Material and Design Considerations for Improved Buoy Reliability in Wave Energy Converter Systems

ABSTRACT

Wave energy converters are frequently subjected to cyclic fatigue loads, making them prone to structural failure. This study presents a comprehensive design for reliability analysis of buoy structures used in ocean energy converters. A finite element model (FEM) was developed using ABAQUS to evaluate the effects of different materials—linear low-density polyethylene (LLDPE) versus high-density polyethylene (HDPE)—as well as variations in rib spacing and structural thickness under uniform pressure conditions. The analysis considered configurations with 3, 5, and 7 ribs, and wall thicknesses of 0.5, 0.7, and 1 inch. Results indicated that increasing the number of ribs and wall thickness significantly reduces deflection and von Mises stress, enhancing structural stability. HDPE demonstrated superior strength and lower deflection compared to LLDPE, although with reduced ductility. This study provides critical insights into optimizing buoy design parameters to improve the structural performance and durability of wave energy converter buoys, ensuring their reliability and longevity in harsh marine environments.

Keywords: Finite Element Analysis; Buoy; Wave Energy; Structural Integrity; Design Review

1. INTRODUCTION

The escalating demand for renewable energy has positioned wave energy as a promising yet underdeveloped source of sustainable power. Ocean wave energy converters, designed to harness and transform wave energy into electricity, are still in the nascent stages of technical feasibility and commercial availability. Despite this, the potential of wave energy, particularly due to its higher power density and reliability compared to solar and wind energies, underscores the importance of advancing wave energy converters technologies as described by Falcão[1]. With numerous concepts being tested globally, some have reached full-scale trials but still fall short of competitiveness, necessitating extensive research in structural dynamics and material science as mentioned by Drew et al. [2].

Finite Element Analysis (FEA) is a computational tool extensively applied in various engineering fields, particularly for structural and fatigue analysis. In the renewable energy sector, FEA's application has predominantly focused on wind systems, with less emphasis on wave energy devices as highlighted by Jonkman et al [3]. Current research primarily targets mooring systems for wave energy converters, drawing from the established knowledge of offshore structures such as oil platforms and shipbuilding as mentioned by Santos et al. [4]. This gap in research highlights the need for detailed FEA studies on the structural components of WECs to enhance their reliability and operational longevity.

Various wave energy harvesting technologies have been developed, initially designed for supplying power grids (Clément et al.[5]; Cruz [6]; Drew et al. [2]; Falcão [1]; Pelc and Fujita [7]; Thorpe [8]). These concepts are mainly based on the oscillating-water-column (OWC) mechanism or the multi-body structure. The OWC mechanism uses the impact of waves to continuously squeeze the air in a chamber to drive an air turbine, generating electricity. The multi-body structure, on the other hand, relies on the relative motion of rigid bodies. For example, a flap-type wave energy converter utilizes the rising and falling of waves to drive a rotor, as described by Mi et al. [9]. However, for self-powering marine observation buoys, which require long-term operation with maintenance in remote ocean areas, these complex and exposed systems can be challenging due to high maintenance costs and vulnerability to harsh marine conditions.

Recent advancements in wave energy harvesting have focused on developing one-body enclosed wave-powered marine buoys, where the energy harvesting system is integrated within an enclosed buoy structure. These systems utilize various power take-off mechanisms, including triboelectric, piezoelectric, and electromagnetic methods, which offer a more compact and protected design compared to traditional exposed systems. Enclosed designs for wave energy converters have gained attention due to their potential to reduce maintenance needs and improve durability in harsh marine environments. By protecting the energy harvesting components from direct exposure to seawater, these systems can potentially extend the lifespan and reliability of marine buoys. Research on electromagnetic wave energy harvesters, for example, has shown that integrating the power take-off system within the buoy can effectively harness wave energy while minimizing the impact of corrosive seawater and biofouling. Additionally, hybrid systems that combine multiple energy harvesting methods can maximize energy output by capturing both dynamic wave energy and static energy from ambient sources such as solar and thermal energy. Overall, these advancements highlight the shift towards more integrated and enclosed designs for wave energy harvesters, aiming to improve the robustness and efficiency of these systems for long-term deployment in marine environments.

Previous investigations have emphasized the importance of material properties and structural design in extending the lifespan of marine energy devices. Bai and Bai [10] mentioned thatattributes such as tensile strength, elongation at break, and fatigue resistance significantly impact the durability of WEC components. Moreover, advancements in FEA techniques allow for detailed stress distribution analysis and identification of failure mechanisms in complex structures, providing crucial insights for design optimization (Bathe[11]).

This study aims to conduct a comprehensive design for reliability analysis of buoy structures used in ocean energy harvesters, focusing on the optimization of design parameters such as material selection, rib spacing, and structural thickness. Utilizing a finite element model, the study compares the performance of buoys constructed from LDPE and HDPE. The objective is to identify configurations that maximize structural integrity and minimize the risk of plastic deformation and fatigue failure under cyclic loads.

