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Numerical Analysis of Openings in Stiffeners under Impact Loading: Investigating Structural Response and Failure Behavior

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Abstract
As the demand for lightweight ships continues to rise, there is a growing necessity to explore innovative methods that can reduce the weight of ship structures without altering the materials used. This research addresses this challenge by investigating the effect of opening in stiffener under impact loading. The research aims to provide valuable insights into optimizing weight reduction strategies while ensuring the ship's overall strength and performance remain uncompromised. To achieve this goal, the study employed the finite element method as a solver. By simulating impact scenarios and analyzing stiffener responses, the numerical analysis quantified the structural behavior and failure modes. The focus was on understanding the impact of openings on the structural integrity and how it relates to their positioning relative to the impact point. The results of the study indicate that opening slightly distant from the impact point exhibit greater strength, showcasing a counterintuitive relationship between opening placement and structural response.

1 Introduction

Collision and grounding accidents continue to occur despite continuous efforts to prevent them. With the increasing demand for safety at sea and protection of the environment, it interesting to predict an accident, assess its consequences, and ultimately minimize the damage of an accident to ships and the environment [1,2]. A wide range of issues on collisions and groundings has been subject to extensive investigation [3]. The advancements in technology have significantly contributed to our comprehension of this intricate problem [4]. Notably, research endeavors have yielded valuable and practical outcomes across several domains. For instance, Kumar et al. [5] have demonstrated that the type of stiffener employed plays a crucial role in determining the force-displacement during ship-to-ship collisions. Furthermore, assessing model ship crashworthiness through finite element analysis necessitates the consideration of failure criteria, as highlighted by previous studies [6,7]. Prabowo et al. [8] work has shed light on the influence of the collision angle on model deformation. Lehmann and Peschmannn [9], who considered the energy generated during such incidents also thoroughly examine the impact between ships.

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Nevertheless, evaluating opening in stiffeners under impact loading remains an unexplored aspect that warrants further investigation. The research by [10] delved into the composite stiffened panels made of Glass Fiber Reinforced Polymer (GFRP) examination, particularly those featuring square openings. The study investigated various scenarios, including stiffened panels without openings, those with square openings in their original state, and those with reinforced square openings. The investigation encompassed the analysis of failure loads and failure patterns. Detailed load versus displacement curves were generated for each scenario, considering different loading conditions. In a related study, Liu et al. [11] focused on experimental and numerical analyses to explore the ultimate compressive strength of stiffened panels containing openings. This research aimed to offer practical insights into the influence of large and small openings on the ultimate compressive strength of deck panels found in large passenger ships. The experimental results, showcasing load-displacement and strain, and overall and local structural collapse, aligned well with simulations conducted using the ABAQUS finite element solver. Notably, the outcomes indicated that the unique shape of the opening in the panel and its reinforcements altered the global buckling and collapse behavior of the stiffened panel when subjected to compressive loads. The finite element analysis also discussed how factors like initial imperfections, lateral loads, and different types of openings impacted the ultimate compressive strength of the stiffened panel. While prior studies explored the deformation mechanisms of stiffened plates in marine structures under impact loads [12-14], the evaluation of openings in stiffeners under impact loading remains an aspect that has yet to be thoroughly investigated.

This study investigates the impact of opening on stiffeners and its implications on force-displacement, energy generation, and model deformation. The examination will be conducted using the finite element method to analyze these factors comprehensively. Additionally, a benchmarking study will be undertaken to evaluate the reliability of this research, comparing its findings to actual experimental procedures.

2 Method

2.1 Benchmarking and analysis tools

The benchmarking process in finite element analysis involves comparing various numerical models to evaluate their performance and accuracy in representing a physical system. A benchmark finite element model serves as a dependable and accurate representation of the actual behavior of a structure, having undergone thorough validation through field tests. Furthermore, it is crucial to validate assumptions and approximations made during the finite element formulation, including material properties, boundary conditions, and mesh size. A benchmark is carried out during the initial stage to validate the existing methodology of Finite Element Analysis (FEA) in this study. The laboratory test conducted by Alsos and Amdahl [15] is the reference for comparison, with the obtained data from this study used for evaluation. The test involved a scaled model of a medium-sized tanker structure, which was numerically idealized using ANSYS [16] in FEA. The concept entailed the lateral loading of a plate panel by a rigid indenter until material fracture or failure occurred. The contact point between the plate and the indenter was positioned at the center of the plate, which had dimensions of 720 x 1200 x 5 mm.

