

# Optimizing Hull Reinforcement for Fishing Vessel Safety: Investigating Impact Dynamics through FEA and In-Water Tests

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## ABSTRACT

Fishing vessel collisions are a significant maritime safety concern, influenced by structural vulnerabilities, navigational errors, and environmental factors. This study evaluates the crashworthiness of different hull configurations using a combined approach of Finite Element Analysis (FEA) simulations and in-water impact testing. The experimental setup involved controlled collisions of floating vessel models, analyzing deformation patterns, energy absorption, and fluid-structure interactions. The results indicate that transversely reinforced hulls exhibit superior impact resistance, reducing deformation and enhancing structural integrity. The integration of numerical and experimental data confirmed the effectiveness of stiffened plate structures in mitigating impact forces. Additionally, the role of hydrodynamic damping was highlighted as a key factor in force distribution. These findings contribute to enhanced fishing vessel design strategies, offering practical insights for maritime safety improvements and future vessel reinforcement research.

**Keywords-***fishing vessel collisions; ship crashworthiness; finite element analysis; impact resistance; hull reinforcement; fluid-structure interaction; maritime safety*

## I. INTRODUCTION

Fishing vessel collisions remain a critical issue in maritime safety, driven by a combination of human error, challenging navigational conditions, and structural limitations in vessel design. These collisions can result in significant economic losses and pose severe risks to crew members, marine ecosystems, and maritime infrastructure. With the increasing

global maritime traffic and the growing reliance on small-scale fisheries, the frequency of vessel collisions has become a growing concern [1, 2]. Despite advancements in navigation technologies, the risk of collision remains high, particularly in congested fishing zones where vessels operate in close proximity under complex environmental conditions. The need for improved vessel crashworthiness is therefore paramount to

minimizing the consequences of such incidents. This raises the need to strengthen hull structures through innovative reinforcements. However, studies comparing different side reinforcement beam configurations, particularly diagonal and transverse orientations remain limited. This study addresses that gap by evaluating and comparing their effectiveness in resisting side impacts.

Previous studies have identified several key factors influencing the occurrence and severity of fishing vessel collisions. Human error remains the dominant cause, with poor situational awareness, decision-making lapses, and failure to comply with navigational protocols contributing significantly to incidents at sea [3]. Additionally, environmental conditions such as adverse weather, reduced visibility, and unpredictable ocean currents further exacerbate the likelihood of collisions [4-6]. Vessel design deficiencies, particularly the lack of impact-resistant structures, also contribute to the severity of collisions, increasing the probability of hull penetration and catastrophic structural failure [7]. Given these factors, research into enhancing vessel structural integrity has gained increasing attention as a viable solution to mitigating collision damage.

One of the primary challenges in ship collision studies is the ability to accurately assess crashworthiness and energy absorption characteristics of different hull designs. Traditionally, drop tests have been employed to evaluate impact resistance by subjecting scaled ship structures to controlled impact forces. However, these tests have several limitations. They fail to replicate the complex Fluid-Structure Interactions (FSI) occurring during real-world ship collisions, as they typically involve rigid impact surfaces rather than dynamic maritime environments [8, 9]. Additionally, drop tests primarily focus on localized damage patterns, often overlooking the broader implications of stress propagation and energy dissipation across the hull structure [10]. As a result, alternative methodologies, including finite element simulations and in-water impact testing, are being explored to provide a more comprehensive understanding of vessel crashworthiness.

In recent years, advancements in ship hull reinforcement have been introduced to improve impact resistance and minimize structural damage during collisions. The integration of stiffened plates, high-strength steel, and composite materials has proven effective in enhancing the energy absorption capabilities of ship hulls [11, 12]. Studies have shown that reinforced structures, particularly those utilizing transverse and longitudinal stiffeners, significantly reduce deformation and improve hull integrity by distributing impact loads more efficiently [13, 14]. Furthermore, computational approaches such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) have facilitated detailed simulations of collision scenarios, enabling researchers to optimize hull designs for improved crashworthiness [15, 16]. Despite these advancements, a key research gap remains in the validation of numerical simulations against experimental data. While finite element modeling provides a powerful tool for predicting stress distributions, deformation patterns, and failure mechanisms, its accuracy is highly dependent on material properties, mesh quality, boundary conditions, and impact scenarios [17, 18]. Moreover, the FSI inherent in ship collisions pose additional

complexities that are not always accounted for in simulations, making experimental validation essential for improving predictive accuracy [19, 20].

