Finite Element Modeling and Simulation of Collision Analysis of a Ship

By Dr. Md Shahidul Islam, Md Kaykuj Taky & Nusrat Jahan Omaia

Bangladesh University of Engineering & Technology

Abstract- Improving the structural integrity of ships against collisions has received much attention due to the recent rise in maritime safety regulations, such as SOLAS (Safety of Life at Sea), and the increasing number of accidents involving displacement-type general cargo vessels. Collisions are a constant danger for ships like displacement-type general cargo vessels, which face the greatest number of accidents due to the presence of stationary objects or other vessels in high-traffic maritime zones. In collision analysis, the influence of engine mass on structural behavior during collisions is neglected in the literature. Finite element analysis (FEA) was utilized to simulate various collision scenarios, focusing on how engine mass and speed variations affect structural integrity in the case of the vessel colliding against a rigid wall. The study focuses on the modeling of a displacement ship made of 6061-T6 aluminum.

FINITEELEMENTMODELINGANDSIMULATIONOFCOLLISIONANALYSISOFASHIP

Strictly as per the compliance and regulations of:

1. E. Cakir, C. Sevgiliand R. Fiskin, "An analysis of severity of oil spill caused by vesselaccidents", Transportation Research Part D: Transport and Environment, vol. 90,(2021), p. 102662.

Finite Element Modeling and Simulation of Collision Analysis of a Ship

Dr. Md Shahidul Islam [α], Md Kaykuj Taky [σ] & Nusrat Jahan Omaia [ρ]

Abstract- Improving the structural integrity of ships against collisions has received much attention due to the recent rise in maritime safety regulations, such as SOLAS (Safety of Life at Sea), and the increasing number of accidents involving displacement-type general cargo vessels. Collisions are a constant danger for ships like displacement-type general cargo vessels, which face the greatest number of accidents due to the presence of stationary objects or other vessels in high-traffic maritime zones. In collision analysis, the influence of engine mass on structural behavior during collisions is neglected in the literature. Finite element analysis (FEA) was utilized to simulate various collision scenarios, focusing on how engine mass and speed variations affect structural integrity in the case of the vessel colliding against a rigid wall. The study focuses on the modeling of a displacement ship made of 6061-T6 aluminum. We simulated different collision scenarios and studied how resultant stress distributions and plastic deformations occur in the ship structure. The bow, keel, and longitudinal girders, where stress concentration levels are higher, are found to be the most critical region of concern in the case of a bow collision. The findings of this study provide important insights into the factors that influence the magnitude of ship damage during collisions. The results offer guidance for future ship designs aimed at enhancing safety and reducing the chance of catastrophic structural failure. The modeling and simulation procedure discussed in the paper is also expected to benefit the readers.

Keywords: ship structural integrity, collision dynamics, engine mass impact, energy absorption, stress distribution, displacement-type vessel, collision resistance, finite element modeling, ship safety design, plastic deformation.

I. Introduction

Ship impact simulations are important for the analysis of safety and structural integrity of ships and offshore marine structure. These simulations play a crucial role in improving ship design, ensuring compliance with industry safety standards, and mitigating risks associated with maritime accidents. However, there is still a gap in research regarding full-scale ship collision analysis, which this study aims to address. Oil spills are a major environmental hazard, and accidents involving oil tankers or barges are the main reasons for such incidents [1]. In many cases, these spills are a direct consequence of ship collisions, which not only lead to severe structural damage but also contribute to environmental disasters. For example, the MV Wakashio oil spill in 2020 led to severe ecological damage off the coast of Mauritius, while the collision of the Baltic Ace in 2012 resulted in significant loss of life and financial setbacks. The substantial market size for ship repair and maintenance services reflects the recurring costs associated with ship damage, including repair expenses and downtime losses. The worldwide market for ship repair and maintenance services was worth USD 35.72 billion in 2023 and is expected to increase from USD 37.14 billion in 2024 to USD 53.23 billion by 2032 [2]. The economic, safety, and environmental consequences of ship collisions are significant,

Author α σ ρ: Bangladesh University of Engineering & Technology, Bangladesh. e-mail: shahid777@name.buet.ac.bd

affecting not only ship operators but also marine ecosystems and global trade logistics. These impacts can be categorized as follows, as summarized in Table 1.

Table 1: Potential impacts of ship collision

The potential consequences associated with a ship collision		
Economic	**Safety**	**Environment**
Loss of asset	Injuries	Oil spillage
Damage to ship operator's reputation	Loss of life or fatalities	Introduction of invasive species through ballast water
Repair costs		
Loss of revenue		

As ships are expensive to manufacture, direct collision tests which are destructive in nature and also very expensive, are not feasible. The most viable alternative to such tests is FEA, as it provides accurate and realistic results that are consistent with the experimental results[3] [4]. Collision analysis provides dynamic response of structures and has great importance in designing safe ships and marine structures. Many previous studies have focused on collision analyses using the portions that are adjacent to the impact zones without modeling and meshing the whole ship[5] [6]. However, there is an absence of the study of full body ship analysis. Without the modeling and meshing of a complete ship, it is unclear whether the result will be accurate enough to show the stress distribution properly. Because of the nature of dynamic analysis, simple discrepancies in simulation parameters can cause large deviations in the obtained results[7].

Zhang et al. (2019) derived analytical formulae for energy absorption in ship collisions leading to rupture, and validated their results using finite element analysis and experimental results. Their study supported the use of FEA as an alternative to experimental methods[8].

Aluminum 6061-T6 is widely used as a common construction material in the shipbuilding industry owing to its high strength-to-weight ratio, corrosion resistance, and energy absorption capabilities. Crum et al. (2011) highlighted the growing use of aluminum in modern ship designs, particularly in naval vessels[9]. As the ship we are studying is smaller in size, aluminum is chosen as the construction material.

This study investigates the effects of collisions on a ship structure in which all the structural members are meshed with and without engine mass. As speed greatly affects the impact force [10], the analysis is performed under two different speed settings.

The main objective of this research is to model and mesh a displacement-type vessel with all the structural members and then analyze it with a rigid wall using LS-DYNA. The generated stress and internal energy in both these cases are compared.

