Design and Analysis of Support System for the Medieval Newport Ship by Using High Density Polyethylene material

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Abstract

This research focuses on the design and structural analysis of a support system for the preservation of the Medieval Newport Ship. The support system is critical for ensuring the long-term preservation and structural integrity of this significant historical artifact. The support structure was modelled using SolidWorks, while the structural analysis was conducted in Ansys. High-Density Polyethylene (HDPE) was selected as the primary material, and various section profiles were analysed to evaluate its suitability for this application. The performance of the HDPE support system was assessed based on deflection and Von Mises stress criteria, ensuring that the material could withstand the load conditions

Key words:

Structural integrity, Historical artifact, SolidWorks, Ansys, High-Density Polyethylene (HDPE), Section profiles, Deflection, Von Mises stress, Structural analysis

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Declaration

I herby declare that

The research presented in this dissertation, titled “Design and Analysis of a Support System for the Medieval Newport Ship Using High-Density Polyethylene Material,” has been conducted by me under the supervision of Xiaojun Yin. All content, information, and data derived from external sources whether books, journals, documents, websites, or personal communications used directly or indirectly in the form of quotes, summaries, or references, have been properly acknowledged and documented throughout this work.

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1 INTRODUCTION

The Newport medieval ship which has been discovered is one of the most preserved vessels because it was covered with sediments and very little amount of oxygen was able to reach to the timber . It was built in 1450 in Spain and after 20 years it was left abandoned in River Usk in the southern edge of Newport City when it was undergoing for repairs. After its discovery in 2002, many archeological investigations of its timbers and associated artefacts have told about ship technology in its time. This ship had estimated capacity of 160 tons. Therefore, it was considered one of the large ships of that time.(3)

The discovery of a ship During Construction of the Arts Centre on the Right Bank of the River Usk highlights the connections between the western seaboard, the Mediterranean, and France. The clinker-built hull, found in Spain, suggests Spanish origin due to its construction style. This ship likely transported goods such as olive oil and wine from Spain to Britain and exported commodities like clothing and iron to the Iberian region. The ship's remains, uncovered during excavation, included framing timbers fastened to oak planks with iron nails, confirming it as a vessel. The ruins in the excavation area are surrounded by slabs measuring 22.5 meters long and 7.65 meters wide.(4)

Displaying the Newport Ship is essential because it represents a significant piece of cultural and historical heritage, offering a unique glimpse into medieval shipbuilding and trade. By putting the ship on display, it will not only preserve this rare artifact but also make it accessible to the public, providing an invaluable educational resource for historians, students, and visitors. The ship serves as a powerful connection to the past, fostering a deeper understanding of the region's maritime history. Moreover, exhibiting the Newport Ship can boost local tourism, bringing economic benefits to the area and enhancing community pride. It also ensures that the ship is maintained and conserved in optimal conditions, securing its preservation for future generations.

This research will analyse that whether the support cradle for the Newport Medieval Ship made of High Density Polyethylene is possible or not. The project faces several conflicting objectives; on one hand, it is crucial to design a cradle that minimizes interference with the ship's structure to allow the public to fully appreciate the hull's form and dimensions. At the same time, the design must also create an engaging display that draws and holds the attention of visitors.

2 DEGRADATION AND CONSERVATION OF WATERLOGGED ARCHAEOLOGICAL WOOD

Archaeological wood is characterized as old wood that shows signs of human workmanship, while the term "waterlogged" refers to a condition in which all pore spaces, such as capillaries and microcapillaries, are completely saturated with water.(5)

While these waterlogged wooden artifacts may retain their visual appearance and structural form, the wood itself is significantly deteriorated. The saturation with water, coupled with the absence of oxygen, inhibits fungal growth, which would typically accelerate decay. However, this environment still leaves the wood vulnerable to bacterial degradation and chemical breakdown, both of which can severely compromise the wood's strength and integrity. Conservation efforts are therefore important to ensure the stability of the wood, to prevent it from collapsing during drying and to maintain its strength. However, many of the methods used to collect the history were surprising and highlight the difficulties inherent in preserving sensitive information over time.

The preservation of waterlogged archaeological wood is essentially a reactive process, requiring intervention due to the degradation of the wood. In many contexts, this approach could be seen as a form of continuous crisis management, as the material remains at high risk of being lost without substantial intervention to counteract the harmful effects of prolonged submersion in a marine environment . Upon recovery, waterlogged artifacts must be kept wet to prevent further degradation, yet indefinite wet storage is not a viable long-term solution. Such an approach merely preserves the current state of the wood, leading to increased long-term expenses, ongoing risks, and the potential for catastrophic failure as the material continues to degrade.

Extensive research over several decades into reburial and in situ preservation offers promise as potential future storage solutions, as these methods aim to recreate the stable, low-oxygen conditions that initially preserved the wood.(6)

However, these techniques do not guarantee the long-term stability of the numerous artifacts that have been uncovered, and the associated costs of continuous monitoring are not eliminated merely because the artifact is no longer visible. Although an anaerobic burial environment may slow the rate of deterioration, it does not completely halt the process, meaning that the wood remains at risk of further degradation over time.

In the natural environment, wood deterioration is affected by a variety of abiotic and biotic factors, including ultraviolet radiation, temperature and humidity changes, wind, precipitation, and the activity of fungi, diseases, and insects (5). These factors combine to accelerate the decomposition of wood. However, in a waterlogged environment, the effect of these decomposers is reduced, which causes the decay process and allows wood to be preserved for hundreds or even thousands of years (Figure 2, left).

Despite this, microbiological factors affect the degradation of waterlogged wood. Typically embedded within bottom sediments that restrict oxygen availability, waterlogged artifacts are protected from fungal proliferation. However, certain bacteria can persist in these low-oxygen conditions, leading to wood deterioration primarily caused by erosion bacteria. Although the affected wood may appear intact externally, it often becomes spongy in texture as the decay process progresses slowly, beginning at the surface and gradually penetrating deeper until the cellulose is entirely consumed.(Figure 1,right) (2)

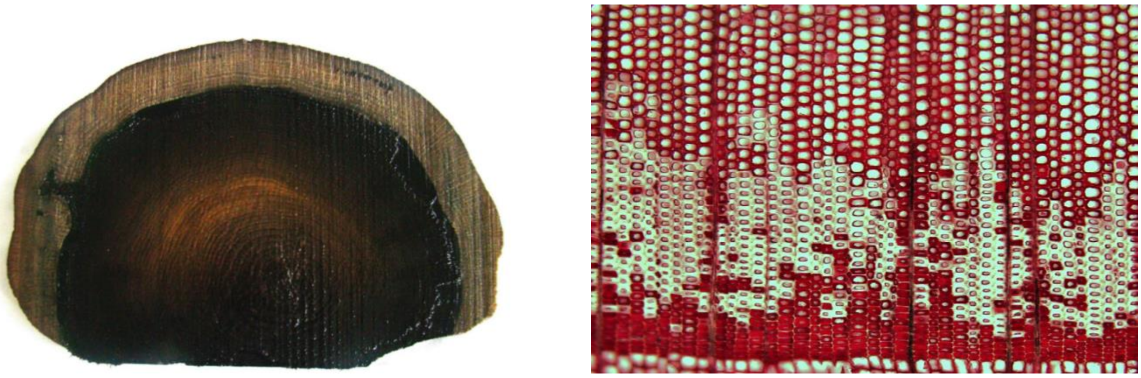

Figure 1 Right: Spongy structure of wood due to the bacterial action on the wood; Left: Change in colour of wood due to the reaction of iron sulphides(2)

Additionally, the interaction of iron and sulphur in anaerobic conditions presents further challenges. Bacteria interact with the organic components of the wood, producing hydrogen sulphide. When iron is present, it reacts with hydrogen sulphide to form iron sulphide, which can discolour the wood, a phenomenon seen in many artificial products. Environmental changes can cause iron sulphide to react with atmospheric oxygen, leading to oxidation and the formation of sulfuric acid. This acid attacks the cellulose within the wood, compromising its strength and leading to further degradation. Moreover, the expansion in volume caused by this reaction can further undermine the wood's structural integrity (7)

Chemical and physical deterioration of waterlogged wood primarily involves the degradation of its polysaccharide components, particularly cellulose (5). In waterlogged conditions, the cellulose's relative crystallinity decreases, although the width of the crystals remains unchanged. For example, studies on the oak wood of the Vasa ship revealed that Xylan, a key polysaccharide, underwent depolymerization, resulting in the formation of water-soluble fragments. Additionally, there has been a loss of carboxyl groups related to glucuronic acid in hemicelluloses and a reduction in ester linkages within the lignin-carbohydrate complex (LCC)(8) These changes indicate that the chemical cellular structure of waterlogged wood can be significantly altered over time.

Bacterial degradation also affects the physical properties of waterlogged wood, leading to a spongy structure that increases its ability to absorb water. As a result, the maximum moisture content (MWC) of the wood can exceed that of freshly cut wood, which further indicates the extent of deterioration. If the MWC of waterlogged wood becomes more than 1.5 times that of fresh wood, it is classified as degraded. If the MWC increases to four times that of fresh wood, the wood is considered severely deteriorated. This bacterial degradation also reduces the residual weight and density of the waterlogged wood, further compromising its structural integrity(9)

3 NECESSITY OF STABILIZING WATERLOGGED WOOD OF NEWPORT SHIP

Maintaining the integrity of waterlogged wood during the drying process is crucial to preventing structural damage that can occur as the wood loses moisture. Waterlogged wood is highly susceptible to shrinkage, which can cause severe deformation, cracking, or even complete collapse if not carefully managed. Preserving the wood's integrity during drying is essential not only to maintain its physical structure but also to safeguard its historical and cultural significance. These artifacts are often valuable representations of past craftsmanship, and any irreversible changes during drying can diminish their authenticity and educational value. Furthermore, proper drying techniques ensure the long-term stability of the wood, reducing the need for future conservation efforts and helping to preserve the artifact for future generations. By maintaining the wood’s integrity, it also becomes easier to restore and prepare the artifact for public display, ensuring that it remains an accurate and meaningful representation of its original form.(10)

3.1 METHODS USED FOR STABILIZING WATERLOGGED WOOD OF NEWPORT SHIP

Stabilization of water-resistant wood, such as the salvage of Newport ships, is a complex process that requires careful consideration of the wood's sensitivity. After cleaning and documenting the timbers, the conservation team initiated the active preservation process. The wood from the Newport Ship was found to be contaminated with iron corrosion deposits from the thousands of iron clench nails embedded in it. If left untreated, these deposits would have accelerated further deterioration, leading to significant challenges in the future when the ship would be reassembled and displayed. To address this issue, the timbers were immersed in a solution of ammonium citrate for several months. This process enabled the dissolution (chelation) of the soluble iron salts, which were then washed out.(11)

Newport Boats uses polyethylene glycol (PEG) to preserve the wood. PEG works by keeping water away from the wood walls, preventing the wood from shrinking, warping or cracking as it dries. The PEG molecules penetrate the wood, filling the voids left by water and providing structural stability. This treatment helps maintain the shape and integrity of the wood, ensuring that it does not deform when exposed to air.

