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Optimizing the Mooring Configurations for Enhancing Safety in Ship to Ship (STS) Operations

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ABSTRACT

Ship-to-Ship (STS) transfers represent complex and high-risk maritime operations that demand effective management to minimize accidents and environmental hazards. A critical factor in ensuring vessel stability during these operations is the mooring arrangement, yet current practices remain inconsistent and lack standardized guidelines, resulting in operational inefficiencies and safety concerns. While existing studies often emphasize hydrodynamic forces or operational procedures, few have comprehensively assessed the risks and performance of mooring systems across both static and dynamic STS environments. This paper systematically reviews mooring arrangement models with the objective of enhancing safety and efficiency in STS oil transfer operations. Practical data, numerical simulations, and case studies are employed to compare conventional and innovative mooring systems under varying environmental and operational conditions. The study aims to identify key risk factors, quantify forces acting on mooring lines, and propose new guidelines for optimal mooring system application. A phased, mixed-methods research design was adopted, integrating computational modelling using Optimoor, statistical analysis of incident reports, and expert surveys from professionals in the STS domain. Anticipated findings indicate that hybrid mooring systems with symmetric layouts and integrated tension monitoring can significantly reduce slippage, lower peak loads, and adapt more effectively to complex wave–current interactions compared to fixed or elastic systems. The outcomes of this research contribute to a comprehensive framework for improving STS operational safety by combining theoretical insights with practical applications. Ultimately, the study seeks to advance best practices, establish standardized guidelines, and support sustainable maritime energy logistics.

Keywords: Hydrodynamic forces; Mooring arrangements; Mixed-methods research; Optimoor; STS operations

1. Introduction

An essential part of international energy logistics is ship-to-ship (STS) operations, which entail the transfer of oil cargoes between vessels at sea (Ventikos & Stavrou, 2013). Particularly for Very Large Crude Carriers (VLCCs) and Suezmax tankers operating in congested or deep-sea routes, these operations allow for flexibility in the distribution of crude oil. Despite their significance, STS transfers are intrinsically risky because of intricate hydrodynamic interactions, erratic environmental conditions, and practical difficulties (Lee et al., 2019). Uneven freeboards, resonance from long-period swells, and suction effects between hulls are some of the factors that can seriously raise mooring line tensions and jeopardize vessel stability (Jin, 2018). Although current industry practices, which are governed by frameworks such as the International Safety Guide for Oil Tankers and

Terminals (ISGOTT6), the Oil Companies International Marine Forum (OCIMF) guidelines, and MARPOL Annex I, provide baseline safety standards, they frequently rely on static mooring protocols that do not take dynamic environmental variability into account (Salah et al., 2026).

The issue stems from the limited flexibility of traditional mooring arrangements, which cannot adapt to changes in wind speed, wave height, and vessel interactions in real time (Kamis et al., 2026; Yang et al., 2026). The shortcomings of current models are demonstrated by incidents such as collisions during STS transfers, delayed abort decisions, and line failures (Jaiswal & Ruskin, 2019). For instance, even under the supervision of certified mooring masters, improper weight distribution has been linked to accidents, and resonance effects under beam waves can overload inner mooring lines (Tuswan et al., 2025). These drawbacks highlight the critical need for a dynamic, data-driven approach to mooring optimization that incorporates environmental thresholds, vessel-specific parameters, and sophisticated simulation tools such as Optimoor (Rajendran et al., 2026).

This study is significant in two ways. By going beyond quasi-static analyses to dynamic modelling of mooring forces, it first closes substantial safety gaps and lowers the likelihood of collisions, line breaks, and oil spills. Second, it complies with current industry standards by using predictive analytics, automated tension monitoring, and synthetic ropes to reduce human error and improve operational effectiveness. The study contributes to environmental protection and regulatory compliance by encouraging international standardization and sustainable maritime energy logistics (Oduro et al., 2024).

This study aims to, i) identify common issues and risks related to vessel mooring compatibility during STS operations, ii) use simulation to calculate forces on mooring lines and ship structures under various operational and environmental conditions; and, iii) describe mitigation strategies for extreme weather or equipment failure scenarios.

This study's scope is restricted to open-ocean STS operations with petroleum cargoes; port-based transfers are not included. According to OCIMF and IMO guidelines, environmental parameters are limited to wind speeds of 30 knots or less and swells of up to 3 meters (Formela et al., 2016). Optimoor software is used to simulate vessel pairings, such as VLCCs and Suezmax tankers, to establish adaptive thresholds for line angles, fender spacing, and load distribution. The models will be validated by incorporating case studies from high-risk regions like Southeast Asia. The study's limitations include its preference for traditional mooring equipment over experimental hardware and its reliance on simulated data for extreme conditions, despite its emphasis on practical solutions.

This introduction lays out the foundation for a thorough investigation into mooring configuration optimization for STS operations. The research attempts to improve maritime energy logistics' sustainability, efficiency, and safety by combining dynamic simulations, expert insights, and case study validation.

2. Literature Review

2.1 Risk Factors in STS Operations

Ship-to-Ship (STS) transfers are inherently high-risk due to hydrodynamic interactions, environmental variability, and human factors (Lee et al., 2019). Close vessel proximity can generate suction effects, resonance from long-period swells, and uneven freeboards, all of which increase mooring line tensions and compromise vessel stability. Studies highlight that wind speeds above 30 knots and swells exceeding 1.5 meters significantly raise collision risks and line failures. For instance, miscalculated closest point of approach (CPA) combined with wind forces and current interactions has been linked to accidents during STS transfers. These findings emphasize the need for dynamic modelling of mooring loads rather than reliance on static thresholds (Stavrou & Ventikos, 2014).

2.2 Regulatory Frameworks and Best Practices

International conventions and industry guidelines provide baseline safety measures for STS operations. MARPOL Annex I requires pre-approved STS plans for oil tankers above 150 GT, including risk assessments and emergency abort criteria. The OCIMF Ship-to-Ship Transfer Guide and ISGOTT outline standards for fender specifications, mooring line strength, and communication protocols (Bedekar et al., 2025). Compliance with these frameworks reduces risks such as hose delamination and fender failure. However, gaps remain in

standardizing dynamic load thresholds across vessel types, particularly in Suezmax-to-Suezmax transfers compared to smaller coastal tankers. This lack of harmonization underscores the need for adaptive guidelines that account for vessel-specific and environmental variability (Feng et al., 2020).

2.3 Technological Solutions for Mooring Optimization

Advances in simulation and monitoring technologies have transformed mooring analysis. Tools such as Optimoor integrate static and dynamic assessments to model line tensions, vessel drift, and fender compression under varying environmental conditions (Guo-song & Guangzhou, 2012). Predictive modelling compensates for resonance effects, shallow-water additional mass, and vessel coupling, offering greater accuracy than traditional static methods. Real-time monitoring systems for line tension and vessel positioning further enhance decision-making during operations, enabling adaptive responses to changing conditions. These technologies provide a foundation for developing hybrid mooring systems that combine symmetric layouts with automated tension monitoring (Aamo & Fossen, 2003).

2.4 Gaps and Future Research Directions

Despite progress, several gaps persist in STS mooring research. Most studies emphasize static thresholds, leaving dynamic interactions during underway transfers underexplored (Wu & Moan, 2017). Compatibility issues remain in mixed mooring systems, such as steel wires versus synthetic ropes, particularly for chemical tankers prone to rolling-induced collisions. Furthermore, regional disparities in regulatory enforcement limit global standardization. Future research should explore machine learning applications for real-time risk prediction, adaptive fendering systems responsive to vessel motion, and AI-driven analytics to optimize line tensions (Jiang et al., 2025). These directions promise to bridge existing gaps and support safer, more efficient STS operations worldwide (Xu et al., 2021).

3. Methodology

3.1 Research Design

This study adopts a quantitative-dominant mixed-methods approach to optimize mooring configurations for Ship-to-Ship (STS) oil tanker operations (Murdjito et al., 2023). Numerical simulations using Optimoor software form the core of the analysis, modelling hydrodynamic forces, line tensions, and vessel motions under varying environmental conditions such as wind, waves, and currents (Lee et al., 2019). Sensitivity analyses and optimization algorithms are applied to identify safety-critical configurations (Rajendran et al., 2026). To complement simulations, structured surveys are distributed to evaluate existing scholarly work such as books and articles, and to validate assumptions and provide a comprehensive understanding (Wan et al., 2017). Case studies of historical STS incidents and successful operations are also examined to compare simulated outcomes with empirical data, ensuring model accuracy and industry relevance. The figure below displays the research framework of this study.

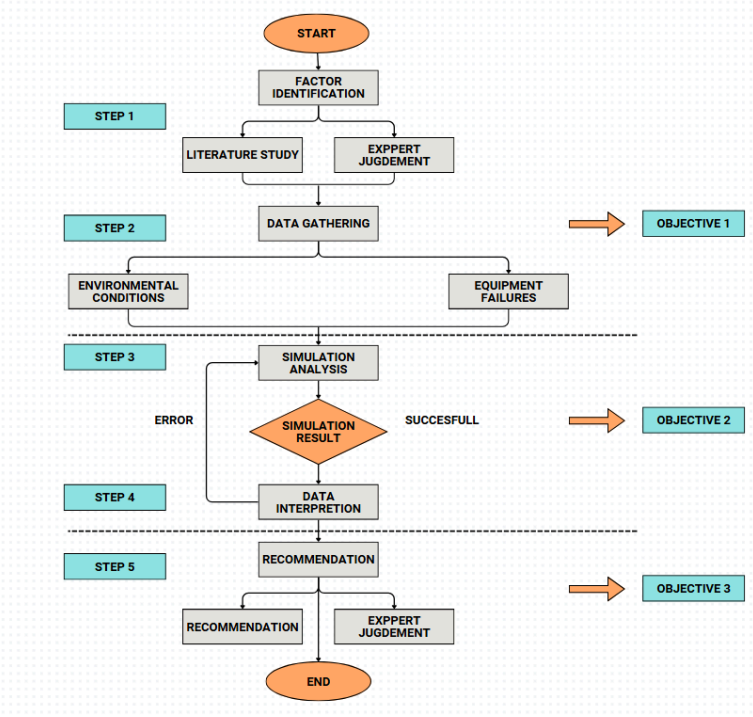


Figure 1. Research Framework

Step 1: Factor Identification

The first step involves identifying key factors that influence mooring safety during STS operations. This is achieved through a combination of literature study and expert judgement. Regulatory documents such as MARPOL Annex I, OCIMF guidelines, and ISGOTT6 are reviewed to extract operational thresholds and procedural standards. Expert input from mooring masters and engineers helps validate practical ranges and highlight overlooked risks. The identified factors include wind speeds (10, 15, and 30 knots), current ranges (0.5–0.8 knots), mooring line types (steel wire and synthetic HMPE), and a 20% degradation allowance to simulate aged equipment. Hydrodynamic interactions such as suction effects, resonance, and vessel coupling are also considered to ensure comprehensive modelling.

Step 2: Data Gathering (Objective 1)

This step focuses on collecting data to identify common challenges and risks in STS mooring compatibility. Environmental conditions such as wind, wave, and current parameters are analysed alongside equipment failure scenarios including line breaks and fender collapse. Data sources include structured surveys distributed to maritime professionals, historical incident reports from IMO and OCIMF databases, and synthesized findings from academic literature. This phase supports Objective 1 by establishing a baseline understanding of operational vulnerabilities and informing simulation parameters.

Step 3: Simulation Analysis (Objective 2)

Numerical simulations are conducted using Optimoor software to model mooring performance under varying environmental and operational conditions. Each configuration includes vessel specifications, mooring layout, degraded line strength, and environmental loads. The simulation results are monitored for convergence and accuracy. If errors occur, parameters are refined and the simulation is repeated. Successful outputs include line tension profiles, vessel drift, and safety margins. This step fulfills Objective 2 by quantifying the forces acting on mooring systems and identifying configurations that maintain stability under stress.

Step 4: Data Interpretation (Objective 2)

Simulation results are analyzed to derive safe operational thresholds and compare the performance of different mooring configurations. The analysis focuses on identifying acceptable tension limits, evaluating the effectiveness of symmetric layouts and tension monitoring systems, and comparing steel wire versus synthetic lines under identical conditions. Risk patterns are mapped to environmental triggers, such as excessive wind or current speeds, and validated against case studies and expert feedback. This step ensures that the findings are both technically sound and operationally feasible.