II. Methodology

This section outlines the step-by-step process used for the modeling, mesh generation, and simulation of the selected ship.

a) Ship Model Generation and Material Selection

The ship is initially generated using Rhino 3D and its geometric details are simplified as it is a global analysis. In this context, simplification means reducing minor design features that do not significantly affect the overall structural response, ensuring computational efficiency while preserving essential load-bearing elements. The impact on elements away from the collision region is minimal, so they are simplified or removed to focus computational resources on the critical impact areas. The isometric view of the

3. D. Moulas, M. Shafieeand A. Mehmanparast, *"Damage analysis of ship collisions with offshore wind turbine foundations"*, Ocean Engineering, vol. 143, (2019) pp. 149-162.

Ref

whole model is given in Figure 1. For global analysis, the primary objective is to understand the overall structural response rather than the localized effects of intricate details. Therefore, only essential structural components are retained, while minor design elements are omitted.
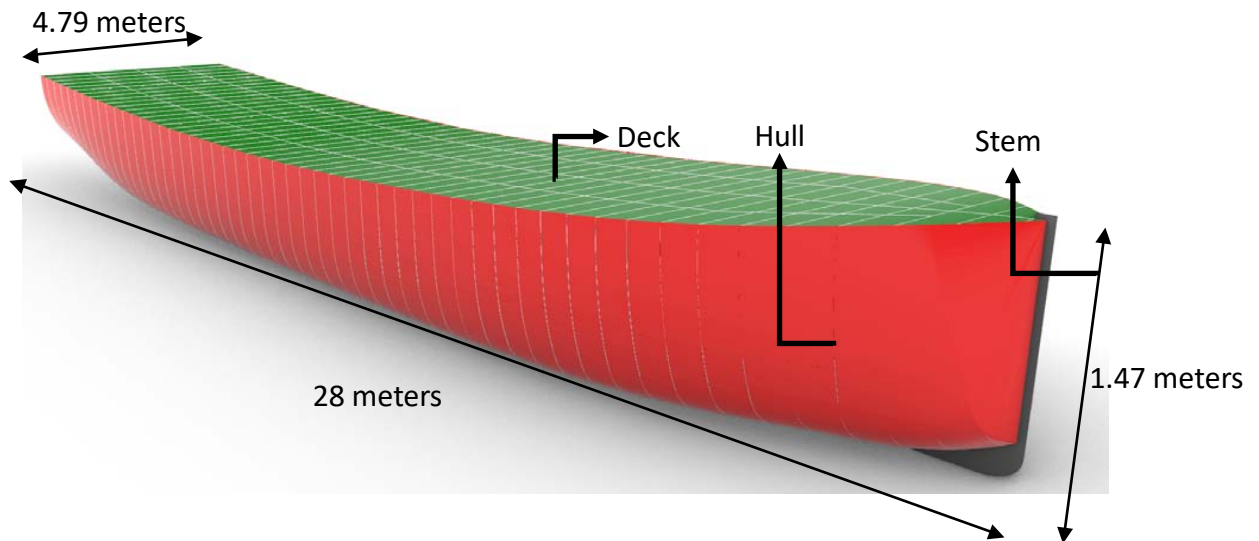
Figure 1: External view of ship model

Key internal structural members, such as girders, frames, bulkheads, and pillars, are modeled and are shown in Figure 2 and 3.
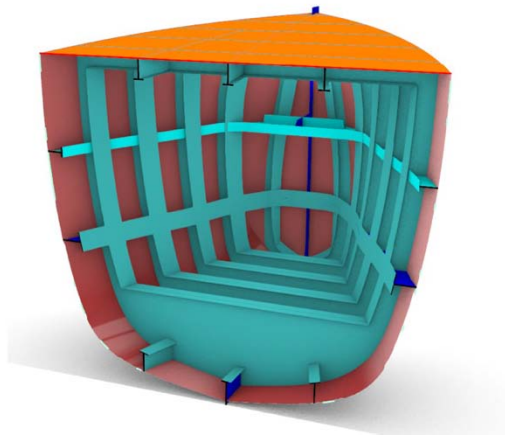

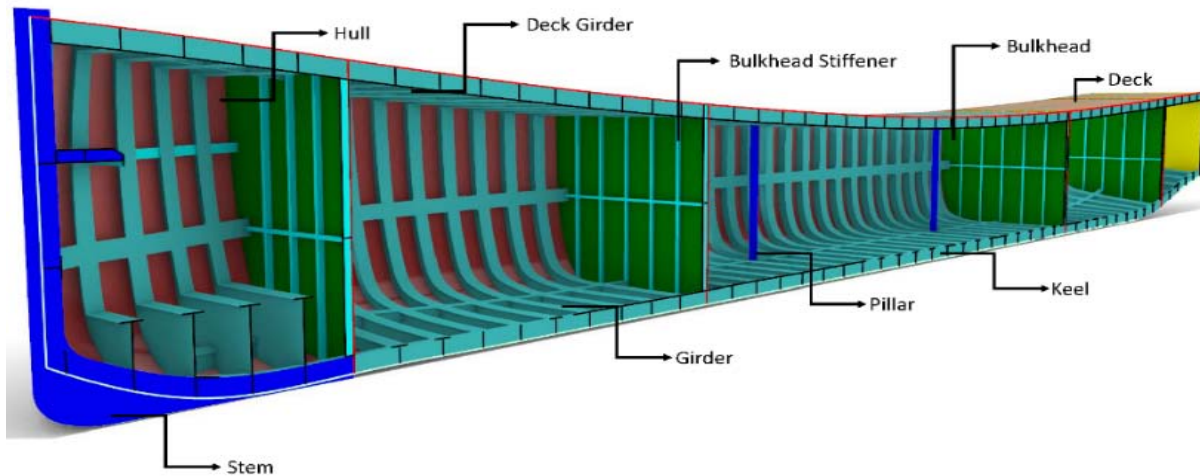*Figure 2:* Ship with structural members (Fore portion)

Figure 3: Ship with structural members

Shell elements with reduced integration (Belytschko-Tsay formulation) are chosen for the modeling to improve computational efficiency while maintaining accuracy. The ship is 28 meters long, 4.79 meters in width, and has a draught of 1.47 meters. To increase the efficiency of the simulation process, non-load-bearing and aesthetic features that do not contribute to impact resistance are removed in accordance with previous studies[11]. Aluminum 6061‑T6 is chosen for its high strength‑to‑weight ratio, corrosion resistance, and energy absorption, making it ideal for impact scenarios. It is lighter than steel while maintaining structural integrity, improving fuel efficiency and speed. Its ductility allows plastic deformation, effectively dissipating impact energy and enhancing crash resistance. These qualities make it a preferred material for naval and commercial vessels needing durability and lightweight construction. Detailed material characteristics [12] are given in Table 2.