However, PEG application can have long-term effects on the wood. Over time, the treated wood can become heavier due to the presence of PEG, which may also lead to a slight darkening of the wood's colour. In some cases, excessive amounts of PEG can cause the wood to become brittle or can interfere with further conservation efforts. Despite these potential drawbacks, PEG remains a key method for stabilizing waterlogged wood, as it effectively prevents the catastrophic collapse that can occur during the drying process.(12)

Following the PEG treatment, freeze-drying was employed as the next step in the conservation process. This method involves freezing the PEG-treated wood and then sublimating the ice directly into vapor, bypassing the liquid phase, which significantly reduces the risk of structural damage such as cracking or collapse. The freeze-drying process, particularly under vacuum conditions, complements the initial PEG treatment by ensuring that the wood remains stable and light, with minimal shrinkage and no significant loss of shape.(13)

4 PRESERVING THE NEWPORT SHIP: THE CRUCIAL ROLE OF SUPPORT STRUCTURES IN MAINTAINING STRUCTURAL INTEGRITY AND CONSERVING WATERLOGGED WOOD

Medieval ships, when excavated after centuries of submersion, are often in an extremely fragile state due to the prolonged waterlogging of their timbers. The wood, having absorbed water for such an extended period, loses much of its original strength and rigidity, making the vessel prone to collapsing under its own weight once it is lifted from the water. Without sufficient and carefully designed support, the weakened timbers can easily bend, crack, or even disintegrate completely, leading to irreversible damage. A robust support structure is essential not only during the excavation process but also afterward, as it ensures the ship's structural integrity is maintained. By evenly distributing the weight of the ship, this support system prevents concentrated stress on any single area, which could otherwise lead to structural failure.(14)

Conservation treatments are also vital for preserving the waterlogged wood of medieval ships and other archaeological artifacts. However, these treatments can sometimes introduce side effects that negatively affect the wood's properties and stability. After centuries underwater, the wood is so delicate that it requires meticulous handling to prevent collapse during and after its removal from the aquatic environment. Treatments like polyethylene glycol (PEG) and freeze-drying are commonly used to preserve such wood, but they can result in a decrease in mechanical strength. PEG is effective in preventing shrinkage by keeping the wood swollen, yet it also reduces the wood's rigidity, making it more vulnerable to physical damage. Causing mechanical damage and a further reduction in strength. Another challenge involves chemical alterations. The application of PEG can change the wood's original chemical structure, which might lead to unforeseen changes in its behaviour and stability over time. The long-term effects of PEG on the wood's chemical stability are not fully understood and could result in unexpected degradation.(15)

As the waterlogged wood dries, it naturally tends to shrink and warp, necessitating meticulous control of the drying process. Inadequate management can lead to uneven shrinkage and warping, distorting the wood and causing structural issues. Rapid or improper drying can also result in cracking and splitting, further compromising the wood's integrity.

Dry drying can also change the physical properties of wood, such as density and flexibility. Additionally, while chemical treatments aim to protect the wood, they may not fully eliminate the risk of microbial growth or could inadvertently create conditions that promote biological contamination if not carefully managed.(16)

Once a medieval ship is placed in a museum, maintaining its structural integrity becomes paramount. The support structure is crucial for preventing deformation of the weakened, waterlogged wood, which is prone to distortion due to its fragile state. A well-engineered support system ensures that the ship retains its shape in which it was found, preserving its historical accuracy and enhancing its presentation. Additionally, as the ship undergoes prolonged conservation treatments such as drying and chemical stabilization, the support structure provides continuous stability and can be adjusted as needed to accommodate changes in the wood's condition. This ongoing adaptability is essential for maintaining the ship's preservation and ensuring its integrity for future generations.(14)

4.1 CASE STUDY

4.1.1 Support Structure of the Batavia Ship

The Batavia, a Dutch East India Company ship built in 1628, met its tragic fate off the coast of Western Australia in 1629 and remained submerged until it was discovered in 1963. Its recovery and conservation presented unique challenges, primarily due to the fragile, waterlogged state of the ship's timbers. Waterlogged wood, although preserved to some extent by its submersion, loses much of its original strength and becomes prone to collapse or deformation once exposed to air. The Batavia's timbers required both chemical treatments and a carefully engineered support structure to ensure their preservation for future generations (17).

One of the primary chemical treatments used in the conservation of the Batavia was the application of polyethylene glycol (PEG), a compound commonly used to stabilize waterlogged wood. PEG replaces the water in the wood's cellular structure, preventing the severe shrinkage and cracking that would otherwise occur as the wood dries (18). This method is important to maintain the overall integrity of the wood and reduce the risk of damage during drying. However, given the size of the Batavia and the sensitivity of the trees, PEG treatment alone is not sufficient to ensure the structural stability of the Batavia.A physical support system was also necessary to protect the ship from collapsing under its own weight.

To address this issue, a steel framework was designed, incorporating padded wooden cradles to support the ship's remains. This system provided even weight distribution across the entire structure, ensuring that no single area was subjected to excessive stress that could lead to deformation or breakage (19). The padded cradles held the ship's timbers securely without causing further damage, while the steel framework offered the strength needed to support the large, delicate structure. In addition, adjustable bolting mechanisms were included in the support system, allowing for modifications to be made as the condition of the ship changed over time. These bolts enabled conservators to fine-tune the support as needed, ensuring that the ship remained stable throughout the conservation process .

Another important aspect of the Batavia's support system was the use of synthetic padding materials. These materials were placed within the cradles to provide cushioning, which helped to prevent mechanical damage to the timbers during movement or display. This soft tissue is important because it absorbs minimal change or movement, reducing the risk of further damage to existing wood (18).

The combination of chemical stabilization with PEG and the carefully engineered support structure successfully preserved the Batavia during the long conservation process. The support system played a crucial role in preventing warping and cracking of the wood, while the PEG treatment maintained the wood's overall shape and integrity. Today, the Batavia is displayed at the Western Australian Museum in Fremantle, where the support structure continues to ensure its stability and upright position, offering visitors an authentic representation of the ship's size and structure (. The adjustable nature of the support system has also proven beneficial for long-term preservation, as it allows for ongoing modifications in response to changes in the condition of the wood over time (19).

Figure 2 Visual representation of support system for the Batavia Ship(1)

Despite its successes, the support system for the Batavia has its drawbacks. The steel and wooden framework, while necessary for the ship's stability, is visually intrusive, obstructing the view of parts of the ship and detracting from the visitor's experience of its craftsmanship (17). Additionally, the adjustable bolts require regular monitoring and maintenance to ensure they continue functioning properly as the wood naturally settles over time (19). Furthermore, while the system was designed to distribute weight evenly, changes in the wood's structure may lead to occasional uneven stress, requiring periodic adjustments to the support (18). Moreover, PEG can attract and hold moisture, which can lead to steel corrosion over time. Steel exposed to water or humid environments can corrode, forming iron oxides (rust). If the PEG-treated wood remains damp, the risk of steel corrosion increases, particularly if oxygen and electrolytes (such as salts) are present(20).

Overall, the Batavia's preservation represents a successful integration of chemical and physical conservation techniques. Although the support system has some limitations, it has played an essential role in stabilizing the ship and ensuring that it can be viewed and studied by future generations.

4.1.2 Vasa Ship

The Vasa, a historic Swedish warship that met an ill-fated end on its maiden voyage in 1628, remains a significant cultural symbol. The vessel, originally designed for battle, sank due to severe stability and balance issues, making its retrieval in 1961 a complex process(21). The preservation efforts that followed, spanning over 17 years, included the application of polyethylene glycol (PEG), which was crucial in stabilizing the waterlogged wood. This chemical treatment effectively replaced the water in the wood's cellular structure, preventing it from shrinking and distorting. However, while the PEG treatment succeeded in protecting the form of the wood, it weakened its mechanical strength, compromising the ship's structural resilience over time (15)

The chosen support system for the 800-tonne Vasa was relatively simple. The structure involved stanchions, which were installed externally around the hull, transferring the ship's weight down to a concrete foundation. Between these stanchions and the hull, wooden wedges were strategically placed to provide localized support. The internal framework of the ship was bolstered with steel bolts, replacing the rusted originals, and approximately 5000 bolts were utilized to hold the ship together. Additionally, main frames, deck beams, and internal columns between decks were added to strengthen the vessel's internal structure .(21)

However, this support system did not work. The use of mild steel for the bolts and the cradle led to several complications. The PEG-treated wood reacted poorly with the steel, resulting in corrosion that further weakened the ship's structural integrity. Moreover, the system's load transfer mechanism was inadequate, the reason behind it was the deflections of side structure, deck beams and deformation of bilge. It was the poor stiffness of the structure, poor connection in the deck and hull that was creating the whole trouble. It is illustrated in the Figure below. These issues have been compounded by the ship's degraded wood and PEG (12, 21)

