastic buckling mode is used to assume the initial shape deflections (see Figure 2). The equation below provides it.

$$W_i = A_o \sin \frac{mnx}{a} sin \frac{mny}{b} \qquad (1)$$

Where; m is a half-sinusoidal wave number that separates the longitudinal stiffeners. Stiffener sideways, stiffener lateral, and form initial deflection amplitude of the plate between stiffeners are denoted by A0, B0, and C0, respectively.

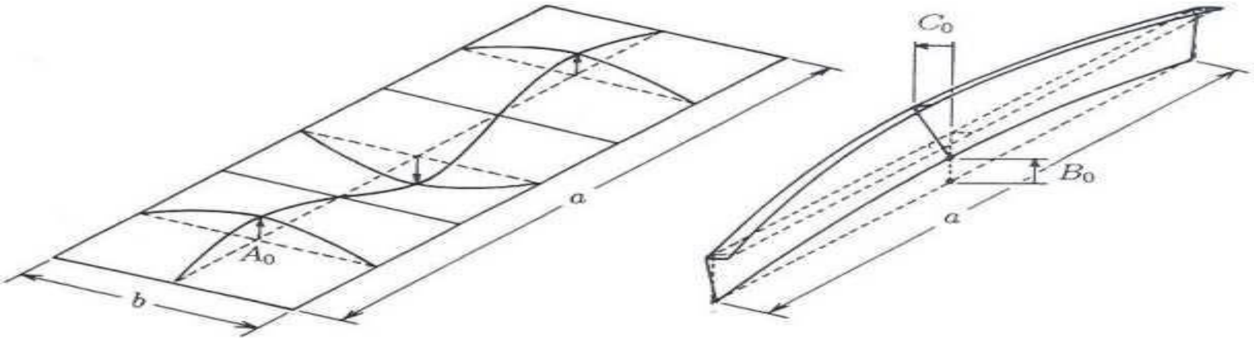

Figure 2. Assumed initial deflections in stiffened plates

Residual Stress

Hughes' equation is used in this work to evaluate the residual stresses resulting from welding.

$$\sigma_r = \frac{2\eta}{\frac{s}{t}-2\eta}\sigma y \qquad (2) \qquad\qquad \eta = \frac{1}{tp}\left[\frac{tw}{2} + 0.26 + \frac{\Delta Q}{tw} + 2tp\right] \qquad (3)$$

where:

Web thickness is denoted by tw

tp is the thickness of plate

$\Delta Q = 78.8l2$, $l = 0.7tw$ when $0.7tw < 7.0$ mm, $l = 0.7$ when $0.7tw \geq 7.0$ mm.

BENDING MOMENT (BM) CALCULATION

The bending moment at a section of a ship's hull can be calculated using:

$$BM = \frac{wl^2}{8} \qquad (4)$$

Where:

w = uniform load per unit length (N/m)

L = length of the section (m)

SHEAR FORCE (SF) CALCULATION

The shear force at a section can be calculated as:

$$SF = \frac{wl}{2} \qquad (5)$$

STRESS CALCULATION

The bending stress (σ) at the neutral axis can be calculated using:

$$\sigma = \frac{m.c}{I} \qquad (6)$$

Where:

M= bending moment (Nm)

C = distance from the neutral axis to the outer fiber (m)

I = moment of inertia (m^4)

DEFLECTION CALCULATION

The deflection (δ) at midpoint of a beam with simple support can be calculated using:

$$(\delta) = \frac{5wl^4}{384EI} \qquad (7)$$

Where:

E = (Pa) = modulus of elasticity
I = m^4 (m = moment of inertia)

GOVERNING EQUATIONS

Governing equations for a beam under bending are given by:

$$\frac{d2}{dx2}\left(\frac{EId2y}{dx2}\right) = \mathrm{q(x)} \qquad (8)$$

LONGITUDINAL BENDING STRESS

The longitudinal bending stress (σb) can be calculated using

$$\sigma b = \frac{M.y}{I} \qquad (9)$$

Where:

M = bending moment (Nm)

y = distance from the neutral axis (m)