Step 5: Recommendation (Objective 3)

The final step involves developing recommendations based on interpreted data and expert judgment. These include adaptive mooring configurations tailored to vessel pairings and environmental conditions, real-time tension monitoring thresholds, and procedural enhancements to reduce human error. Technology adoption strategies such as AI-driven risk models and automated mooring systems are also proposed. These recommendations support Objective 3 by offering practical solutions to mitigate risks during extreme weather or equipment failure scenarios, ultimately contributing to safer and more efficient STS operations.

3.2 Objective 1 (Identify Common Risks in STS Operations)

The first objective of this research is to identify the common challenges and risks that arise during Ship-to-Ship (STS) operations, focusing on two main categories of information: environmental data and mooring line data. Environmental data provides insight into the external forces and conditions that influence vessel stability and safety, while mooring line data reflects the technical performance and limitations of the equipment used to secure vessels during transfers. By examining these two dimensions together, the study establishes a comprehensive understanding of how natural conditions interact with operational constraints, forming the foundation for subsequent simulation analysis and the development of safer mooring configurations.

3.3 Environmental Data

A purposive sampling strategy is employed to capture diverse perspectives and operational scenarios (Bouncken et al., 2025). Numerical simulations will model 6 mooring configurations under environmental conditions ranging from wind speeds of 10–30 knots and change of current ranging from about 0.5–0.8 knots, focusing on oil tankers between 120,000–200,000 DWT (Wu & Moan, 2017). Case studies will include 1–2 incident reports and successful operations documented by IMO and OCIMF, prioritizing cases with verifiable safety metrics. This approach balances computational feasibility, empirical rigor, and industry relevance (Forsell et al., 2016). Tables show a model of configurations.

Table 1. Environment Data Configurations Model

Configuration	Wind Speed (knots)	Current Velocity (knots)
C1	10	0.5
C2	20	0.5
C3	30	0.5
C4	20	0.8
C5	20	0.5
C6	20	0.5

3.4 Mooring line data

Mooring line data refers to the characteristics and condition of the lines used to secure vessels during STS operations. It includes the type of lines, their strength, arrangement, and performance under load, as well as degradation factors that reduce capacity over time. This data is essential for assessing safety margins, identifying risks of line failure, and ensuring simulations reflect realistic operational practices.

Table 2. Mooring Line Data Configurations Model

Configuration	Mooring Line Type	Line Degradation (%)
C1	Synthetic (HMPE)	0

Configuration	Mooring Line Type	Line Degradation (%)
C2	Synthetic (HMPE)	0
C3	Synthetic (HMPE)	0
C4	Synthetic (HMPE)	0
C5	Steel Wire	0
C6	Synthetic (HMPE)	20

3.5 Objective 2 (Conduct Simulation Analysis of Mooring Configurations)

The second objective of this research is to analyze mooring performance through numerical simulations, focusing on how different vessel configurations respond under varying operational and environmental conditions during ship-to-ship (STS) operations. Using specialized software such as Optimoor, the study models vessel parameters, mooring line arrangements, and environmental forces to calculate line tensions, fender compression, and vessel drift. This objective emphasizes testing the reliability of mooring systems by incorporating realistic conditions, including degraded line strength and fluctuating external loads, to identify safe operational thresholds.

3.6 Study Location: Labuan Integrated Maritime Hub

The study is conducted at the Labuan Integrated Maritime Hub (LIMH), a strategic transshipment and logistics center in the South China Sea that supports oil and gas operations, bunkering, and ship-to-ship (STS) transfers. Its facilities accommodate vessel pairings such as VLCCs and Suezmax tankers, making it highly relevant to this research. Environmental conditions in Labuan, including wind speeds up to 30 knots, currents of 0.5–0.8 knots, and swells of up to 3 meters, provide realistic parameters for simulation analysis using Optimoor software. By situating the research in Labuan, the study aligns with Malaysia's ambition to strengthen the hub as a competitive maritime center while generating practical recommendations to improve mooring safety, efficiency, and sustainability in STS operations (Singh et al., 2023).



Figure 2. Location of Labuan Integrated Maritime Hub for research

3.7 Vessel modeled during STS operation

For this research, both vessels modeled in the simulation are Suezmax-class crude oil tankers, selected to represent realistic ship-to-ship transfer scenarios in open-sea conditions (Hennø & Schøyen, 2024). These vessel characteristics provide the baseline for Optimoor simulations, enabling the study to calculate mooring line

forces, assess vessel stability, and propose adaptive configurations for enhanced safety in STS transfers as presented in the table below.

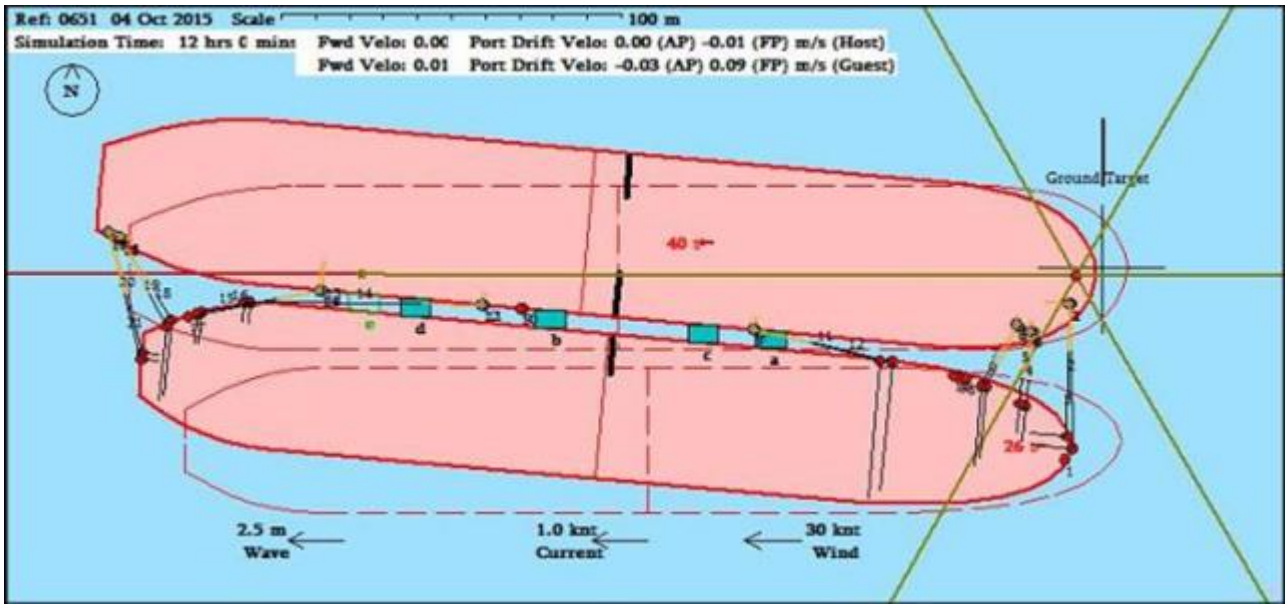


Figure 3. Example model structure of STS operation in Optimoor software

Table 3. Model of vessel characteristics for research

Parameter	Mother vessel (Suezmax)	Daughter vessel (Suezmax)
Deadweight Tonnage (DWT)	~ 160,000 DWT	~ 160,000 DWT
Length Overall (LOA)	~ 274 m	~ 274 m
Beam (Width)	~ 48 m	~ 48 m
Draft (Operational)	14 – 17 m	14 – 17 m
Freeboard (Approx.)	12 – 15 m	12 – 15 m

3.8 Dynamic mooring analysis

In this study, the dynamic mooring analysis was conducted using Optimoor software, with each simulation run lasting approximately one hour to capture vessel motions and line responses under varying environmental conditions. The one-hour duration was selected to ensure sufficient time for the system to stabilize and for transient effects such as surge, sway, and yaw to be observed. During the simulation, mooring line tensions were continuously monitored, with outputs recorded for both peak and sustained loads. The results provided insight into how line forces fluctuated in response to wind, current, and wave interactions, as well as the influence of line degradation factors. By analyzing tension profiles, the study was able to identify safe operating thresholds, highlight risks of line overload, and evaluate the effectiveness of different mooring configurations in maintaining vessel stability during Ship-to-Ship (STS) operations (Djatmiko et al., 2017).

3.9 Maximum breaking limit (MBL%)

Maximum Breaking Load (MBL) is the minimum force required to break a mooring line when tested under controlled conditions. In mooring analysis, MBL is expressed as a percentage (%), which indicates the proportion of the line's breaking strength being utilized during operations. Monitoring MBL% is critical to ensure mooring lines are not overstressed and remain within safe working limits.

According to the Oil Companies International Marine Forum (OCIMF) Mooring Equipment Guidelines (MEG4), mooring lines should not exceed 50% of their MBL during normal operations for their Working Load Limit (WLL). In Design Load Limit (DLL), peak dynamic loads may reach up to 60% of MBL, but this should be considered the upper safe threshold. Exceeding 60% MBL indicates a high risk of line failure and requires corrective action.

In the one-hour dynamic simulation using Optimoor, mooring line tensions were observed to remain within 40–55% of MBL, depending on environmental conditions and line degradation factors. This indicates that the mooring system operated within OCIMF's recommended safety margins, though peak loads approached the upper threshold during high wind and swell scenarios. The results highlight the importance of line condition monitoring and adaptive mooring configurations to prevent overload.

$$\text{MBL\%} = \frac{\text{Line Tension}}{\text{Maximum Breaking Load}} \times 100 \quad (1)$$

Where:

Line Tension = force experienced by the mooring line during simulation (kN)

Maximum Breaking Load (MBL) = certified breaking strength of the line (kN)

MBL% = percentage of MBL utilized

3.10 Objective 3 (Recommendation for safer Mooring)

The third objective is to develop practical recommendations for safer mooring configurations in STS operations. Based on the risks identified and simulation results, this includes guidance on line arrangements and operational limits, aligned with OCIMF standards. The aim is to provide adaptive solutions that reduce overload risks and improve safety during transfers.

3.11 Data discussion

This study employed a qualitative approach to develop mitigation strategies for extreme weather and equipment failure scenarios in Ship-to-Ship (STS) operations. The methodology was based on a structured literature review of authoritative sources, ensuring that the strategies proposed were grounded in established regulatory frameworks and technical studies.

The review incorporated international guidelines, technical reports, and scholarly publications relevant to mooring safety and operational risk management. Key references included the OCIMF Mooring Equipment Guidelines (MEG4), IMO SOLAS regulations, and peer-reviewed studies addressing rope degradation, mooring line performance, and operational thresholds. These sources provided the regulatory and technical foundation for identifying environmental limits, material performance characteristics, and procedural safeguards.

The data discussion within this methodology highlighted recurring themes across the literature. Suspension protocols were consistently emphasized as critical measures during adverse conditions, with wind speeds above 30 knots and currents exceeding 1 knot identified as thresholds for halting operations. Rope integrity emerged as a central factor in maintaining safety margins, with degradation beyond 20% of original strength shown to significantly compromise line performance. Material selection was also highlighted, with synthetic HMPE lines preferred over steel wire due to their elasticity and resilience under dynamic loads. Procedural safeguards, including crew training, inspection routines, and contingency planning, were identified as essential components of risk mitigation.

Synthesizing these findings produced a framework of mitigation strategies that are both technically justified and aligned with international standards. The literature provided clear evidence that operational suspension thresholds, material management, and procedural safeguards form the basis of safe and reliable mooring practices during STS operations under extreme weather or equipment failure scenarios.

Theme

Table 4. Literature-Derived Mitigation Strategies for STS Operations

Theme	Key Findings from Literature	Mitigation Strategy

Theme	Key Findings from Literature	Mitigation Strategy
Suspension Thresholds	OCIMF MEG4 and IMO guidelines emphasize halting operations when wind exceeds 30 knots or current exceeds 1 knot.	Establish operational suspension limits to prevent line overload during extreme weather.
Rope Integrity	Studies highlight that degradation beyond 20% of original strength significantly reduces safety margins.	Implement strict monitoring and replacement intervals to ensure rope degradation remains below 20%.
Material Selection	Synthetic HMPE lines preferred over steel wire due to their elasticity and resilience under dynamic loads.	Prioritize use of synthetic HMPE lines for STS mooring to reduce risk of sudden failure.
Procedural Safeguards	Literature stresses importance of crew training, inspection routines, and contingency planning.	Strengthen procedural safeguards through regular training, inspections, and emergency preparedness.