The panel part was constructed from the material: the plate, made of steel grade S235JR-EN10025, possessed a yield strength of 285 MPa, a hardening coefficient of 0.24, and a failure strain of 0.35. The conducted experiments took place within the setup depicted in Figure 1. Plate deformation was induced using a hydraulic jack with a maximum capacity of 250 tons. The force and displacements resulting from the indentation were measured directly on the jack's crosshead through the cylinder. Due to the substantial forces involved during testing, it is necessary to consider the potential stretching of the rig. A displacement transducer, securely attached to the ground, was employed to measure the indenter displacement to ensure accurate displacement measurements. All components were subjected to displacement control, applying a loading rate of 10 mm/min. This approach guarantees precise and controlled conditions throughout the testing procedure.

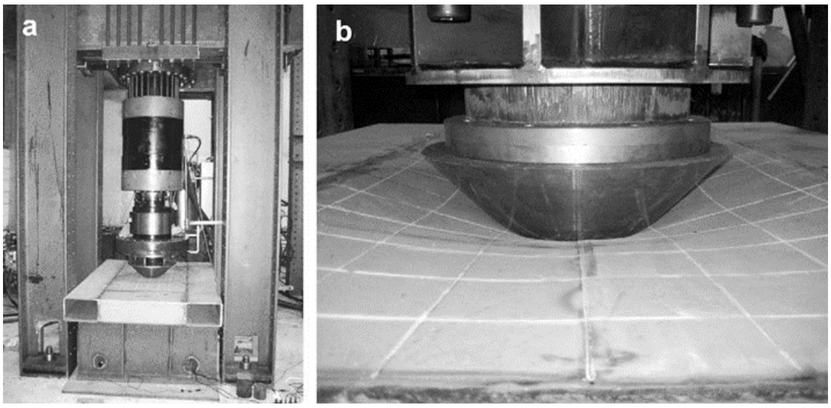


Figure 1. (a) The setup consisting of the rigging, hydraulic jack, and the test component, and (b) The configuration of the indenter-plate arrangement during the indentation process [15]

2.2 Experimental – Numerical validation

The purpose of experimental-numerical validation within the context of the finite element method is to establish the accuracy and reliability of numerical simulations conducted using this powerful computational technique. The finite element method divides complex structures or systems into smaller, manageable elements to approximate their behavior. The numerical results obtained from these simulations are compared against real-world experimental data through experimental-numerical validation. This validation process verifies the model's ability to predict physical behavior accurately, ensuring that the finite element method captures the intricate mechanics and interactions within the system under study. By assessing the agreement between numerical predictions and experimental observations, engineers and researchers can confidently utilize the finite element method for analysis, design, and optimization, leveraging its efficiency while maintaining fidelity to the underlying physical phenomena.

The benchmarking study compare the simulation results using mesh sizes of 15, 20, 25, and 30 with the experimental data obtained. The simulation results show that using a mesh size of 15 gives a displacement of 212.5 mm and a maximum force of 1541.1 kN, while in the experiment, the measured displacement is 200 mm, and the maximum force is 1500 kN. For a mesh size of 20, the resulting displacement is 215.0 mm with a maximum force of 1560.7 kN. In the case of a mesh size of 25, the resulting displacement is 205.0 mm with a maximum force of 1459.9 kN. Finally, a mesh size of 30 produces a displacement of 210.0 mm with a maximum force of 1527.5 kN, Figure 2. Thus, this simulation results give a maximum displacement and force that differ slightly from the experimental data with quite good agreement.

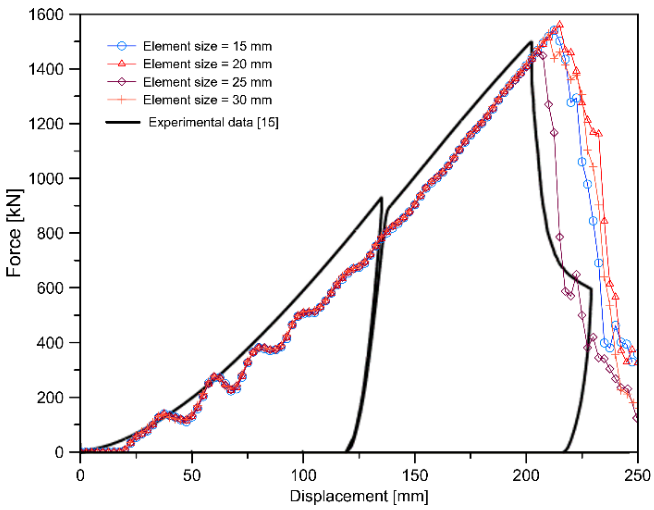


Figure 2. Force – Displacement curve using current finite element analysis

2.3 Extended study

As the demand for lightweight ships continues to rise, there is a growing necessity to explore innovative methods that can reduce the weight of ship structures without altering the materials used. One such approach involves strategically introducing openings like holes into specific sections of the ship's structure, focusing on areas like stiffeners. By implementing openings in a carefully planned manner, significant reductions in weight can be achieved while maintaining structural integrity. However, the effectiveness of this technique depends on factors such as the size, shape, and distribution of these openings. In this study, special attention is dedicated to evaluating the orientation of these openings. By assessing the impact of different opening orientations, the research aims to provide valuable insights into optimizing the weight reduction strategy while ensuring the ship's overall strength and performance remain uncompromised.