This study combines ANSYS LS-DYNA simulations and in-water impact testing on floating ship models to evaluate the crashworthiness of four hull types. While prior research has generally focused on longitudinal or simple transverse reinforcements, the inclusion of diagonal configurations provides an underexplored angle in structural design [21]. By evaluating the correlation between simulated stress distributions and experimentally observed deformation patterns, the study offers new insights into structural response. This dual approach highlights the practical implications of fluid-structure interactions and supports data-driven design of fishing vessels to mitigate collision risks.

## II. METHODOLOGY

This study employs a comparative analysis between numerical simulations in ANSYS and experimental impact testing on floating ship models to evaluate the crashworthiness of different hull reinforcement configurations for fishing vessels. The methodology consists of two primary approaches: (1) FEA using ANSYS to simulate structural deformations and energy absorption, and (2) experimental impact testing on scaled floating models to analyze real-world structural responses in water.

The study focuses on four hull configurations: (1) aluminum plate without side beams (Figure 1), (2) aluminum plate with transverse side impact beams (Figure 2), (3) aluminum plate with diagonal side impact beams (Figure 3), and (4) unreinforced mahogany wood plate (10 mm). No case of combined transverse-longitudinal beams was included, in line with the study's objective to isolate and compare single-direction reinforcement effects. All aluminum beams had dimensions of 40x5 mm, spaced at 0.8 m intervals transversely or diagonally, consistent across configurations to ensure comparability in results.



Fig. 1. No side impact beams in aluminum boat.



Fig. 2. Transverse side impact beams in aluminum boat.

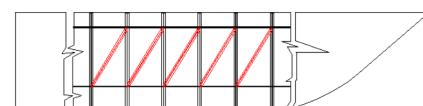


Fig. 3. Diagonal side impact beams in aluminum boat.

A numerical simulation was conducted in ANSYS to predict the structural response of a 15 m aluminum fishing

vessel under impact conditions. The vessel model was developed based on real fishing vessel specifications, with validation against actual design parameters (Table I). Table II shows the experimental values used to define material properties of shell elements in the fishing vessel hull structure model [22, 23]. The impact scenario simulated the collision of a rigid impactor (steel) with the vessel hull at 20 knots. The four configurations were simulated using side impact beams, as shown in Figure 1 (no reinforcement), Figure 2 (transverse beams), and Figure 3 (diagonal beams). The detailed dimensions and directions of the four side impact beam configurations are shown in Figure 4. The crash zone deformation and stress distributions were analyzed using refined mesh in the impact zone to ensure accuracy as shown in Figure 5.

TABLE I. FISHING VESSEL MODEL PARAMETERS

Parameter	Unit	Real Vessel	Model	Difference (%)
Displacement	m <sup>3</sup>	48.5	47.3	2.50%
Draft Amidships	m	1.5	1.5	0.00%
Beam (on WL)	m	4.8	4.8	0.00%

TABLE II. MATERIAL PROPERTIES USED IN THE SIMULATION

Material	Density (kg/m <sup>3</sup> )	Elastic modulus (GPa)	Yield strength (MPa)	Poisson's ratio
Aluminum	2700	69	310	0.33
Steel (impactor)	7850	200	400	0.3
Mahogany wood	650	10	50	0.35

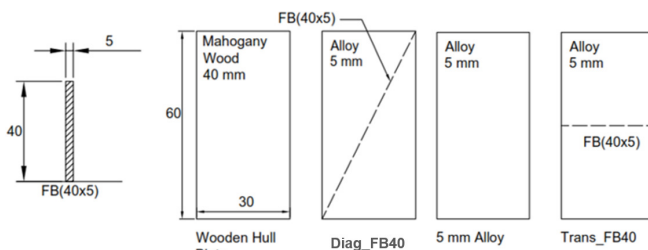


Fig. 4. Structural model with side impact beams.