I = moment of inertia (m^4)

AXIAL STRESS CALCULATION

The axial stress (σa) in a beam subjected to axial load can be calculated using:

$$\sigma a = \frac{P}{A} \qquad (10)$$

Where:

P = axial load (N)

A = cross-sectional area (m^2)

BUCKLING STRESS

For a slender column (or beam) under axial load, the critical buckling stress (σcr) can be calculated using:

$$(\sigma cr) = \frac{\pi 2E}{(KL)2} \qquad (11)$$

Where:

- E = modulus of elasticity (Pa)
- L = effective length of the column (m)
- k = column effective length factor (for a pinned-pinned column, k=1)

DEFLECTION DUE TO POINT LOAD

The deflection (δ) at the midpoint of a simple support beam under a point load PPP can be calculated using:

$$(\delta)= \frac{PL3}{48EI} \qquad (12)$$

3.RESULTS AND DISCUSSIONS.

Since the MST-3 model is 540 mm long, the finite element model's overall length is 3x540 mm (Figure 3). Figure 3 displays the cross section box girder scantlings.

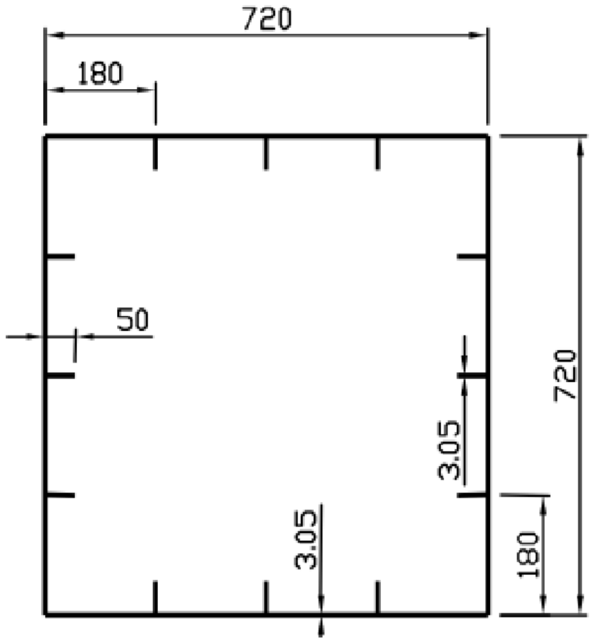

Figure 3: The MST-3 model's cross section scantling

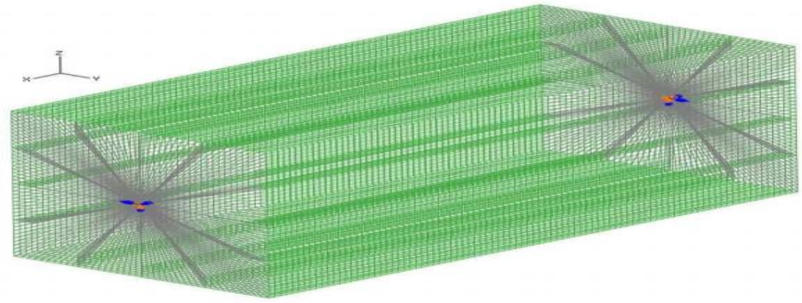

Figure 4: MST-3's finite element model

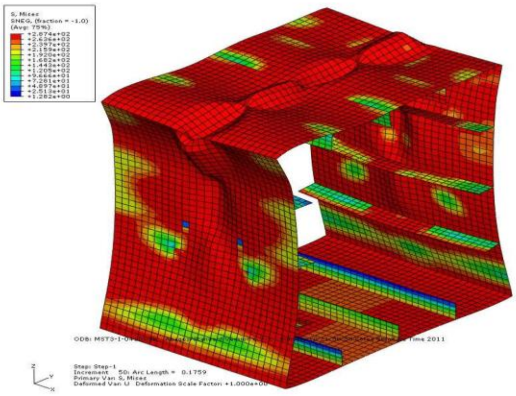

Figure 5 Von-Mises stress plot of validation part in sagging condition

The longitudinal strength of the FEM data is displayed in Table 2. It is evident that the FEM results correspond well with the experiment. For sagging conditions, the difference between the FEM case with residual stress and the case without is approximately 3%, whereas for hogging conditions, it is approximately 1%.