The extended study focused on investigating the mechanical behavior of a stiffened plate under the influence of an indenter. The plate, with 720 x 1200 x 5 mm dimensions, featured a contact point positioned precisely at its center. The indenter used in the study had a diameter of 200 mm. Notably, the stiffener on the plate incorporated various openings, one of which was denoted as Opening 1. Located perpendicular to the indenter, the Opening 1 had a radius of 50 mm. To better understand the structural response of the plate, Figures 3 and 4 provided detailed dimensions of the openings and their respective locations. The panel component, fabricated from steel grade S235JR-EN10025, comprises a plate with a yield strength of 285 MPa, a hardening coefficient of 0.24, and a failure strain of 0.35.

2.4 Boundary conditions

In the study, the boundary conditions applied to the stiffened plate played a crucial role in understanding its response to the indenter. All edges of the plate were fixed in terms of both translations and rotations to ensure stability and accurate analysis. This constraint prevented any movement or rotation along the plate's boundaries. The indenter's translations in the *x* and *z* directions, denoted as *Ux* and *Uz*, respectively, were also fixed. However, the indenter’s translation in the *y* direction, *Uy*, was left free, allowing it to move vertically. As for rotations, the indenter was fixed in all three axes, *Rx*, *Ry*, and *Rz*, which restricted any rotation of the indenter during the simulation. A velocity of 5 m/s was assigned to simulate the indenter's downward motion.

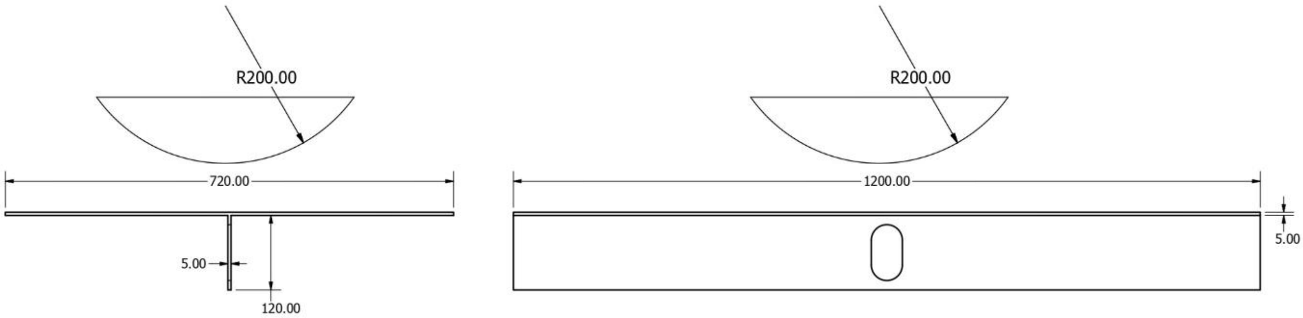


Figure 3. Component arrangements (dimension in mm)

Within the scope of this investigation, a mesh size of 25 mm was chosen for the numerical simulations. The decision to opt for this specific mesh size was guided by a careful consideration of simulation time, aiming to strike a balance between computational efficiency and accuracy. Through extensive analysis, it was determined that the selected mesh size yields result that deviate by approximately 2.7% from the experimental outcomes, which have been comprehensively detailed in Section 2.2 of the study. Figure 5 displays the diagram outlining the progression of the present investigation.

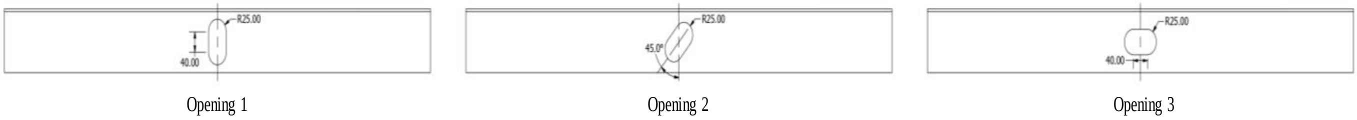


Figure 4. Opening arrangements are located on the stiffener (dimension in mm)