Building on this foundation, our research explores the comparative effectiveness of LDPE and HDPE for buoy construction, alongside the impact of varying rib spacing and structural thickness. By simulating different sea conditions and hydrodynamic forces, the study aims to elucidate the relationships between material properties, design dimensions, and stress distribution. The findings are expected to offer practical guidance for the development of more robust and durable buoy structures, facilitating their integration into the renewable energy infrastructure.

This study not only addresses the current limitations in ocean energy harvester design but also contributes to the broader field of renewable energy by providing a detailed analysis of buoy structural performance under realistic operating conditions. Through the application of FEA and design for reliability principles, the research aims to pave the way for more efficient and reliable wave energy harnessing technologies, supporting the global transition towards sustainable energy sources., proposed solution, a brief literature survey and the scope and justification of the work done.

2. STRUCTURAL COMPONENTS OF WEC

The general arrangement of a bottom-hinged flap-type WEC is illustrated in Figure 1. This system leverages the oscillatory motion induced by cyclic incident waves near the shoreline to generate electrical power. The key components and operational principles of this energy converter involve several stages of energy transformation and mechanical complexity.

At the heart of the system is a large, buoyant flap that is hinged at its bottom to the seabed. This flap is designed to oscillate back and forth in response to the passing waves. As waves impact the flap, they induce an oscillating motion that is critical to the energy conversion process. The hinge mechanism, located at the bottom of the flap, allows it to pivot freely around its base. This hinge is strategically placed to maximize energy capture from the oscillating motion of the waves, and it must be robust enough to withstand the dynamic loads and corrosive marine environment (Falcão [1]; Drew et al. [2]).

Attached to the flap is a shaft that translates the oscillatory motion into rotational motion. A set of clutches is mounted on the seabed, connected to this shaft. These clutches ensure that the energy from the oscillating flap is efficiently transferred to the rotational system, allowing unidirectional rotation regardless of the direction of the flap's movement. This mechanism is crucial for converting the bidirectional wave motion into a more consistent rotational motion suitable for energy generation (Polinder and Scuotto [12]).

The rotational motion generated by the flap shaft is typically low-speed and high-torque. To make it suitable for driving a generator, the rotational speed needs to be increased. This is accomplished using a gearbox, which increases the rotation speed while reducing the torque. The gearbox is a critical component as it directly influences the efficiency and reliability of the energy conversion process. By increasing the rotational speed, the gearbox ensures that the mechanical energy can be effectively used by the generator.

The high-speed rotational output from the gearbox is then used to drive an electrical generator, which converts the mechanical energy into electrical energy. This electricity can be harnessed to supply power directly to the grid. The type of generator used can vary, but it is typically selected based on efficiency, durability, and compatibility with the marine environment. The final stage involves conditioning the generated electricity to ensure it meets the grid requirements. This involves converting the electrical output to a form that is compatible with the grid, including transforming the voltage level and ensuring the frequency of the electricity matches that of the grid (Falcão [1]).

The entire system is designed to operate autonomously and efficiently in the marine environment. The bottom-hinged flap-type WEC capitalizes on the natural energy of ocean waves, offering a renewable and sustainable source of electricity. The effectiveness of this technology depends on the precise engineering and integration of each component, ensuring maximum energy capture and conversion efficiency (Drew et al. [2]).

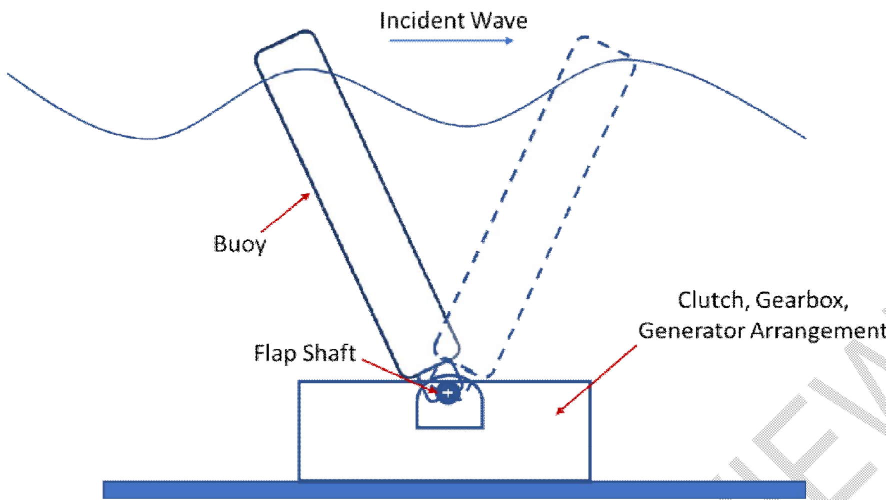


Fig. 1: Sketch of bottom hinged flap type WEC

The structural analysis of buoys or flaps in bottom-hinged flap-type WECs is of paramount importance due to the demanding marine environment in which these devices operate. The oscillating motion induced by waves subjects the structures to cyclic loading, which can lead to fatigue and eventual failure if not properly accounted for. A detailed structural analysis helps in identifying stress concentrations, understanding load distributions, and evaluating the impact of dynamic forces on the components. By optimizing the design through such analyses, engineers can enhance the durability and efficiency of the WECs, ensuring that they can withstand harsh conditions and maintain reliable performance over their operational lifespan (Chakrabarti [13]; Falcão [1]). This approach not only improves the safety and longevity of the devices but also contributes to the economic viability of wave energy as a sustainable power source.