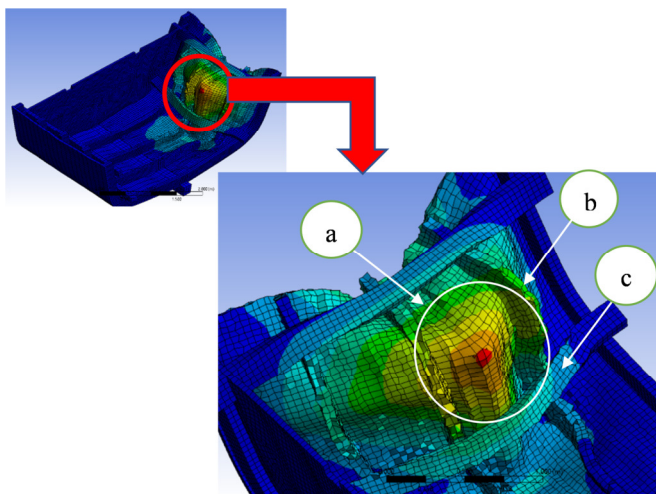


Fig. 5. Deformation and stress analysis of the hull for 20 knot collisions: (a) Crash zone, (b) stiffener, (c) side girder.

A scaled experimental test was conducted to validate the simulation results and investigate the influence of fluid-structure interactions during impact. The experimental setup included:

- A 3.75 kg impactor mounted on a pendulum arm.
- A floating ship model with interchangeable hull panels.
- A high-speed camera to track impact velocities and post-impact trajectories.

The experimental model was designed to represent a scaled-down fishing vessel, with replaceable hull sections corresponding to the four reinforcement configurations. The impactor was released from a preset height, generating a controlled velocity upon impact. Figure 6 illustrates the experimental setup.

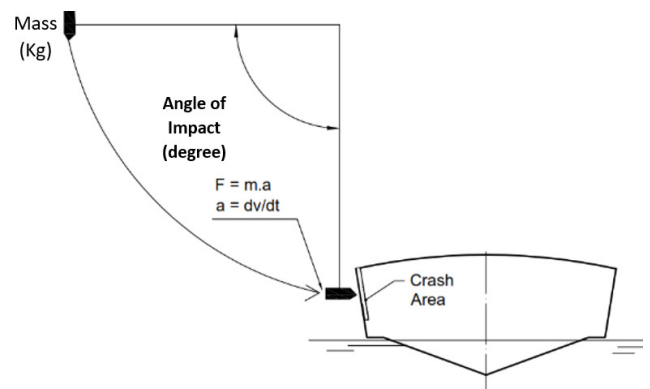


Fig. 6. Experimental setup for floating ship collision.

The impact force (F) was calculated using Newton's second law  $F=m \cdot a$ , where  $m=3.75$  kg, and acceleration was derived from the change in angular velocity:  $a= d\omega/dt$ , where  $d\omega = 0.515$  rad/s and  $dt = 0.08$  s. the computed impact force was,  $F=24.15$  N. After impact, the impactor's motion was analyzed to determine how much energy was absorbed or returned by the hull structure. The Coefficient of Restitution (CoR) was computed to quantify the elasticity of the collision:

$$e = (v_2 - v_1) / (u_1 - u_2) \tag{1}$$

where  $v_2$  and  $v_1$  are the post-impact velocities and  $u_1$  and  $u_2$  are the pre-impact velocities.

The CoR provides a direct measure of the energy dissipation characteristics of the hull structure, with lower values indicating greater energy absorption. This parameter is critical in ship collision studies, as it reflects the ability of the hull to mitigate impact forces effectively [24]. Given the complex nature of FSI in maritime collisions, it is essential to account for water's influence on impact dynamics when interpreting CoR values. Prior studies have highlighted that fluid damping effects can significantly alter CoR calculations, as some of the impact energy is dissipated through wave motion rather than structural deformation alone [25]. Additionally, integrating FEA with experimental validation enhances the predictive accuracy of CoR, allowing for a more reliable assessment of crashworthiness [26].