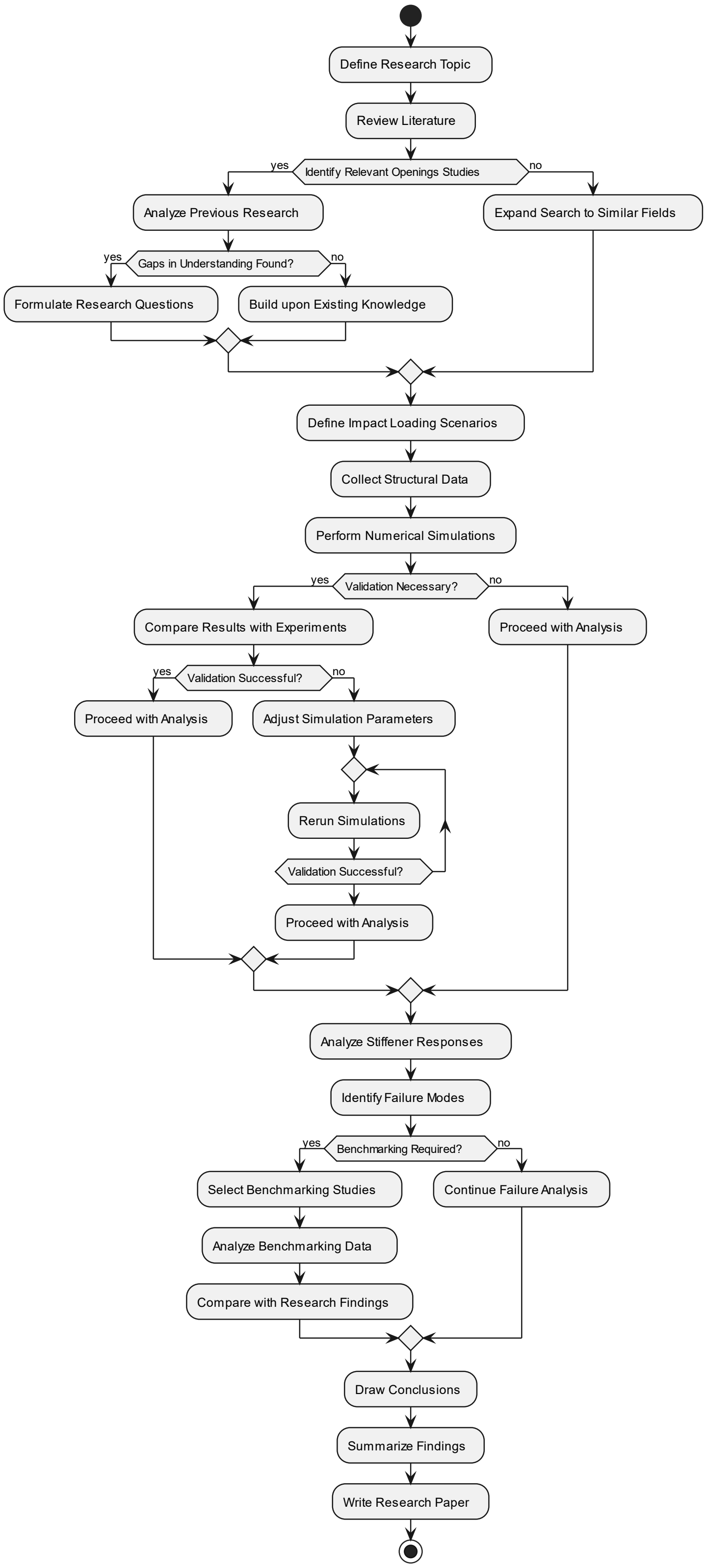
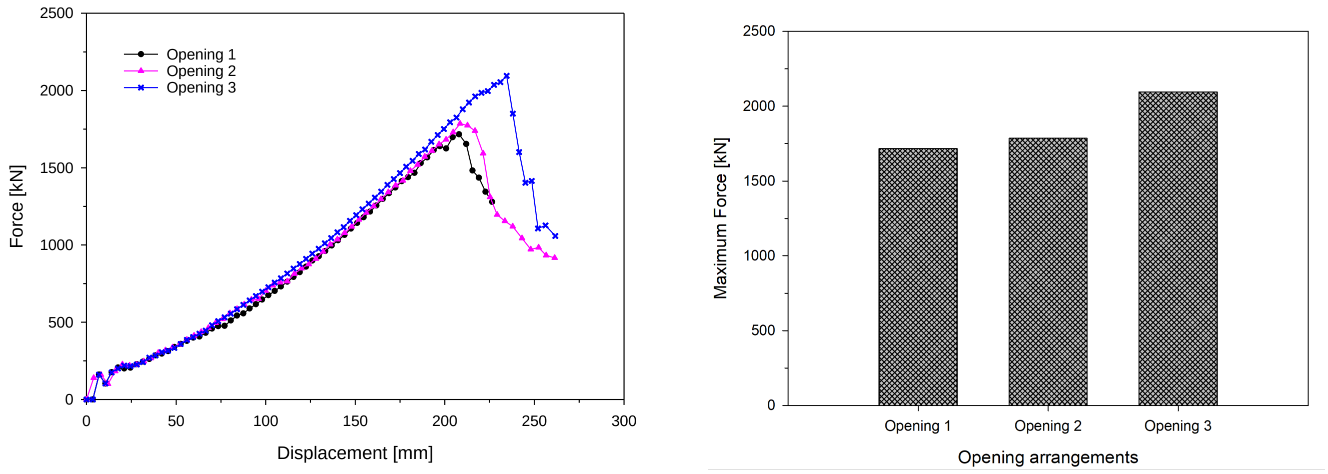