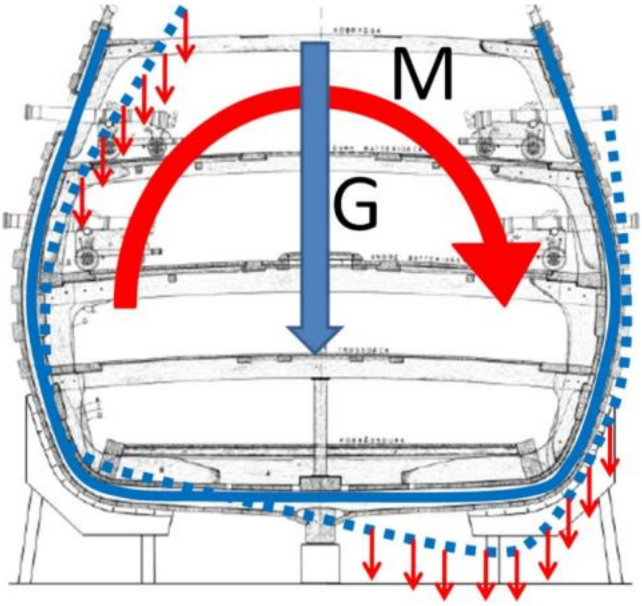

Figure 3 Side Deformation of the Vasa ship due to poor stiffness of the structure(21)

To better understand the ship's physical state and ensure its long-term preservation, continuous monitoring of the Vasa's structural condition has been in place since 2001. This data revealed significant deformations, both translational and rotational, particularly influenced by the ship's own weight. The uneven weight distribution, exacerbated by heavy masts and weakened wood, has created torsional stress, which poses ongoing challenges to maintaining the ship's integrity.(21)

In response to these challenges, some interim measures have been implemented. The number of stanchions and wedges supporting the ship was increased, and aluminium columns were installed in place of some of the original wooden ones to provide greater stiffness. Although these adjustments have alleviated some immediate concerns, they are not a permanent solution. The ongoing research aims to develop a more comprehensive support system, which would include internal reinforcement of the deck beams, joints, and columns. This future system is expected to be built from non-corrosive materials, such as fibre composites, that are compatible with PEG-treated wood and will not deteriorate over time (12, 21).

Ultimately, the complexity of the Vasa's structure and the unique challenges posed by centuries of water exposure have made its preservation a monumental task. The current system, while necessary to prevent immediate damage, will likely be replaced in the coming years by a more advanced design. As research progresses, there is hope that the new support system will provide more durable, long-term protection for this iconic ship.

4.2 Support Structure of Newport Ship

Designing a support structure for the Newport Ship requires learning from the limitations of previous systems used for ships like the Batavia and Vasa. The Batavia's steel framework, though effective, was visually intrusive and required constant monitoring due to the ship's evolving condition. The Vasa's use of mild steel bolts led to corrosion and structural deformities due to chemical reactions with the PEG-treated wood, emphasizing the need for more compatible materials.

For the Newport Ship, modern materials such as HDPE, Fibres reinforced polymers offer a better solution which should be lightweight, strong, non-corrosive, and has been successfully for structural purposes.. This material should avoid the chemical issues experienced by the Vasa while providing a flexible and stable structure.

4.2.1 Key Considerations for the design of support system

When designing the support system for the Newport Ship, flexibility in both the design and construction processes is essential. Given the complex geometry of the hull and potential challenges during reassembly, the ability to adapt as the project progresses will help address unforeseen issues. Additionally, the support system must be strong enough to avoid creating excessive point loads that could damage individual timbers or cause deformations.

- Protecting the keel from bearing the full weight of the ship is critical. It should not serve as the primary longitudinal support to avoid excessive compression, which could lead to damage over time. A design that distributes weight evenly across the structure would help safeguard the keel.

- It is also important to allow for future disassembly. By constructing the system in a way that permits easy reversion, the long-term preservation of the ship can be better ensured, allowing for future adjustments or conservation efforts without compromising the ship's integrity.

- Access to the ship's components for preventative conservation is another key consideration. The support system should allow conservators to easily reach various parts of the ship once it is installed in the museum.

- To prevent any deterioration of the ship's structure, the support materials should be corrosion-resistant. High Density Polyethylene(HDPE) could be considered for this purpose, as they offer durability and compatibility with waterlogged timbers without the risk of corrosion.

- Ease of installation is another factor that can enhance both the efficiency and economic feasibility of the project. Ideally, the support system should be simple to install, requiring minimal heavy machinery, which would reduce costs and streamline the construction process.

- In terms of aesthetic , the support should be minimalistic, allowing visitors to appreciate the ship's craftsmanship, tool marks, and overall shape without being obscured by an elaborate framework. Where possible, the support should be subtly integrated into the hull to maintain a clear view of the ship's structure, enhancing the visual experience.

- Finally, the support system must be durable enough to last for an extended period. It should offer consistent, uniform support that prevents the need for future alterations due to deformation or wear, ensuring the long-term stability and preservation of the Newport Ship.(6)

The Newport Ship presents a challenge due to its asymmetric structure, with significantly greater weight distributed on the starboard side.(22) Due to this asymmetry in the ship structure, load on the starboard (left side of Figure 4) will be more as compare to the port side(Right of Figure 4). This situation will cause the tipping of the ship towards the starboard side.

Figure 4 A 3D model of Newport Ship(22)

The original keel of the Newport Ship was severely damaged during recovery, particularly due to the penetration of piles into the ship. (4) This situation suggests that the keel of the of the ship should not ube used for bearing the load of the. All of the previous explained conditions suggest that the support system should be designed in such a way that it not only uplift the ship but also resist the tipping of ship. Therefore, in one of the previous studies a three point based system was suggested.(Figure 5)

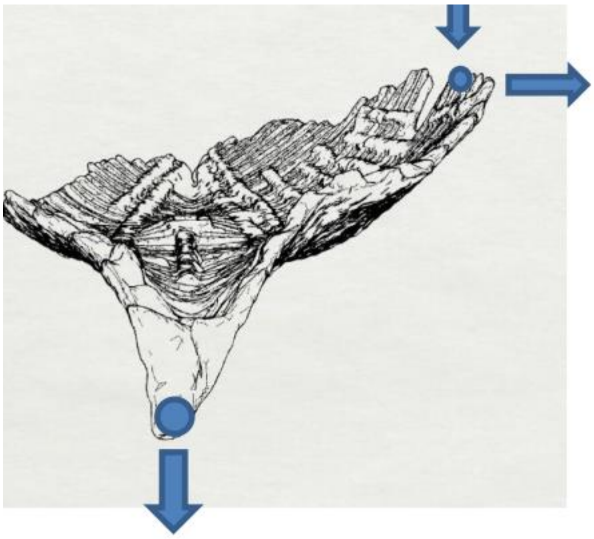

Figure 5 Three point system with horizontal support along the keel and top support for the resistance against tipping over(23)

Moreover, since the ship's timbers were individually treated with polyethylene glycol (PEG) during preservation, it is highly improbable that all components will fit together exactly as they originally did, due to shrinkage and deformation. (10)This offers an opportunity to reassemble the hull and frames independently, allowing for the design of a support system that is more cost-effective, regular, and structurally sound. For instance, the angle between the frames and the keel in the original ship is not uniform, and some frames deviate from a straight line. If the ship were to be reconstructed precisely as it was found, the secondary support structure[2] would have to match the irregular shape of each frame, requiring custom-bent frames and individual joints.

Allowing flexibility in the placement of frames, by adjusting them forward or backward as needed, can significantly simplify the support structure. This approach eliminates the need for custom joints or bent frames, resulting in a more efficient design while still ensuring the stability and preservation of the Newport Ship.

This method of reconstruction integrates modern engineering techniques, accommodating the natural irregularities in the ship's design while ensuring its long-term structural stability. A three-point support system, when used alongside a linear keel support, offers a more robust and stable solution. While relying solely on linear support along the keel can generate significant forces and deformation, the three-point configuration distributes the load more effectively, reducing stress and minimizing the need for additional reinforcements. This strategy not only addresses the structural challenges posed by the ship's unique design but also ensures its preservation for conservation and display purposes.(23)

5 EVALUATING HIGH DENSITY POLYETHYLENE (HDPE) FOR THE NEWPORT SHIP'S SUPPORT NEEDS

When evaluating materials for the Newport Ship's support structure, it is essential to consider several key factors. These include the material's durability, its adaptability to the required geometry and section designs, as well as its workability and ease of installation. High-Density Polyethylene (HDPE) is one option that can be used , given its unique properties and potential suitability for this project.

In 1953, two German chemists, Karl Ziegler and Erhard Holzkamp, created high-density polyethylene (HDPE), a major advance in plastics technology. Just two years later, in 1955, high-density polyethylene (HDPE) was first used as a pipe material. Ziegler's pioneering work on HDPE earned him the Nobel Prize in Chemistry in 1963 (24). Synthetic wood uses. These different applications arise from the chemical composition and properties of HDPE.