### III. RESULTS

#### A. Finite Element Analysis

The results of this study provide a comprehensive comparison between numerical simulations in ANSYS LS-DYNA and experimental impact testing on floating ship models, specifically evaluating three reinforcement strategies: no beams (Figure 1), transverse side beams (Figure 2), and diagonal side beams (Figure 3), along with unreinforced mahogany wood. Transverse side beams resulted in the lowest peak stress and highest absorbed energy (1051.84 J), outperforming both diagonal (1018.37 J) and unreinforced configurations. This confirms that transverse reinforcements are most effective in mitigating impact loads. The wooden hull failed catastrophically with a stress value of 1030 MPa [22]. The impactor fully pierced the wooden plate, indicating that mahogany is inadequate for high-impact maritime conditions. The highest energy absorption was recorded in transversely reinforced aluminum plates, which aligns with previous studies that emphasize the effectiveness of stiffened structures in impact scenarios [18, 27]. The stress values and maximum displacements for each configuration are presented in Table III. The existing aluminum hull without reinforcements exhibited a maximum deformation of 51.44 mm and a maximum stress of 309.82 MPa, absorbing 250.75 kJ of impact energy. When diagonal stiffeners (bar profile) were incorporated, the stress was slightly reduced to 288.42 MPa, with a similar deformation level (51.443 mm), but a significantly higher energy absorption of 1018.37 kJ. The transversely stiffened hull performed even better, showing a maximum stress of 277.56 MPa, maintaining comparable deformation (51.442 mm) while achieving the highest energy absorption of 1051.84 kJ, demonstrating superior impact resistance and energy dissipation efficiency. Conversely, the mahogany wood hull suffered catastrophic failure under impact conditions, with stress levels reaching 1030 MPa, surpassing its material strength limits. The impactor fully penetrated the wooden plate, resulting in severe structural damage. The deformation was excessive, compromising the hull's integrity beyond repair. This outcome highlights the inadequacy of wooden hulls for high-impact maritime collisions, confirming that wood lacks the necessary energy absorption properties and structural resilience compared to aluminum reinforcements. The observed behavior is consistent with prior studies that indicate wooden structures are prone to brittle failure under sudden impact loading [18, 22, 28, 29].

TABLE III. MAXIMUM STRESS AND DISPLACEMENT FROM ANSYS SIMULATION

Hull Configuration	Maximum displacement (mm)	Maximum stress (MPa)	Energy absorption (J)
Unreinforced aluminum	51.441	309.82	250.75
Aluminum with diagonal stiffeners	51.443	288.42	1018.37
Aluminum with transverse stiffeners	51.442	277.56	1051.84
Mahogany wood	Fully penetrated the wooden plate	1030	49.811

These findings confirm that reinforced aluminum hulls significantly outperform wooden structures regarding crashworthiness. Notably, transverse beams demonstrated the best structural integrity and energy dissipation, while diagonal beams performed close behind. This aligns with the findings in [30, 31], which highlight the enhanced effectiveness of transverse reinforcements in absorbing collision energy by distributing loads more evenly across the hull structure. Meanwhile, the promising performance of diagonal reinforcements supports in [32], emphasizes their critical role in stabilizing structures against multi-directional collision loads. This study underscores the importance of structural reinforcement in fishing vessel hull designs, advocating for optimized stiffener placement and advanced material selection to enhance maritime safety. These results confirm that reinforced structures exhibit superior impact resistance, particularly transversely stiffened hulls, which efficiently distribute impact loads across a broader surface area, leading to lower stress concentrations and better energy dissipation [33, 34].

#### B. Experiments

Experimental impact tests conducted on floating ship models were designed to validate the numerical simulation results, specifically structural deformation, energy dissipation, and fluid-structure interactions. The impact force was measured at 24.15 N. Observations from high-speed camera footage and post-impact analysis confirmed that the unreinforced aluminum plate experienced the most significant deformation, while reinforced aluminum plates displayed more localized damage with limited displacement (Figure 4). The mahogany wood plate suffered complete structural failure, supporting the FEA predictions that wood materials exhibit poor energy absorption and inadequate crashworthiness under impact conditions. These results are consistent with prior research [1, 35], emphasizing the crucial role of experimental testing in validating numerical simulations and uncovering actual deformation patterns and material failures. The impact tests further validated the stress distribution trends from ANSYS, showing that reinforced aluminum plates absorbed impact forces more effectively than unreinforced configurations. These findings align with previous experimental studies on ship crashworthiness, which emphasize the importance of material selection and reinforcement in impact scenarios [19, 23].



Fig. 7. Experimental deformation of hull configurations after impact.