Figure 5. Flowchart in the current study

3 Results

3.1 Force vs displacement

The results obtained from the study provided valuable insights into the behavior of the stiffened plate with different openings under the applied loading conditions. Opening 1 exhibited a displacement at failure of 207.98 mm, accompanied by a maximum force of 1716.2 kN. Comparatively, Opening 2 displayed a slightly higher displacement at failure of 208.55 mm, along with a maximum force of 1785.3 kN. These findings suggest that Opening 2 had a marginally higher resistance to failure compared to Opening 1, as indicated by the increased displacement and maximum force values in Figure 6.



(a) (b)

Figure 6. Force – Displacement curve for Openings 1, 2 and 3: (a) Progressive force, and (b) Maximum force

Moreover, the study also investigated the behavior of Opening 3, which exhibited a larger displacement at failure of 234.5 mm, accompanied by a significantly higher maximum force of 2095.3 kN. It indicates that Opening 3 had a considerably higher resistance to failure compared to both Opening 1 and Opening 2. The larger displacement and maximum force values observed in Opening 3 suggest that it could withstand higher loading conditions before reaching failure, making it more structurally robust than the other openings studied. In order to investigate the influence of different opening configurations on the mechanical performance of the stiffened plate, this study conducts a comparative analysis of various scenarios. The results demonstrate that the presence and size of openings have a significant impact on the plate's failure resistance and force-bearing capacity, which are critical parameters for evaluating structural performance. This information provides valuable insights for engineering applications that require designing and optimizing stiffened structures, as it enables engineers to select appropriate opening configurations that can ensure structural stability and security.

3.2 Generated energy

The total energy generated during the impact loading is presented in Figure 7. Opening 1 generated total energy at the failure of 156.13 kJ, while Opening 2 exhibited a slightly higher total energy at the failure of 162.49 kJ. This comparison suggests that Opening 2 had a slightly higher capacity for energy absorption and dissipation compared to Opening 1, as indicated by the increased total energy value. The total amount of energy that was produced when the load was applied to the structure is shown in Figure 7. The structure had three openings, labeled Opening 1, Opening 2, and Opening 3, that were designed to allow some deformation and reduce the stress concentration. When the structure failed, Opening 1 generated a total energy of 156.13 kJ, while Opening 2 generated a slightly higher total energy of 162.49 kJ. This comparison implies that Opening 2 was more effective in absorbing and dissipating the energy from the load than Opening 1, as evidenced by the higher value of the total energy at the point of failure.

Furthermore, the study also examined the energy dissipation behavior of Opening 3, which generated a significantly higher total energy at failure of 213.46 kJ. It indicates that Opening 3 had a considerably greater ability to absorb and dissipate energy compared to both Opening 1 and Opening 2. The larger total energy value observed in Opening 3 suggests that it could withstand and dissipate higher levels of applied energy before reaching failure, making it more effective in energy absorption and structural robustness.