5.1 PHYSICAL AND CHEMICAL PROPERTIES OF HDPE

Polyethylene is a semi-crystalline polymer with crystalline regions and amorphous regions. The presence of molecular chains in the crystalline regions gives the product strength and rigidity, and high-density polyethylene (HDPE) has more of these regions than low-density polyethylene (LDPE). This molecular chain is mostly linear, making it more compact and higher than LDPE. Figure 6 shows the linear molecular structure of HDPE. HDPE behaves differently than other polyethylene when heat, force, and other stresses are applied. Heat causes the crystalline structure to change to an amorphous state, allowing for thermal welding and assembly. Polyethylene, especially HDPE, can crack under high stress. As a result of the released tensile strength, cracks propagate in stress concentrations characterized by localized stress concentrations. When molecular chains slip during flexure, irreversible elongation occurs and the ultimate tensile strength is reached. This dissipates the stored energy in the bone, altering

[2] The structural frames which will be placed inside the empty spaces between the wooden frames of the ship.

the stress/response and causing the energy to soften. Continuous deformation under load causes plastic yielding, and stress relaxation allows internal stress to decrease over time.(24)

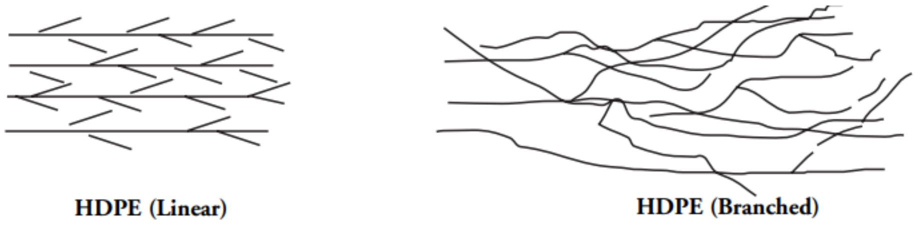

Figure 6 Schematic arrangement of molecules of HDPE(24)

The physical qualities of high-density polyethylene (HDPE) as shown in Table 1 make it a highly effective material for many structural and industrial uses. Its balance of lightweight and strength allows for efficient construction, especially in support structures. HDPE's ability to bear substantial loads without deforming is key to ensuring the long-term stability of any project. Its elasticity allows the material to flex under stress, which helps it maintain integrity when faced with varying forces.(24)

Moreover, HDPE's resistance to bending makes it particularly suitable for load-bearing applications, and its toughness enables it to withstand impacts without breaking. This resilience contributes significantly to its overall durability. HDPE’s stability at higher temperatures ensures that it can function effectively in a variety of conditions, including outdoor environments. Altogether, these properties make HDPE a dependable option for projects like the Newport Ship’s support structure, where both strength and adaptability are crucial.

Table 1 Physical properties of HDPE(25)

Property	SI
Density	0.933-1.27g/cm3
Yield Strength	6.89476-30 MPa
Modulus of Elasticity	0.483-1.45 GPa
Flexural Yield strength	16-92 MPa
Izod Impact, Notched	0.20-7.50 J/cm
Maximum Service Temperature	80.0-120 C

High-density polyethylene (HDPE) is known for its excellent resistance to many chemicals, making it the product of choice for many industries. HDPE pipes, for instance, demonstrate resistance to acids like sulfuric, hydrochloric, and phosphoric acids, along with other aggressive substances. Additionally, HDPE exhibits robust resistance to alkalis, salts, and organic solvents, making it a reliable choice for environments where exposure to such substances is commonplace.(26, 27)

Beyond its chemical resistance, HDPE boasts exceptional durability against aging and environmental factors. Its inherent UV resistance allows it to endure prolonged exposure to sunlight without significant degradation, rendering it suitable for outdoor applications like pipes and playground equipment. Moreover, HDPE's resistance to oxidation, temperature stability, and low creep behaviour further contribute to its longevity and reliability in various settings. With its ability to withstand environmental stressors and maintain structural integrity over time, HDPE continues to be a preferred material for industries seeking durability and resilience in their applications.(28)

5.2 Manufacturing Process of HDPE

The production of high-density polyethylene (HDPE) has many polymerization methods, including high-tech liquid phase. In low-pressure liquid processes such as slurry and solution processes, polymerization generally occurs at pressures above 2 MPa. The most common slurry method used in China has small cases and uses Ziegler catalysts. In contrast, the gas phase method operates at high temperatures and pressures; the fluidized bed reactor maintains a temperature of 85 to 100 ° C and a pressure of around 2 MPa. At the same time, the polymerization solution requires higher temperature (~140 ° C) and pressure (4~5MPa) to balance the ethylene and polyethylene in the solvent. These temperature and pressure changes play an important role in determining the reaction kinetics, polymer properties and process efficiency of different polymerization processes.

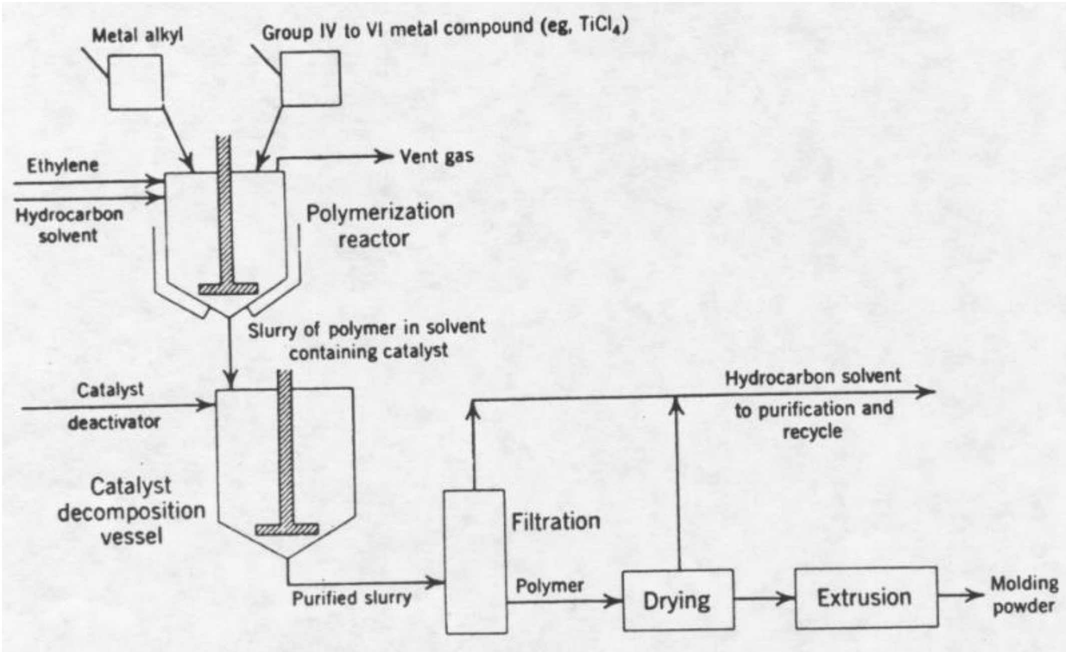

Figure 7 Schematic Diagram of production of HDPE[3]

5.2.1 Impact of Different Manufacturing processes on Mechanical Properties of HDPE

The electrical properties of high-density polyethylene (HDPE) are greatly affected by the manufacturing process, affecting its tensile strength, impact resistance, flexibility and overall durability. These variations are linked to changes in the molecular structure, crystallinity, and the distribution of polymer chains.(29)

5.2.1.1 Injection Molding

In contrast, injection molding, frequently used for producing complex HDPE parts, results in higher tensile strength due to the enhanced crystallinity achieved during the process (Peacock, 2000). However, this improvement in tensile strength often comes at the expense of impact resistance, as the material tends to become more rigid and less capable of absorbing shocks . Injection molded HDPE typically offers superior dimensional stability, which is crucial in applications that require precision (Thompson (30, 31)

[3] High Density Polyethylene (buffalo.edu)

5.2.1.2 Extrusion

Extrusion, which is commonly used to produce HDPE sheets, pipes, and films, results in material with high tensile strength and stiffness. The process allows for controlled cooling and drawing, which enhances the crystallinity and mechanical strength of the material. However, this increased stiffness often reduces impact resistance, making extruded HDPE less suitable for applications requiring high toughness. Despite this, extruded HDPE films maintain good flexibility, especially in packaging applications .(30)

5.2.1.3 Compression Molding

Compression molding is known for producing HDPE parts with high tensile strength. The uniform distribution of polymer chains during this process results in superior mechanical properties, including excellent impact resistance . Compression molded HDPE also exhibits good dimensional stability, making it suitable for industrial applications that require durability and strength (31, 32)

5.3 WELDING TECHNIQUES OF HDPE

High-Density Polyethylene (HDPE) is widely used in various industries due to its exceptional mechanical properties, durability, and resistance to environmental factors. One of the key challenges in working with HDPE is ensuring effective and reliable joining methods. Various welding techniques have been developed to meet this challenge, each tailored to suit specific applications and ensure strong, durable bonds.

5.3.1 Hot wedge welding

It is particularly effective for joining HDPE geomembranes. It uses a heated wedge to bond overlapping layers, creating two parallel seams. This technique is favored in large-scale applications, such as lining containment areas, due to its ability to create long, continuous welds.(33)

5.3.2 Hot air welding

It relies on controlled heat and air pressure to melt HDPE surfaces, allowing them to fuse. This method is versatile and produces strong, airtight seams, making it suitable for applications like industrial fabric joining. Temperature control is critical to avoid damaging the material.(33)

5.3.3 Butt fusion welding

It is another popular method for joining HDPE pipes. It involves heating the pipe ends and pressing them together to fuse as they cool. The process requires precise control of pressure, temperature, and cooling time to ensure a robust and reliable bond. Cleanliness is also critical to prevent contamination from affecting weld quality.(33)

5.3.4 Emerging techniques

Friction stir welding (FSW) and vibration welding are gaining attention for their ability to join HDPE. FSW uses mechanical motion and pressure to generate frictional heat at the weld interface, while vibration welding relies on high-frequency vibrations to produce heat and fuse the materials. These methods are advantageous due to their efficiency and ability to create strong bonds without external heat sources.(34)

5.4 Structural Advantageous of uses HDPE

5.4.1 HDPE Piping System

HDPE piping systems are known for their durability and resistance to corrosion, rust, and rot, making them a reliable choice for various applications. Their welded joints create leak-tight connections that are stronger than the pipe itself, minimizing the risk of leaks. HDPE pipes are flexible, allowing them to withstand strain and adapt to different environmental conditions without cracking, which reduces the likelihood of breaks, even during freeze-thaw cycles. The smooth interior of HDPE pipes prevents tuberculation and biological build-up, ensuring optimal flow rates and reducing friction loss for efficient fluid transport.(35)

5.4.2 HDPE Geomembranes

HDPE geomembranes exhibit high tensile strength, often exceeding 20 MPa, making them resistant to tears and punctures, ensuring a durable barrier against physical stresses. With a low permeability coefficient reaching 10^-14 m/s or less, these geomembranes effectively block the passage of water, gases, and other liquids, which is crucial for containment purposes. They are also enhanced with UV inhibitors to withstand prolonged exposure to sunlight without degradation. Additionally, HDPE geomembranes have broad chemical resistance, allowing them to handle exposure to acids, bases, oxidizers, and saline solutions. Their thermal stability, shear resistance, and abrasion resistance make them suitable for various environmental conditions and applications where long-term durability is essential.(36)