Table 2: Properties of material chosen

Material Name	Density	Young's Modulus	Poisson's Ratio	Strength Coefficient	Hardening Exponent	Initial Yield Strength
Aluminum 6061-T6	2700 kg/m₁	68900 MPa	0.33	410 MPa	0.05	276 MPa

b) Mesh Generation and Boundary Conditions

Femap and Hypermesh software are chosen to generate mesh to proceed with the FEA. In complex structures such as ships, it is difficult to maintain mesh coupling and connections, making it harder to maintain a good mesh quality. Both of these programs are used to decide which software is better suited for this specific task. The mesh generated by us by Femap is of poorer quality than that generated by Hypermesh, which is compared in Figure 4.
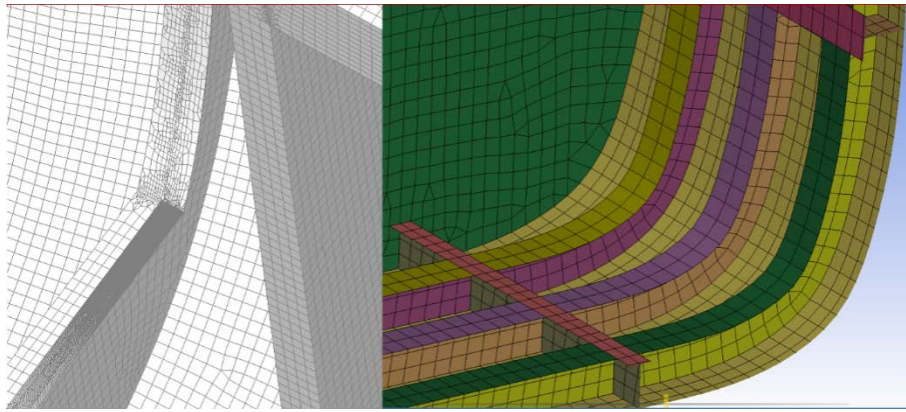
11. M. Melchiore and T. Duncan, *"The fundamentals of FEA meshing for structural analysis"*. Ansys, 2021.

Ref

Ref

13. Y. Liu and G. Glass, *"Effects of mesh density on finite element analysis"*, (2013).

Figure 4: Mesh quality comparison in Femap and Hypermesh

So, generated mesh using Hypermesh is used for the analyses. Three mesh densities are used to obtain more accurate results. As the mesh becomes finer, the accuracy of the non-linear analyses increases so does the calculation time[13]. These densities are shown in Figure 5.
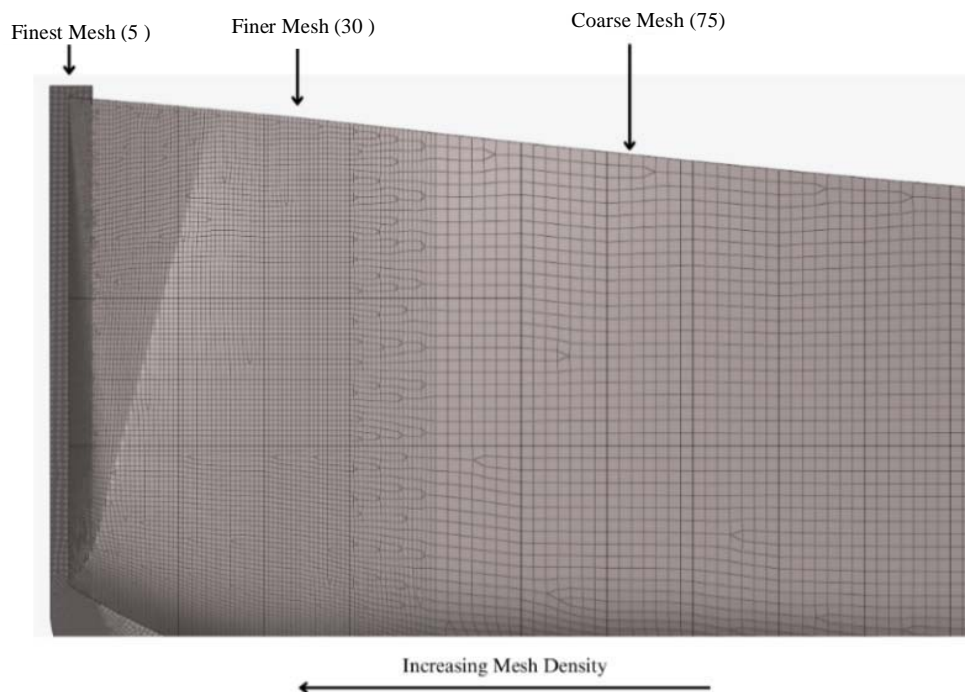