3.12 Expert judgement

All recommendations proposed in this study will be subjected to expert review to validate their practicality and alignment with industry standards. The recommendations include measures to limit mooring line degradation to not more than 20%, such as regular inspection and discard criteria, proper handling and storage, calibrated winch brake settings, balanced load distribution, strict adherence to weather limits, crew training, documentation of line usage, rotation of lines, and maintaining spare certified ropes. Additional recommendations cover monitoring line tension and suspending operations when environmental thresholds are exceeded.

These recommendations will be presented to maritime professionals and subject matter experts for evaluation. The expert judgement process will determine whether the proposed measures are sufficient or if further refinements and additions are necessary. This ensures that the final set of recommendations is not only academically sound but also operationally viable, reflecting real-world practices and enhancing safety during Ship-to-Ship (STS) operations.

4. Results and Discussions

The results of this study provide a comprehensive examination of the factors influencing the safety and reliability of Ship-to-Ship (STS) mooring operations. The analysis demonstrates that mooring performance is primarily governed by environmental conditions, rope integrity, and operational practices. The literature review established that failures in mooring systems are frequently associated with line overload, rope degradation, improper arrangements, and adverse weather forces. These findings are consistent with international guidelines such as the OCIMF Mooring Equipment Guidelines (MEG4), which emphasize the importance of effective line management and adherence to safe working limits.

Simulation analysis further reinforced these insights by quantifying mooring line behavior under dynamic operational stresses. The results indicated that while mooring lines remained intact during testing, tension levels fluctuated significantly in response to wind, current, and wave forces. Peak loads were observed within the range of 50–55% of the Maximum Breaking Load, aligning with established safety margins. Rope degradation beyond 20% and uneven load distribution were shown to increase the likelihood of overload, underscoring the necessity of continuous monitoring and strict rope management. Building upon these findings, practical recommendations were formulated to mitigate risks, including balanced line arrangements, adherence to environmental thresholds, calibrated winch brakes, and enhanced crew training. Collectively, the results and discussion highlight a progression from risk identification to quantitative validation and the development of actionable safety measures, thereby contributing to safer and more reliable STS operations in compliance with international standards.

4.1 Simulation Analysis

The simulation analysis provided quantitative evidence of mooring line performance under dynamic operational conditions, showing that while lines remained intact during testing, tension levels fluctuated significantly in response to wind, current, and wave forces, with peak loads approaching 50–55% of the Maximum Breaking Load (MBL), consistent with the safety margins outlined in the OCIMF Mooring Equipment Guidelines (MEG4). The findings confirmed that rope degradation beyond 20% substantially reduced safety margins and increased the likelihood of overload, while uneven load distribution created localized stress

concentrations that compromised overall stability. These results validate the literature review by demonstrating that environmental thresholds, rope integrity, and proper load sharing are decisive factors in ensuring safe Ship-to-Ship (STS) mooring operations, thereby reinforcing the need for continuous monitoring and optimized configurations to maintain compliance and operational reliability.

4.2 Identification of Mooring Risks

The analysis of incident records and regulatory guidelines highlights that mooring safety in Ship-to-Ship (STS) operations is strongly influenced by both environmental conditions and equipment integrity. High wind speeds above 30 knots were found to significantly increase drift forces and line tension, making it difficult to maintain safe vessel separation. The (Forum et al., 2013) recommends suspending or aborting operations when wind thresholds exceed this limit. Long-period swells and waves, particularly those approaching 3 meters, amplify mooring line loads and vessel motions through resonance effects. The (2018) guidelines emphasize that inner breast and spring lines are especially vulnerable under beam seas, underscoring the importance of environmental monitoring. Hydrodynamic interactions, such as suction forces between closely positioned hulls, further exacerbate risks by unexpectedly pulling vessels together, particularly during initial contact or when fender spacing is insufficient.

Equipment-related failures also pose significant risks. Incident reports (Southwold, 2015) indicate that steel wire mooring lines are more prone to failure under beam wave conditions due to their limited elasticity, whereas synthetic lines demonstrate greater resilience but require careful tension monitoring to avoid creep (Riviera, 2015). Weak or aged mooring lines, particularly those not certified to OCIMF standards, are more likely to rupture under dynamic loads. The (2018) framework mandates regular inspection, certification, and replacement schedules to ensure compliance with safe working loads. Collectively, these findings establish a structured overview of risks that must be addressed to optimize mooring configurations and enhance safety in STS operations.

Table 5. Identified Risk Factors in STS Mooring Operations

Risk Category	Description	Supporting Guidelines/Reports
High Wind Speeds (>30 knots)	Strong winds increase drift forces and line tension, compromising vessel separation.	Oil Company International Marine Forum (OCIMF) STS Transfer Guide (2013)
Swell & Long-Period Waves (≤3 m)	Long-period swells cause resonance, amplifying mooring line loads and vessel motions.	Mooring Equipment Guidelines (MEG4) (2018)
Hydrodynamic Interactions (Suction Effects)	Water flow between hulls creates suction forces, pulling ships together unexpectedly.	Oil Company International Marine Forum (OCIMF) STS Transfer Guide (2013)
Mooring Line Material Compatibility	Steel wire lines prone to failure under beam waves; synthetic lines more resilient but require monitoring.	Southwold (2015); Riviera (2015)
Weak or Aged Mooring Lines	Worn or uncertified lines more likely to snap under dynamic loads.	Mooring Equipment Guidelines (MEG4) (2018)

4.3 Mooring Line Tension and MBL

Mooring line tension is a critical indicator of the forces acting on vessels during Ship-to-Ship (STS) operations, and excessive loads can compromise stability or cause line failure. The Minimum Breaking Load (MBL) defines the maximum strength of a line, with safety margins established by the OCIMF Mooring Equipment Guidelines (MEG4) at ≤50% for the Working Load Limit and ≤60% for the Design Load Limit. Based on this framework, simulation results showed that mooring lines remained intact but experienced fluctuating tensions under environmental forces, with peak loads reaching 50–55% of MBL, rope degradation beyond 20% reducing safety margins, and uneven load distribution creating localized stress concentrations.

4.4 Configuration 1

Table 6. Mooring Line Tension with MBL for Configuration 1

Configuration	Value

Configuration	Value
Wind Speed (knots)	10
Current, V (knots)	0.5
Mooring Line Type	Synthetic (HMPE)
Line Degradation (%)	0
Mooring Line Tension & MBL	
Headline [MBL, %]	7.5 [10.00]
Forward Breast Line [MBL, %]	8.8 [11.73]
Forward Breast Line 2 [MBL, %]	13.0 [17.33]
Forward Breast Line 3 [MBL, %]	16.5 [22.00]
Forward Spring Line [MBL, %]	5.7 [7.60]
Aft Spring Line [MBL, %]	29.5 [39.33]
Aft Breast Line [MBL, %]	9.2 [12.27]
Aft Breast Line 2 [MBL, %]	11.4 [15.20]
Stern Line [MBL, %]	16.3 [21.73]