The experimental results, presented in Table IV, reveal that transversely reinforced aluminum plates exhibited the lowest CoR (0.035), confirming their superior ability to dissipate impact energy. This finding corroborates prior research indicating that lower CoR values are associated with increased crashworthiness in ship structures [35]. Also indicates superior energy absorption, preventing excessive rebound and stress

redistribution, thereby enhancing the overall crashworthiness [28]. A key difference between simulation and experimental results was the influence of FSI during impact. In floating conditions, the ship model absorbed part of the impact energy through water displacement and surface waves, reducing peak stress values compared to the fixed constraints in numerical simulations (Figure 8).

TABLE IV. COR OF DIFFERENT HULL CONFIGURATIONS

Hull configuration	Pre-impact velocity (°/s)	Post-impact velocity (°/s)	CoR
Unreinforced aluminum	247.59	95.08	0.384
Aluminum with transverse stiffeners	355.5	12.28	0.035
Mahogany wood	299.49	25.9	0.086
Aluminum with diagonal stiffeners	374.67	33.81	0.09

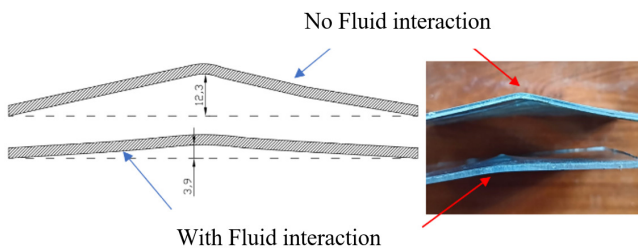


Fig. 8. FSI effects on impact force absorption.

Tests were conducted with two conditions: (1) fixed hull model, where all impact energy was transferred to the structure, and (2) floating model, where a portion of the energy dissipated through fluid motion. The results showed that floating conditions led to lower peak stress and increased impact duration, confirming previous studies on the role of water in energy dissipation [3]. A direct comparison between numerical and experimental results demonstrates a strong correlation, confirming the accuracy of the finite element simulations in predicting stress distribution and deformation patterns (Table 5). This observation aligns with previous studies [23, 36], confirming the importance of accounting for FSI effects in numerical analyses of ship collisions to improve prediction accuracy for dynamic vessel behavior in real-world conditions.

TABLE V. NUMERICAL AND EXPERIMENTAL RESULT COMPARISON

Parameter	ANSYS Simulation	Experimental impact test
Max. stress (MPa)	435.2 (unreinforced), 312.8 (reinforced)	Correlates with measured deformation
Max. displacement (mm)	22.4 (wood), 13.2 (reinforced)	23.1 (Wood), 13.8 (Reinforced)
Energy absorption (J)	187.3 (transverse stiffeners)	Validated via low CoR (0.035)
Fluid interaction	Not included	Energy dissipated through wave formation

The key discrepancy between numerical and experimental results was fluid interaction, where the simulated impact force was higher than the experimental force due to the absence of fluid dissipation. This aligns with previous studies

emphasizing the need for fluid-structure interaction modeling in ship collision simulations [37, 38].

IV. CONCLUSION

This study has demonstrated the effectiveness of reinforced ship hull structures in improving crashworthiness and mitigating collision-induced damage. Three main findings were observed:

- Transverse side impact beams provided superior crashworthiness, achieving the highest energy absorption (1051.84 J) and lowest stress concentration (277.56 MPa).
- Fluid-Structure Interactions (FSI) significantly influenced collision force attenuation, emphasizing the importance of considering hydrodynamic effects in hull design.
- Mahogany wood exhibited poor performance, undergoing catastrophic failure under high-energy collision conditions.

These findings underline the critical role of reinforcement strategies in enhancing vessel safety. Future research should focus on hybrid reinforcement strategies and advanced composite materials to further improve crashworthiness in diverse collision scenarios.