Figure 5: Mesh density regions

The generated mesh is quad-heavy as quad elements provide greater efficiency in the analysis [14]. Some complex areas have tri-elements, and areas where the mesh density changes also comprise of some triangular elements. Node connectivity was thoroughly checked for all connected elements and parts. Total number of elements is 2,55,859 and node is 2,48,146. Calculated mass is 14.82 tonnes without the engine. A 4-node shell is created for the rigid mild steel wall. The distance between the stem and rigid wall is kept at a minimum (5.65mm)to avoid the node penetration chances and to lessen the computation time. This has been shown in Figure 6.
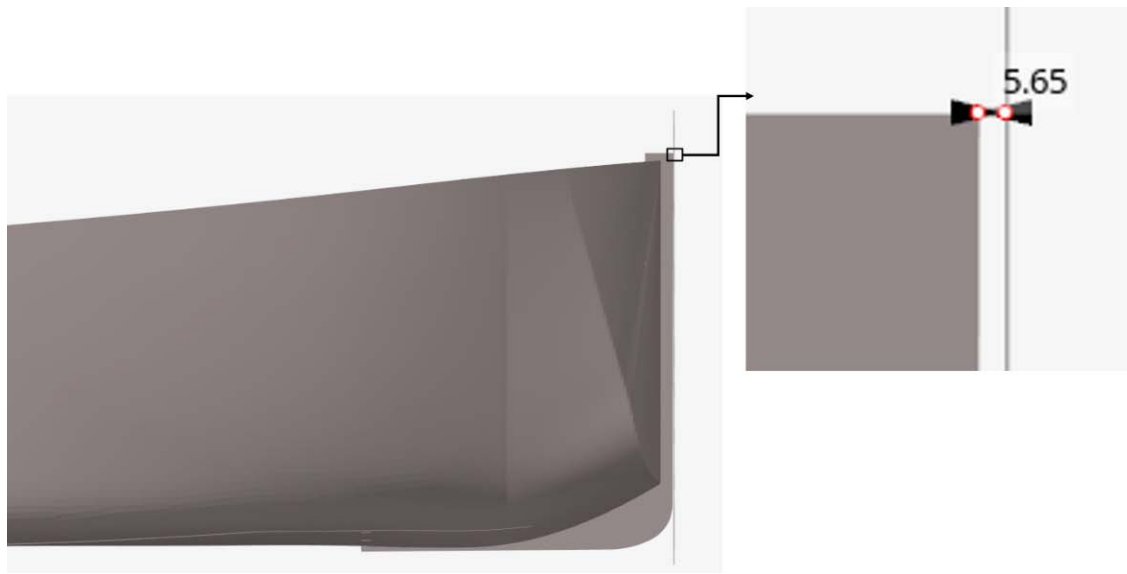
Figure 6: Distance between ship and rigid wall

Because the wall is stationary, all edge nodes of the rigid wall are fixed (encastré) to ensure they remain in place during the collision, as showed in Figure 7 and the node containing engine mass is shown in Figure 8. Then, all mesh qualities are checked using the built-in quality index in the Hypermesh software after meshing the whole model.
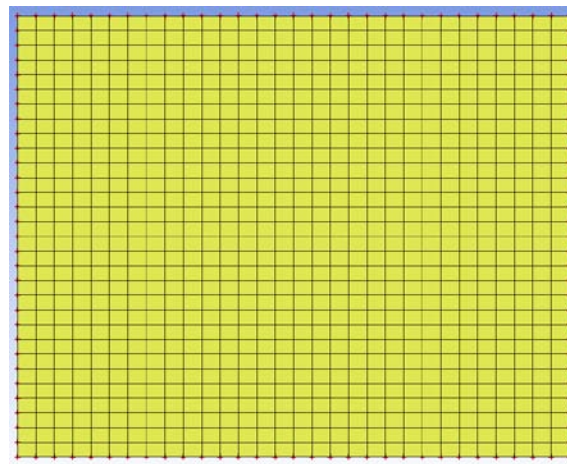

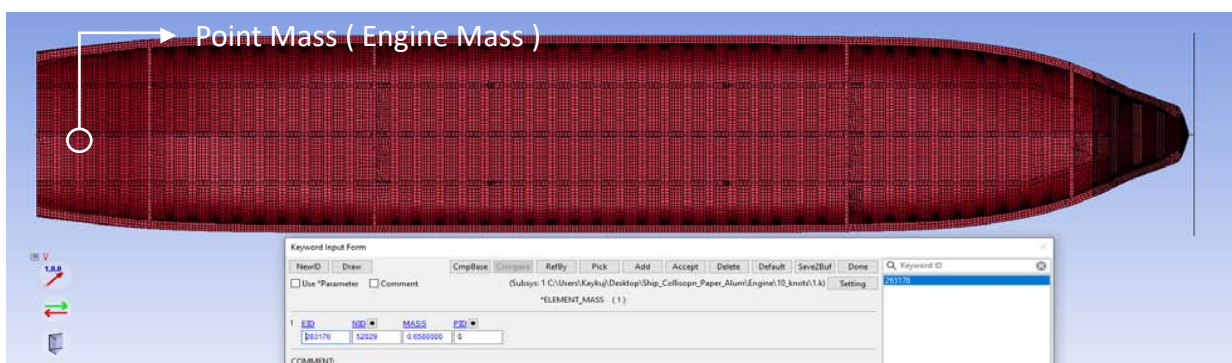*Figure 7:* Boundary condition of rigid-wall

Figure 8: Location of engine and mass

c) Collision Simulation using LS-DYNA

LS-DYNA is an advanced general purpose finite element program which was developed by the Livermore Software Technology Corporation (www.lstc.com). This software package is capable of simulating complex real-world problems within the automotive, aerospace, construction, military, manufacturing, and bioengineering industries [15]. So, for simulation LS-Dyna is chosen. The mesh is exported for use in the solver deck of LS-DYNA. Initially, modal analysis is performed to ensure proper connectivity among all members. The analyses are performed under two speed settings. All nodes comprising the ship are assigned a specified speed. In the first simulation, engine mass is not taken into consideration. Only the mass of the bare ship is used and the stresses are measured. In the second simulation, the engine mass is included as a point mass. The chosen engine is Cummins qsb6.7, weighing 658 kgs, making the total weight of the ship 15.478 tones. As this is a single-screw ship, only one point-mass is added, and the stresses are measured at different time stamps. Subsequently, these values and the regions of plastic deformation are compared.