3. FINITE ELEMENT MODEL OF BUOY

FEA using ABAQUS model (ABAQUS Analysis User's Manual, 2014 [14]) was conducted on a buoy structure to examine the effects of rib spacing, buoy wall thickness, and buoy material properties under uniform pressure conditions. To investigate these factors, FEA was performed using three different configurations of rib numbers (3, 5, and 7 ribs) with HDPE materials and buoy wall thickness of 0.7 inch as shown in Figure 2. The analysis was conducted under a uniform pressure of 800 psi. For computational efficiency, only one-fourth of the buoy was analyzed, taking advantage of symmetry. Axisymmetric boundary conditions were applied along the X and Z axes, with the Y-axis serving as the buoy axis as shown in Figure 3. The finite element meshes comprised 8-node linear brick elements with a reduced integration technique as shown in Figure 4.

To account for large displacements, geometric nonlinearity was considered by incorporating an updated Lagrangian formulation (by turning on ‘Nlgeom’). It is important to note that the deformation of the buoy under uniform loading induces severe mesh distortions that can lead to erroneous results. Therefore, the adaptive remeshing technique available in ABAQUS has been employed to periodically minimize the distortions in the mesh. The modified RIKS algorithm was employed to manage unstable behavior, providing equilibrium states during the unstable phases of the load-deflection response as demonstrated by Rahman et al [15]. The modified RIKS algorithm controlled both the pressure and deflection to obtain an equilibrium solution.

For each configuration, the stress history and displacement history were compared. The results demonstrated that increasing the number of ribs led to a gradual decrease in the deflection at the midpoint of the ribs, thereby enhancing the structural stability of the buoy. The initial considered materials for the buoy, HDPE and LDPE, both possess low flexural modulus and high ductility. This makes the structure susceptible to undergo large plastic strain and deformation, emphasizing the importance of parameters such as rib spacing and wall thickness for durability.

These parameters were selected to provide a comprehensive understanding of the structural behavior of the buoy under various loading conditions, ultimately aiming to optimize the design for enhanced reliability and longevity in marine environments.

Table 1: Geometry and material properties used for the simulation

Design Parameters			
Buoy Length (inches)	288		
Buoy Radius (inches)	9		
Wall Thickness (inches)	0.5	0.7	1
Material of Construction	HDPE: Tensile Strength: 3500 psi Flexural Modulus: 160,000 psi Density: 0.0344492 lb/in^3	LDPE: Tensile Strength: 2600 psi Flexural Modulus: 110,000 psi Density: 0.03285 lb/in^3	

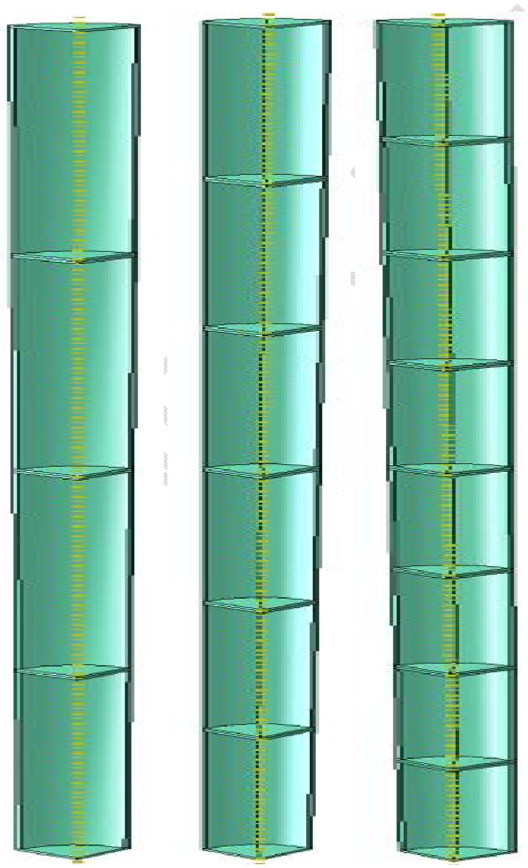
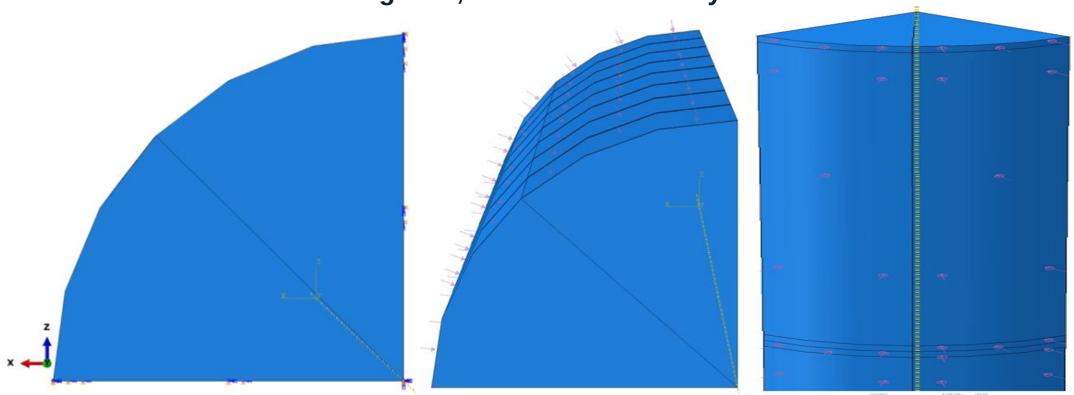