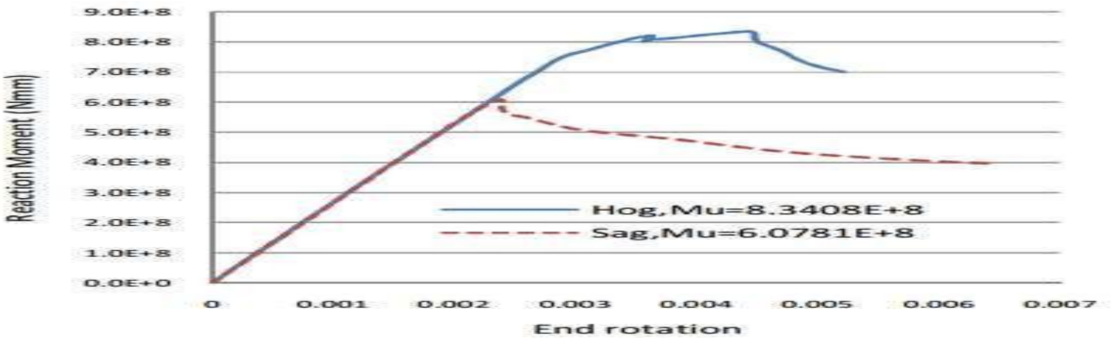

Figure 6 showing FEM results of hogging and sagging conditions

The FEM Method on A 1/3 Scale

Dow created the 1/3-scale Frigate model, which has the following overall measurements: 18 m in length, 4.1 m in width, and 2.8 m in depth. In Figure 10, the scantling is displayed. The validation portion measures 457.2 mm, or one frame space.

.

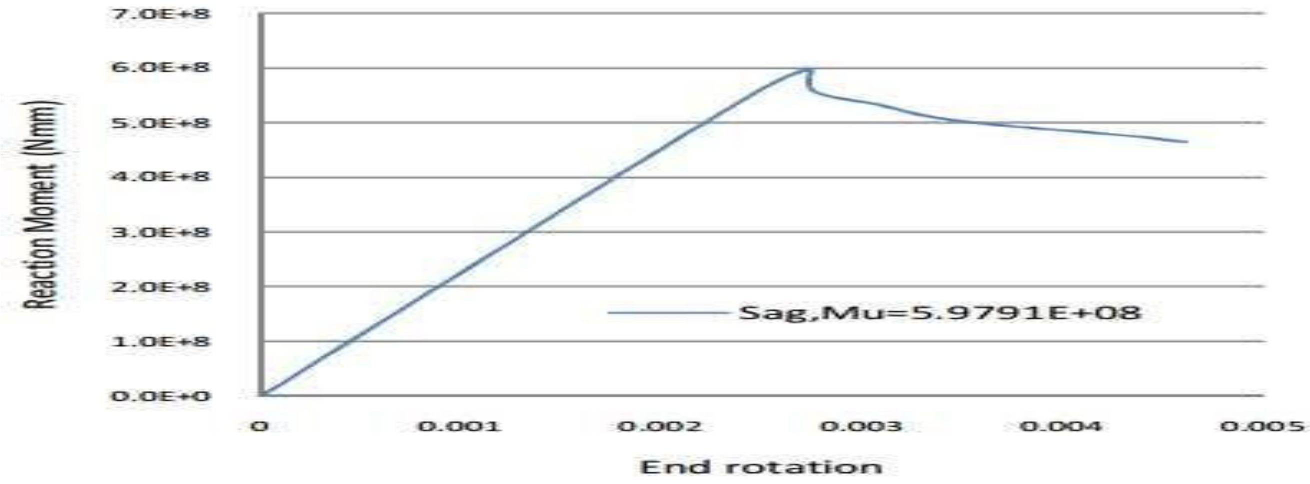

Figure 7 The MST model's ultimate longitudinal strength (MU) under sagging conditions when there is no residual stress