III. Results

In this section relevant results from the simulation are shown and comparisons are made between different conditions of the ship. In this study, different conditions refer to different simulation scenarios involving variations in speed (5 knots and 10 knots) and internal weight (with and without the engine). These factors influence the ship's energy absorption and structural response during collisions.

a) Energy Absorption and Distribution

The energy curves in Figures9a, 9b, 9c and 9d highlight the variation in energy distribution during the ship's collision at different speeds with varying internal weight (with engine and without it).
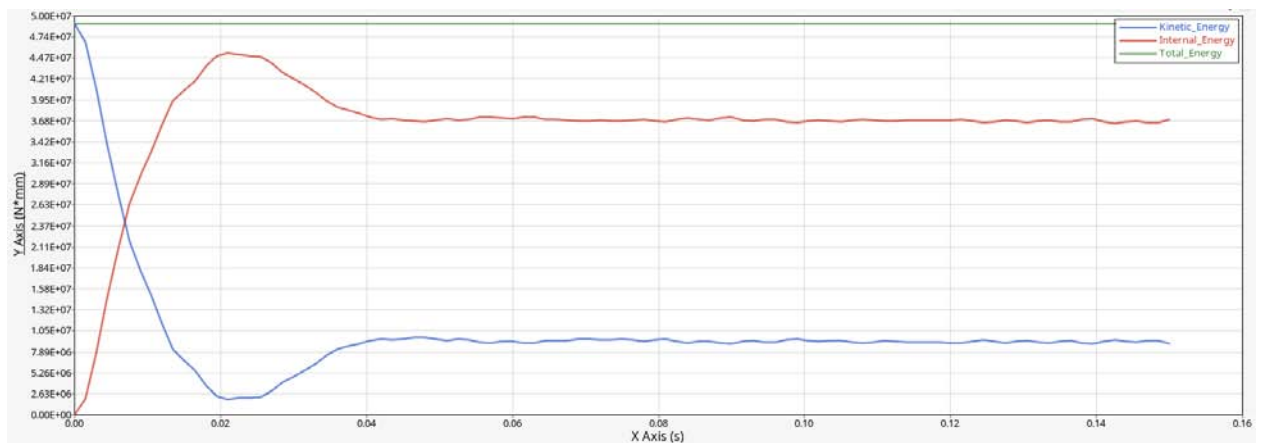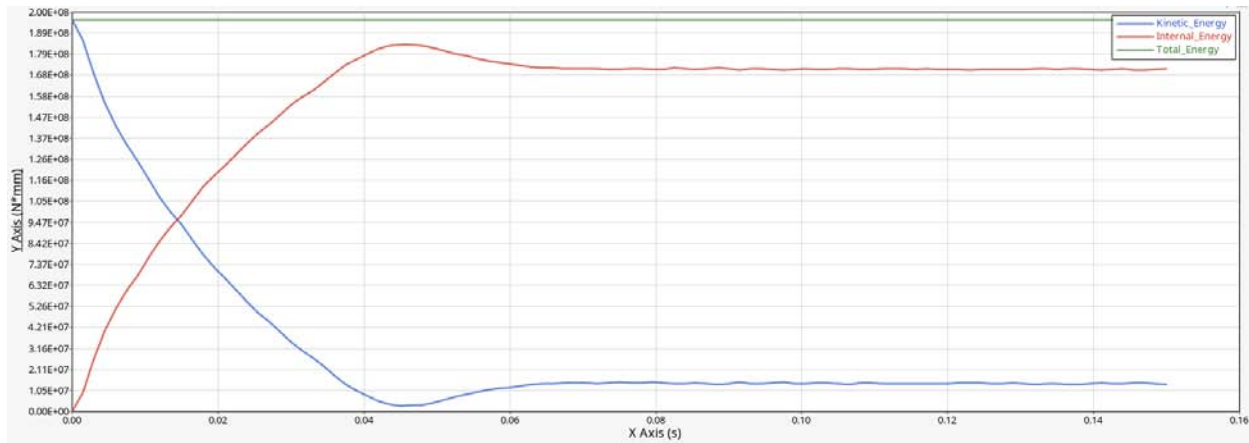

Figure 9a: Energy curves at 5 knots without engine

15. A. Chaulagain, "Nonlinear finite element modelling of a simply supported beam at ambient temperature and under fire", (2020).

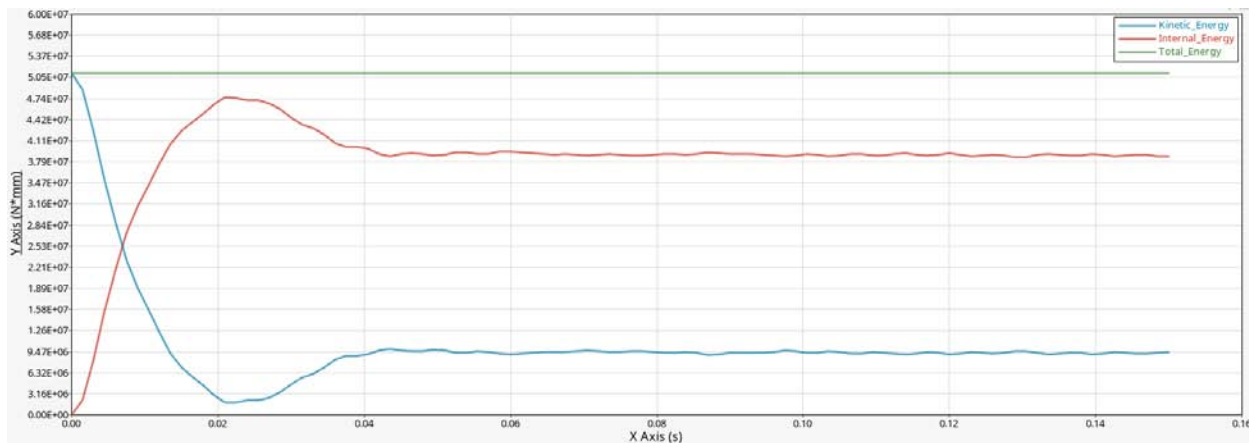*Figure 9b:* Energy curves at 10 knots without engine