Fig. 2: 3, 5 and 7 ribs in buoy



(a) (b) (C)

Fig. 3: (a) Axis- symmetric boundary condition in X and Z-axis; (b) and (c) shows buoy under uniform pressure

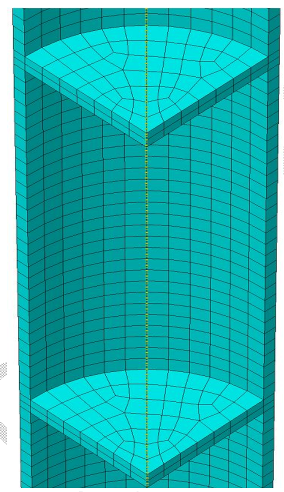


Fig. 4: FE meshes for analyses of buoy

4. SIMULATION RESULTS

4.1. *NUMBER OF RIBS EFFECT*

As the buoy structure undergoes cyclic loads in the marine environment, internal ribs provide critical structural support to prevent the buoy wall from collapsing. The number of internal ribs in a buoy is a key design consideration in preventing structural failure. This study investigates the structural deformation of buoys with different numbers of ribs. The deformed meshes are shown in Figures 5 and Figure 6, illustrating the buoy structure after 50% and 100% pressure increments for buoy configurations with 3, 5, and 7 ribs, respectively. These deformed shapes clearly indicate that as the spacing between ribs decreases, the stress level and deflection of the buoy wall between the ribs also decrease. By looking at the deformed mesh, it is evident that stress concentration occurs at the side walls between two ribs as well as in the walls adjacent to the rib area. The buoy wall section closer to the ribs undergoes a combined loading condition, involving both tension and shear loading. This observation is crucial as areas experiencing combined loading are more susceptible to failure due to the complex stress state. Notably, the shear-dominated failure mechanism in similar engineering materials has been studied by Rahman et al. [16], who explored void clustering and its impact on material integrity. This study aligns with the current findings, highlighting the importance of considering both tensile and shear stresses in the design and analysis of buoy structures to mitigate potential failure points and enhance overall durability.

The von Mises stress developed in the buoy wall is monitored using a scale displayed alongside the deformed shapes. For the configuration with 3 ribs, the stress reaches 3500 psi, which is significantly higher compared to the configurations with 5 ribs and 7 ribs, which exhibit Mises stress levels of 500 psi and 320 psi, respectively. This analysis demonstrates that increasing the number of ribs effectively reduces the stress and deflection, thereby enhancing the structural stability and reliability of the buoy. However, increasing the number of ribs has some setbacks, such as the proportional increase in the weight of the buoy.

