Structural Response Analysis During Slamming Events on Speedboats Using Aluminum Material

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(Received: 10 September 2025 / Revised: 12 September 2025 /Accepted: 17 September 2025 / Available Online: 26 September 2025)

***Abstract*— The structural response analysis of an aluminum speedboat during slam-ming due to regular waves was conducted using the one-way fluid-structure interaction method. This method involves generating waves through hydrody-namic diffraction to obtain loads, which are then applied to the ship's struc-ture and analyzed using finite element analysis. It is known that the greater the force generated from slamming , the stress and deformation at the critical load point will increase. In addition to being influenced by the critical point, the maximum stress is also influenced by the ship's construction design. It has been found that the highest stress and deformation occur on the surface of the plate that is not supported by the transverse construction. Therefore, it can be concluded that the construction design can influence the magnitude of the structural response to the slamming event . Efforts that can be made by ship designers and manufacturers are to convert ships by using materials that are better at absorbing loads, such as the use of sandwich materials**

Keywords— Aluminum, FEM, Hydrodynamic Diffraction, Slamming, Small craft.

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I. INTRODUCTION

Slamming, in the context of small craft , refers to the phenomenon in which a boat's hull repeatedly strikes the water's surface with great force while operating at high speed. This is a common occurrence on motorboats, especially those designed for high performance such as small craft. When a speed boat moves through the water at high speed, it creates waves and displaces water. Slamming occurs when the boat falls from the crest of a wave and lands hard on the water's surface rather than gliding smoothly. Slamming is primarily caused by the interaction between the boat's hull and the water's surface. When the boat is moving at a speed too high for the prevailing sea conditions, separation occurs between the hull and the water, and the hull then falls to the trough or the back of another wave. This results in a strong impact between the hull and the water's surface. [1]. The impact of slamming can be significant for a ship's structure. The repeated shocks resulting from a slamming impact can cause high blunt loads on the hull, deck, or other components. This can lead to structural damage, such as cracking or fracturing of the ship, especially in areas that experience the greatest stress during the impact. Extreme or unpredictable sea conditions can still cause slamming [2], [3].

Previous studies have explored various aspects of slamming and its consequences on ships but often address these elements in separation rather than as an integrated motion–impact scenario. Li et al. [4] conducted an experimental study on stern slamming using a segmented cruise ship model and demonstrated that low longitudinal deadrise angles in following seas can cause significant impact loads and excite whipping responses in the hull girder. However, this work focused solely on physical model tests without extending the analysis through numerical simulations that could broaden its applicability. In parallel, Mousavi and Khoob [5] numerically investigated ways to strengthen ship structures against bottom slamming by using steel–concrete–steel composite plates with ultra-lightweight, high-ductility cementitious materials. Their findings confirmed that advanced structural configurations can greatly reduce local strains and stress transfer caused by slamming impacts, but their study concentrated on material performance rather than the operational conditions or ship motions that generate slamming events in the first place. Ghao and Zhou [6] added further insight by analyzing bow slamming pressures through fluid–structure interaction modeling, showing how vessel speed, entry angle, and draft depth influence local impact forces along the bow. Despite this, their focus remained on localized pressure characteristics, with no direct link to how ship motions and wave interactions contribute to repeated slamming occurrences. Overall, while these studies provide valuable understanding of localized slamming loads and structural responses, they reveal a gap in connecting motion analysis, impact risk, and structural consequences within sea conditions, particularly for small craft, which due to their lightweight construction, shallow drafts, and limited structural redundancy are especially vulnerable to repeated slamming events in moderate to rough seas.

One-way fluid-structure interaction (FSI) refers to the phenomenon where fluid flow influences the behavior of a solid structure, while the solid structure has little or no

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influence on the fluid flow. It is a simplified modeling approach that considers a one-way interaction between a fluid and a structure, where the fluid influences the structure but the reverse does not occur. In one-way FSI interactions, the fluid flow is generally modeled by motion or fluid analysis, while the solid structure is modeled using structural analysis methods such as finite element analysis (FEA). This one-way FSI approach is used in engineering applications where the fluid flow has a significant impact on the structure [7].

This study was designed to investigate the structural response of an aluminum speedboat subjected to wave-induced slamming loads. The analysis was carried out in two stages, combining hydrodynamic and structural modeling within a sequential framework. In the first stage, the fluid motion generated by incident waves was evaluated using the Boundary Element Method (BEM). This approach allowed accurate estimation of the wave excitation forces and resulting slamming pressures acting on the hull surface. In the second stage, these hydrodynamic loads were transferred to a structural model of the vessel, developed and analyzed using the Finite Element Method (FEM). Through this coupled procedure, it was possible to capture both the distribution of external pressures and the internal stress–strain response of the structure. The primary aim of the study was to identify how slamming loads influence the stress distribution and deformation characteristics of the hull, with particular attention to the concentration load point of the slamming. By integrating hydrodynamic predictions with structural assessment, the study seeks to evaluate the vulnerability of small aluminum craft under realistic wave conditions and to provide insights that can inform safer and more efficient structural design.