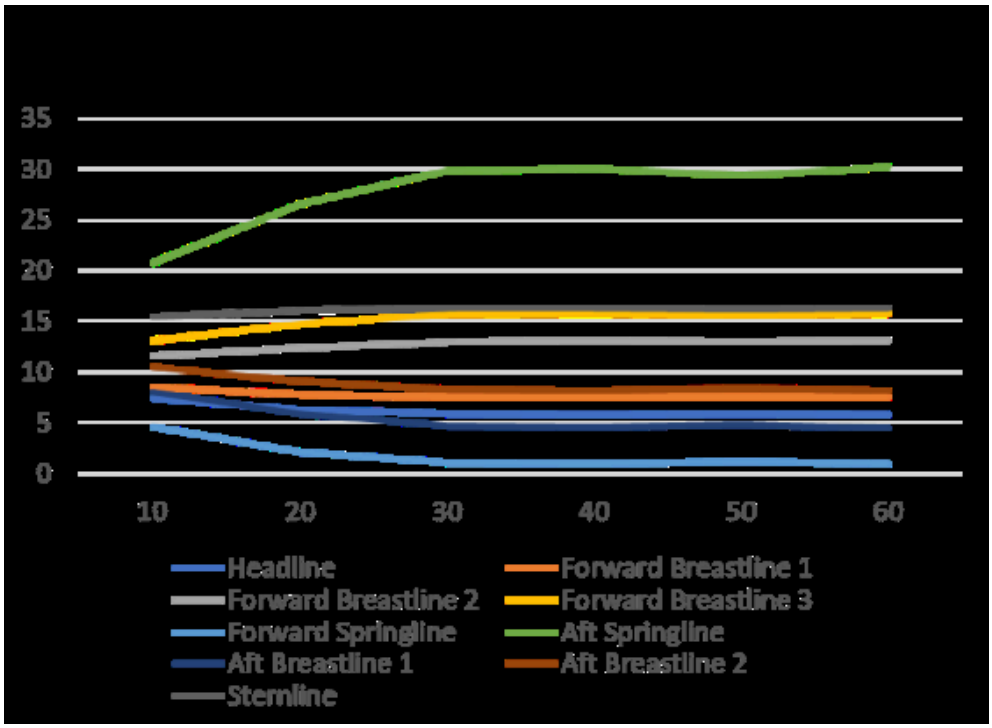


Figure 4. Mooring Line Tension (t) – Time (min) Graph

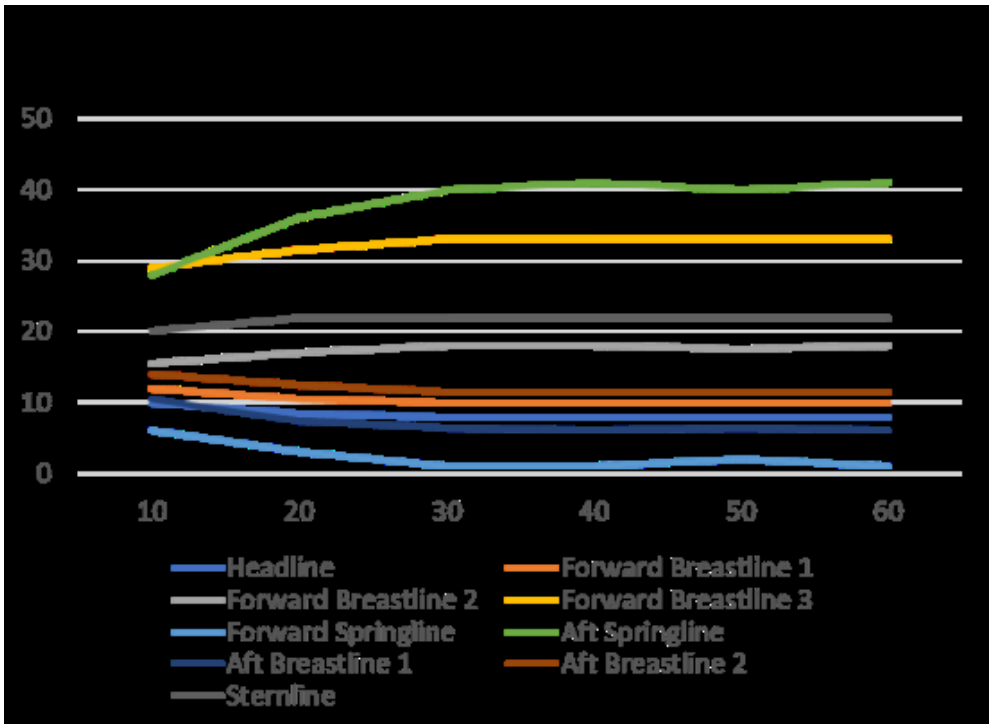


Figure 5. Minimum Breaking Load (MBL) (%) – Time (min) Graph

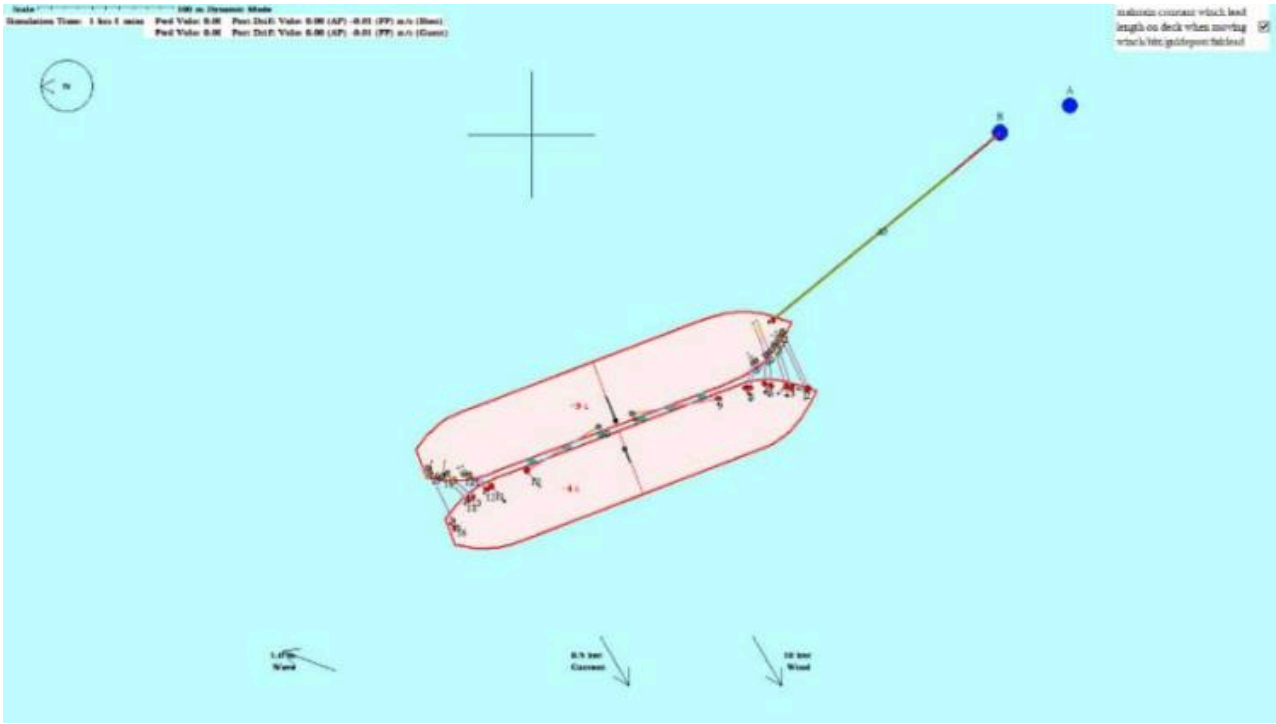


Figure 6. Ship Model Structure after a 1-Hour Simulation

Configuration 1 was evaluated under mild environmental conditions, with wind velocity set at 10 knots and current flow at 0.5 knots. Synthetic HMPE mooring lines were employed with no degradation, ensuring optimal line integrity throughout the simulation. The analysis revealed that all mooring lines operated within safe tension limits, with the highest stress observed on the aft spring line, reaching 39.33% of its Minimum Breaking Load (MBL). Other lines, including the forward breast, aft breast, and stern lines, registered lower stress levels, ranging between 7% and 22% MBL.

The time-series graphs confirmed stable load behavior across all lines over the 60-minute simulation period, with no abrupt fluctuations or overloads. The MBL percentage remained consistently below critical thresholds, indicating balanced load distribution and effective mooring performance. The accompanying ship model structure further validated the spatial arrangement of lines and their contribution to overall system stability.

In summary, Configuration 1 demonstrated a compliant and resilient mooring arrangement under low-stress conditions. The results affirm the suitability of this configuration for Ship-to-Ship (STS) operations in calm environments, with all components performing within internationally accepted safety margins.

4.5 Configuration 2

Table 7. Mooring Line Tension with MBL for Configuration 2

Configuration	Value
Windspeed (knots)	20
Current, V (knots)	0.5
Mooring Line Type	Synthetic (HMPE)
Line Degradation (%)	0
Mooring Line Tension & MBL	
Headline [MBL, %]	8.1 [10.80]
Forward Breast Line [MBL, %]	9.7 [12.93]
Forward Breast Line 2 [MBL, %]	14.7 [19.60]
Forward Breast Line 3 [MBL, %]	19.4 [25.87]
Forward Spring Line [MBL, %]	8.0 [10.67]
Aft Spring Line [MBL, %]	31.7 [42.27]
Aft Breast Line [MBL, %]	10.6 [14.13]
Aft Breast Line 2 [MBL, %]	12.2 [16.27]
Stern Line [MBL, %]	16.2 [21.60]

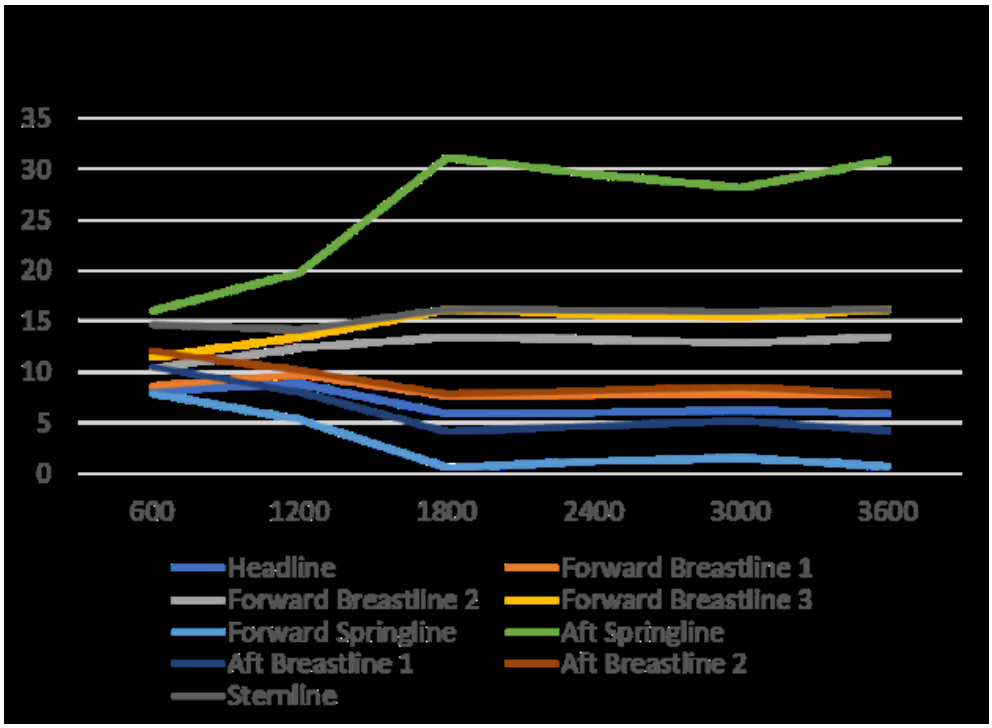


Figure 7. Mooring Line Tension (t) – Time (min) Graph

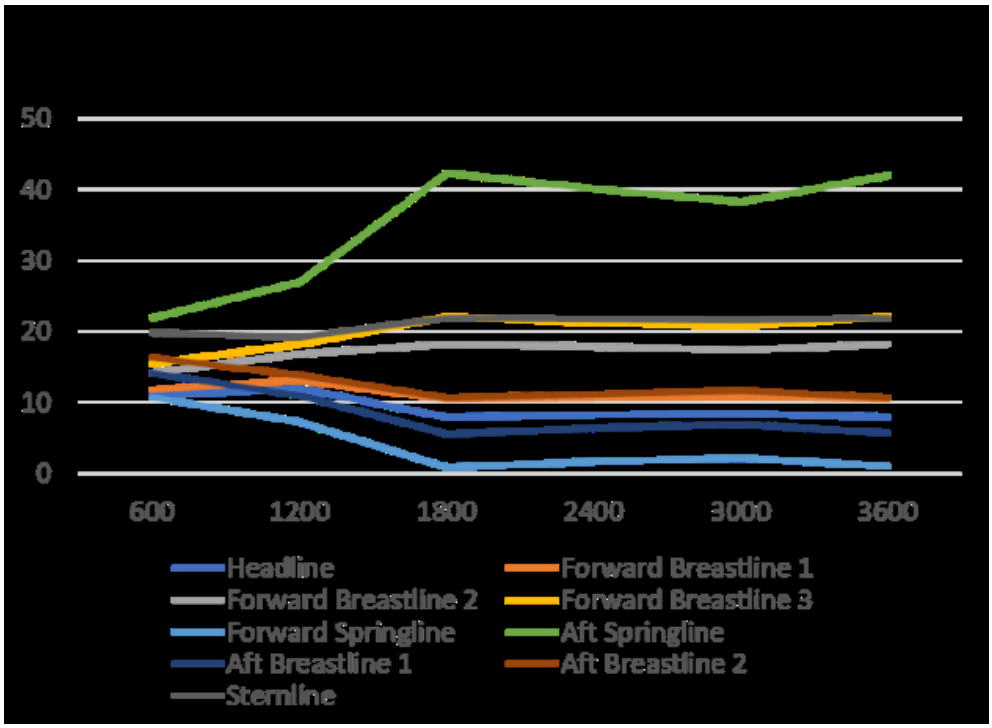


Figure 8. Minimum Breaking Load (MBL) (%) – Time (min) Graph

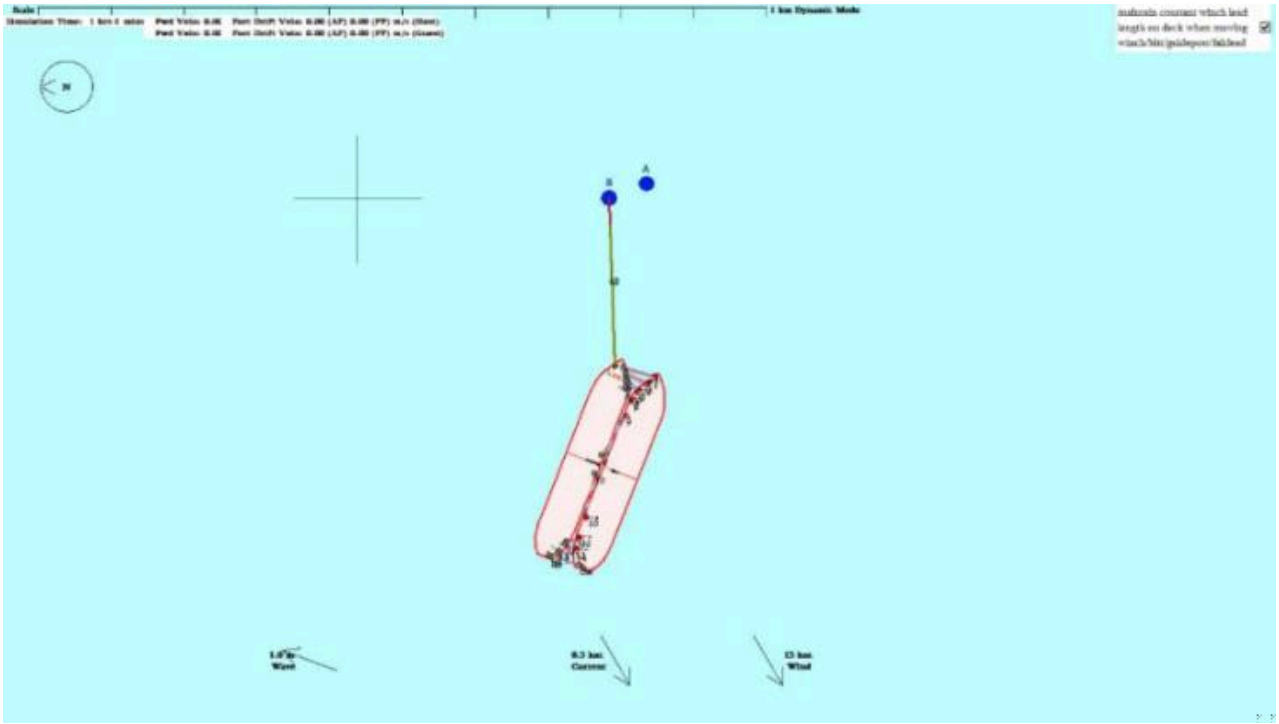


Figure 9. Ship Model Structure after 1 Hour Simulation

Configuration 2 was simulated under moderate environmental conditions, with wind speed increased to 20 knots and current velocity maintained at 0.5 knots. Synthetic HMPE mooring lines were used with no degradation. The analysis revealed elevated tension levels across several lines, particularly the aft spring line, which reached 42.27% of its Minimum Breaking Load (MBL). Forward spring and breast lines also showed increased stress, ranging between 19% and 26% MBL, while other lines remained within lower operational margins.