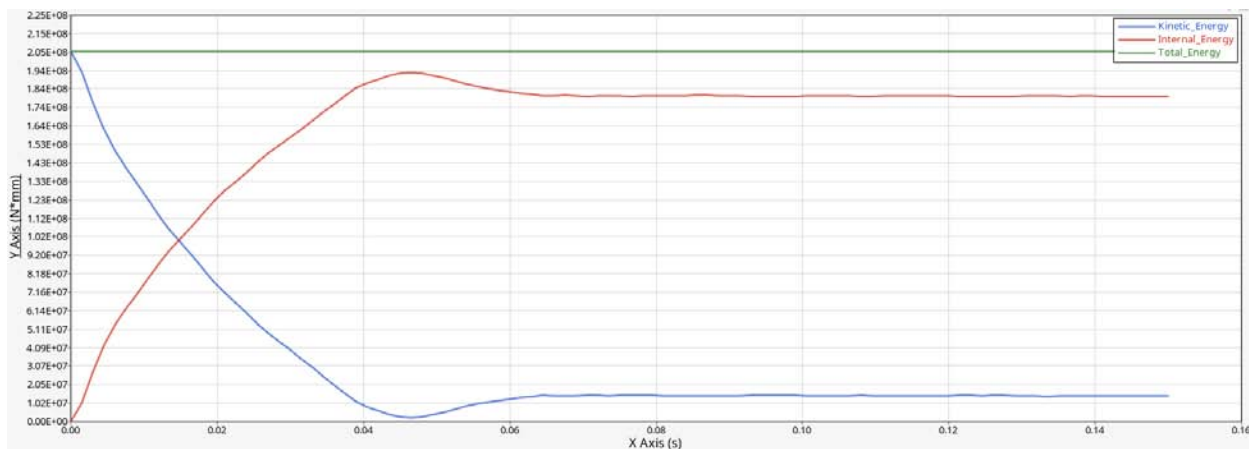*Figure 9c:* Energy curves at 5 knots with engine

Figure 9d: Energy curves at 10 knots with engine

The three key factors, namely – kinetic, internal and total energies are analyzed.

- *5 knots without engine:* At the outset of the simulation, the initial kinetic energy is maximum at $4.902 \times 10^7 N.mm$. Upon collision, the kinetic energy rapidly converts into internal energy in the form of deformation, then levels at around $9.11 \times 10^6 N.mm$. The crest value for internal energy is $4.531 \times 10^7 N.mm$. The total energy remains constant at $4.902 \times 10^7 N.mm$ validating energy conservation.

- *5 knots with engine:* At the outset of the simulation, the initial kinetic energy is maximum at $5.119 \times 10^7 N.mm$. Upon collision, the kinetic energy rapidly converts into internal energy in form of deformation and levels at around $9.36 \times 10^6 N.mm$. The maximum internal energy value is approximately $4.761 \times 10^7 N.mm$ The total energy remains constant at $5.119 \times 10^7 N.mm$ validating energy conservation.

- *10 Knots without Engine:* The initial kinetic energy at starting time is $1.96 \times 10^8 N.mm$ and after decrement, stabilizes at $1.41 \times 10^7 N.mm$ After the collision, the internal energy increases and reaches the peak value at $1.838 \times 10^8 N.mm$. The total energy remains constant.

- *10 Knots with Engine:* The initial kinetic energy at starting time is $2.047 \times 10^8 N.mm$ and after decrement, stabilizes at $1.424 \times 10^7 N.mm$ After the collision, the internal energy increases and reaches the peak value at $1.933 \times 10^8 N.mm$. The total energy remains constant.

b) Stress Analysis

The von Mises stress distribution maps are crucial in understanding the stress responses and locations of plastic deformation. The stresses are shown in Figures 10,11 and 12 at the different times. The Figure 10 shows the wall and for a clearer visualization the wall has been hidden in Figures 11 and 12.
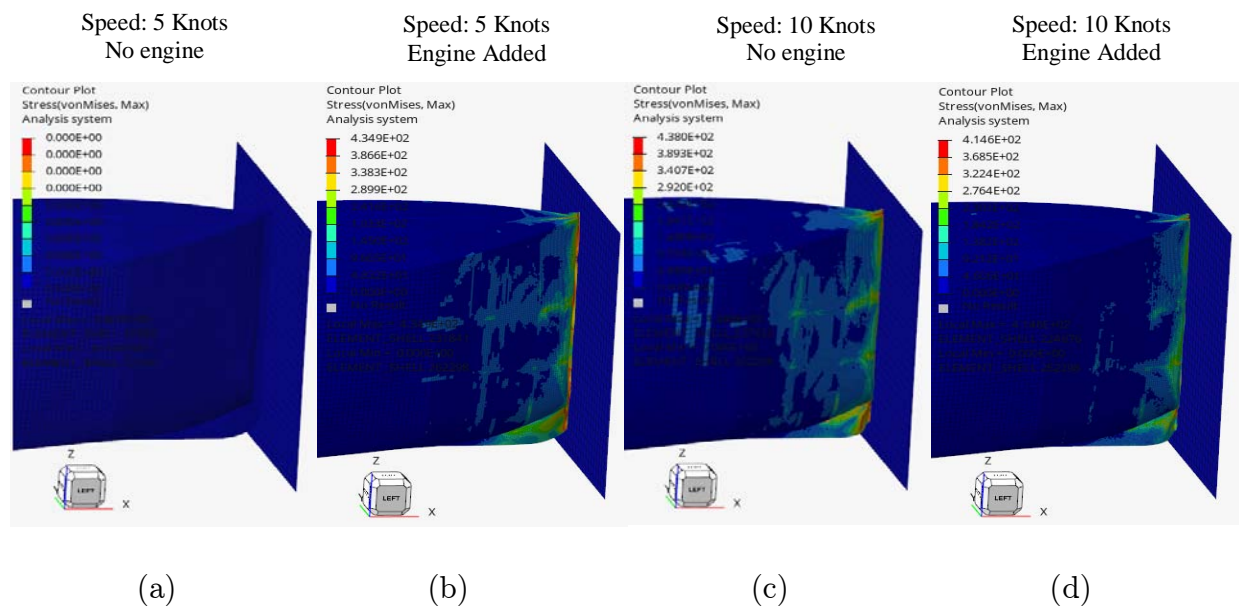