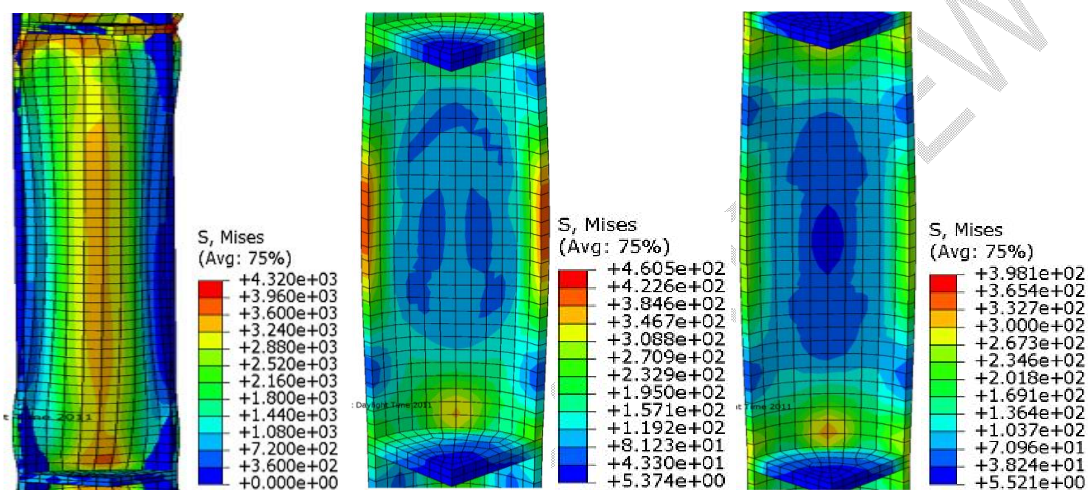


Fig. 5: Deformed mesh at 50% pressure increment for 3, 5 and 7 ribs respectively

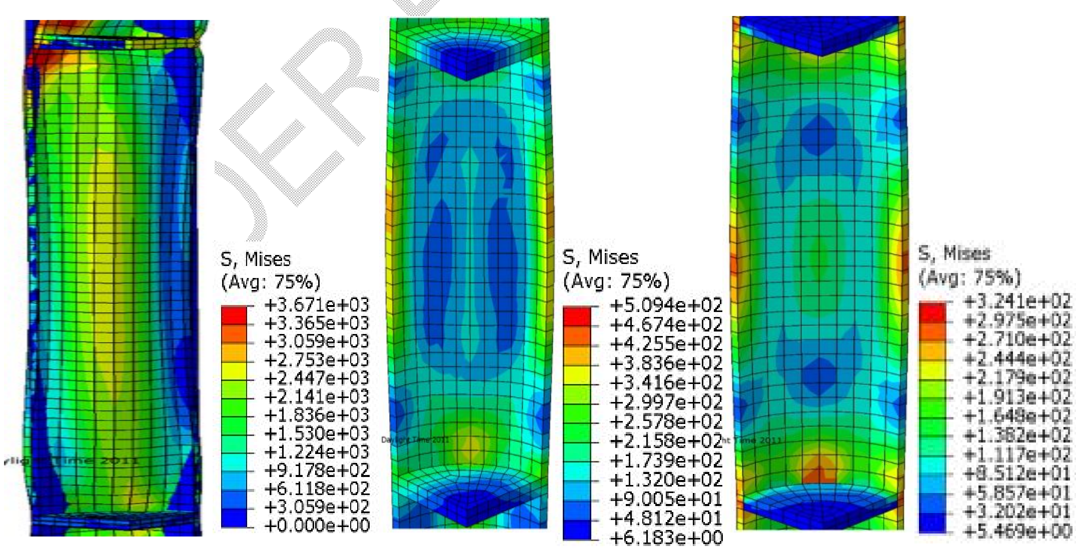


Fig. 6: Deformed mesh at 100% pressure increment for 3, 5 and 7 ribs respectively

In addition to Mises stress, the buoy wall also exhibits significant deflection, which is monitored by measuring the displacement at the midpoint between two ribs. Figure 7 illustrates the midpoint displacement between ribs. The buoy wall with 3 ribs undergoes much larger deflection at the same level of pressure increment. Specifically, the midpoint deflection for the 3-rib configuration is approximately 7.8 inches, while the deflection for the 5-rib and 7-rib configurations is about 3 inches and 1.5 inches, respectively. These results indicate that increasing the number of ribs significantly reduces the deflection of the buoy wall, thereby contributing to the overall structural stability and reliability of the buoy under cyclic loads.

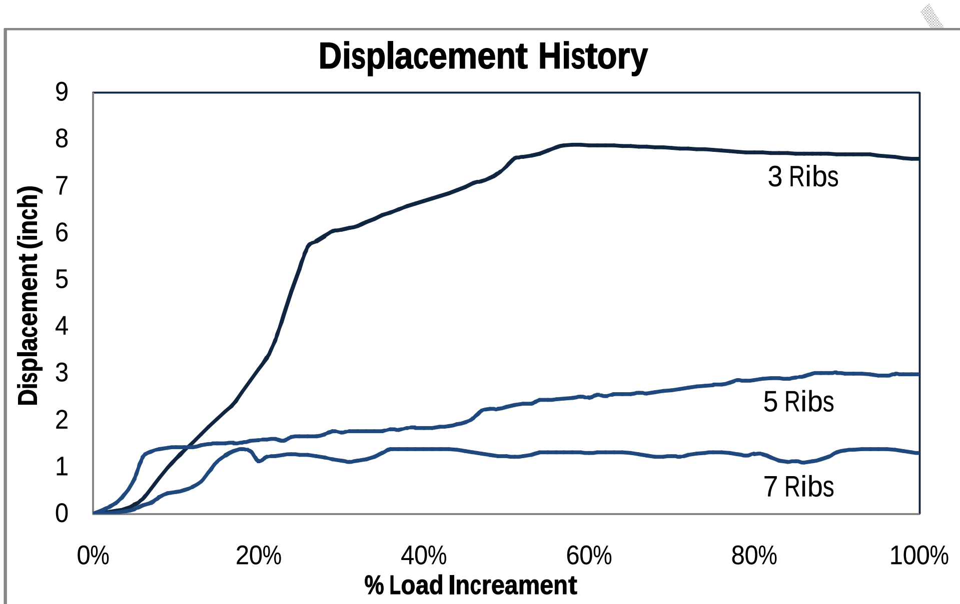


Fig. 7: Displacement of buoy midpoint between ribs with 3, 5 and 7 ribs

4.2. *THICKNESS EFFECT*

This study investigates the effect of wall thickness on the stress distribution within an HDPE buoy with 3 ribs configuration using FEA. Three different wall thicknesses—1 inch, 0.7 inches, and 0.5 inches—were examined to determine their influence on the developed stress and structural integrity of the buoy. The buoys were subjected to identical loading conditions, representing typical operational pressures. The analysis focused on identifying the point of maximum stress and plotting the corresponding von Mises stress for each wall thickness. The deformed mesh and stress distribution patterns were analyzed to assess the performance of each configuration. The FEA results indicated that the maximum stress points were consistently located at critical nodes of the buoy structure, as shown in Figure 8. The von Mises stress plots for different wall thicknesses revealed significant variations in the stress levels sustained by the buoy. For a wall thickness of 1 inch, the buoy demonstrated a superior ability to withstand higher pressures without failure, as evidenced by the lower von Mises stress levels compared to the thinner walls. Conversely, buoys with wall thicknesses of 0.7 inches and 0.5 inches experienced rapid failure under the same loading conditions, with significantly higher stress concentrations. Higher stress concentrations are critical in the design and analysis of marine structures. These concentrations often occur at points of geometric discontinuity or where material properties change. Understanding these stress concentrations is vital for predicting potential failure points and improving design robustness (Pilkey and Pilkey [17]).