II. METHOD

2.1 Research Framework

In this study, a numerical simulation framework was developed to examine the probability of bottom slamming in small craft. The analysis began with the construction of a detailed hull model using specialized marine design software, referencing the actual principal dimensions and hull form of the aluminum speedboat under investigation. Once the geometry was established, the vessel's motion characteristics were evaluated using computational tools that implement boundary element method to determine the ship's dynamic response to incident waves. Simulations were carried out across a representative range of operating conditions, including different wave heights. From these simulations, motion parameters such as vertical acceleration and relative vertical displacement were extracted and subsequently applied to probabilistic formulations to estimate the likelihood of slamming events.

One of the key strengths of this methodology lies in its use of full-scale vessel geometry rather than simplified models. This ensures that the resulting simulations capture the unique characteristics of small craft, where lightweight structures and compact hull forms amplify motion sensitivity [8]. For aluminum speedboats in particular, the combination of shallow draft and high operating speed makes the hull especially responsive to wave-induced motions, underscoring the importance of modeling based on the actual structural and hydrodynamic form. Another advantage is the efficiency of the numerical approach. By avoiding costly and time-consuming experimental procedures, such as towing tank or sea trial campaigns, the simulation enables systematic analysis across a broad range of operating scenarios in a fraction of the time [9]. This flexibility makes the method highly valuable for early-stage design evaluations and for operational planning in environments where slamming are likely to occur. Finite element method (FEM) utilized as the primary tool for assessing the structural response of the small craft under slamming conditions. Unlike simplified analytical approaches, which often rely on broad assumptions about load distribution and structural behavior, FEM allows the hull and supporting structures to be discretized into smaller elements, each governed by well-defined material properties and boundary conditions. This discretization provides the ability to capture localized stress concentrations, such as those occurring on unsupported plates or at structural joints, which are often the critical points of failure during slamming impacts which assume as the load [10].

Nonetheless, several limitations of the approach should be acknowledged. The absence of experimental validation, such as full-scale trials or model testing, introduces a degree of uncertainty into the predictive accuracy of the simulations, an issue also noted in related slamming studies such as that by Li et al. [4]. such nonlinearities become increasingly important in higher sea states, where impact loads and structural responses deviate significantly from linear assumptions. A further limitation is the reliance on regular wave input rather than irregular, multidirectional sea spectra that more closely replicate real ocean conditions. The study by Jifaturrohman et al.[11]. demonstrated that irregular seas can alter the frequency and severity of slamming events, which implies that the present method may underestimate the variability of operational risk. Lastly, despites the references [12], [13], [14], [15], [16], [17], lack of experimental validation for the structure in FEM analysis shows disadvantages [18], [19].

Despite these limitations, the simulation framework provides a practical and insightful tool for assessing the slamming risk and seakeeping performance of small craft. By identifying trends in motion behavior and estimating probabilistic risks of impact events, the approach contributes meaningfully to the early identification of structural vulnerabilities. Ultimately, the methodology not only aids in evaluating operability but also offers guidance for enhancing the design and safety of aluminum speedboats, ensuring improved resilience against slamming across a wide range of operational conditions.

2.2 Study Objects and Operational Condition

Ship structures are fundamental to maritime transportation, serving to guarantee not only safety but also performance and long-term durability of vessels [20]. Within the field of shipbuilding, particularly for high-performance small craft, two structural material systems are widely utilized: aluminum alloys and sandwich composites. Both materials present unique advantages that align with the requirements of lightweight, high-speed marine applications. Aluminum, in particular, is valued for its favorable strength-to-weight ratio, inherent corrosion resistance, and ease of fabrication, which collectively make it a leading choice in small craft construction [21]. Commonly used marine-grade aluminum alloys, such as 5083 and 6061, offer excellent mechanical performance and weldability, enabling the reduction of structural weight without compromising overall integrity.

The principal dimensions of the small craft analyzed in this study are summarized in Table 1, while the selected material specifications are presented in Table 2. These tables provide the key mechanical properties employed to assess the vessel's structural behavior under wave-induced loading conditions.

TABLE 1.
SMALL CRAFT PRINCIPLE DIMENSIONS

Dimension	Size	Unit
Length	6.041	m
Breadth	2.432	m
Depth	1.795	m

Aluminum is widely applied in small craft construction due to its mechanical efficiency, resistance to seawater corrosion, and ease of fabrication [22]. In this study, aluminum alloy 6061 was selected as the primary material for the hull structure. The principal structural elements consist of the deck, side plating, and bottom plating, each designed with a thickness of 4 mm to maintain an optimal balance between strength and weight. To further reinforce the structure, several stiffening components were incorporated: T-profiles (30 mm wide × 50 mm high), transverse frames (4 mm thick), flat bars (50 mm wide × 5 mm thick), and angle keelsons (60 mm wide × 6 mm thick). These reinforcements collectively improve hull rigidity, enhance load-carrying capacity, and increase resistance to slamming-induced dynamic stresses during operation, as illustrated in Figure 1.