The time-series graphs confirmed consistent tension behavior across all mooring lines throughout the simulation period, with no abrupt spikes or failures. The MBL percentage graph indicated that all lines remained below the OCIMF MEG4 safety thresholds of 50% for Working Load Limit and 60% for Design Load Limit.

The ship model structure visually supported the line arrangement and demonstrated effective load dispersion under increased wind influence.

In summary, Configuration 2 exhibited a resilient mooring arrangement capable of maintaining compliance and operational stability under moderate wind conditions. The results affirm the configuration's suitability for Ship-to-Ship (STS) operations in environments with elevated external forces.

4.6 Configuration 3

Table 8. Mooring Line Tension with MBL for Configuration 3

Configuration	Value
Windspeed (knots)	30
Current, V (knots)	0.5
Mooring Line Type	Synthetic (HMPE)
Line Degradation (%)	0
Mooring Line Tension & MBL	
Headline [MBL, %]	9.5 [12.70]
Forward Breast Line [MBL, %]	10.3 [13.73]
Forward Breast Line 2 [MBL, %]	15.2 [20.26]
Forward Breast Line 3 [MBL, %]	22.0 [29.33]
Forward Spring Line [MBL, %]	8.4 [11.20]
Aft Spring Line [MBL, %]	36.8 [49.07]
Aft Breast Line [MBL, %]	10.7 [14.26]
Aft Breast Line 2 [MBL, %]	12.3 [16.40]
Stern Line [MBL, %]	17.0 [22.67]

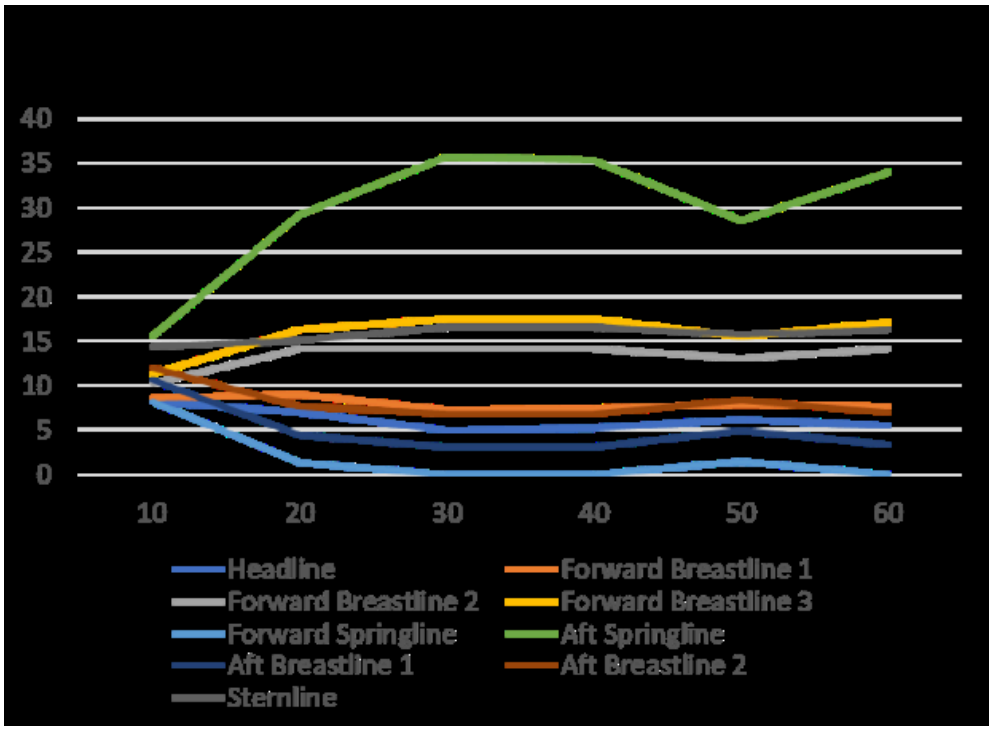


Figure 10. Mooring Line Tension (t) – Time (min) Graph

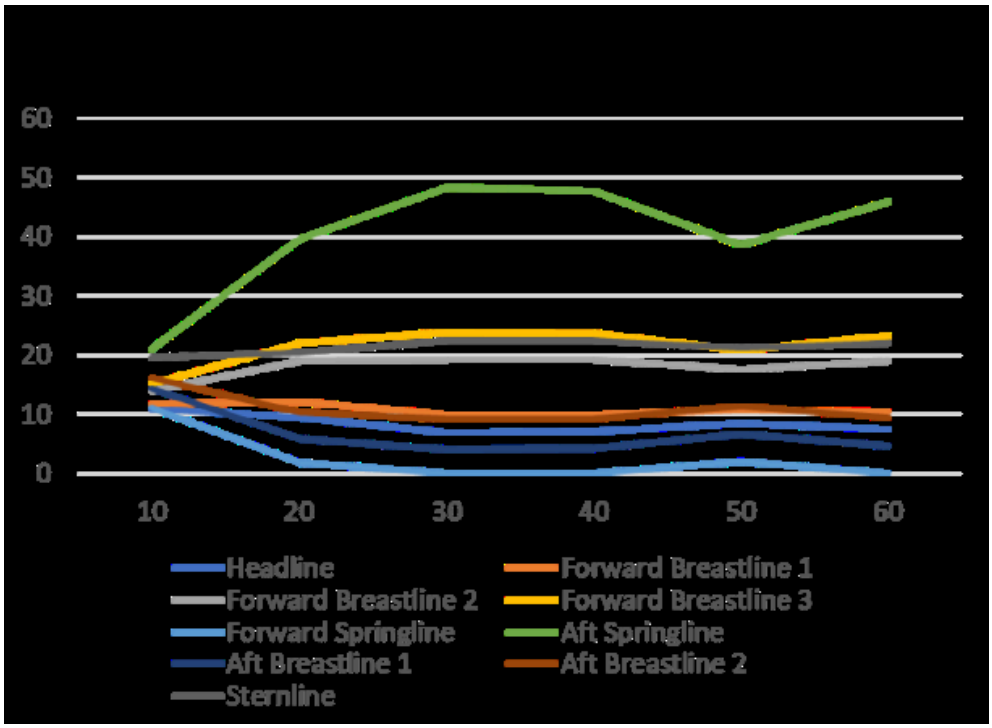


Figure 11. Minimum Breaking Load (MBL) (%) – Time (min) Graph

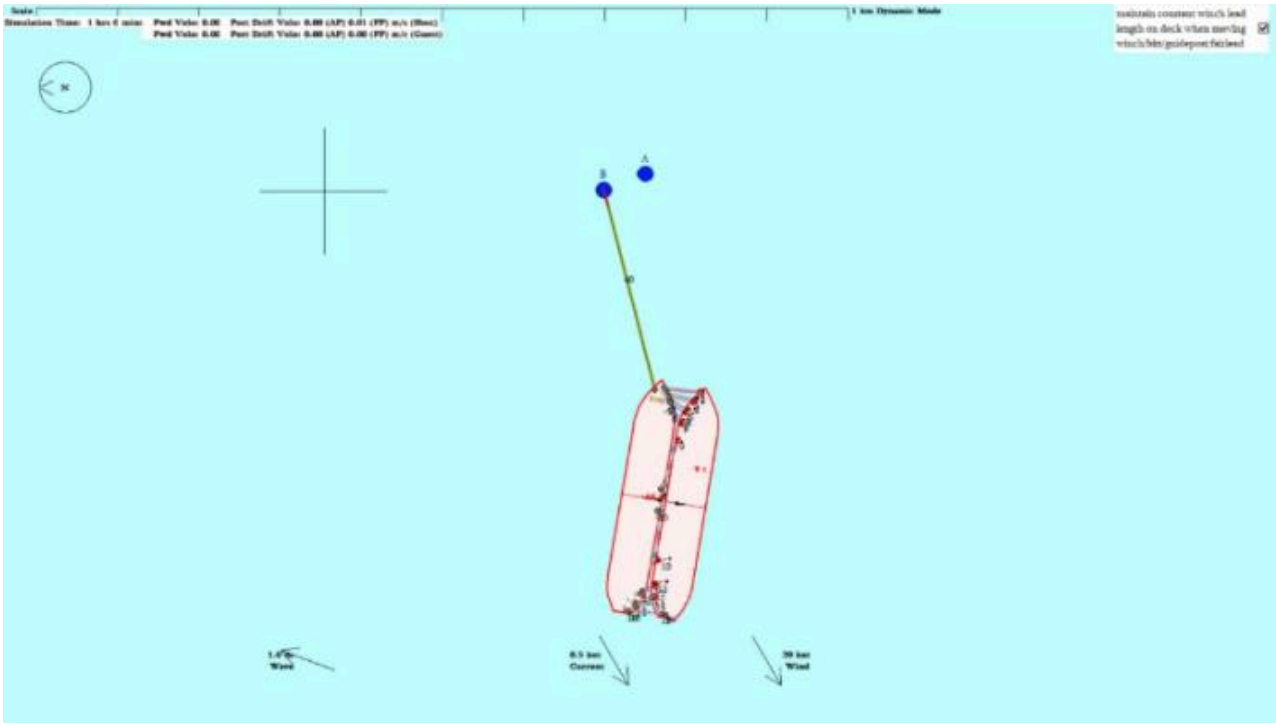


Figure 12. Ship Model Structure after 1 Hour Simulation

Configuration 3 was simulated under elevated environmental conditions, with wind speed increased to 30 knots and current velocity maintained at 0.5 knots. Synthetic HMPE mooring lines were used with no degradation. The results indicated a rise in overall line tension, particularly on the aft spring line, which approached 49.07% of its Minimum Breaking Load (MBL), nearing the OCIMF MEG4 Working Load Limit threshold of 50%. Forward spring lines also exhibited increased stress, with values ranging between 20% and 29% MBL, while other lines remained within lower operational margins.

The time-series graphs showed consistent tension behaviour across all mooring lines throughout the 60-minute simulation, with no abrupt overloads or failures. The MBL percentage graph confirmed that all lines remained below the Design Load Limit of 60%, despite the intensified wind conditions. The ship model structure

visually supported the mooring arrangement and illustrated effective load dispersion across the vessel's longitudinal and transverse axes.

In summary, Configuration 3 demonstrated a mooring system operating near its upper safety threshold under high wind conditions. While the arrangement remained compliant, the results highlight the importance of continuous monitoring and stress balancing to ensure operational integrity during Ship-to-Ship (STS) operations in exposed environments.

4.7 Configuration 4

Table 9. Mooring Line Tension with MBL for Configuration 4

Configuration	Value
Wind speed (knots)	20
Current, V (knots)	0.8
Mooring Line Type	Synthetic (HMPE)
Line Degradation (%)	0
Mooring Line Tension & MBL	
Headline [MBL, %]	11.6 [15.46]
Forward Breast Line [MBL, %]	11.3 [15.07]
Forward Breast Line 2 [MBL, %]	13.5 [18.00]
Forward Breast Line 3 [MBL, %]	20.5 [27.33]
Forward Spring Line [MBL, %]	2.1 [2.80]
Aft Spring Line [MBL, %]	29.3 [39.07]
Aft Breast Line [MBL, %]	13.1 [17.47]
Aft Breast Line 2 [MBL, %]	13.6 [18.13]
Stern Line [MBL, %]	14.8 [19.73]