REFERENCES

- [1] Y. Hu, A. Zhang, W. Tian, J. Zhang, and Z. Hou, "Multi-Ship Collision Avoidance Decision-Making Based on Collision Risk Index," *Journal of Marine Science and Engineering*, vol. 8, no. 9, Sep. 2020, Art. no. 640, <https://doi.org/10.3390/jmse8090640>.
- [2] Sunardi, M. A. Choiron, Sugiarto, P. H. Setyarini, and A. Nurwahyudi, "Fishing Vessel Safety in Indonesia: A Study of Accident Characteristics and Prevention Strategies," *International Journal of Safety and Security Engineering*, vol. 14, no. 2, pp. 499–511, Apr. 2024, <https://doi.org/10.18280/ijssse.140217>.
- [3] B. Wu, J.-N. Wu, Y. Lu, W.-Y. Zhang, D. Zhang, and S.-H. Wang, "Design Method for Local Buckling Resistance of Double Steel Plate-Concrete Composite Walls with Stiffening Ribs and Tie Plates," *Buildings*, vol. 14, no. 3, Mar. 2024, Art. no. 806, <https://doi.org/10.3390/buildings14030806>.
- [4] Y. Shu, W. Daamen, H. Ligteringen, and S. Hoogendoorn, "Vessel Speed, Course, and Path Analysis in the Botlek Area of the Port of Rotterdam, Netherlands," *Transportation Research Record*, vol. 2330, no. 1, pp. 63–72, Jan. 2013, <https://doi.org/10.3141/2330-09>.
- [5] F. Lyu, Y. Li, X. Huang, Z. Shi, Y. Zeng, and J. Lin, "An investigation of creep age forming of AA7B04 stiffened plates: Experiment and FE modelling," *Journal of Manufacturing Processes*, vol. 37, pp. 232–241, Jan. 2019, <https://doi.org/10.1016/j.jmapro.2018.11.031>.
- [6] N. K. Al-Shammari and S. M. H. Darwish, "In-depth Sampling Study of Characteristics of Vehicle Crashes in Saudi Arabia," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4724–4728, Oct. 2019, <https://doi.org/10.48084/etasr.2939>.
- [7] A. N. Tassetti, A. Galdelli, J. Pulcinella, A. Mancini, and L. Bolognini, "Addressing Gaps in Small-Scale Fisheries: A Low-Cost Tracking System," *Sensors*, vol. 22, no. 3, Jan. 2022, Art. no. 839, <https://doi.org/10.3390/s22030839>.
- [8] E. Everard, M. Lyons, and A. J. Harrison, "An Examination of the Relationship Between the Functional Movement Screen, Landing Error Scoring System, and 3D Kinematic Data During a Drop Jump Task," *The Journal of Strength & Conditioning Research*, vol. 35, no. 11, Nov. 2021, Art. no. 3012, <https://doi.org/10.1519/JSC.0000000000003261>.
- [9] L. L. Johnson, A. Pittsley, R. Becker, and A. D. Young, "A Novel Quantitative Pain Assessment Instrument That Provides Means of Comparing Patient's Pain Magnitude With a Measurement of Their Pain