(a)   (b)   (c)   (d)
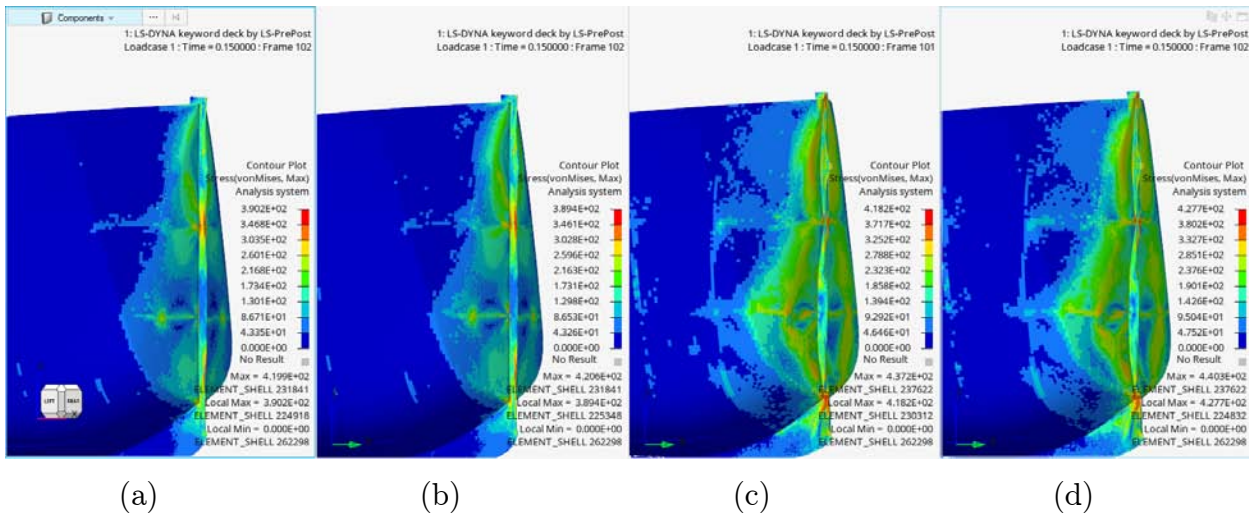
Figure 10: Initial stress contours at different conditions

Speed: 5 knots
No engine

Speed: 5 knots
Engineadded

Speed: 10knots
No engine

Speed: 10knots
Engineadded

(a)   (b)   (c)   (d)

Figure 11: Stress contours at final time stamp

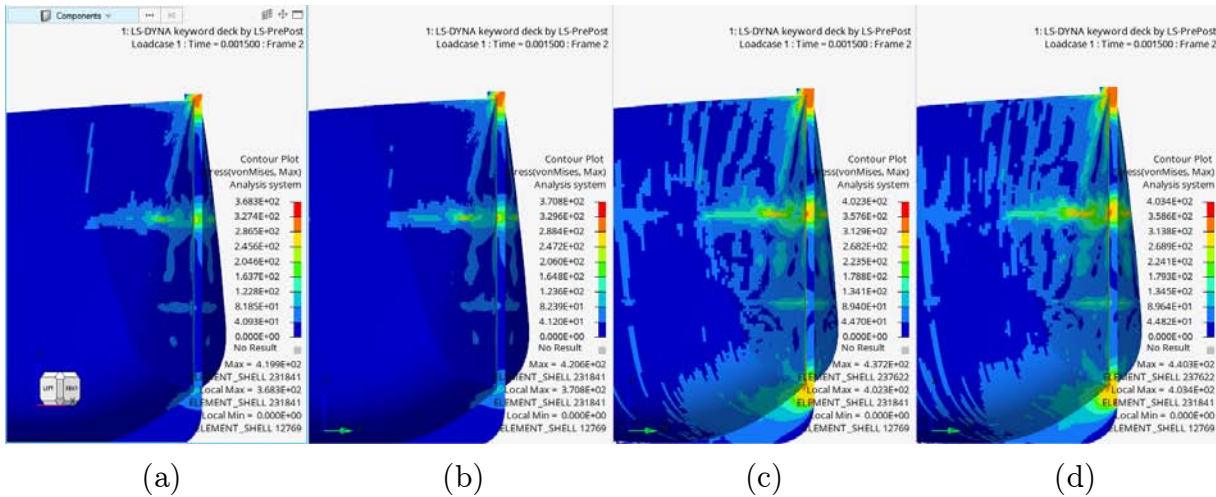(a)   (b)   (c)   (d)

Figure 12: Stress contours at initial time stamp

Case Studies:

- 5 Knots without Engine, Figures 10 (a), 11(a) and 12(a): In this case, the von Mises stress peaks at 368 MPa at initial impact, concentrated around the bow, especially near the stem. The stress diminishes as it propagates through the structure, indicating localized plastic deformation but without significant stress propagation into other parts of the ship. Maximum stress generated is 419.9 MPa in the stem because of the collision.

- 5 Knots with Engine, Figures 10 (b), 11(b) and 12(b): The initial impact causes a stress value of 370.8 MPa at the same locations. Peak value of generated stress is 420.6 MPa. This is a 0.76% increase in initial impact stress and a 0.17% increase in maximum stress to the added engine mass.

- 10 Knots without Engine, Figures 10 (c), 11(c) and 12(c): The initial impact causes a stress value of 402.3 MPa at the same locations. Highest stress value is 437.2 MPa. Which is a significant increase from the previous two. And the deformation is much more noticeable.

10

Notes

- 10 Knots with Engine, Figures 10 (d), 11(d) and 12(d): The maximum value at the initial collision is 403.4 MPa. Maximum stress value is 440.3 MPa. Which is a 0.27% and 0.7% increment from the previous simulation at the same speed at initiation and max value respectively.

All the values are summarized in Table 3.

Table 3: Comparison of internal energy and stress

Speed (Knots)	Addition of Engine Mass	Initial Stress (MPa)	Max Stress (MPa)	Kinetic Energy (N.mm)	Max Internal Energy (N.mm)	Percent Increment from5 Knots without Engine Initial Impact Maximum Local Stress (%)	Percent Increment from 5 Knots without Engine Max Overall Stress (%)	Percent Increment of Max Internal Energy from5 Knots without Engine (%)
	No	368	419.9	4.9×10^7	4.5×10^7	0	0	0
5	Yes	370.8	420.6	5.1×10^7	4.7×10^7	0.76	0.17	5.08
10	No	402.3	437.2	1.9×10^8	1.8×10^8	9.33	4.12	305.71
10	Yes	403.4	440.3	2.0×10^8	1.9×10^8	9.62	4.86	326.93

The comparison of Von Misses stresses between the two speed settings at 5-knots and 10-knots collisions clearly shows in Figures 10-12 that there exists a relationship between speed and structural deformation. At higher speeds, significantly higher amount of kinetic energy is transferred, leading to greater plastic deformation. The structural components go through higher forces, necessitating design improvements for ships or the inclusion of collision resistance devices.