TABLE 2.
ALUMUNIUM MATERIAL PROPERTIES

Properties	Magnitude	Unit
Density	2700	Kg/m3
Young's Modulus	68900	MPa
Ultimate Tensile Strength	165	MPa
Poisson's Ratio	0.33	

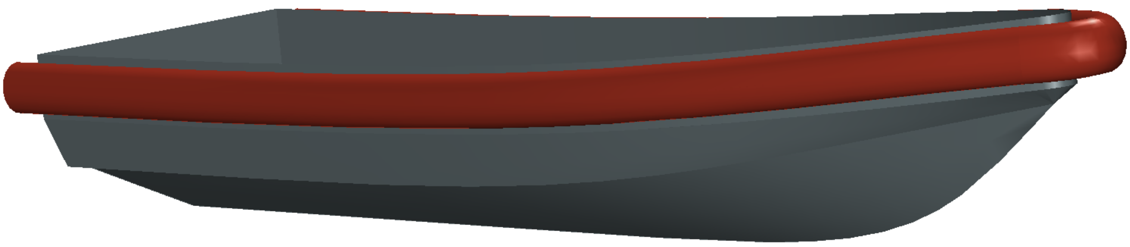


Figure 1. Aluminum Speedboat 3D model

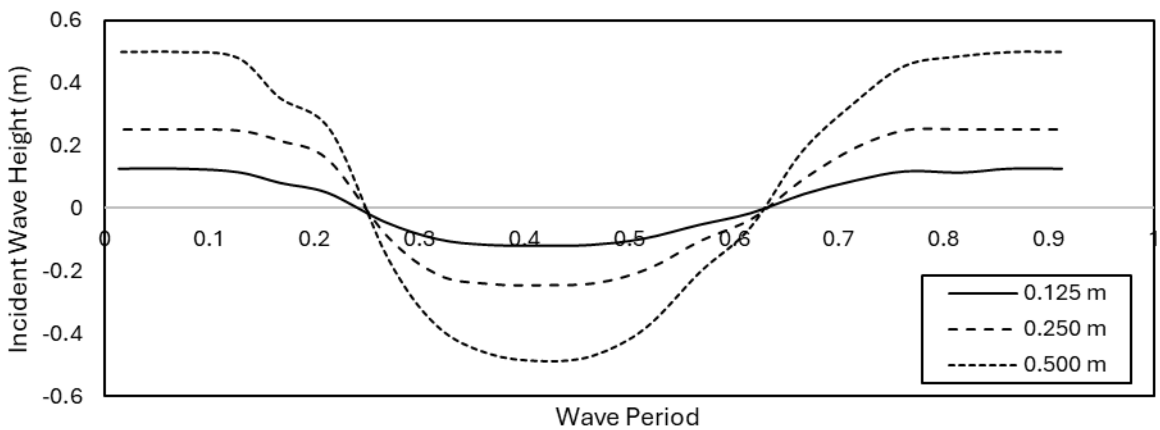


Figure 2. Comparison of each incident wave height

The operational environment of the small craft under study was represented through numerical simulations conducted across a range of wave conditions. The significant wave heights adopted for the analysis are presented in Table 3 and Figure 2. These values were chosen as representative parameters to evaluate how variations in wave height influence the structural response of the vessel, reflecting the conditions that may realistically be encountered within its intended operating area [23].

TABLE 3.
SIGNIFICANT WAVE HEIGHT FOR THE ANALYSIS

Wave Height (m)
0.125
0.250
0.500

2.3 Hydrodynamic Analysis

This study applies two complementary numerical approaches to evaluate the hydrodynamic behavior and structural response of small craft hulls subjected to wave loading: a finite element method (FEM) for structural assessment and a boundary element method (BEM) for hydrodynamic analysis. The BEM model, derived under the framework of potential flow theory, enables efficient estimation of vessel motion responses and wave-induced hydrodynamic forces. In contrast to FEM, which discretizes the entire structural domain and solves the governing partial differential equations internally, BEM reformulates the problem into boundary integrals. This reduces the problem dimensionality, requiring only the wetted hull surface to be discretized. Such a simplification is particularly advantageous in wave–structure interaction problems, as it eases the meshing process and is well-suited for modeling infinite fluid domains like open seas [24]. The motion of the small craft is governed by the interaction between incident wave fields and the submerged geometry of the hull. As the vessel oscillates in response to waves, the wetted surface area changes dynamically, which alters the pressure distribution along the hull and directly influences both its motion characteristics and internal structural loads. For the hydrodynamic model, the flow is assumed to be inviscid, incompressible, and irrotational, leading to the governing Laplace equation for the velocity potential, ϕ, expressed in Eq. (1).

$$\nabla^2 \phi = 0 \tag{1}$$

In Cartesian coordinates (x,y,z), the Laplace equation expands to Eq. (2). The Appropriate boundary conditions are enforced on the free surface, hull boundary, and seabed. For example, at the seabed, a no-flux condition is applied as in Eq. (3).