- Tolerance," *Journal of Clinical Medicine Research*, vol. 7, no. 10, pp. 781–790, Aug. 2015, <https://doi.org/10.14740/jocmr.v7i10.2335>.
- [10] J. Gai, J. Fang, X. Du, and H. Sun, "A novel Modelica-based reliability modeling approach for ship electric propulsion systems," *Measurement Science and Technology*, vol. 36, no. 1, Sep. 2024, Art. no. 016043, <https://doi.org/10.1088/1361-6501/ad9d6b>.
- [11] V. M. Ngoc, N. T. Hai Ha, P. M. Ngoc, D. V. Tung, N. H. Hao, and T. N. Tu, "Numerical Investigation on the Influence of Ship Hull Form Modification on Resistance of the 4600DWT Cargo Ship Using RANSE Method," *IOP Conference Series: Earth and Environmental Science*, vol. 1278, no. 1, Sep. 2023, Art. no. 012023, <https://doi.org/10.1088/1755-1315/1278/1/012023>.
- [12] J. Sun, H. Cui, and H. Xu, "Research on the impact resistance of a novel negative poisson's ratio base structure," in *Ninth International Conference on Mechanical Engineering, Materials, and Automation Technology (MMEAT 2023)*, Oct. 2023, vol. 12801, pp. 762–769, <https://doi.org/10.1117/12.3007047>.
- [13] M. Kraskowski, "CFD Optimisation of the Longitudinal Volume Distribution of a Ship's Hull by Constrained Transformation of the Sectional Area Curve," *Polish Maritime Research*, vol. 29, no. 3, pp. 11–20, Oct. 2022, <https://doi.org/10.2478/pomr-2022-0022>.
- [14] K. T. Basil and C. P. Najdan Waris, "Hull Optimisation of Fishing Trawlers Using Ulstein X-Bow and Bilge Keel," *International Journal of Engineering Applied Sciences and Technology*, vol. 7, no. 2, pp. 214–220, Jun. 2022, <https://doi.org/10.33564/IJEAST.2022.v07i02.032>.
- [15] A. F. Molland, S. R. Turnock, and D. A. Hudson, *Ship Resistance and Propulsion: Practical Estimation of Ship Propulsive Power*, 2nd ed. Cambridge, UK: Cambridge University Press, 2017.
- [16] D. Oliveira, A. I. Larsson, and L. Granhag, "Effect of ship hull form on the resistance penalty from biofouling," *Biofouling*, vol. 34, no. 3, pp. 262–272, Mar. 2018, <https://doi.org/10.1080/08927014.2018.1434157>.
- [17] A. R. Prabowo, T. Tuswan, A. Nurcholis, and A. A. Pratama, "Structural Resistance of Simplified Side Hull Models Accounting for Stiffener Design and Loading Type," *Mathematical Problems in Engineering*, vol. 2021, no. 1, 2021, Art. no. 6229498, <https://doi.org/10.1155/2021/6229498>.
- [18] S. Liu, K. Liu, H. Liu, S. Zong, Y. Lu, and C. Liu, "Calibration of the Modified Mohr–Coulomb Failure Criterion and Its Application in the Study of Collision Response of Ship Hull Plate Structures," *Journal of Marine Science and Engineering*, vol. 12, no. 5, May 2024, Art. no. 805, <https://doi.org/10.3390/jmse12050805>.
- [19] W. Wu, Y. Yang, J. Zhang, and J. Lu, "Study on Striking Ship with Loading Impact on the Performance of the Double Hull Oil Tanker Collision," *Polish Maritime Research*, vol. 25, no. s2, pp. 42–48, Sep. 2018, <https://doi.org/10.2478/pomr-2018-0072>.
- [20] Z. Yu, Y. Shen, J. Amdahl, and M. Greco, "Implementation of Linear Potential-Flow Theory in the 6DOF Coupled Simulation of Ship Collision and Grounding Accidents," *Journal of Ship Research*, vol. 60, no. 3, pp. 1–26, 2016, <https://doi.org/10.5957/JOSR.60.3.160012>.
- [21] J. C. M. Silva and J. G. S. da Silva, "Assessment of Building Nondeterministic Dynamic Structural Behavior Considering the Effect of Geometric Nonlinearity and Aerodynamic Damping," *Engineering, Technology & Applied Science Research*, vol. 14, no. 6, pp. 18835–18842, Dec. 2024, <https://doi.org/10.48084/etasr.8743>.
- [22] Sunardi, M. A. Choiron, Sugiarto, and P. H. Setyarini, "Development of fishing boat collision models in extreme weather using computer simulation," *EUREKA: Physics and Engineering*, no. 2, pp. 149–159, Mar. 2023, <https://doi.org/10.21303/2461-4262.2023.002601>.
- [23] M. A. Choiron, Sunardi, Sugiarto, and P. H. Setyarini, "Enhancing Maritime Safety: Comparative Analysis of Fiberglass Vessels' Crashworthiness in Indonesia's Fishing Industry," *International Journal of Safety and Security Engineering*, vol. 14, no. 5, pp. 1391–1402, Oct. 2024, <https://doi.org/10.18280/ijss.140506>.