	Sagging (E+8 Nmm)			Hogging (E+8 Nmm)		
		FEM			**FEM**	
		Only initial deflection	**Initial deflection and residual stress**		**Only initial deflection**	**Initial deflection and residual stress**
MU	5.9330	6.0781	5.9028	8.3847	8.3408	8.3117
Difference		2.4 %	- 0.51 %		- 0.5 %	- 0.87 %

Table 2 The ultimate longitudinal strength of MSD model

Table 2 displays the findings of the FEM, whereas Figures 6 and 7 display the ultimate longitudinal strength MU of the MST-3 model under sagging conditions. There is a noticeable discrepancy in the FEM results. This indicates that the FEM's forecast of the ultimate longitudinal strength is accurate and true.

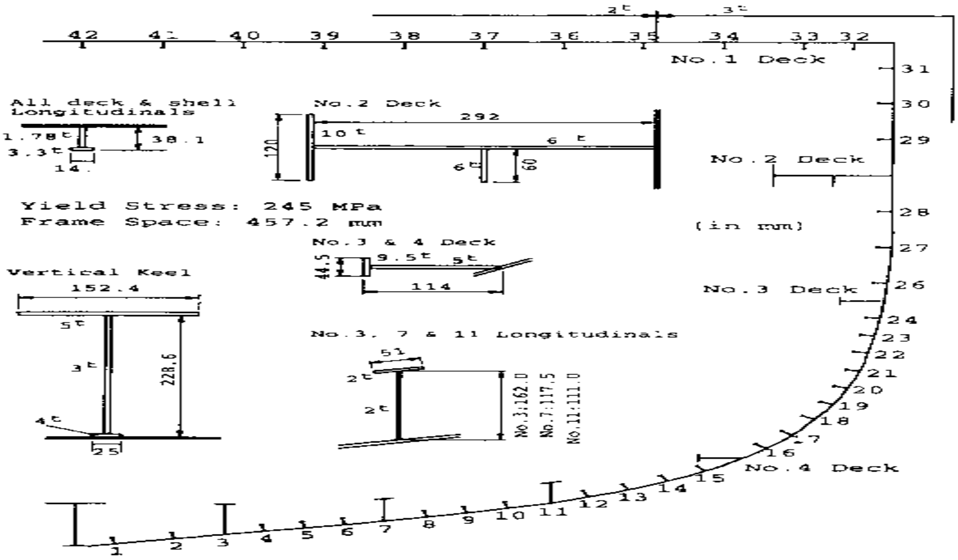

Figure 8 The 1/3-scale FEM model's cross section

.