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} \tag{2}$$

$$\frac{\partial \phi}{\partial z} = 0 \tag{3}$$

The computational setup used in this analysis is illustrated in Figure 3. The domain is defined with an overall length of 10L and a width of 5L, where L denotes the vessel's length. The upstream boundary is placed 2L ahead of the fore perpendicular (FP), while the downstream boundary extends 7L aft of the aft perpendicular (AP). This configuration ensures sufficient spatial allowance for wave development and propagation, minimizing the risk of artificial wave reflections or boundary-induced distortions during the simulation.

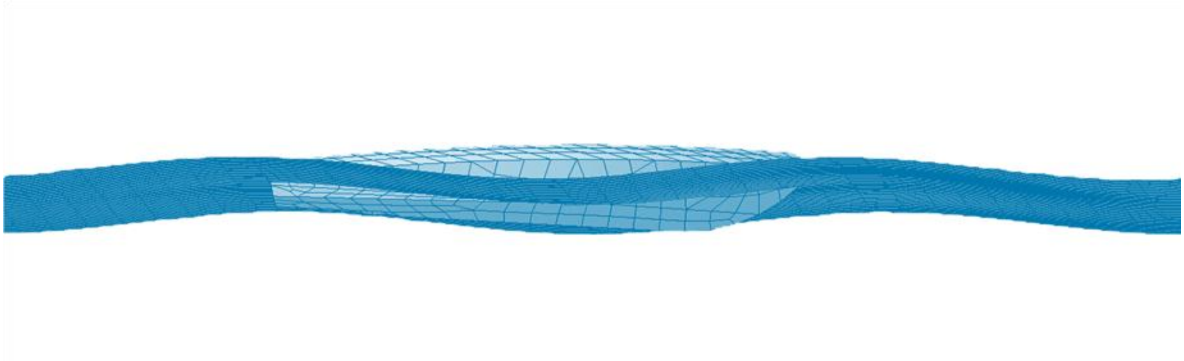
2.4 Structural Response Analysis

Structural behavior can be investigated through two main approaches: numerical and experimental. Experimental methods such as model testing and sea trials provide valuable data, but they are often costly and time consuming. Numerical analysis, by contrast, offers a more practical and efficient means of evaluating structural performance. Numerical methods may involve mathematical modeling, analytical modeling, or the use of empirical formulas. However, purely mathematical approaches rarely yield closed-form solutions in engineering practice, as they still result in highly complex expressions that depend on boundary conditions and material properties. For this reason, numerical modeling techniques, particularly the Finite Element Method (FEM), have become a preferred choice for analyzing complex structural problems with improved accuracy [25]. The fundamental principle of FEM is to represent a structural system as an assembly of smaller, manageable elements, referred to as finite elements, which are interconnected at specific points known as nodes [26].

The Finite Element Method has become one of the most effective computational techniques for studying the structural response of marine vessels under slamming loads. In the context of small craft, where lightweight materials such as aluminum are commonly employed, FEM provides a systematic framework to examine how impulsive, high-magnitude pressures translate into stresses, deformations, and potential modes of structural failure. The application of FEM in slamming studies generally begins with the development of a detailed hull model. The vessel's geometry is discretized into finite elements, with material properties and boundary conditions defined to represent actual construction practices. External loads representative of slamming events is then applied to this structural model, enabling evaluation of both global responses and local responses, including stress concentrations in unsupported plating or deflection in stiffened panels[27].

One of the key strengths of FEM in slamming research is its ability to account for non-uniform load distributions across the wetted surface. Unlike simplified beam or plate theories that assume uniform or idealized loading, FEM can capture the spatial variations typical of real slamming impacts. This makes it possible to evaluate critical regions such as the bow flare, bottom shell, or deck edge with a higher level of detail and accuracy. For small craft, where structural redundancy is limited, such insight is vital since localized failures can quickly compromise the vessel's overall integrity [28], [29], [30]. Furthermore, FEM supports time-dependent simulations, allowing the transient nature of slamming events to be examined in detail. These dynamic analyses capture phenomena such as strain-rate sensitivity, energy absorption, and post-impact vibration responses. This capability is particularly relevant to aluminum hulls, which are prone to fatigue damage when subjected to repeated impact loading cycles. In addition to simulating structural responses, FEM can also be applied to parametric studies, where the influence of design variations such as hull form, material selection, or stiffener arrangement can be systematically explored. This provides designers with a predictive tool not only for diagnosing structural weaknesses but also for guiding improvements. By quantifying stresses, deformations, and potential failure zones, FEM outputs support design optimization strategies, such as adjusting stiffener spacing, reinforcing unsupported areas of plating, or adopting alternative material systems like sandwich composites. In this way, FEM serves both as an analytical method for understanding slamming-induced structural behavior and as a prescriptive tool for enhancing safety, durability, and performance in small craft construction.