5.4.3 Use of HDPE in Bridge Construction

In bridge applications, HDPE sheathings provide excellent protection against corrosion, particularly for steel tendons in post-tensioned structures. The flexibility of HDPE allows it to conform to the shape of steel tendons, even at points of deviation where stress is exerted. This material is available in different thicknesses and layer configurations, providing tailored protection levels depending on environmental exposure and structural requirements. HDPE sheathings maintain their integrity under stress and resist wear, ensuring the longevity of the structural components they protect.(37)

5.4.4 Use of HDPE as Storage Tanks

HDPE sheets used in tanks are durable and resistant to harsh weather conditions, UV rays and temperature changes. They are also resistant to corrosion and chemicals, making them suitable for storing many items without deteriorating or deteriorating over time. The lightness of HDPE makes tanks easier to transport and install than heavier materials such as steel or concrete. Furthermore, HDPE sheets can be easily cut and melded to fit different tank sizes and shapes, offering versatility in design and application. The material's durability results in low maintenance requirements and a long service life, leading to cost savings over time.(28, 38)

5.4.5 Innovative Uses of HDPE in Enhancing Construction Materials and Sustainability

The construction industry is exploring innovative uses of HDPE (high-density polyethylene) to enhance material properties and sustainability. In 3D-printed structures, incorporating HDPE into concrete mixes can significantly increase tensile strength, allowing for more resilient and complex designs. Research has shown that HDPE-enhanced concrete can achieve a tensile strength of 3 MPa, making it a promising component in 3D-printed construction.(22)

HDPE fibres in fibre-reinforced concrete (FRC) improve ductility and post-cracking flexural toughness. While not increasing compressive strength, HDPE fibres maintain consistent tensile capacity, reduce water permeability, and mitigate early plastic shrinkage cracking, enhancing durability. Using recycled HDPE fibres in concrete structures like bridge decks and industrial slabs adds economic and environmental value.(39)

HDPE is also being used as a bitumen modifier in asphalt concrete mix, improving the performance and extending the service life of pavements. Adding 4% HDPE to asphalt mixes has shown to enhance durability, offering a sustainable use for waste HDPE.(40)

These applications highlight HDPE's potential to improve the strength, toughness, and sustainability of construction materials, paving the way for more innovative and durable structures.

6 THE USE OF HDPE FOR THE NEWPORT MEDIEVAL SHIP

High-Density Polyethylene (HDPE) stands out as a practical choice for constructing support structures, particularly for sensitive projects like the conservation of the Medieval Newport Ship. The material's inherent properties not only meet the technical demands of supporting a historical artifact but also align with contemporary consideration of long-term preservation. The following discussion, will delve into why HDPE is suitable for this purpose, focusing on its chemical and physical attributes, welding capabilities, and its role in sustainable practices, including recycling.

6.1 CHEMICAL AND ENVIRONMENTAL RESISTANCE

One of the foremost reasons HDPE is selected for support structures in conservation projects is its remarkable chemical resistance. Unlike metals that can corrode or wood that can rot or warp, HDPE is largely inert. This means it doesn’t react with most chemicals, including acids, bases, and solvents, which is crucial when supporting an artifact like the Newport Ship. The ship, having been submerged and exposed to various elements for centuries, requires a support system that won't introduce new risks. HDPE's resistance to moisture and most chemicals ensures that it remains stable over time, providing a consistent level of support without contributing to the ship’s degradation.

In environments where the artifact is displayed or stored, factors such as humidity and temperature can fluctuate. HDPE's low water absorption rate prevents it from swelling or shrinking in response to these changes. Unlike wood, which can expand or contract depending on the humidity, or metal, which can oxidize and corrode, HDPE maintains its shape and integrity. This is particularly important for the Newport Ship, as any shift in the support structure could potentially damage the fragile wood.

6.2 DURABILITY AND STRENGTH

HDPE offers a unique combination of strength and flexibility, making it ideal for supporting large and delicate structures like the Newport Ship. Despite being a type of plastic, HDPE has a high tensile strength and can withstand significant loads. Its strength-to-density ratio is particularly advantageous; it can provide substantial support without adding unnecessary weight.

Another critical aspect of HDPE's durability is its impact resistance. In a museum or storage setting, the support structure might be subjected to movement or accidental impacts. HDPE can absorb shocks without cracking or breaking, ensuring that the structure remains intact and continues to provide stable support. This resilience is key in preserving the integrity of the ship, as it prevents sudden stresses or shifts that could occur with less durable materials.

6.3 WELDING AND FABRICATION

The ease of welding HDPE is one of its significant advantages in constructing custom support structures. HDPE can be welded using various methods, such as butt welding and extrusion welding, to create strong, seamless joints. The welding process involves heating the edges of HDPE components until they become malleable and then pressing them together to form a solid bond as they cool. This method allows for precise customization of the support structure to fit the unique contours of the Newport Ship, providing a snug and secure fit that distributes the weight evenly.

Welding HDPE is also a relatively clean process. It does not require the use of solvents or adhesives that could introduce volatile organic compounds (VOCs) or other harmful substances into the environment around the artifact. This cleanliness is vital in conservation settings, where maintaining a stable and non-reactive environment is crucial for the artifact's preservation. Additionally, the welded joints in HDPE are nearly as strong as the material itself, ensuring that the support structure has the necessary integrity to bear the ship's weight over time.

6.4 Lightweight and Cost-Effectiveness

One of the practical benefits of HDPE is its lightweight nature. Despite its strength and durability, HDPE is much lighter than metals like steel or aluminum. This reduced weight simplifies the process of fabricating, transporting, and installing the support structure. For a large and complex artifact like the Newport Ship, this ease of handling is invaluable. It allows for the careful positioning of the support structure around the ship without the need for heavy lifting equipment that could pose a risk to the artifact.

From a financial perspective, HDPE is also more cost-effective than many alternative materials. While metals like stainless steel offer durability, they come with a significantly higher price tag. HDPE provides a durable and stable option at a fraction of the cost, making it an attractive option for large-scale projects. This cost savings can be redirected towards other aspects of the ship's conservation, such as environmental controls, ongoing monitoring, or educational displays, ensuring a comprehensive preservation effort.

6.5 Sustainability and Recycling

In addition to its technical advantages, HDPE is also an environmentally friendly choice. In an era where sustainability is increasingly important, selecting materials that have a minimal environmental impact is a priority. HDPE fits this criterion well, as it is fully recyclable. Unlike some materials that degrade in quality with recycling, HDPE can be recycled multiple times without a significant loss of properties. This recyclability is crucial in reducing the environmental footprint of the conservation project.

The use of HDPE in the support structure means that at the end of its useful life whether due to changes in display or the need for refurbishment the material can be recycled rather than sent to a landfill. Recycling HDPE involves reprocessing it into pellets that can then be used to manufacture new products. This process reduces the demand for new plastic production, conserving resources and reducing environmental impact. For the Newport Ship project, using a recyclable material like HDPE aligns with a sustainable approach to artifact preservation, demonstrating a commitment to environmental responsibility.

Furthermore, the production of HDPE itself has a relatively low environmental impact compared to some other materials. It requires less energy to produce than metals and generates fewer emissions. HDPE's lightweight nature also means that transporting it has a smaller carbon footprint, as it requires less fuel than heavier materials. When considering the full life cycle of the material from production to end-of-life recycling HDPE presents a lower overall environmental burden.

7 GEOMETRY AND CROSS SECTION OF SHIP

Given the geometry of the hull, it seems possible to use the space between the wooden frames to improve the interior structure. These frames are usually hidden between the exterior and interior panels. As the keel of ship was partially discovered due to the intervention of piles into the structure and is in delicate form(4), it is advisable to replace the keel with the beam structure which will be supported on the ground to transfer the load of the ship to the foundation.

Designing this internal structural framework requires detailed knowledge of the specific geometry of the recovered ship components, which are highly irregular in certain areas. For the purposes of this report, model was constructed from individually printed timbers, was used which was provided in the form of iges file(22). The model of support framework was made into the SolidWorks software into the guidance of ship model. (Figure 8)

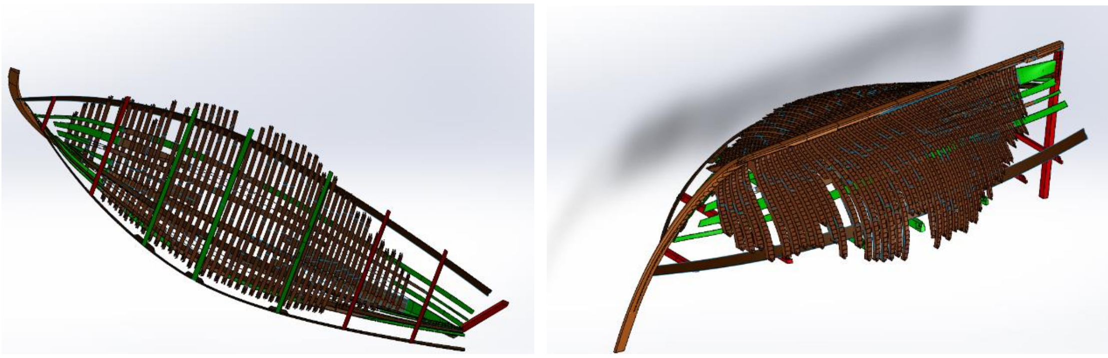

Figure 8 Left: Top view of the model created shown in SolidWorks; Right :Inverted model of ship in SolidWorks to have clear view of the discovered timber of ship(Model from iges)

One challenge with this method is the change in shape between the waterlogged and dried wood. Even with minimal shrinkage, it becomes significant over the ship's entire 23-meter length. Due to wood's anisotropic properties, it shrinks at different rates in radial, tangential, and longitudinal directions (10), making it difficult to accurately calculate overall shrinkage and determine the exact shape of the dry, reassembled hull.