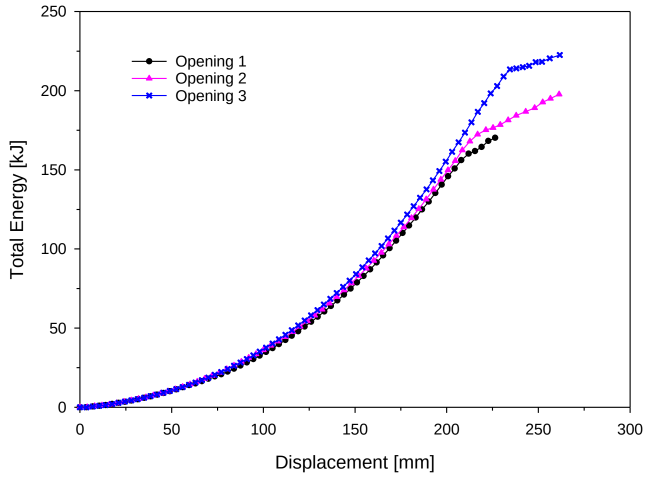


Figure 7. Total energy of Openings 1, 2 and 3

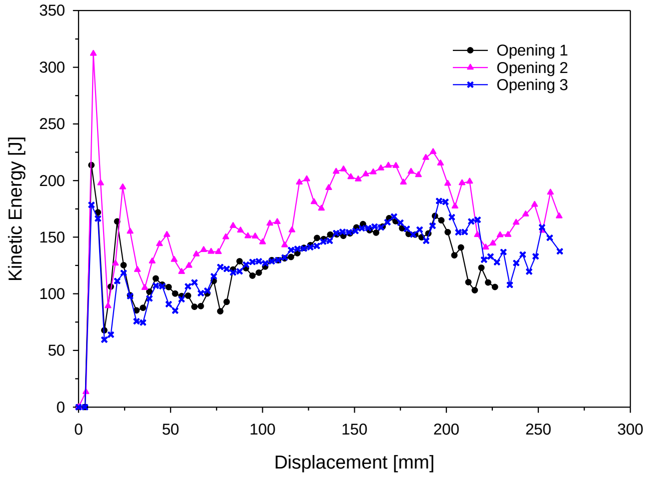


Figure 8. Kinetic energy of Openings 1, 2 and 3

The comparison of kinetic energy at the initial impact between the different openings provides insights into their initial energy absorption capabilities. Opening 1 exhibited an initial kinetic energy of 213.48 J while Opening 2 displayed a higher value of 311.99 J. This higher value suggests that Opening 2 had a greater capacity to absorb and dissipate kinetic energy during the initial impact compared to Opening 1. Interestingly, in accordance with the visual representation presented in Figure 8, it becomes evident that when the impactful event took place, Opening 3 displayed a notably diminished initial kinetic energy value at 178.53 J. This numerical value of initial kinetic energy distinctly contrasts with the corresponding measurements observed for both Opening 1 and Opening 2, both of which exhibited higher levels. The implications drawn from this comparative analysis are significant, pointing towards the deduction that during the initial phase of the loading process, Opening 3 effectively harnessed and subsequently dissipated a considerably lesser of the initial kinetic energy, thereby showcasing a greater capability for energy absorption and dissipation in contrast to its counterparts.

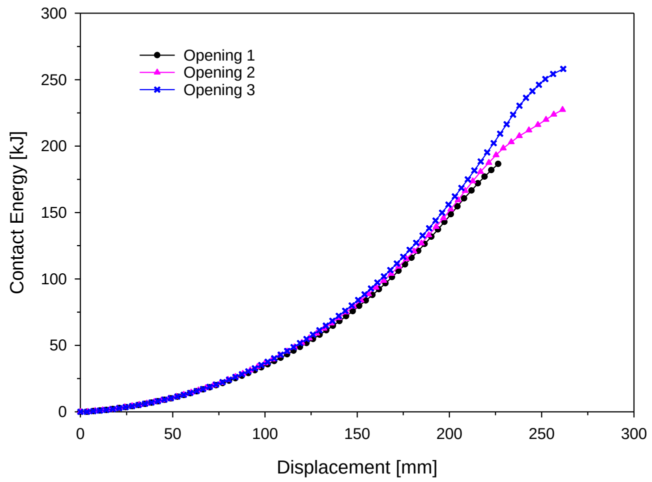


Figure 9. Contact energy of Openings 1, 2 and 3

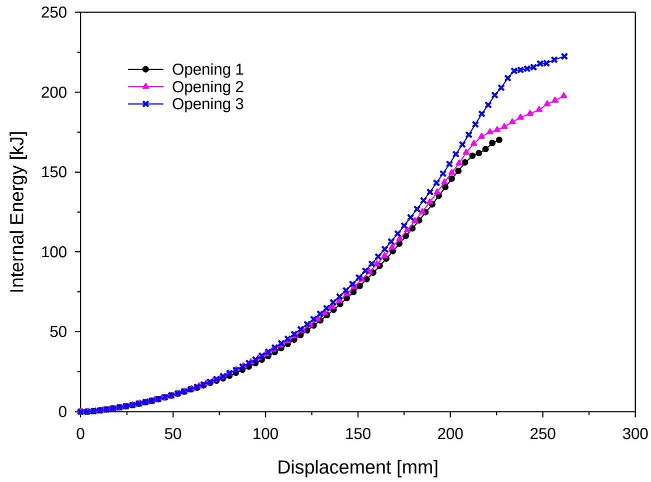
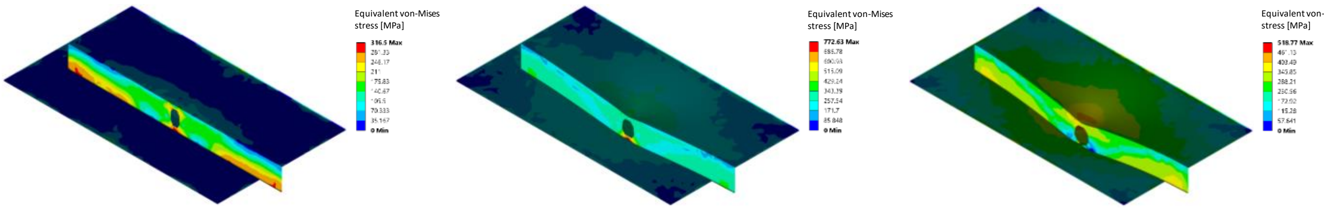