(a)



(b)

Figure 3. Hydrodynamic analysis configuration using Boundary Element Method (BEM); (a) Boundary condition, (b) Illustration of wave simulation along the hull

III. Results and Discussion

3.1 Slamming Analysis and Accumulated Load

The load calculation in this study uses a hydrodynamic diffraction approach, which analyzes the effect of regular waves on small craft, particularly in relation to the onset of slamming. Hydrodynamic diffraction refers to the phenomenon where incoming waves are bent or curved around the hull of the vessel, resulting in changes to the wave pattern and the forces acting on the structure [31]. In this stage, regular waves with defined characteristics are generated numerically and used as input for the hydrodynamic analysis. The interaction between these incident waves and the hull of the small craft is then simulated using the Boundary Element Method (BEM). Within this framework, the fluid domain is modelled under potential flow theory, and the governing Laplace equation for velocity potential is solved to capture the wave–structure interaction. This approach enables the calculation of key hydrodynamic properties, including pressure distribution along the wetted hull surface and the resulting forces acting on the vessel [32].

The fluid flow properties obtained from the hydrodynamic analysis, particularly the pressure distribution along the hull surface, are then used to assess the likelihood of slamming. A slamming event is generally identified when pressure peaks exceed a defined threshold and when the resulting impact force acting on the hull is of significant magnitude. Once a slamming occurrence is detected, the corresponding impact forces on the hull are quantified. These include not only the hydrodynamic pressures but also the contributions from added mass effects and other relevant dynamic factors. The load evaluation process involves determining both the magnitude and spatial distribution of these impact forces across the structural components of the vessel. For the wave conditions considered in this study, the calculated maximum loads acting on the small craft structure are summarized in the following table and further summarized in Table 4.