A potential solution is to reassemble the hull on a continuous support system, like scaffolding, and scan the structure to capture its shape. This scanned data could then be used to define the geometry for the final supporting framework. This approach removes the need for on-site adjustable joints to correct for inaccuracies in shrinkage modelling, resulting in a more economical design. The main element of the support system would be the structural framework, allowing nearly continuous support of the wood depending on the spacing of the frames.(23) There are different available options as clear from the Figure 9. One is that the support element between every space, second in the one after the other and the third one is after each two spaces. These options are highly dependent on the cost of the structure, material availability and strength of the selected material for the support structure.

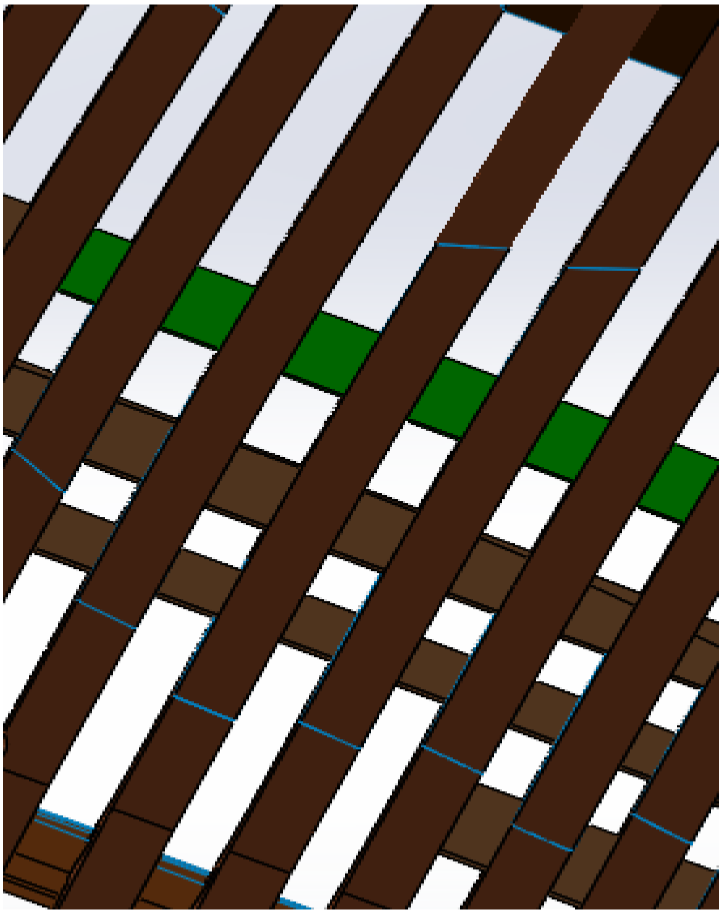

Figure 9 Option 1: Use each empty space for support frame in the wooden frames ;Option 2: One support frame after two wooden frames; Option 3: Support frame in the third empty space after leaving two spaces and so on.

7.1 Cross Section Selection for Analysis

For the structural analysis of the support system designed for the Newport Ship, it is imperative to examine the entire assembly to ensure its overall integrity and functionality. However, due to the limitations imposed by the teaching version of the software, which restricts the number of elements that can be analysed simultaneously, a more focused approach was adopted. This involved analysing the most critical section of the support structure the central part of the ship. This specific area was chosen because it is subjected to the highest levels of stress and strain, and therefore, is most likely to reveal potential points of failure within the design.

The design of the support structure must conform to the spatial constraints dictated by the ship's timber framework. The structure will be integrated into the available spaces between the ship's timbers, ensuring that it does not interfere with the existing wooden elements. The empty spaces in the timber in the central section of the ship have been measured to be approximately 200 mm. This dimension serves as a critical parameter in defining the geometry of the support elements.

Furthermore, the vertical depth of the wooden components in this central region varies significantly, with a maximum depth of 285 mm and a minimum depth of 140 mm. This variation necessitates a support structure that can accommodate these changing dimensions while providing consistent support. The dimensions of the HDPE (High-Density Polyethylene) support elements must, therefore, be carefully selected to optimize the fit and function within this variable depth.

Given these constraints, the initial design employs a rectangular section of HDPE with dimensions of 200 mm in height, 120 mm in width, and a thickness of 10 mm. These dimensions were chosen as a starting point to match the spatial allowances within the timber structure, providing a balance between adequate support and ease of installation. HDPE was selected due to its versatility in moulding and shaping, which allows it to be formed into virtually any required profile without significant difficulty. This material's malleability ensures that even complex or non-standard cross-sectional shapes can be produced to meet the unique demands of the project.

When examining the keel of the Newport Ship, the original wooden structure exhibits considerable variation in its dimensions. The width of the keel ranges from 180 mm to 270 mm, while the height spans from 170 mm to 240 mm. This variability necessitates a careful and flexible approach in designing a support structure that can effectively conform to these dimensions. Furthermore, the presence of a limber hole at the bottom of the wooden frames adds another layer of complexity to the design. The limber hole, which facilitates drainage and reduces water accumulation within the ship's hull, measures approximately 130 mm in width and 60 mm in height. Its position and dimensions must be carefully considered when designing the support structure to ensure that its functionality is not impeded.

Given these parameters, a cross-sectional dimension of 200 mm in width and 120 mm in height was selected for the HDPE support structure. This dimension strikes a balance between providing adequate support to the keel while accommodating the spatial constraints imposed by the varying dimensions of the wooden keel and the limber hole. The chosen cross-section also ensures that the support structure does not obstruct the limber hole, thus maintaining its essential function in the ship's design.

In the context of the structural analysis, the keel was modelled using a simplified rectangular section with the dimensions specified. This approach allows for an effective representation of the support system's interaction with the keel under various loading conditions. By implementing the keel as a rectangular section, the analysis can focus on assessing the structural behaviour, such as stress distribution and potential deformation, within the support structure. This simplification is particularly useful in identifying critical points along the keel where the support structure may experience the highest stress concentrations, enabling targeted reinforcement in those areas.

8 DESIGN METHODOLOGY

The design methodology for the Newport Ship support structure primarily focused on addressing the unique material properties of High-Density Polyethylene (HDPE), as this material has not traditionally been used in such structural applications. Unlike conventional designs, no established guidelines or standards were directly applicable to the use of HDPE in this context. Consequently, the approach was to base the design purely on the load considerations derived from the mass and distribution of the ship itself, without reliance on predefined engineering codes.

The ship will be housed within a controlled museum environment, which ensures a stable and regulated atmosphere with minimal external factors such as temperature fluctuations, humidity, and exposure to environmental forces. Given these controlled conditions, the design primarily considered the static load of the ship, along with a variable load ranging from 0.0 to 1.0 (41)kN/m². This variable load accounts for potential operational and maintenance activities within the exhibit space. For the purpose of structural analysis, a load of 0.58 kN/m² was applied to the support structure, simulating the realistic pressure that might be exerted on the structure over time.

The load of the ship was taken as it is, accounting for its weight, dimensions, and the environmental forces acting on it within this controlled setting. This simplification was made to streamline the design process while maintaining a focus on ensuring structural integrity and safety. Given that HDPE has distinct mechanical properties such as high flexibility, low density, and significant resistance to environmental degradation its behaviour under load differs considerably from traditional materials like steel or wood, which are typically used in ship support structures. These characteristics of HDPE, particularly its flexibility, necessitated a design approach that did not conform to established guidelines, as these would have been overly conservative or not reflective of the material's true performance.

As part of the design requirements, deflections in the cantilevered support structure were considered with reference to timber standards, where deflections should not exceed the length divided by 125. For the Newport Ship, this translates to a maximum allowable deflection of 45.8 mm on the starboard side (5723.25 mm / 125 mm) on Portside it should not exceed(3031/125) the value of 24.25 mm (23, 41). Ensuring these limits were met was essential for maintaining the structural integrity and aesthetic presentation of the ship within the museum exhibit.

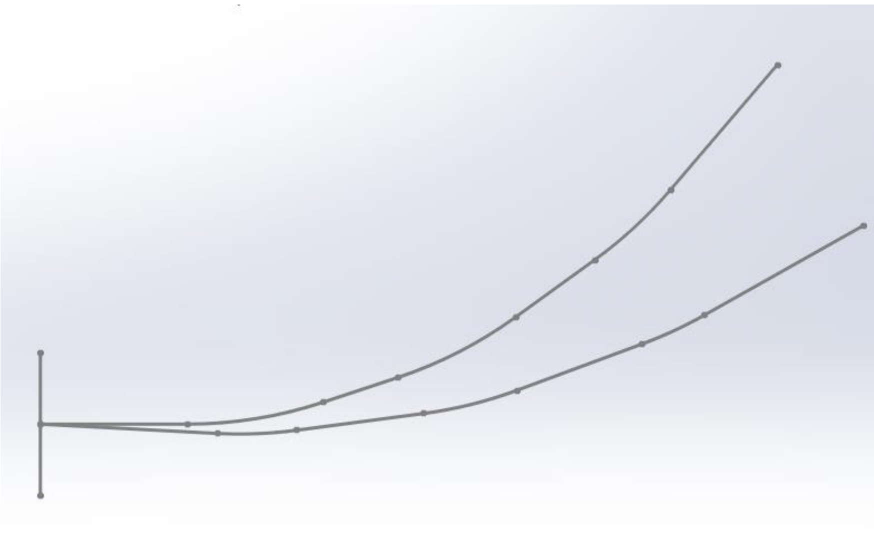

Figure 10 Illustration of deflection of cantilever beam [Top one when placed and bottom is deflected shape of beam]

Additionally, this design exploration was an innovative effort, aiming to assess how HDPE performs under such specific loading conditions. In the absence of relevant historical data or empirical research, the design relied on simplified assumptions and direct analysis of load paths through the structure. This allowed for a more adaptive design, wherein the material's behaviour under stress could be observed and optimized in subsequent stages. By forgoing established design guidelines, the process facilitated a direct evaluation of how HDPE responds to the real-world constraints of supporting the Newport Ship.