The addition of engine mass in the ship structure amplifies the energy absorbed during collisions, even more so at higher speeds. Although, the increment is negligible as the engine is quite lightweight. The increased kinetic energy translates into higher internal energy, meaning the structure undergoes more plastic deformation. The stress concentration results emphasize the need for additional structural reinforcements at the effected regions when engine mass is factored into ship designs, especially in the bow and stem.

The results emphasize the need for robust structural design in ships intended for high-speed operations or heavy loads. The higher stress concentrations and plastic deformation in the affected zones observed with increased speed and engine mass suggest that such vessels should incorporate reinforced keel, bulkheads, longitudinal girders and incorporation of shock absorbing mechanisms to better absorb impact energy without compromising the ship's integrity and ensure safety.

Using *6061-T6 aluminum* as the material of the ship in the simulations provided valuable insights into the material's performance under high-speed impact conditions. The material exhibited significant plastic deformation, particularly at higher speeds and some deformation at low speed collision.

11

The fine mesh resolution near the bow was critical in accurately predicting the stress concentrations and potential failure points, suggesting that future simulations should maintain a high mesh density in critical regions to ensure highest possible accuracy in results.

IV. Conclusions

This study employed FEA to investigate the effects of speed and engine mass on the structural integrity of a displacement-type vessel after collisions. The simulations were conducted at two speeds (5 knots and 10 knots), with and without engine mass, to assess their influence on energy absorption and stress distribution. The results demonstrated a clear trend in how these variables influence the ship's energy absorption and stress distribution. The following conclusions can be made:

1. At 5 knots, 82% of the total kinetic energy is transferred to the ship structure, while at 10 knots, this increases to 93%. This higher energy transfer at greater speeds results in more significant energy absorption and greater plastic deformation, particularly around the bow and stem. These findings highlight the need for design improvements, such as reinforced structural components or collision resistance devices, to mitigate damage.

2. The addition of engine mass in the ship structure amplifies the energy absorbed during collisions, even more so at higher speeds. However, the increase in maximum stress is minimal, with a 0.17% rise at 5 knots and a 0.75% rise at 10 knots, as the engine contributes relatively little additional weight.

3. The results emphasize the need for robust structural design in ships intended for high-speed operations or heavy loads. The bow and stem experience the highest stress concentrations because these regions are the first to impact the obstacle, absorbing most of the collision force. The higher stress concentrations and plastic deformation in the affected zones observed with increased speed and engine mass suggest that such vessels should incorporate reinforced keel, bulkheads, longitudinal girders and incorporation of shock absorbing mechanisms to better absorb impact energy without compromising the ship's integrity and ensure safety.

4. Figures 10-12 shows variation of stresses only in the fore part of the ship in all conditions, which verifies the validity of previous study of Moulas et.al. [3], where they considered modeling of only the fore part.

5. A finer mesh near the bow is essential for accurately predicting stress concentrations and identifying potential failure points, further confirming the importance of localized meshing strategies in ship collision simulations.

Acknowledgements

Notes

References Références Referencias

1. E. Cakir, C. Sevgiliand R. Fiskin, "*An analysis of severity of oil spill caused by vesselaccidents*", Transportation Research Part D: Transport and Environment, vol. 90, (2021), p. 102662.
2. Ship Repair and Maintenance Services Market Size, Share, 2032.
3. D. Moulas, M. Shafieeand A. Mehmanparast, "*Damage analysis of ship collisions with offshore wind turbine foundations*", Ocean Engineering, vol. 143,(2019) pp. 149-162.
4. W. K. Liu, S. Liand H. S. Park, "*Eighty years of the finite element method: Birth, evolution, and future*", Archives of Computational Methods in Engineering, vol. 29, no. 6,(2022) pp. 4431-4453.
5. P. Woelke, N. Abboud, D. Tennant, E. Hansenand C. McArthur, "*Ship impact study: Analytical approaches and finite element modeling*", Shock and Vibration, vol. 19, no. 4, (2012), PP. 515-525.
6. D. Solis and M. Samuelides, "*Ship collision analysis using finite elements*", 1999.
7. Z. Chen, H. Fang, L Zhu, Y. Maoand W. Liu, "*Experimental tests and numerical simulations of circular reinforced concrete piers under ship impact*", Advances in Bridge Engineering, vol. 1, 00. 1, (2020), p. 5.
8. S. Zhang, R. Villavicencio, L Zhuand P. T. Pedersen, "*Ship collision damage assessment and validation with experiments and numerical simulations*", Marine Structures, vol. 63, (2019), pp. 239-256.
9. K. A. Crum, J. McMichaeland M. Novak, "*Advances in aluminum relative to ship survivability'*, in American Society of Naval Engineers Day 2012 Conference, (2012), pp.122-131.
10. K. Peng and Q. Pan, "*Study on the Influence of Ship Speed and Ship Weight on Ship-Bridge Collision Force*", Hydraulic and Civil Engineering Technology VII, (2022), pp. 1047-1053.
11. M. Melchiorre and T. Duncan, "*The fundamentals of FEA meshing for structural analysis*". Ansys, 2021.
12. *A.* N. Abood, A. H. Salehand Z. W. Abdullah, "*Effect of heat treatment on strain life of aluminum alloy AA 6061'*, Journal of Materials Science Research, vol. 2, no. 2, (2013) p. 51.
13. Y. Liu and G. Glass, "*Effects of mesh density on finite element analysis*", (2013).
14. J. Ezeh and J. Enem, "*Comparative study on use triangular and rectangular finite elements in analysis of deep beam*", Academic Research International, vol. 3, no. 3, (2012), p.131.
15. A. Chaulagain, "*Nonlinear finite element modelling of a simply supported beam at ambient temperature and under fire*", (2020).