TABLE 4.
LOAD ON EACH WAVE VARIATION

Wave Height (m)	Load (MPa)
0.125	2.28E-03
0.250	4.55E-03
0.500	9.10E-03

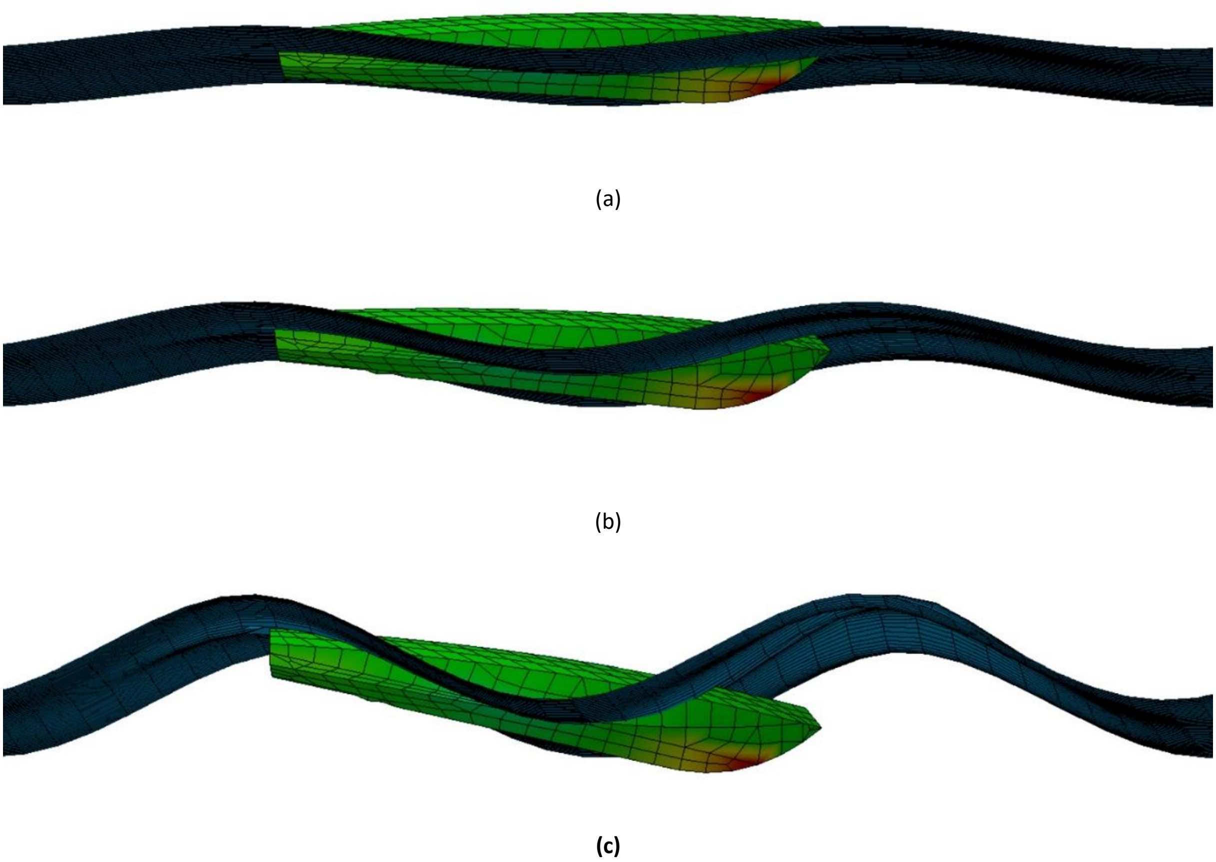
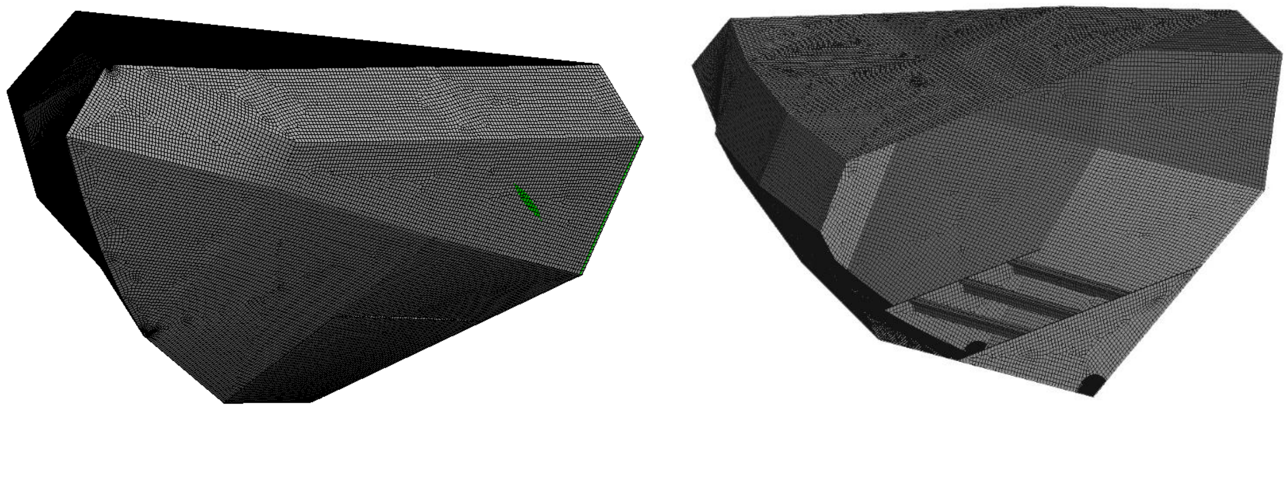


Figure 4. Slamming occurrence on the small-craft encountering the wave on each wave height; (a) 0.125 m, (b) 0.250 m, (c) 0.500 m

Figure 4 illustrates the interaction between the small craft and incident waves of varying heights: (a) 0.125 m, (b) 0.250 m, and (c) 0.500 m. The simulations clearly show the onset and progression of slamming loads as the hull makes repeated contact with the wave surface. At the lowest wave height of 0.125 m (Figure 4a), the hull maintains relatively smooth contact with the wave crest, though localized impact is already visible near the forward bottom plating. Stress concentrations begin to develop in this region, indicating that even mild wave encounters can generate impulsive pressures sufficient to excite structural response. As the wave height increases to 0.250 m (Figure 4b), the hull experiences more pronounced separation and re-entry, leading to higher impact forces. The visualization shows intensified loading around the bow flare region and the forward mid-bottom plating, where the hull geometry directly meets the incoming wave. These areas exhibit concentrated pressure zones, suggesting they are the primary structural positions subjected to repeated slamming. At the largest simulated wave height of 0.500 m (Figure 4c), the effect of slamming becomes most severe. The hull exhibits significant penetration into the wave trough followed by forceful re-entry onto the rising wave crest. This results in widespread pressure distribution, with critical loading observed at the keel line near the bow and extending aft along the forward bottom plating. These regions absorb the brunt of the impact, and the stresses here are expected to be substantially higher than in lower wave conditions. Overall, the visualization demonstrates that the forward bottom structure and bow flare are the most significantly impacted areas under slamming conditions. The severity of loading increases with wave height, confirming that unsupported plating and regions near the bow are particularly vulnerable. These findings emphasize the importance of reinforcing the forward bottom structure with transverse frames or stiffeners and considering alternative materials or configurations to enhance energy absorption during repeated slamming events.