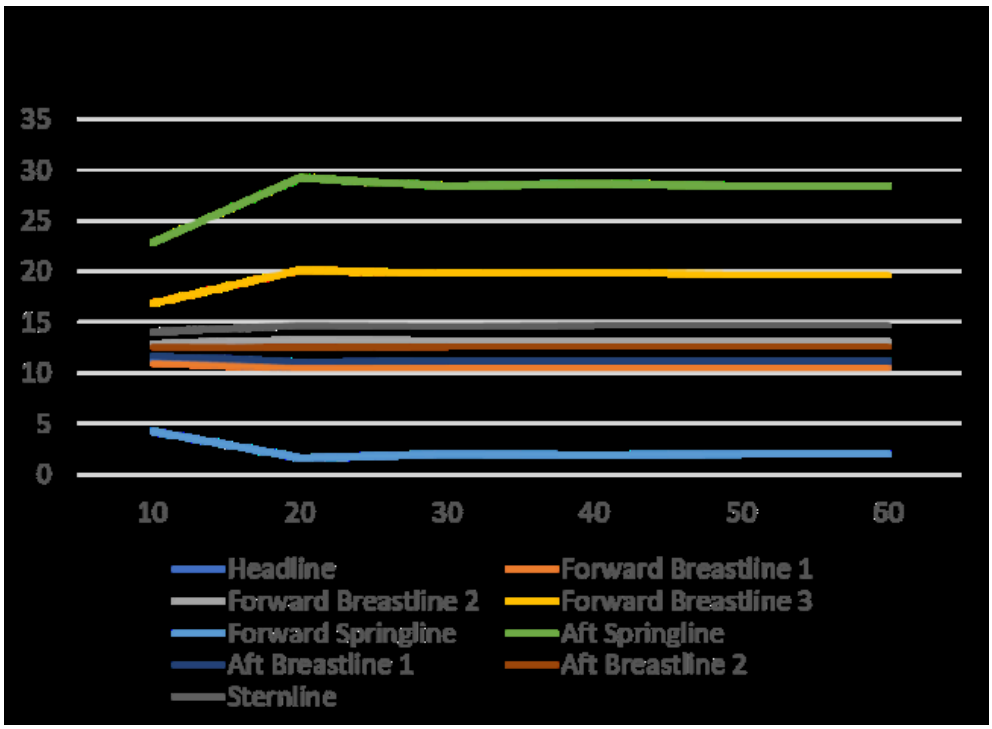


Figure 13. Mooring Line Tension (t) – Time (min) Graph

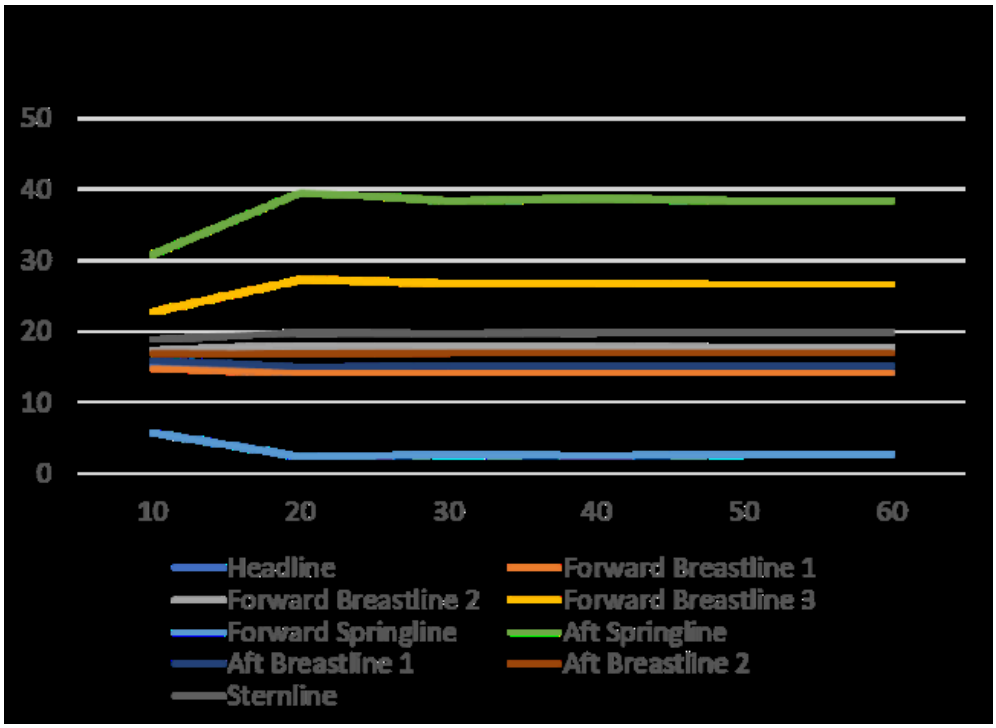


Figure 14. Minimum Breaking Load (MBL) (%) – Time (min) Graph

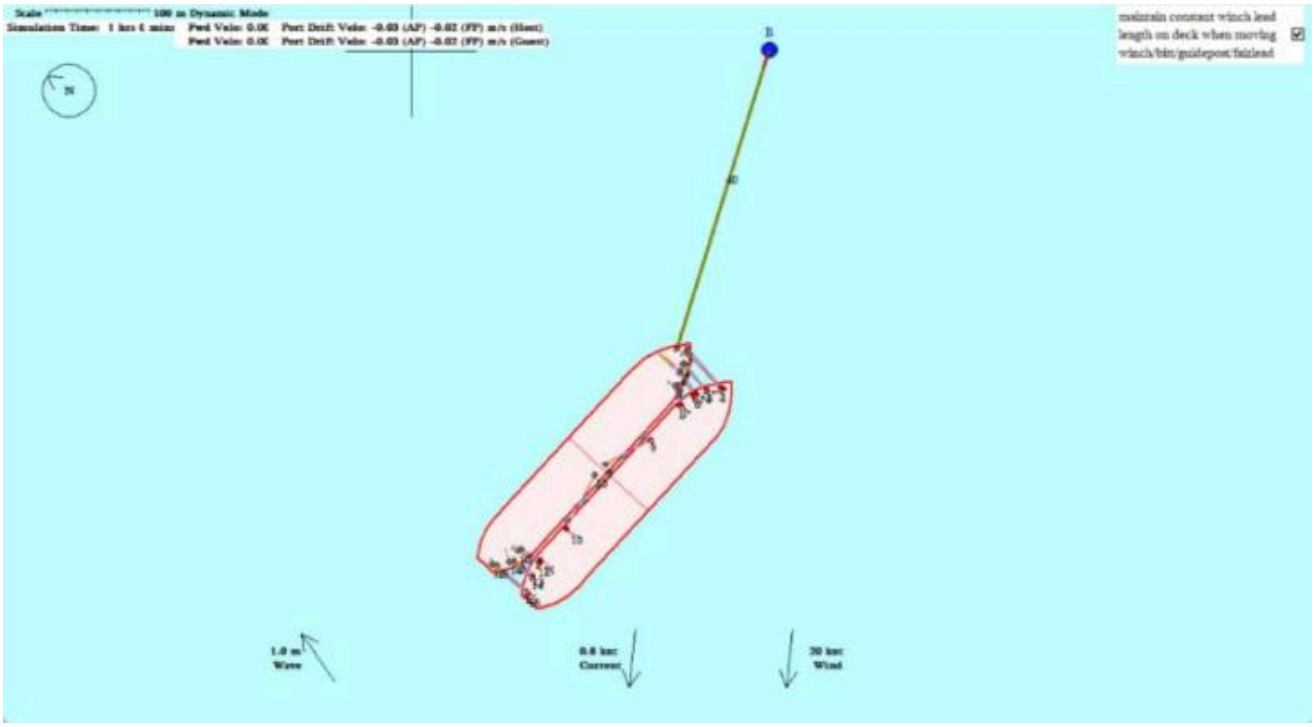


Figure 15. Ship Model Structure after 1 Hour Simulation

Configuration 4 was simulated under moderately intensified environmental conditions, with wind speed set at 20 knots and current velocity increased to 0.8 knots. Synthetic HMPE mooring lines were used with no degradation. The results showed that the mooring system remained operationally stable, though certain lines experienced elevated tension due to the stronger current influence. The stern line recorded the highest stress, reaching 39.07% of its Minimum Breaking Load (MBL), while the aft spring line followed closely at 27.33% MBL. Other lines, including the forward spring, forward breast, and headline, ranged between 15% and 18% MBL, with the aft breast line notably lower at 2.80% MBL.

The time-series graphs confirmed consistent tension behaviour across all mooring lines over the 60-minute simulation period, with no signs of overload or structural failure. The MBL percentage graph indicated that all lines remained below the OCIMF MEG4 safety thresholds of 50% for Working Load Limit and 60% for Design

Load Limit. The ship model structure visually supported the mooring layout and illustrated effective line placement in response to increased hydrodynamic forces.

In summary, Configuration 4 demonstrated a compliant and resilient mooring arrangement under moderate wind and current conditions. The results affirm the configuration's suitability for Ship-to-Ship (STS) operations in semi-exposed environments, with adequate load distribution and safety margin retention.

4.8 Configuration 5

Table 10. Mooring Line Tension with MBL for Configuration 5

Configuration	Value
Wind speed (knots)	20
Current, V (knots)	0.5
Mooring line type	Steel Wire
Line Degradation (%)	0
Mooring Line Tension & MBL	
Headline [MBL, %]	8.1 [11.25]
Forward Breast Line [MBL, %]	9.9 [13.75]
Forward Breast Line 2 [MBL, %]	14.9 [20.70]
Forward Breast Line 3 [MBL, %]	23.9 [33.19]
Forward Spring Line [MBL, %]	8.1 [11.25]
Aft Spring Line [MBL, %]	40.0 [55.56]
Aft Breast Line [MBL, %]	11.0 [15.27]
Aft Breast Line 2 [MBL, %]	12.4 [17.22]
Stern Line [MBL, %]	17.4 [24.17]