Figure 10. Internal energy of Openings 1, 2 and 3

Figure 9 shows the contact energy, which is the work done on the system by external forces. The contact energy at failure was 160.7 kJ for Opening 1 and 166.43 kJ for Opening 2, indicating slightly higher work done on Opening 2 than on Opening 1. However, Opening 3 had much higher contact energy at the failure of 223.67 kJ, implying a greater resistance to external forces. Figure 10 displays the internal energy of the proposed models. The internal energy at failure was 155.99 kJ for Opening 1 and 162.29 kJ for Opening 2, suggesting a slightly higher.

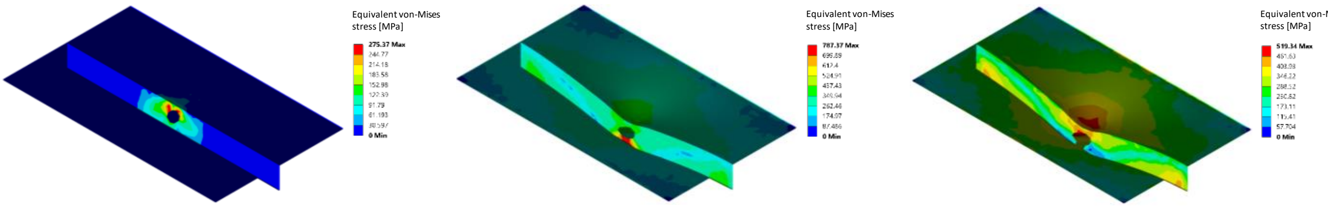
3.3 Deformation

The comprehensive utilization of von-Mises stress analysis stands as an invaluable asset in the assessment and evaluation of the structural integrity exhibited by the stiffened plate under scrutiny, especially when subject to diverse opening configurations. Upon scrutinizing the specifics of Opening 1, the insights garnered from the von-Mises stress analysis unveil a multifaceted understanding of the stress distribution dynamics. During the preliminary stages of loading, precisely at the point of initial impact, the von-Mises stress quantified an imposing value of 316.5 MPa. This substantial numerical figure serves as a direct indicator of the magnitude of stress experienced by the constituent material during the inception of the loading process. This stress, specifically the von-Mises stress at the precise point of structural failure for Opening 1, reached a magnitude of 518.77 MPa. Within the realm of engineering, this critical juncture represents the definitive threshold beyond which the plate succumbed to the overwhelming stress forces, effectively reaching the limit of its sustainable structural integrity. This compelling visualization of the relationship between stress and failure is vividly captured within the illustrative context of Figure 11.



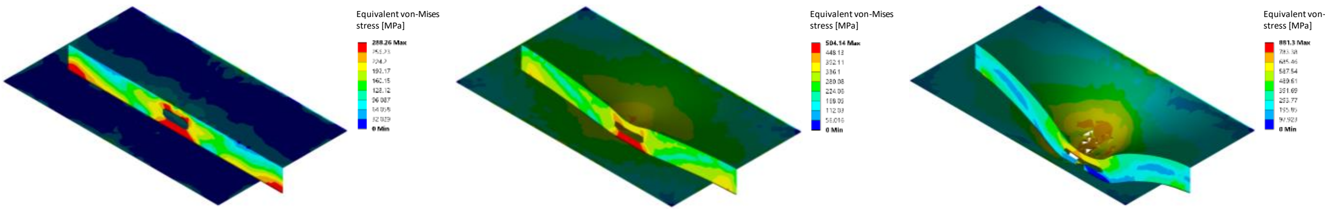
(a) (b) (c)

Figure 11. Equivalent Von – Mises stress for opening 3: (a) Initial impact, (b) 1.15 s, and (c) Failure condition



(a) (b) (c)

Figure 12. Equivalent Von – Mises stress for opening 2: (a) Initial impact, (b) 1.15 s, and (c) Failure condition



(a) (b) (c)

Figure 13. Equivalent Von – Mises stress for opening 1: (a) Initial impact, (b) 1.15 s, and (c) Failure condition

As shown in Figure 12, the von-Mises stress values for Opening 2 indicate the stress distribution and intensity during the impact loading. The von-Mises stress was calculated to be 275.37 MPa at the initial moment of impact, reflecting the high magnitude of stress that was generated at the beginning of the loading. The von-Mises stress increased as the impact loading continued until it reached the failure point, where the plate could no longer withstand the applied load. The von-Mises stress at the failure point for Opening 2 was determined to be 519.34 MPa, signifying the critical level of stress that caused the plate to fail.