3.2 Slamming Analysis and Accumulated Load

The accuracy of finite element analysis (FEA) is strongly influenced by the number of elements used in the discretization process. In general, a higher number of elements produces more accurate results; however, this improvement comes at the expense of increased computational time and higher processing costs [20]. To address this trade-off, it is common practice to optimize the element size selection, applying finer meshes in regions of interest where stress concentrations are expected such as around structural discontinuities, cutouts, or openings, while using coarser meshes in less critical areas. This approach ensures that computational resources are used efficiently without compromising the reliability of the results. The choice of mesh density is typically guided by prior experience from similar structural analyses, with accuracy being determined by the ability of the finite element model to reproduce convergent and physically consistent solutions [26]. Mesh configuration of this analysis is shown in Figure 5, while the boundary condition is visualized in Figure 6.



(a) (b)

Figure 5. Geometry model of the ship's bow with mesh configuration; (a) Bow viewpoint, (b) Mesh distribution inside the structure

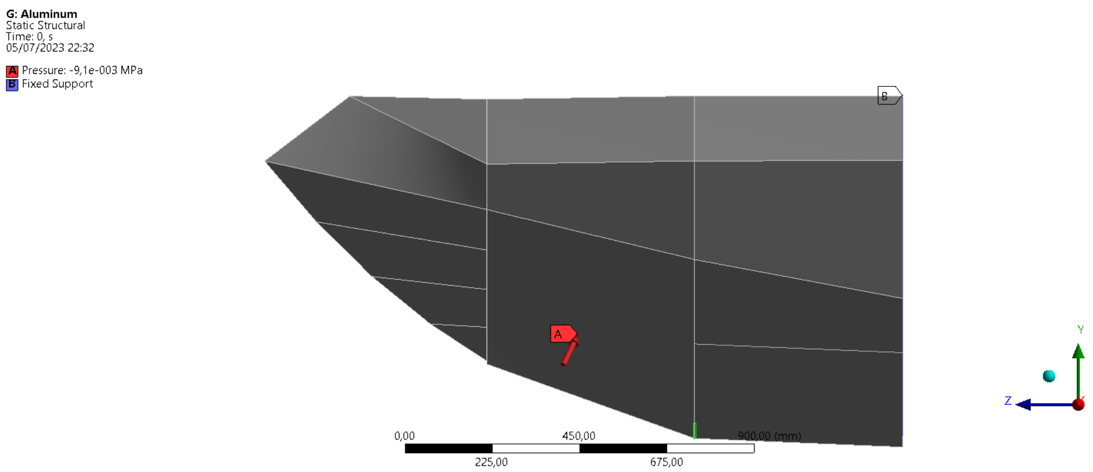


Figure 6. Boundary conditions in finite element analysis

The results of the finite element simulation show the structural response to slamming , illustrated in figure 7-9 for each wave height variation. The simulation results indicate that as the magnitude of slamming loads increases, both stress and deformation at the critical regions of the hull rise significantly. The stress contour plot shows a concentration of equivalent stresses, reaching nearly 19 MPa, on the bottom plating near the bow. These high-stress zones appear in areas not directly supported by transverse frames, highlighting the importance of reinforcement in distributing impact loads. In contrast, regions adjacent to stiffeners show lower stress values, confirming their effectiveness in reducing localized overstressing.

The deformation contour further supports this observation, with maximum displacement of about 0.76 mm forming in a circular pattern on the unsupported bottom plating. This visualization demonstrates that flat plates without sufficient structural support are more susceptible to out-of-plane deflection under impulsive loads. While the deformation remains within acceptable limits for aluminum structures, repeated exposure could accelerate fatigue over time. The combined visualizations provide a clear depiction of how slamming loads are distributed, absorbed, and transferred across the hull structure. Regions of the hull with insufficient reinforcement, particularly unsupported plating, exhibit the highest levels of stress and deformation. By contrast, areas strengthened with transverse frames and stiffeners demonstrate markedly improved resistance to impact loading. This distinction emphasizes the decisive role of structural arrangement in shaping the overall response of the vessel to slamming events. The simulation results summarized in Table 5 further reinforce this conclusion. As slamming intensity increases, both stress and deformation rise proportionally at the critical load locations. Notably, the highest stress and deformation values occur on plate surfaces not supported by transverse framing, confirming their vulnerability under impulsive loading. These findings highlight that beyond the magnitude of the slamming force itself, the structural configuration of the hull including stiffener spacing and transverse reinforcement are significantly governs the severity of the structural response. Therefore, it can be concluded that careful structural design plays a critical role in mitigating slamming effects and enhancing the durability of small craft operating in rough sea conditions.