The decision to use HDPE in this unconventional manner was driven by its long-term durability and resistance to environmental factors, such as moisture and microbial attack, which are critical considerations for the preservation of archaeological artifacts like the Newport Ship. While this design methodology lacks the rigor of traditional guideline-based approaches, it was a deliberate choice aimed at innovation and adaptability, leveraging HDPE's properties to meet the project's specific requirements. In conclusion, the design process for the Newport Ship support structure reflects a non-traditional approach, grounded in the specific load characteristics of the ship, a controlled museum environment, and the unique material properties of HDPE. While no formal design standards were followed, the approach provided an opportunity to explore the potential of HDPE for future applications in structural design, especially in heritage preservation.

8.1 Segmentation and Load Application Strategy for the Newport Ship Support Structure

The model for the Newport Ship support structure was created with careful consideration of the available spaces between the wooden sections of the ship. Specifically, a rectangular section of 200x120x10 mm was used as the basis for the structural design. Due to variations in the thickness of the wooden sections, the model was divided into five distinct segments on the starboard side, where the wood thickness changes progressively. The central section of the ship features the maximum wood thickness, while the thickness reduces toward the top, necessitating this segmentation. On the port side, the structure was divided into three sections to account for the more uniform because the portside of the ship is much smaller as compere to the starboard side, but still variable, thickness of the wooden components.

In addition to this, the variable load ranging from was not only applied as a direct load on the support structure but was also translated into equivalent wood thickness across the different sections of the ship. This division has been illustrated in the Table 2. This conversion allowed for a more realistic simulation of how the load would interact with the ship's varying wooden elements. By distributing the load in this manner, the analysis could more accurately reflect the actual forces and stresses exerted on the ship's hull, ensuring that the support structure could accommodate the unique characteristics of the ship's construction.

The analysis was divided into two cases according to the available empty spaces between the wooden frames. In Case 1 the number of empty spaces in between the support frames were one while in Case 2 there was no empty space in between the support frames.

Table 2 Division of wood thickness along the wooden section of ship

Sectional Thickness(mm)	Average thickness of between two points(mm) t1	Variable Thickness(mm) t2	Total Thicknes s(mm) t=t1+t2	Distribution of width of wood long the width of ship (mm)
285				
146	215.5	80	295.5	1200
146	146	80	226	938
143	144.5	80	224.5	974
136	139.5	80	219.5	1499
120	128	80	208	1132

9 CALCULATIONS WITH ANSYS

For the purposes of analysis, the central section of the support structure was modelled in SolidWorks (Figure 11), utilizing a rectangular cross-section with alternating empty spaces to optimize the design. To maintain consistency and simplicity in the workflow, the structural analysis of this model was also performed within Ansys. The core principle behind the simulation is based on Finite Element Modelling (FEM), a numerical method widely used in engineering analysis.

In FEM, the entire structure is subdivided into a finite number of smaller elements, which are interconnected at specific points known as nodes. At these nodes, fundamental material properties such as stiffness, strength, and elasticity are applied. The software then calculates the deformation and displacement of each element, providing insight into how the structure responds under load.(42)

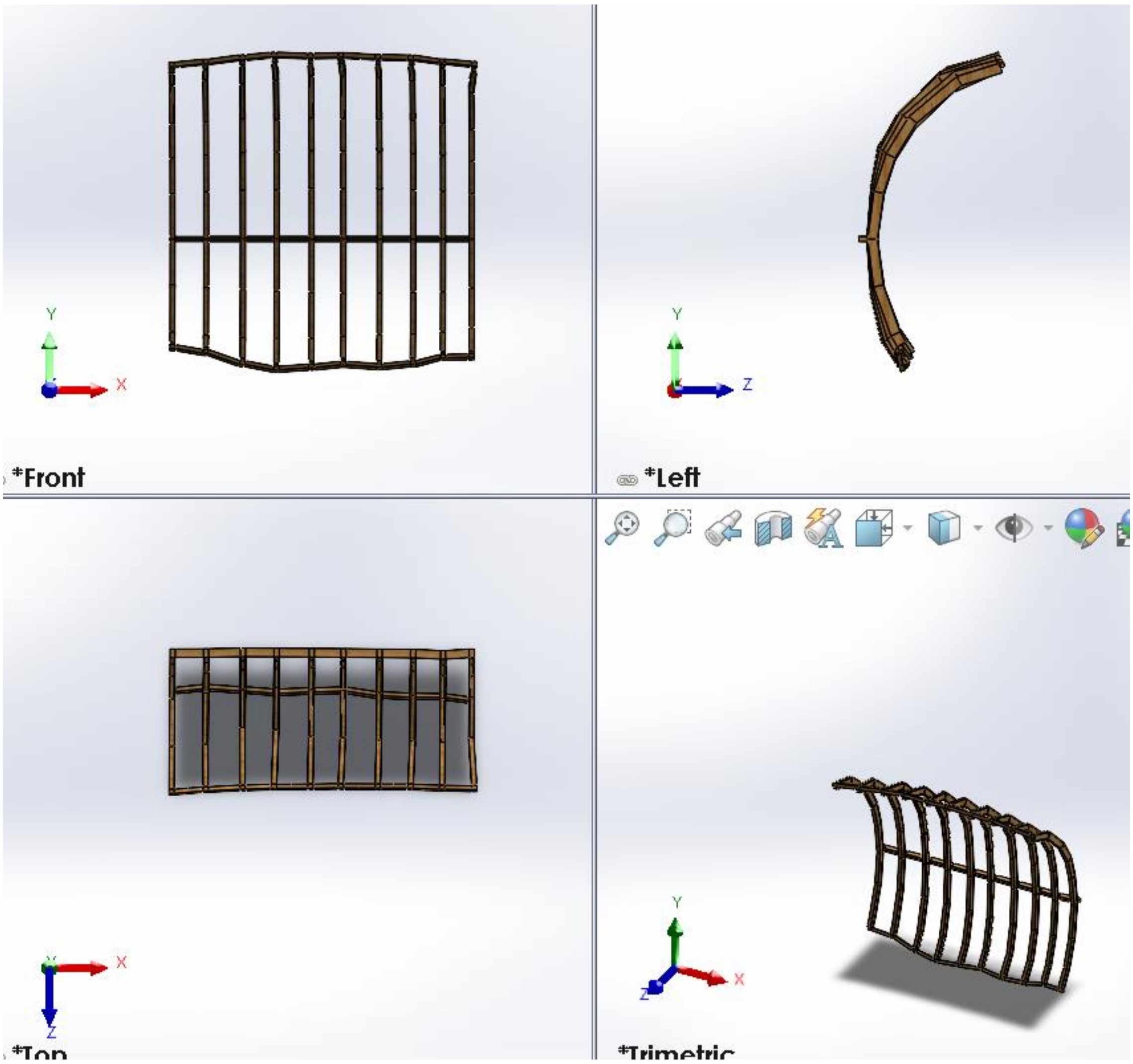

Figure 11 Modelled frame of HDPE with frames in every 2nd empty place

9.1 MATERIAL MODELS

For the material model, High-Density Polyethylene (HDPE) was selected due to its favourable properties for the structural design. HDPE is a thermoplastic polymer known for its high strength-to-density ratio, durability, and resistance to impact and chemicals, making it suitable for applications requiring robust and lightweight materials.

The material properties for HDPE were sourced directly from the SolidWorks material library, ensuring compatibility with the simulation environment(Table 3). These properties were then cross-verified through reliable online sources(43) to ensure their accuracy and relevance for the analysis.

Table 3 Mechanical Properties of HDPE for Analysis

Elastic Modulus	**1070000000**	**N/m^2**
Poisson's Ratio	0.4101	N/A
Shear Modulus	377200000	N/m^2
Mass Density	952	kg/m^3
Tensile Strength	22100000	N/m^2
Yield Strength	25000000	N/m^2
Thermal Conductivity	0.2256	W/(m·K)
Specific Heat	1386	J/(kg·K)

For the analysis of the Newport Ship's support structure, the density of the oak wood used in the ship was an important factor to consider. The historical oak wood had a typical density ranging from 600 to 900 kg/m³, as is common for well-preserved timber (21). However, for the purposes of this analysis, a conservative average density of 750 kg/m³ was selected to account for variations in material composition and potential aging effects.

In addition to adjusting the density, the material properties of the oak wood were modified to simulate a material with zero stiffness. This assumption was made to ensure that the structural model would not rely on the wood's mechanical properties for load-bearing but instead focus entirely on the support structure's capacity to distribute loads effectively in the analysis. By setting the wood's stiffness, including Young's Modulus and other mechanical characteristics, to zero, the model assumes that the wood provides no structural support, allowing for a more conservative and robust design approach (Table 4).

This approach ensures that the support structure will be sufficient in providing long-term preservation and stability for the Newport Ship during display, accurately replicating the behaviour of a non-load-bearing element within a modern engineered context while respecting the historical integrity of the ship.

Table 4 Assumed mechanical properties of oak wood to make it stiffness zero

Elastic Modulus	**1**	**N/m^2**
Poisson's Ratio	0.45	N/A
Shear Modulus	0.333	N/m^2
Mass Density	750	kg/m^3
Tensile Strength	0.1	N/m^2
Yield Strength	0.1	N/m^2

9.2 MESHING

In the Ansys simulation, a high-quality quadratic solid element mesh of was applied to the entire model to ensure accurate and reliable results. This mesh type, which includes midside nodes (Figure 12), was chosen for its ability to capture detailed stress distributions, deformations, and bending effects across the model.(44)

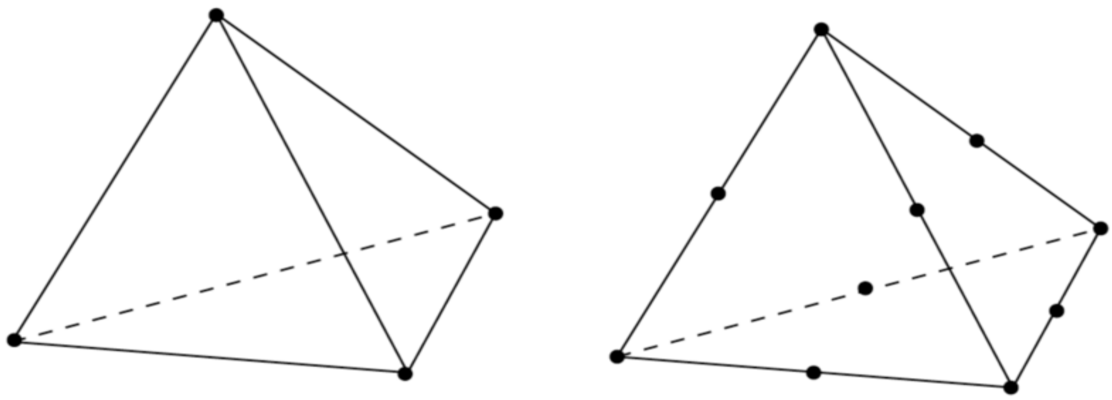

Figure 12 Left: 4 node Linear (First order)element for low quality meshing ;Right: 10 node quadratic(second order) for high quality meshing

The mesh was made finer until the results obtained were consistent and the final selected element size was 40mm.