The analysis highlighted the crucial role of wall thickness in enhancing the structural integrity and load-bearing capacity of buoys. Thicker walls distributed the applied loads more effectively, reducing the risk of localized stress concentrations and subsequent wall failure. This is particularly important for applications involving cyclic loading, where the structural integrity of the buoy must be maintained over prolonged periods (Potter and Jones, 2005).

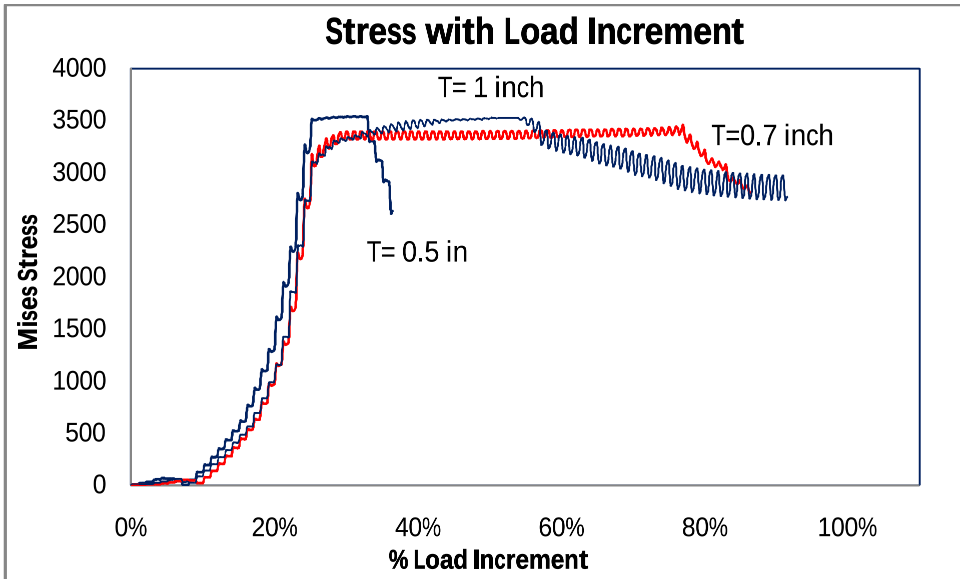


Fig. 8: Stress history of node at which maximum stress developed in the structure for different thickness of 3 ribs buoy.

While thicker walls provide enhanced structural stability and resistance to stress, they also introduce additional weight to the buoy. This added weight can impact the buoy's overall performance, including its buoyancy and ease of deployment. Therefore, achieving an optimal balance between wall thickness and buoy weight is essential for ensuring both reliability and functionality. To optimize buoy design will ensure that the buoy can withstand the cyclic loads encountered in marine environments without compromising its performance or longevity.

The FEA analysis buoys with varying wall thicknesses demonstrated that increased wall thickness significantly enhances the structural integrity and load-bearing capacity of the buoy. However, this comes at the cost of added weight, necessitating a careful balance to achieve optimal performance. Future research should focus on developing advanced material composites and design strategies to further improve the efficiency and reliability of buoy structures under diverse operational conditions.

To further observe the effect of buoy wall thickness, the displacement of the node at the midpoint between two ribs, which undergoes maximum displacement, was plotted. Figure 9 clearly demonstrates that the maximum deflection of the thicker wall is lower than that of the thinner wall under the same pressure. Additionally, structural instabilities are evident in the buoy with a wall thickness of 0.5 inches. The finite element deformed mesh also illustrates the relative displacements of the buoy wall, as shown in Figure 10. These results indicate that increasing the wall thickness not only reduces maximum deflection but also enhances the overall structural stability of the buoy.