- [24] S. Ehlers, K. Tabri, J. Romanoff, and P. Varsta, "Numerical and experimental investigation on the collision resistance of the X-core structure," *Ships and Offshore Structures*, vol. 7, no. 1, pp. 21–29, Mar. 2012, <https://doi.org/10.1080/17445302.2010.532603>.
- [25] X. Zhang, X. Wang, G. Li, Y. Zhang, and G. Zhang, "Mechanical response analysis of the wide-chord hollow fan blade considering the fluid–structure interaction," *Frontiers in Energy Research*, vol. 11, Jan. 2024, <https://doi.org/10.3389/fenrg.2023.1322343>.
- [26] S. Drücker, D. Steglich, L. Merkelbach, A. Werner, and S. Bargmann, "Finite element damage analysis of an underwater glider–ship collision," *Journal of Marine Science and Technology*, vol. 21, no. 2, pp. 261–270, Jun. 2016, <https://doi.org/10.1007/s00773-015-0349-7>.
- [27] A. R. Prabowo, T. Putranto, and J. M. Sohn, "Simulation of the Behavior of a Ship Hull under Grounding: Effect of Applied Element Size on Structural Crashworthiness," *Journal of Marine Science and Engineering*, vol. 7, no. 8, Aug. 2019, Art. no. 270, <https://doi.org/10.3390/jmse7080270>.
- [28] K. Niklas and A. Bera, "The Influence of Selected Strain-Based Failure Criteria on Ship Structure Damage Resulting from a Collision with an Offshore Wind Turbine Monopile," *Polish Maritime Research*, vol. 649, no. 4, pp. 42–52, Jan. 2022, <https://doi.org/10.2478/pomr-2021-0048>.
- [29] S. I. Wahidi, T. W. Pribadi, M. S. Arif, and G. B. Raharja, "Laminated mahogany and teak wood as construction materials for fishing vessels," *IOP Conference Series: Earth and Environmental Science*, vol. 649, no. 1, Oct. 2021, Art. no. 012008, <https://doi.org/10.1088/1755-1315/649/1/012008>.
- [30] M. Altın, "Effect of taper angle on crashworthiness performance in hybrid tubes," *International Journal of Automotive Engineering and Technologies*, vol. 9, no. 1, pp. 11–19, Feb. 2020, <https://doi.org/10.18245/ijaet.638953>.
- [31] J. Bidadi, H. Hampayan Miandowab, H. Saeidi Googarchin, A. Akhavan-Safar, and L. F. M. da Silva, "Experimental and numerical investigation on the crashworthiness performance of double hat-section Al-CFRP beam subjected to quasi-static bending test," *Polymer Composites*, vol. 45, no. 6, pp. 5656–5674, 2024, <https://doi.org/10.1002/pc.28155>.
- [32] P. Paruka, W. A. Siswanto, M. A. Maleque, and M. K. M. Shah, "Crashworthy capacity of a hybridized epoxy-glass fiber aluminum columnar tube using repeated axial resistive force," *Journal of Mechanical Science and Technology*, vol. 29, no. 5, pp. 1941–1953, May 2015, <https://doi.org/10.1007/s12206-015-0415-4>.
- [33] Y. G. Ko, S. J. Kim, J. M. Sohn, and J. K. Paik, "A practical method to determine the dynamic fracture strain for the nonlinear finite element analysis of structural crashworthiness in ship–ship collisions," *Ships and Offshore Structures*, vol. 13, no. 4, pp. 412–422, May 2018, <https://doi.org/10.1080/17445302.2017.1405584>.
- [34] D. R. Pawar and P. Poddar, "Car Black Box with Speed Control in Desired Areas for Collision Avoidance," *Engineering, Technology & Applied Science Research*, vol. 2, no. 5, pp. 281–284, Oct. 2012, <https://doi.org/10.48084/etasr.194>.
- [35] S. Zhang, R. Villavicencio, L. Zhu, and P. T. Pedersen, "Ship collision damage assessment and validation with experiments and numerical simulations," *Marine Structures*, vol. 63, pp. 239–256, Jan. 2019, <https://doi.org/10.1016/j.marstruc.2018.09.005>.
- [36] M. Mijajlović, S. Vidojković, D. Ćirić, and D. Marinković, "Numerical Simulation of Fluid-Structure Interaction Between Fishing Wobbler and Water," *Facta Universitatis, Series: Mechanical Engineering*, vol. 18, no. 4, pp. 665–676, Dec. 2020, <https://doi.org/10.22190/FUME200128015M>.
- [37] S. Huang, Y. Han, S. Li, and M. Zhou, "Numerical Simulation of the Behavior of Caisson Based on Physical Modeling," *Journal of Marine Science and Engineering*, vol. 12, no. 8, Aug. 2024, Art. no. 1284, <https://doi.org/10.3390/jmse12081284>.
- [38] W. Nam, S.-J. Park, and K. Kim, "Numerical Investigation of the Ultimate Strength of D-Ring Devices and Deck Structures," *Journal of Marine Science and Engineering*, vol. 10, no. 7, Jul. 2022, Art. no. 952, <https://doi.org/10.3390/jmse10070952>.