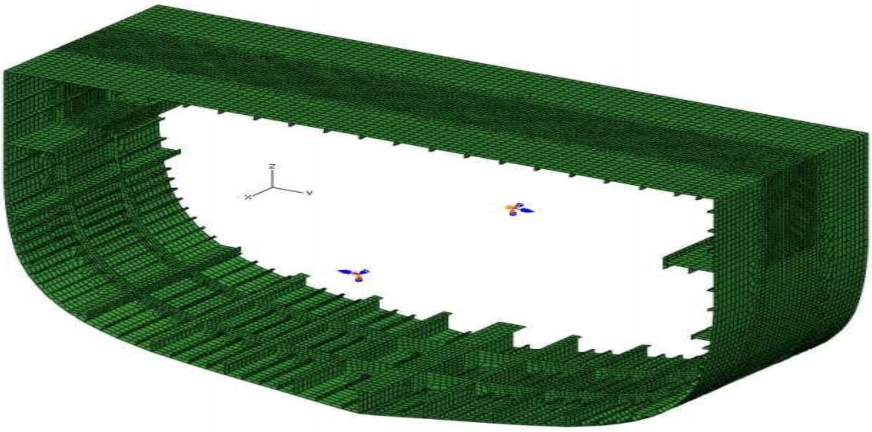

Figure 9 Finite element model of 1/3-scale

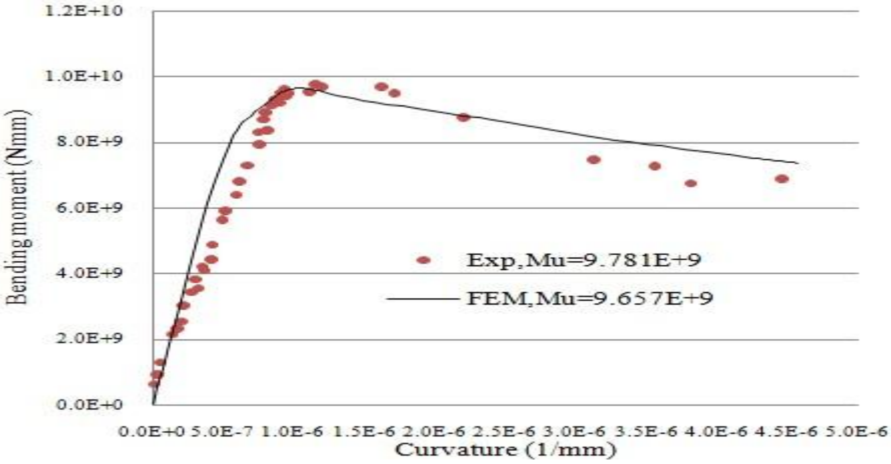

Figure 10 curvature

Figure 10 displays curves that calculated the progressive bending moment based on FEM results (black line) and experimental results (red dot points). This work differs from others in that it includes a web frame in the finite element model. As a result, the FEM results do well with the experimental data inside the post-ultimate regime.

Conclusions

in conclusion, this research underscores the vital role of finite element modeling and nonlinear analysis in evaluating ship longitudinal strength, particularly under complex loading conditions. By employing ABAQUS software and a modified FEM approach, the study achieved the following key outcomes:

1. The three-dimensional finite element model, extending over three web frame spacings, provided a reliable basis for analyzing the structural integrity of the MST-3 vessel. Incorporating web frames into the model further enhanced its accuracy, aligning FEM results closely with experimental data.
2. The findings highlight that hull girder stresses due to bending and torsion significantly influence total stress distribution, especially near critical areas such as cargo hold bulkheads and hatch coamings. These stress concentrations necessitate precise modeling to ensure structural reliability.
3. Analysis of stress distribution in open and closed-deck ships revealed that torsion-induced warping stress is a critical factor in open-deck configurations, contributing approximately 20% of the total stress in inclined conditions. This insight emphasizes the importance of accounting for torsional effects in hull design.
4. The application of FEM effectively captured both linear and nonlinear stress responses, enabling accurate predictions of the ultimate longitudinal strength of the hull girder. The integration of methods for bending moment, shear force, and deflection calculations further supports the robustness of the modeling framework.

This study not only validates the effectiveness of FEM in assessing ship hull strength but also provides a foundation for future research into hydroelasticity, fatigue resistance, and optimization of ship structures under extreme loads. These insights are critical for advancing safe and efficient ship design practices.

Recommendations

1. Incorporation of Advanced Material Models: Future studies should incorporate advanced material models, such as composite materials or high-strength steels, to evaluate their impact on hull longitudinal strength and torsional rigidity under extreme conditions.
2. Dynamic Loading Conditions: Investigate ship performance under dynamic loading scenarios, including extreme weather events, oblique wave interactions, and impact loads. This can provide a more comprehensive understanding of structural behavior in real-world conditions.
3. Hydroelastic Analysis Integration: Explore hydroelastic effects using advanced simulation tools to study the interaction between fluid dynamics and structural responses, especially for ultra-large vessels.
4. Improved Nonlinear Analysis Techniques: Implement refined nonlinear finite element methods to capture progressive collapse, buckling, and residual stress effects with greater accuracy.
5. Optimization of Structural Elements: Conduct parametric studies to optimize critical structural components such as web frames, hatch coamings, and transverse bulkheads for improved strength and weight reduction.
6. Validation with Full-Scale Testing: Perform full-scale experimental validations to verify finite element model predictions, particularly for innovative designs or extreme load cases.