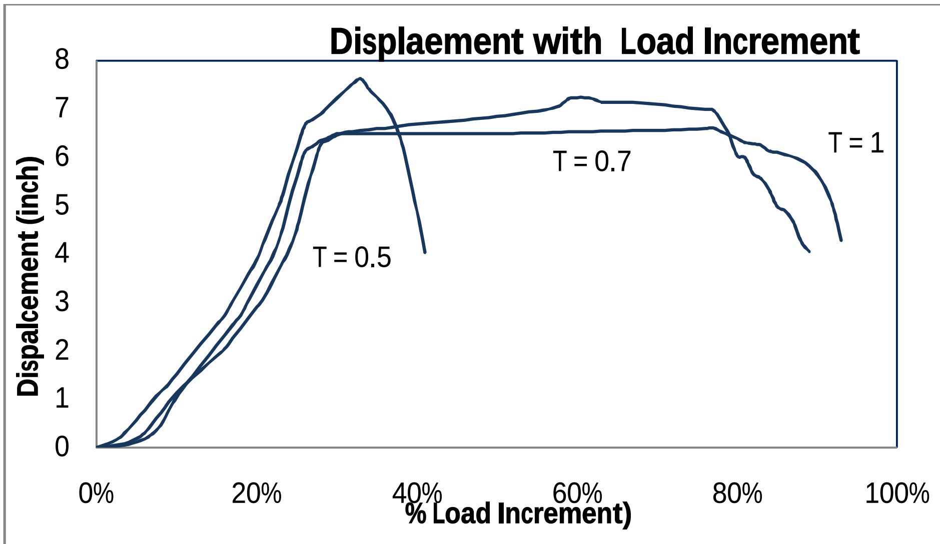


Fig. 9: Displacement history of midpoint between two ribs using 3 ribs buoy with different thickness

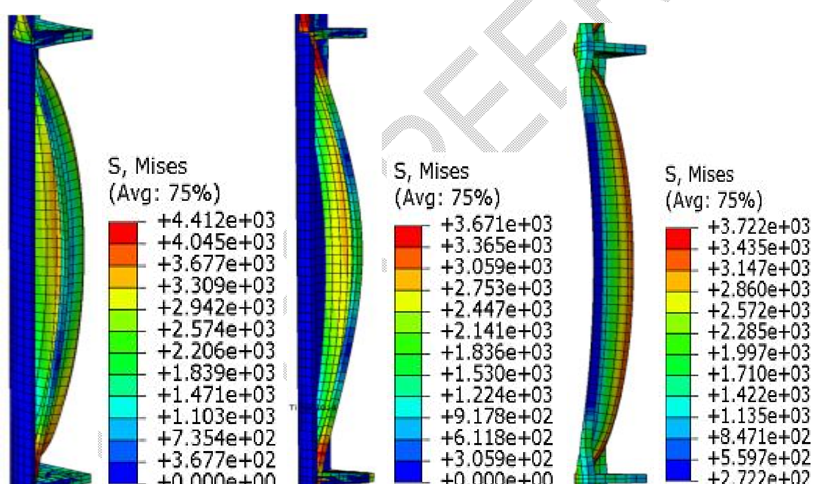


Fig. 10: Displacements between two ribs for buoy wall thickness of 0.5, 0.7 and 1 inches respectively

4.3. *MATERIALS OF CONSTRUCTION*

HDPE is widely favored in buoy construction due to its exceptional mechanical properties, which include a high strength-to-weight ratio and resistance to degradation in marine environments. These attributes make HDPE a reliable choice for applications where buoyancy and durability are critical. However, understanding the impact of material properties on buoy performance is essential for optimizing design and ensuring structural integrity. This study investigates the effect of material properties on stress distribution within buoys using FEA, providing valuable insights into buoy behavior under varying conditions.

The mechanical properties of HDPE and LDPE play a crucial role in determining buoy performance. LDPE, with a tensile strength of 2600 psi and a flexural modulus of 112,000 psi, offers respectable mechanical characteristics suitable for buoy construction. In contrast, HDPE boasts a higher tensile strength of 3500 psi and a flexural modulus of 160,000 psi, indicating superior strength and stiffness. However, it is important to note that HDPE exhibits lower ductility compared to LDPE, as evidenced by maximum strain values of 0.024 and 0.027, respectively, when utilized as buoy materials. These differences in material properties influence how buoys respond to external loads and environmental conditions, underscoring the significance of material selection in buoy design and performance optimization.

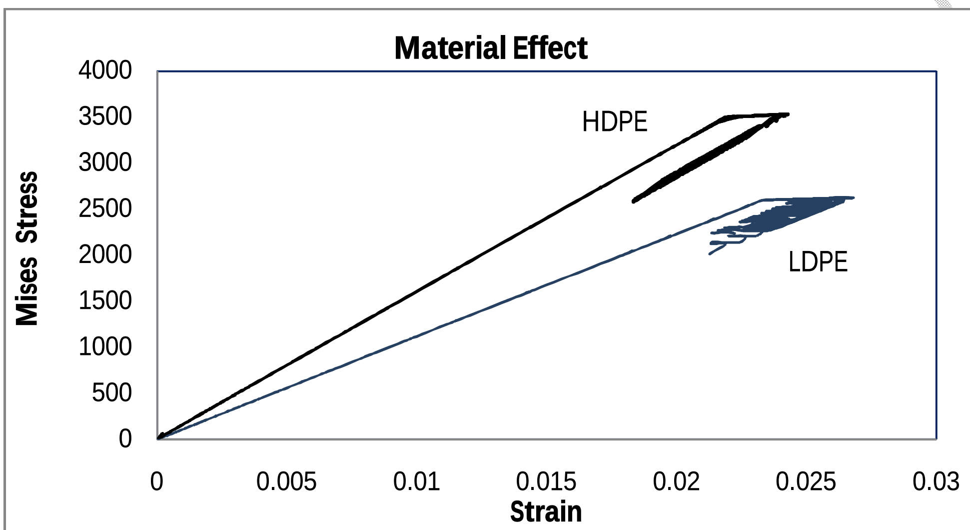


Fig. 11: Stress-strain curve for 3 ribs buoy using LLDPE and HDPE material.