TABLE 5.
STRUCTURAL RESPONSE TO EACH WAVE VARIATION

Wave Height (m)	Stress (MPa)	Deformation (mm)
0.125	4.7744	0.19
0.250	9.5278	0.38
0.500	19.056	0.76

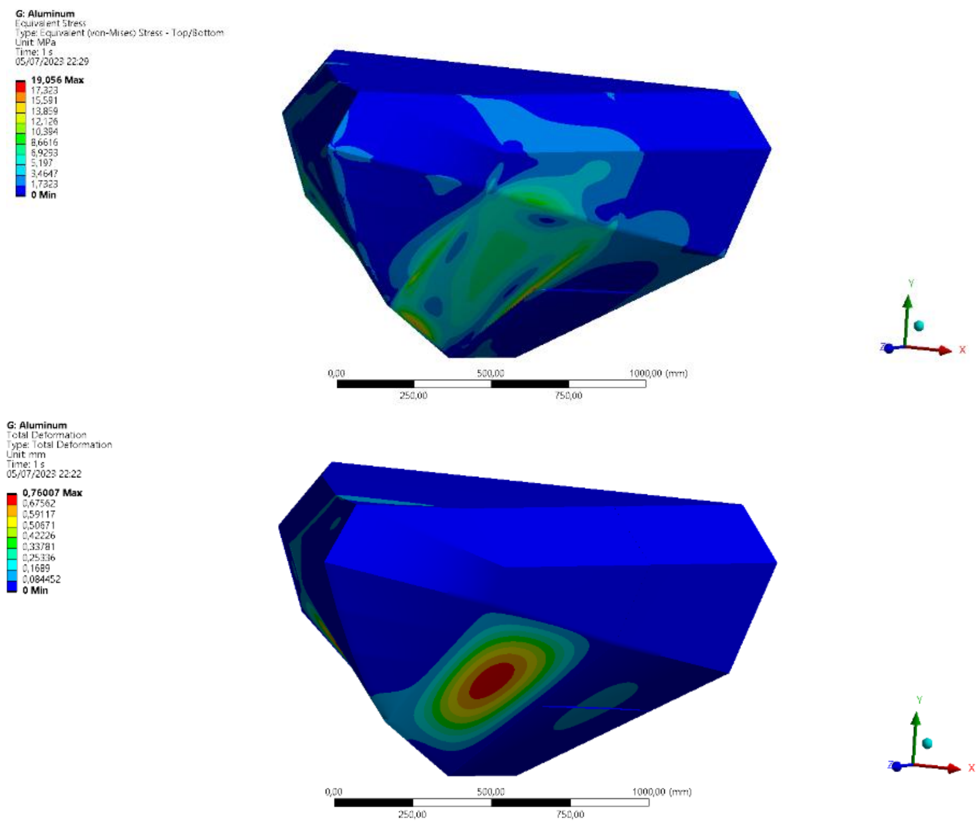


Figure 7. Structural response to a 0.5 m slamming load

IV. CONCLUSION

Slamming is one of the most critical dynamic phenomena affecting small craft, particularly aluminum speedboats, where lightweight construction and high operating speeds make the hull more susceptible to impact loads. Repeated hull–wave impacts can generate significant stresses and deformations, potentially leading to structural fatigue or local failures if not properly addressed in the design stage. Recognizing this, the present study set out to investigate the structural response of an aluminum speedboat under slamming loads using a coupled hydrodynamic–structural approach.

The methodology combined the Boundary Element Method (BEM) to calculate hydrodynamic pressures induced by regular waves and the Finite Element Method (FEM) to analyze the resulting structural response. The hydrodynamic model was based on potential flow theory, solving the Laplace equation with appropriate boundary conditions at the free surface, hull, and seabed. The calculated pressure distributions were then applied as external loads on the structural finite element model of the aluminum hull, which included plating (4 mm thickness) and reinforcements such as T-profiles, transverse frames, flat bars, and angle keelsons.

The simulation results show a clear relationship between slamming load intensity and structural response. As wave height increased from 0.125 m to 0.500 m, the corresponding maximum load values rose from 2.28×10^{-3} MPa to 9.10×10^{-3} MPa. Under these loading conditions, the FEM results revealed that structural stresses increased from 4.77 MPa (at 0.125 m wave height) to 19.06 MPa (at 0.50 m wave height), while deformations grew proportionally from 0.19 mm to 0.76

mm. The visualizations and contour plots confirmed that the highest stresses and deformations were concentrated on bottom plating areas not supported by transverse structures, whereas reinforced regions showed significantly reduced response levels.

From these findings, it can be concluded that both the magnitude of the slamming force and the structural configuration of the hull play decisive roles in determining structural performance. Unsupported plating is the most vulnerable component, while the inclusion of transverse frames and stiffeners effectively reduces stress concentration and deformation. Therefore, optimizing structural design through reinforcement arrangements or the adoption of advanced materials such as sandwich composites can substantially improve the durability and safety of small craft operating in wave conditions where slamming is likely to occur.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to Institut Teknologi Kalimantan (ITK) for providing the facilities and support that made this research possible.

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