References

Ahmed, F. (2017). Development of Guidelines Allowing to Predict the Contribution of the Superstructure to the Hull Girder Strength. *Master's Thesis, University of Liège, Liège, Belgium*, 2017. *Atlantic Dartmouth*: Dartmouth, NS, USA, 1987.

Bauchau, O. A. & Craig, J.I. (2009). Euler-Bernoulli beam theory. In Structural Analysis; Springer: *Dordrecht, The Netherlands*, 2009; pp. 173–221.

Brassey, C. A., Margetts, L., Kitchener, A. C., Withers, P.J., Manning, P.L.& Sellers, W.I. (2013).Finite element modelling versus classic beam theory: Comparing methods for stress estimation in a morphologically diverse sample of vertebrate long bones. *J. R. Soc. Interface* **2013**, 10, 20120823.

Chen, Z.,Gui, H., Dong, P. & Yu, C. (2019). Numerical and experimental analysis of hydroelastic responses of a high-speed trimaran in oblique irregular waves. *International Journal of Nav. Archit. Ocean.* Eng. **2019**, 11, 409–421.

Chiricǎ, R., MUŞAT, S. D., Boazu, D. &Beznea, E. F. (2009). Torsional Analysis of Ship Hull Model. In Proceedings of the International Conference on Diagnosis and Prediction in Mechanical Engineering Systems (DIPRE'09), *Galati, Romania*, 22–23 October 2009.

Elbatouti, A., Liu, D. & Jan, H. (1974).Structural Analysis of Sl-7 Containership under Combined Loading of Vertical, Lateral and Torsional Moments Using Finite Element Techniques (SL-7-3); 1974.

Hossain, M. A. (1997). Beam Model for the Structures of Ship Hull Girder; UNSW Sydney: *Sydney, NSW, Australia*, 1997.

Huang, L., Li, B. & Wang, Y. (2017). FEM and EFG Quasi-Static Explicit Buckling Analysis for Thin-Walled Members. *Open J. Civ. Eng*. **2017**, 7, 432–452.

Iijima, K., Shigemi, T., Miyake, R. & Kumano, A.A (2004). Practical method for torsional strength assessment of container ship structures. *Mar. Structure*. **2004**, 17, 355–384.

Joynal Abedin, Francis Franklin & S. M. Ikhtiar Mahmud (2023). Linear Longitudinal Strength Analysis of a Multipurpose Cargo Ship under Combined Bending and Torsional Load; *Journal of Marine Science and Engineering* 12(1), 59;

Jurišić, P. & Parunov, J. (2021).Structural aspects during conversion from general cargo ships to cement carriers. Brodogr.Teor.I PraksaBrodogr.*I Pomor.Teh*. **2021**, 72, 37–55.

Jurišić, P., Parunov, J. &Garbatov, Y. (2017). Aging effects on ship structural integrity. Brodogr.Teor.I PraksaBrodogr.I Pomor.Teh. **2017**, 68, 15–28.

Librescu, L. & Song, O. (2005). Thin-Walled Composite Beams: Theory and Application; *Springer Science & Business Media: Berlin/Heidelberg, Germany*, 2005; Volume 131.

Mao, F. (2015).Longitudinal Ultimate Bending Strength Analysis of Ship Structure For Emergency Response; Delft University of Technology: Delft, The Netherlands, 2015.

Novikov, V.V., Antonenko, S.V., German, A.P. &Kitaev, M.V. (2015) Effect of Ship Torsion with Wide Hatches on the Hull's Stress State. In Proceedings of the Twenty-Fifth International Ocean and Polar Engineering Conference, Kona, HI, USA, 21–26 June 2015; *OnePetro: Richardson*, TX, USA, 2015.

Okumoto, Y., Takeda, Y., Mano, M. & Okada, T. (2009). Design of Ship Hull Structures: A Practical Guide for Engineers; *Springer Science & Business Media: Berlin/Heidelberg, Germany*, 2009.

Ostapenko, A. & Chu, P. C. (1986).Torsional Strength of Longitudinals in Marine Structures; Lehigh University, Department of Civil Engineering: *Bethlehem*, PA, USA, 1986.