Through detailed analysis, this study aims to elucidate the relationship between material properties and stress distribution within buoys, providing valuable insights for enhancing buoy performance and longevity in marine environments. Comparing the two materials, HDPE exhibited greater strength, but lower ductility compared to LDPE. As shown in Figure 12, the maximum deflection at the midpoint between the ribs was higher for the buoy made of LDPE material (7.45 inches) compared to the one made of HDPE material (7.21 inches). This finding highlight that while HDPE offers greater strength, its lower ductility may influence the overall performance and durability of the buoy under cyclic loads, but with thickness over 0.7 inches can compensate for that.

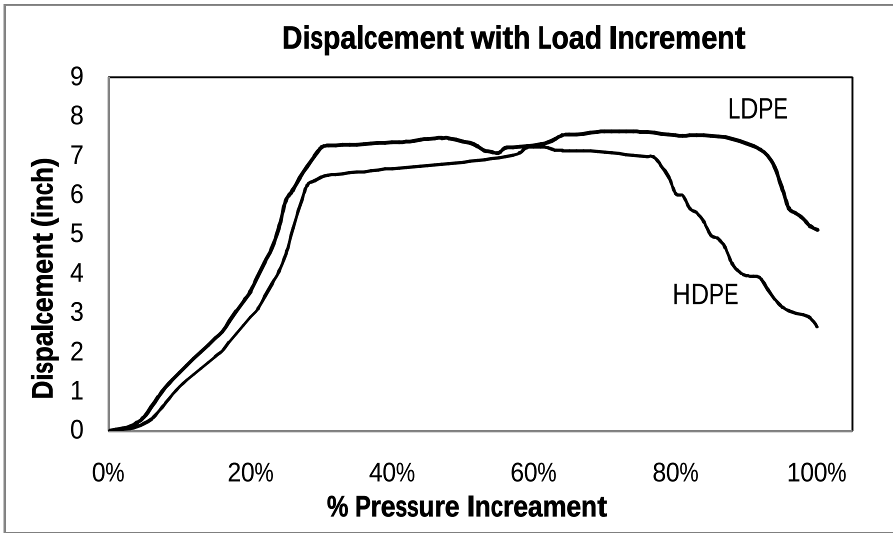


Fig. 12: Displacement history of midpoint between the ribs for 3 ribs buoy using two different materials.

The analysis highlighted the crucial role of wall thickness and material properties in enhancing the structural integrity and load-bearing capacity of buoys. Thicker walls (> 0.7 inches) and stronger materials (HDPE) distributed the applied loads more effectively, reducing the risk of localized stress concentrations and subsequent material failure. This is particularly important for applications involving cyclic loading, where the structural integrity of the buoy must be maintained over prolonged periods.

5. CONCLUSIONS

The analysis demonstrates that the buoy wall exhibits substantial deflection under uniform pressure, making deflection monitoring crucial for assessing structural integrity. This investigation highlights the significant influence of rib spacing, wall thickness, and material properties on deflection and applied stress within the structure. Increasing the number of ribs and wall thickness effectively reduces the deflection of the buoy wall. Specifically, configurations with more ribs (e.g., 5 or 7 ribs) show significantly lower von Mises stress and smaller deflections compared to those with fewer ribs (e.g., 3 ribs). Thicker buoy walls also enhance load-bearing capacity and reduce deflection under pressure, with a 1-inch and 0.7-inch wall performing better than a 0.5-inch wall. HDPE demonstrates superior strength and lower deflection compared to LDPE, though its lower ductility suggests a trade-off in flexibility and impact resistance.

This analysis focuses on the relative effects of rib spacing, wall thickness, and material properties on the buoy. Quantitative assessments can be obtained by varying geometry, loading conditions, and employing finer mesh resolutions for more accurate results. The findings emphasize the necessity of optimizing rib spacing and wall thickness to enhance structural integrity and reliability. Selecting the appropriate material, such as HDPE for its strength and lower deflection, is vital for constructing durable buoys. Designers must balance material properties with specific operational requirements, considering the trade-offs between strength, flexibility, and impact resistance. A thorough analysis of loading conditions is necessary to predict and mitigate potential structural failures, including considering various load types and magnitudes to understand their impact on buoy performance.

Future research should investigate composite materials or hybrid designs that combine the strengths of HDPE and LDPE for improved performance characteristics. Detailed field tests and simulations under varied loading conditions will provide deeper insights into the long-term performance and durability of buoy designs. Employing finer mesh resolutions in FEA can lead to more accurate and reliable results, enhancing the understanding of stress distribution and deflection patterns. By optimizing these parameters and thoroughly analyzing loading conditions, it is possible to develop buoy structures that are resilient, durable, and reliable for deployment in various marine environments. Further research and development in these areas will contribute to the advancement of buoy design, ensuring enhanced structural performance and reliability.

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