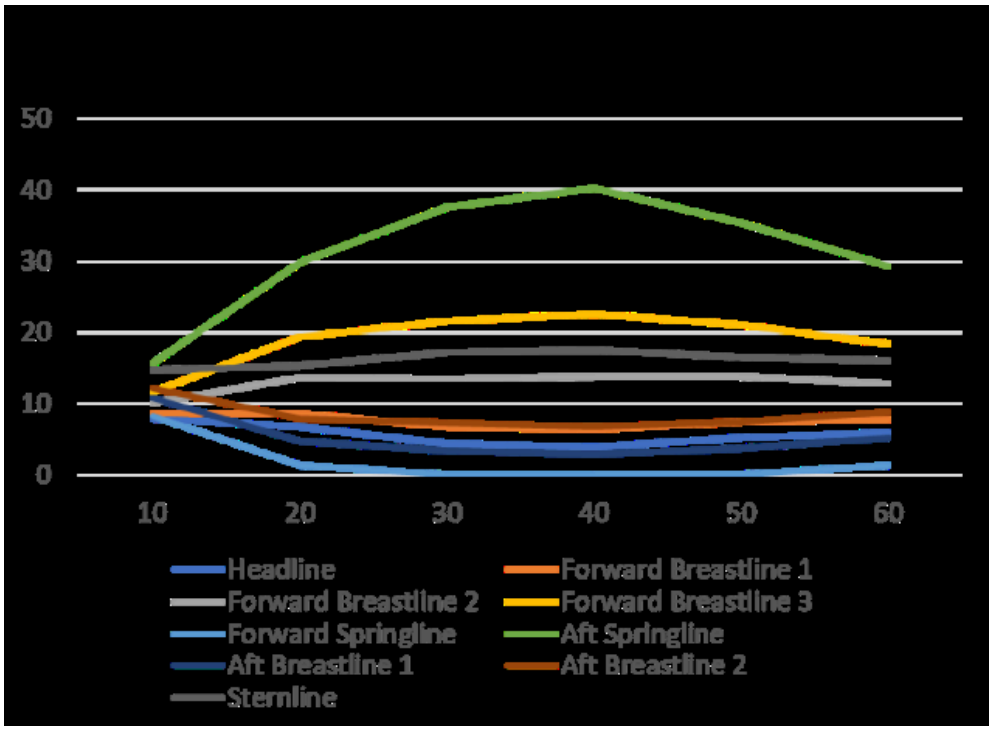


Figure 16. Mooring Line Tension (t) – Time (min) Graph

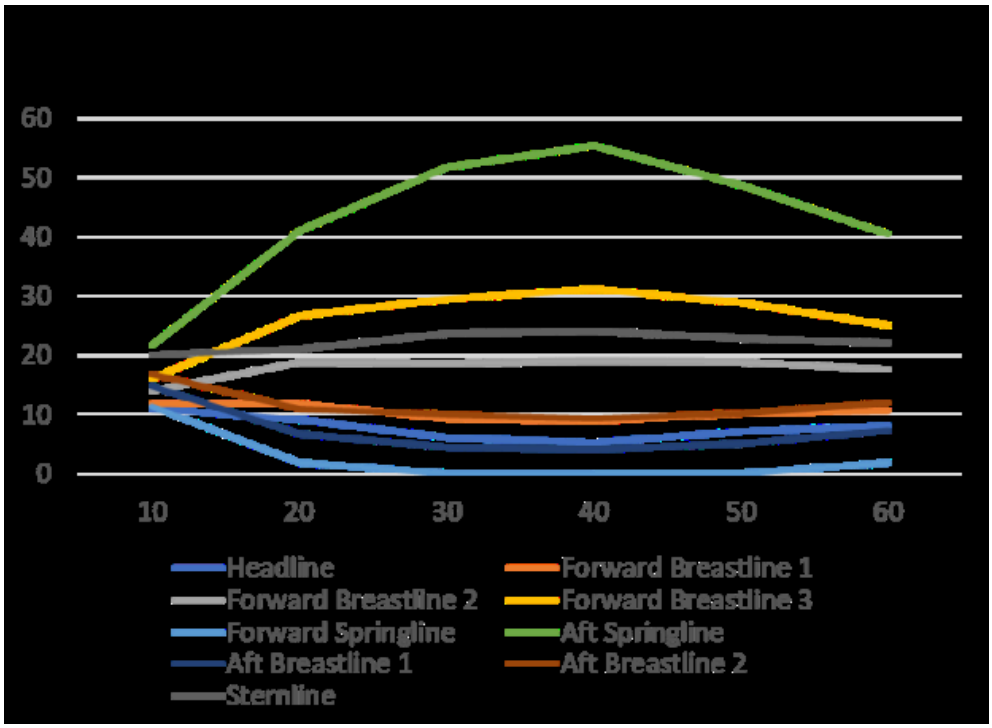


Figure 17. Minimum Breaking Load (MBL) (%) – Time (min) Graph

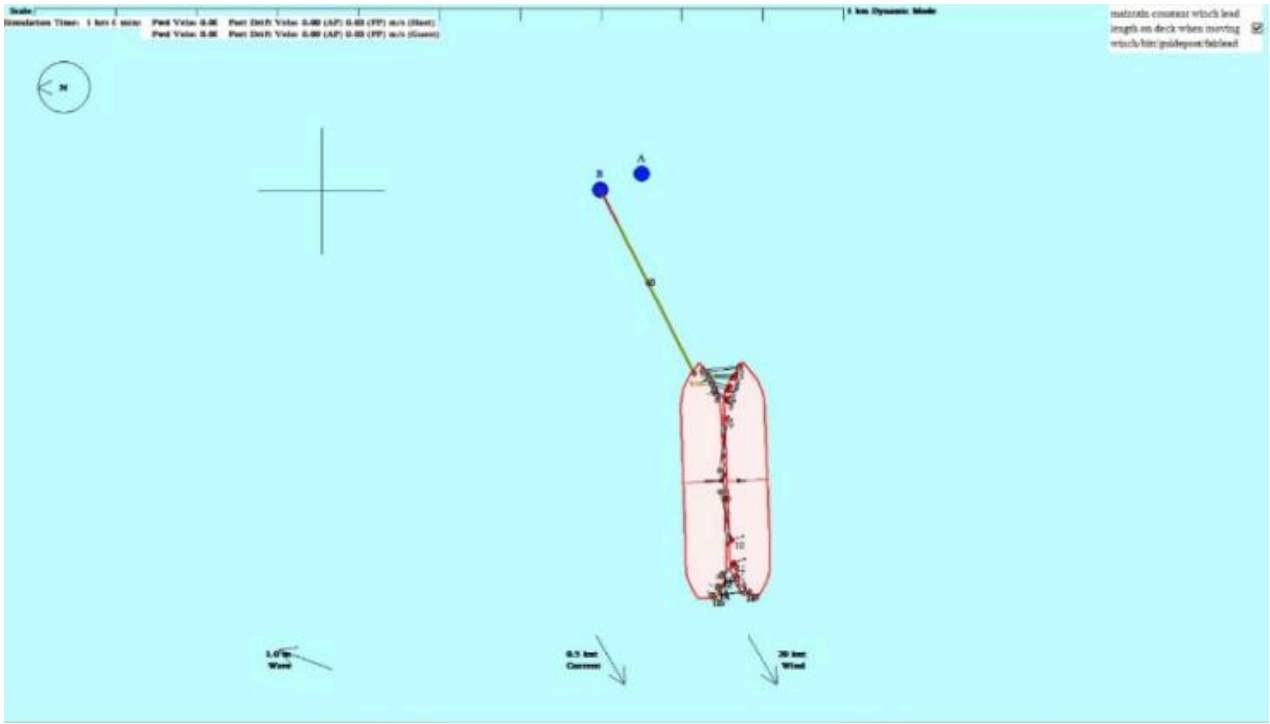


Figure 18. Ship Model Structure after 1-Hour Simulation

Configuration 5 was simulated under moderate environmental conditions, with wind speed at 20 knots and current velocity at 0.5 knots. Unlike previous setups, this configuration employed steel wire mooring lines with no degradation. The results revealed elevated tension levels, particularly on the aft spring line, which reached 55.56% of its Minimum Breaking Load (MBL), slightly exceeding the OCIMF MEG4 Working Load Limit of 50%. Forward spring lines also showed significant stress, with one line reaching 33.19% MBL, while other lines such as the stern and forward breast lines ranged between 11% and 24% MBL.

The time-series graphs indicated stable tension behaviour across all lines over the 60-minute simulation period, with no abrupt overloads or failures. The MBL percentage graph confirmed that most lines remained within acceptable safety margins, though the aft spring line approached the upper threshold. The ship model

structure visually supported the mooring layout and highlighted the influence of line material on load distribution.

In summary, Configuration 5 demonstrated a functional mooring arrangement under moderate conditions, though the use of steel wire lines resulted in higher stress concentrations. The findings underscore the importance of material selection and tension monitoring to ensure compliance and operational safety during Ship-to-Ship (STS) operations.

4.9 Configuration 6

Table 11. Mooring Line Tension with MBL for Configuration 6

Configuration	Value
Wind speed (knots)	20
Current, V (knots)	0.5
Mooring Line type	Synthetic (HMPE)
Line Degradation (%)	20
Mooring Line Tension & MBL	
Headline [MBL, %]	8.4 [11.50]
Forward Breast Line [MBL, %]	9.5 [13.01]
Forward Breast Line 2 [MBL, %]	16.0 [21.92]
Forward Breast Line 3 [MBL, %]	47.8 [65.48]
Forward Spring Line [MBL, %]	0 [slack]
Aft Spring Line [MBL, %]	0 [slack]
Aft Breast Line [MBL, %]	10.1 [13.84]
Aft Breast Line 2 [MBL, %]	15.7 [21.51]
Stern Line [MBL, %]	21.8 [29.86]