Paik, J. K.,Thayamballi, A. K., Pedersen, P. T. & Park, Y.I. (2001). Ultimate strength of ship hulls under torsion. *Ocean*. Eng. **2001**, 28, 1097–1133.

Parunov, J., Uroda, T. &Senjanović, I. (2010).Structural analysis of a general cargoship. Brodogr.Teor.I PraksaBrodogr.I Pomor.Teh. **2010**, 61, 28–33.

Pereira, T. &Garbatov, Y. (2022).Multi-attribute decision-making ship structural design. J. Mar. Sci. Eng. **2022**, 10, 1046.

Rigo, P. &Rizzuto, E. (2003).Analysis and design of ship structure. Ship Des. Constr. **2003**, 1, 1–18.

Rörup, J., Darie, I. &Maciolowski, B. (2017). Strength analysis of ship structures with open decks. *Ships Offshore Struct*. **2017**, 12, S189–S199.

Rörup, J., Maciolowski, B. &Darie, I. (2016). FE-based strength analysis of ship structures for a more advanced class approval. *In Proceedings of the PRADS2016, Copenhagen, Denmark,* 4–8 September 2016.

Senjanović, I., Senjanović, T., Tomašević, S. &Rudan, S. (2008).Contribution of transverse bulkheads to hull stiffness of large container ships. Brodogr.Teor.I PraksaBrodogr.I Pomor.Teh. **2008**, 59, 228–238.

Senjanović, I., Tomašević, S., Rudan, S. &Senjanović, T. (2008). Role of transverse bulkheads in hull stiffness of large container ships. *Eng. Struct*. **2008**, 30, 2492–2509.

Senjanović, I., Vladimir, N. &Tomić, M. (2011).Investigation of torsion, warping and distortion of large container ships. *Ocean. Syst. Eng*. **2011**, 1, 73–93.

Senjanović, I., Vladimir, N., Malenica, S.i. &Tomić, M. (2011).Improvements of beam structural modelling in hydroelasticity of ultra large container ships.*In Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Rotterdam, The Netherlands,* 19–24 June 2011; pp. 219–228.

Shama, M. (2010). Torsion and Shear Stresses in Ships; *Springer Science & Business Media*: Berlin/Heidelberg, Germany, 2010.

Shama, M. (2012). Buckling of Ship Structures; Springer Science & Business Media: *Berlin/Heidelberg, Germany*, 2012.

Sun, H. & Wang, X. (2005).Buckling and ultimate strength assessment of FPSO structures. In Proceedings of the SNAME Maritime Convention, Houston, TX, USA, 19–21 October 2005; p. D021S003R004.

Tang, H., Ren, H. &Zhong, Q. (2019). Design and model test of structural monitoring and assessment system for trimaran. Brodogr.*Teor.I PraksaBrodogr*.I Pomor.Teh. **2019**, 70, 111–134.

Valsgard, S.,Svensen, T. E. &Thorkildsen, H. A. (1995).computational method for analysis of container vessels. In Proceedings of the 6th international Symposium on Practical Design of Ships and Mobile Units, PRADS 95, Seoul, Republic of Korea, 17–22 September 1995.

Veritas, B. (2022). NR 467 Rules for the Classification of Steel Ships. *Paris, France*, 2018.

Vernon, T.A. & Nadeau, Y. (1987). Thin-Walled Beam Theories and Their Applications in the Torsional Strength Analysis of Ship Hulls; *Defence Research Establishment*

Vladimir, N., Senjanović, I.,Malenica, Š., De Lauzon, J., Im, H., Choi, B.-K. &Seung Cho, D. (2016).Structural design of ultra large ships based on direct calculation approach. *Pomor.Zb.* **2016**, 1, 63–79.

Wang, X. & Moan, T. (1996).Stochastic and deterministic combinations of still water and wave bending moments in ships. *Mar. Struct*. **1996**, 9, 787–810.

Jeom K. Paik & Alaa E. Mansour(1995). A simple formulation for predicting the ultimate strength of ships. *Journal of Marine Science and Engineering. Volume 1, pages 52–62,*