For Opening 3, the von-Mises stress at the initial impact was recorded as 288.26 MPa, which indicates the stress level experienced by the material during the initial loading phase. This value is comparable to the other openings, as shown in Figure 13 (a). However, upon reaching failure, the von-Mises stress for Opening 3 increased dramatically to 881.3 MPa, which is much higher than the other openings, as shown in Figure 13 (c). It suggests that Opening 3 underwent significantly higher stress levels before failure compared to the other openings and, therefore, had a lower resistance to fracture. These von-Mises stress values provide insights into the structural response and stress distribution within the stiffened plate under different loading conditions. The findings highlight the varying stress levels experienced by the openings at both the initial impact and failure stages. This information is crucial for engineers to evaluate the structural integrity and design robustness of stiffened plates with different opening configurations.

4 Discussions

This study aimed to examine the impact of the opening model incorporated within the stiffener on the structural behavior under applied loading conditions, using ANSYS finite element analysis. The results revealed that Opening 1 experienced a failure displacement of 207.98 mm and a maximum force of 1716.2 kN, whereas Opening 2 displayed a slightly higher displacement at failure of 208.55 mm and a maximum force of 1785.3 kN. These findings indicate that Opening 2 exhibited a slightly higher resistance to failure compared to Opening 1, as evidenced by the increased displacement and maximum force values (Figure 6). Additionally, the study explored the behavior of Opening 3, which demonstrated a larger displacement at failure of 234.5 mm and a significantly higher maximum force of 2095.3 kN. It indicates that Opening 3 possessed a significantly higher failure resistance compared to both Opening 1 and Opening 2. The presence of stiffeners in the stiffened plates, which are commonly used in ship structures, had a significant impact on their strength [17]. Maximum force and generated energy are typically used as reference data to assess structural strength in ships [18-20].

In the case of Opening 1, a significant concentration of stress was observed specifically at the bottom of the opening, precisely aligned perpendicular to the direction of the impact loading. The von-Mises stress distribution across the structure vividly illustrated this stress concentration, revealing a prominent peak value that centered around 772.63 MPa in Figure 11 (b). The von-Mises stress registers at approximately 787.37 MPa within Opening 2, as shown in Figure 12 (b). Conversely, Opening 3 exhibited a notably different stress distribution pattern, as the concentration of stress appeared to be more evenly spread across the bottom of the opening instead of being localized at a single point around 504.14 MPa in Figure 13. This dispersed stress concentration, while not concentrated in a specific region, still carried the potential to induce failure within that particular area [21], as evidenced by the findings of this study. In addition to the stress concentration effects induced by the openings, it is essential to acknowledge the influence of welding on the joint connecting the stiffener to the plate, as this factor also plays a role in shaping the overall strength and structural behavior of the ship. However, it is worth noting that this particular aspect should have been explored within the scope of the current study. Consequently, this highlights a significant area for future research endeavors, wherein investigations could be conducted to delve into the complexities associated with welding effects and their impact on the strength and performance of ship structures. By addressing these limitations, future studies can provide a more comprehensive understanding of the various factors influencing the structural integrity of ships and help refine design and construction practices in this domain.

5 Conclusions

In conclusion, this study aimed to investigate the mechanical behavior of a stiffened plate with openings when subjected to the influence of an indenter. The results indicate significant variations in failure resistance among the analyzed openings. Particularly, Opening 3 demonstrated notably greater resilience to failure than both Opening 1 and Opening 2. The recorded maximum force values show this distinction (Opening 1 = 1716.2 kN, Opening 2 = 1785.3 kN, Opening 3 = 2095.3 kN). Specifically, Configuration 3 had a 22% higher maximum force than Configuration 1 and a 17.4% higher maximum force than Configuration 2. The analysis of the von-Mises stress distribution further supported these observations, with Opening 1 displaying a localized stress concentration at the bottom of the opening, centered around a peak value of 772.63 MPa. In contrast, Opening 3 demonstrated a different stress distribution pattern, characterized by a more evenly spread concentration of stress across the bottom of the opening. These findings highlight the influence of opening configuration on the structural behavior and failure resistance of stiffened plates. Understanding these effects can contribute to the design and optimization of structures with openings, ensuring enhanced strength and performance in engineering applications.

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