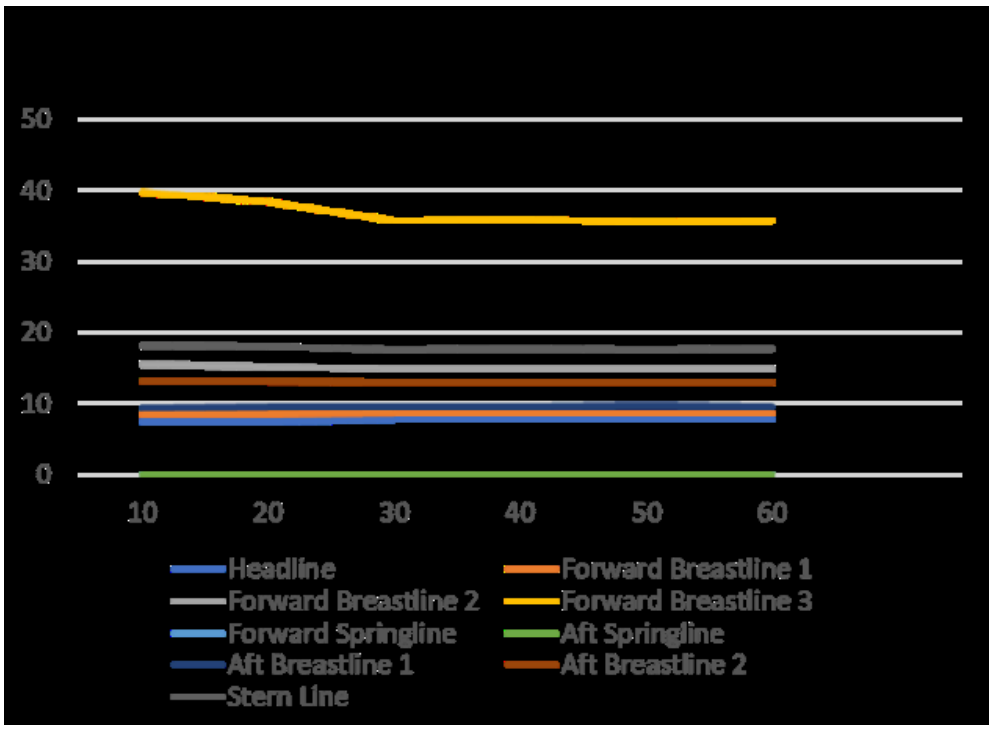


Figure 19. Mooring Line Tension (t) – Time (min) Graph

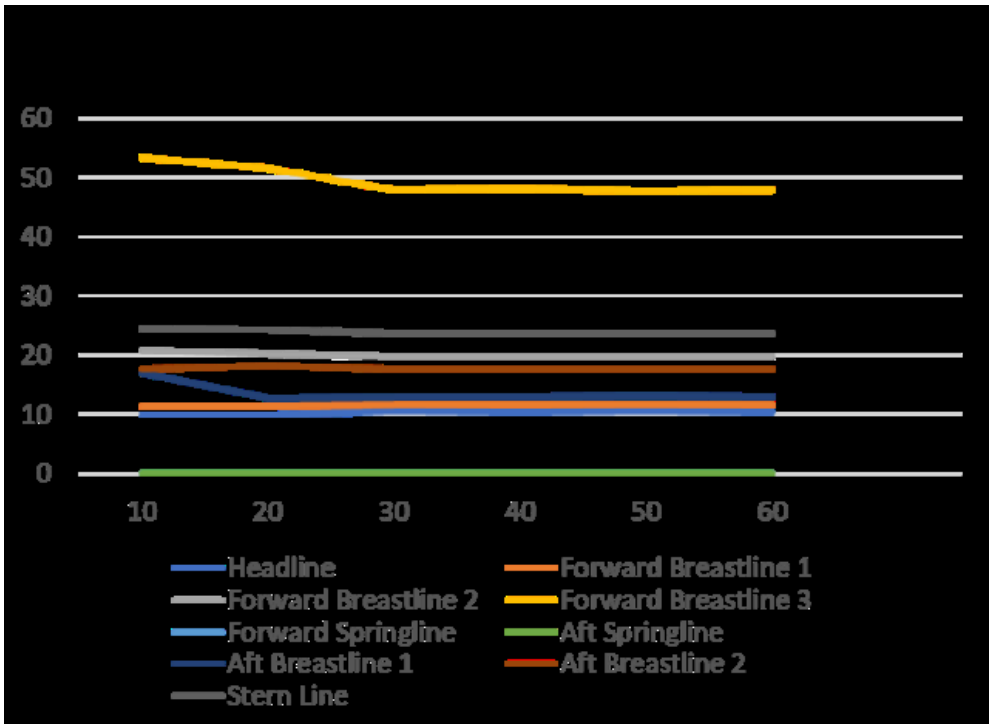


Figure 20. Minimum Breaking Load (MBL) (%) – Time (min) Graph

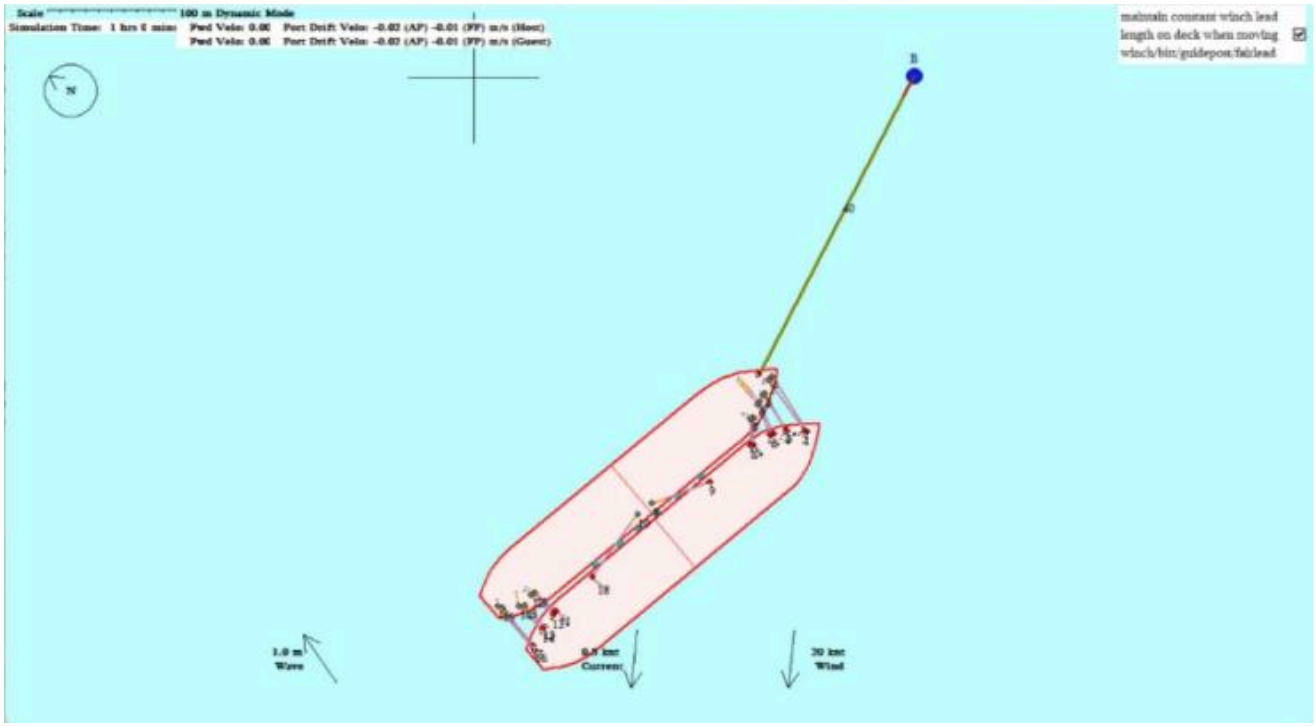


Figure 21. Ship Model Structure after 1 Hour Simulation

Configuration 6 was simulated under moderate environmental conditions, with wind speed at 20 knots and current velocity at 0.5 knots. Synthetic HMPE mooring lines were used with a degradation factor of 20%, representing reduced line strength due to wear or aging. The results revealed a significant increase in stress on the forward spring line, which reached 65.48% of its Minimum Breaking Load (MBL), exceeding the OCIMF MEG4 Design Load Limit of 60%. The stern line also showed elevated tension at 29.86% MBL, while other lines such as the forward breast, headline, and aft breast ranged between 11% and 22% MBL. The forward and aft spring lines remained slack throughout the simulation.

The time-series graphs confirmed consistent tension behaviour across most lines over the 60-minute simulation period, with no abrupt overloads except for the forward spring line, which sustained high stress levels. The MBL percentage graph highlighted the impact of line degradation, particularly on the forward spring line,

which operated beyond recommended safety margins. The ship model structure illustrated the mooring layout and confirmed the influence of degraded line strength on load distribution.

In summary, Configuration 6 demonstrated a partially compliant mooring arrangement under moderate conditions with degraded line integrity. The findings emphasize the operational risks associated with line deterioration and the need for proactive tension monitoring and line replacement strategies during Ship-to-Ship (STS) operations.

4.10 Comparative Analysis of Mooring Configurations

Configuration 1 (Baseline, Mild Conditions) Under calm weather (wind ≤20 knots, current ≤0.5 knots), all mooring lines remained well below 40% of their Minimum Breaking Load (MBL). Load distribution was balanced, with spring lines absorbing moderate forces but not approaching critical thresholds. This baseline confirmed that mooring systems perform reliably under mild conditions when line integrity is intact.

Configuration 2 (Wind at 20 knots) When wind speed increased to 20 knots, spring lines began to show higher tension fluctuations, particularly the aft spring line, which approached 45% MBL. Although the loads remained within the Working Load Limit (WLL), the reduced safety margin highlighted the sensitivity of spring lines to wind-driven forces compared to the baseline.

Configuration 3 (Wind at 30 knots) At a wind speed of 30 knots, the aft spring line reached 49.07% MBL, nearing the OCIMF WLL of 50%. Stern lines also absorbed increased loads. Compared to Configurations 1 and 2, the system operated at the edge of safe margins, showing that operations should be suspended when wind exceeds 30 knots to avoid overload.

Configuration 4 (Current at 0.8 knots) With current velocity increased to 0.8 knots, stern lines absorbed disproportionate loads, reaching 39.07% MBL. The distribution shifted from spring lines to stern lines, confirming that currents primarily affect transverse forces. Compared to Configuration 3, the system remained safer overall, but the imbalance in load distribution highlighted the need for symmetrical line arrangements.

Configuration 5 (Steel Wire Lines) Replacing synthetic lines with steel wire increased stiffness and reduced elasticity, concentrating higher stresses on spring lines. The aft spring line reached 55.56% MBL, exceeding the WLL. Compared to synthetic lines in Configurations 1–4, steel wires demonstrated reduced resilience under dynamic loads, confirming that material choice directly influences safety margins.

Configuration 6 (Degraded HMPE Lines, 20% Reduction) Line degradation had the most severe impact, with the forward spring line exceeding 65.48% MBL, surpassing the Design Load Limit (DLL) of 60%. Even under moderate conditions, degraded lines compromised safety margins, confirming that rope integrity is as critical as environmental limits. Of all the configurations, degradation posed the highest risk.

Spring lines consistently bore the highest loads across all configurations, making them the most vulnerable to overload. Wind stress primarily affected spring lines, while current stress shifted loads to stern lines. Steel wire lines concentrated stress due to reduced elasticity, exceeding safe limits. Degraded HMPE lines posed the greatest risk, surpassing design limits even under moderate conditions. Configurations 3, 5, and 6 demonstrated conditions where safety margins were exceeded, reinforcing the need for strict weather limits, rope management, and balanced line arrangements.

4.11 Recommendation

Simulation analysis demonstrated that mooring lines remained intact during one-hour dynamic tests, with tension levels varying significantly based on wind speed, current velocity, line material, and degradation. Peak loads reached approximately 50–55% of the Minimum Breaking Load (MBL), consistent with the OCIMF MEG4 Working Load Limit of ≤50% MBL, but safety margins narrowed notably when wind speeds exceeded 30 knots or line degradation surpassed 20%, aligning with rope management guidelines (Zhang et al., 2022). These results emphasize the system's sensitivity to environmental stressors and equipment state, highlighting that mooring safety depends not only on line strength but also on environmental awareness, equipment condition, and procedural discipline (Gao et al., 2025). Degraded lines under moderate conditions can compromise safety margins, underscoring the need for redundancy, operational suspension when limits are exceeded, and strict

adherence to international standards such as the STS Transfer Guide, SOLAS Regulation $II - \frac{1}{3} - 8$, and ISPS Code. Mitigation strategies should integrate technical measures like continuous tension monitoring and calibrated winch brakes with operational procedures and crew training to maintain mooring system resilience under dynamic conditions (Lin & Liu, 2020). Collectively, these approaches ensure vessel safety and operational continuity by addressing both environmental and equipment-related risks.

4.12 Mooring Line Arrangement

The arrangement of mooring lines critically influences vessel stability and safety during Ship-to-Ship (STS) operations, with simulations showing that spring and stern lines bear the highest loads, especially in certain configurations where tensions approach or exceed 50% of the Minimum Breaking Load (MBL). This load concentration underscores the vulnerability of these lines under dynamic conditions, highlighting the need for balanced line distribution as recommended by OCIMF's Mooring Equipment Guidelines (MEG4), which advocate symmetrical deployment of head, stern, breast, and spring lines to ensure effective load dispersion and redundancy (Yan et al., 2023). Research supports the finding that unbalanced mooring configurations lead to excessive tension and premature line degradation, increasing the risk of line failure (Tang et al., 2025). Increasing pre-tension and using multiple lines attached to the same bollard can help equalize line forces, though care must be taken to avoid overload on bollards. Optimized mooring configurations, such as balanced bow and stern cable arrangements, improve vessel stability and reduce tension fluctuations, enhancing safety and operational efficiency (Kuang et al., 2024). Overall, adopting balanced mooring arrangements is both a technical requirement and a proactive safety measure to mitigate risks identified in dynamic simulations and operational experience (Liu et al., 2025).

4.13 Weather Limits

Environmental conditions significantly impact mooring line performance, with simulations showing that spring line tensions increase sharply when wind speeds exceed 20 knots, and stern lines bear disproportionate loads when currents surpass 0.8 knots. These findings support the STS Transfer Guide's recommended operational limits of suspending activities if wind exceeds 30 knots, current exceeds 1 knot, or wave height exceeds 3 meters, which are based on extensive industry experience and risk assessments. Exceeding these thresholds raises the risk of line overload, vessel drift, and collision hazards, as environmental forces such as wind, current, and waves act synergistically to amplify mooring line tensions beyond predicted values (Subbulakshmi & Verma, 2024). Studies also highlight that dynamic responses and tension fluctuations in mooring lines increase under extreme environmental conditions, emphasizing the need for real-time meteorological monitoring integrated into STS planning (Liang et al., 2023). Strict adherence to these weather limits is essential to avoid operating at the edge of safety margins and to ensure compliance with international best practices. Overall, proactive environmental monitoring combined with operational discipline reduces exposure to extreme weather risks and enhances mooring system safety.

4.14 Line Tension Control

Maintaining mooring line tensions within safe operational limits is critical for mooring safety, with OCIMF MEG4 recommending that working loads should not exceed 50% of the Minimum Breaking Load (MBL) and design loads should be capped at 60% (Lin & Liu, 2020). Simulations showing spring lines exceeding these limits, reaching up to 65.48% MBL, highlight the increased risk of structural fatigue and sudden failure under dynamic loading conditions. Repeated exposure to high tension accelerates wear and reduces residual strength, particularly in synthetic ropes, emphasizing the need for effective tension control. Technical measures such as calibrated winch brakes are essential to release tension before unsafe limits are reached, preventing catastrophic overloads, while procedural measures include continuous real-time monitoring systems that enable operators to intervene before thresholds are breached (Hageman et al., 2019). Increasing pretension can reduce peak line tensions and improve load sharing among lines, but excessive pretension may accelerate fatigue and failure, indicating the need for balanced tension management. Integrating these technical and procedural controls ensures mooring systems operate within their design envelope, safeguarding vessel integrity and crew safety.

4.15 Degradation Management

Line degradation significantly impacts mooring safety, as shown in simulations where degraded HMPE lines exceeded 65% of their Minimum Breaking Load (MBL) even under moderate conditions, demonstrating that reduced line strength can push systems beyond safe limits without extreme environmental forces. OCIMF guidelines recommend limiting degradation to 20% or less through scheduled inspections, line rotation,

protective coverings, and proper storage to maintain line integrity. Degraded synthetic lines exhibit nonlinear stress behavior and reduced elasticity, increasing the risk of sudden failure, and since degradation is often not visible, structured inspection regimes and residual strength testing are essential. Operational discipline is crucial as the final defense against mooring failures, with real-time tension monitoring systems providing actionable data for timely interventions, and calibrated winch brakes preventing lines from exceeding safe tension limits. Crew training, including simulation-based exercises, enhances practical competence to respond effectively to sudden line failures or worsening weather, aligning with SOLAS and ISPS Code requirements for equipment maintenance and emergency preparedness (Cheng et al., 2021). Together, these technical, procedural, and human factors form a comprehensive approach to managing mooring line degradation and maintaining system resilience against environmental and mechanical stresses.

5. Conclusion

The safety and reliability of Ship-to-Ship (STS) mooring operations are governed by environmental conditions, rope integrity, and mooring line arrangements, with simulations confirming that proper management of these factors reduces the risk of mechanical failure due to tension overloads. However, line tensions vary significantly with wind speed, current velocity, and material degradation, necessitating proactive control and continuous monitoring. The literature review identified common failure modes such as overload, fatigue, misalignment, rope degradation, and line failures, which were validated through deployment results in high-load scenarios. Compliance with SOLAS standards and rope management protocols can mitigate these risks. To enhance operational safety, the study proposed balanced mooring arrangements, strict weather thresholds, and safe loading strategies, with all six rope strength mitigation strategies grounded in simulation data, international standards, and expert judgment. These findings offer practical, validated guidance to ensure STS mooring operations remain safe, resilient, and compliant under both normal and extreme conditions.

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Conflict of Interest

The author(s) declare that there is no conflict of interest regarding the research, authorship, and publication of this article.

Author Contributions

Data Availability Statement

No publicly available data are associated with this study.

Ethics Statement

The author(s) have complied with all applicable research ethics requirements throughout the conduct of this study.

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