9.3 Loading and Boundary Conditions

For the loading conditions in the simulation, gravity loading was applied to represent the weight acting on the structure. Wooden load in varying thickness as discussed earlier was applied.(Figure 13)

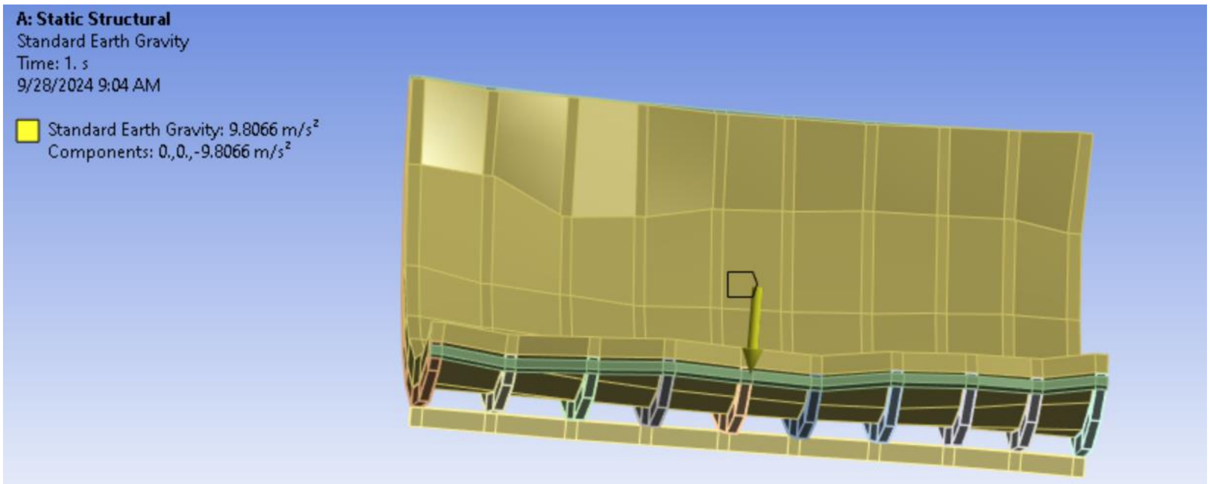

Figure 13 Application of gravity loading

In the simulation, a fixed geometry boundary condition was applied to the keel to prevent any movement or deformation in that region. Additionally, the structure was horizontally restrained on the starboard side, limiting displacement in the horizontal direction.(Figure 14)

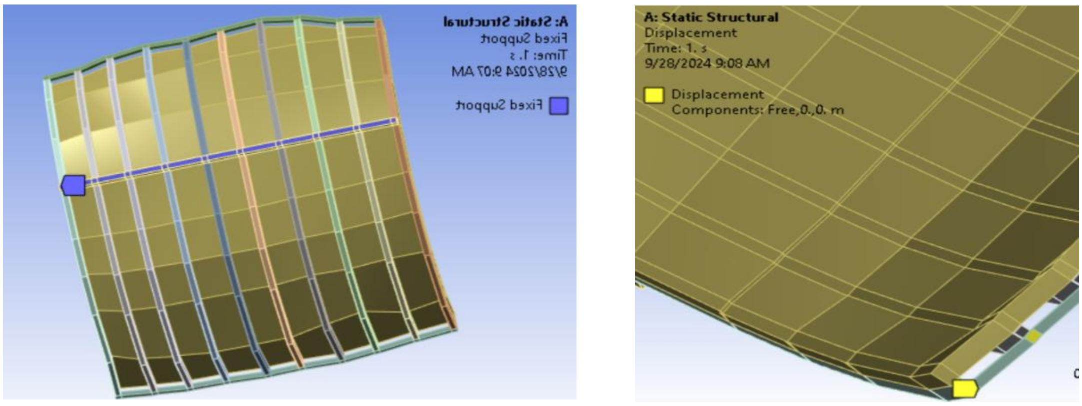

Figure 14 Right: Horizontal support on the starboard side ;Left: fully restrained on the keel

9.4 Results

9.4.1 Case 1: Structural Frames in every second empty space

In the analysis of the medieval ship model, a rectangular section with dimensions of 200 mm (depth) x 120 mm (width) x 10 mm (thickness) was initially utilized. Upon applying the load, the observed maximum deflection on the starboard side was approximately 21 mm, which is within acceptable limits. However, the port side exhibited a significantly larger maximum deflection of 572 mm, far exceeding the permissible value of 28.39 mm (Figure 15).

This substantial disparity indicates a structural imbalance and highlights the inadequacy of the current section's stiffness, particularly on the port side. Consequently, there is a need to revise the section dimensions by increasing the depth and thickness to enhance the overall structural performance and achieve a more uniform load distribution.

Furthermore, a critical review of the stress distribution revealed that the Von Mises stress at a some nodes exceeded the yield strength of the High-Density Polyethylene (HDPE) material, which is 50 MPa (Figure 16). This suggests that the section should be revised.

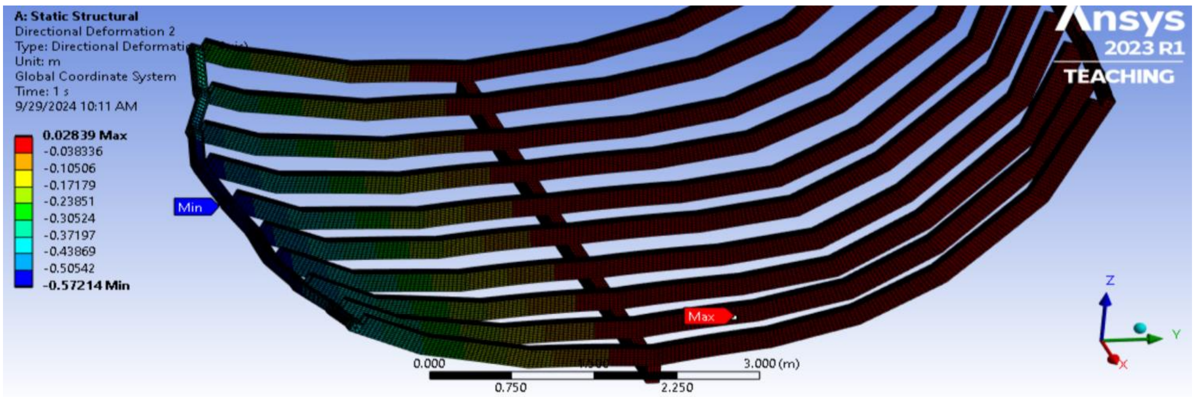

Figure 15 Deformation of HDPE support model in Z-direction

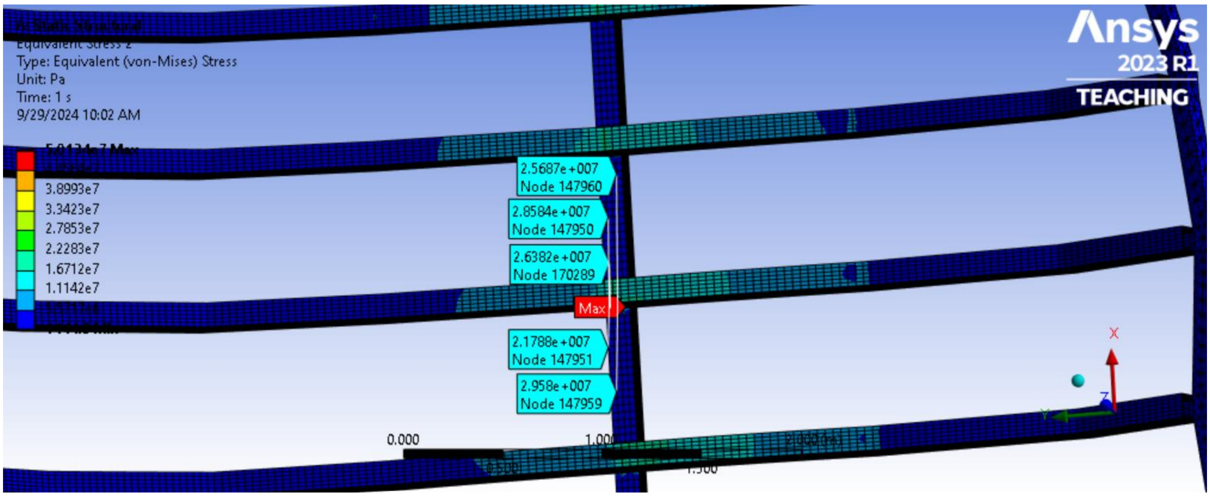

Figure 16 Equivalent von misses stress is mximum at the junction of keel and support frames with the maximum value of 50.42 MPa

Tabel of rection Forces for the horizontal support is following with resultant reaction of 37.28 KN

Table 5 Rection Forces for horizontal Forces

Maximum Value Over Time	
X Axis	0. N
Y Axis	11793 N
Z Axis	35373 N
Total	37287 N

For the revised model with the cross section of 230x120x20 mm the deflection on the portside is still more than allowable limit with the maximum value of 247mm (Figure 17). But the maximum VonMisses stress was reduced considerably with the maximum value of 20.9 MPa (Figure 18)

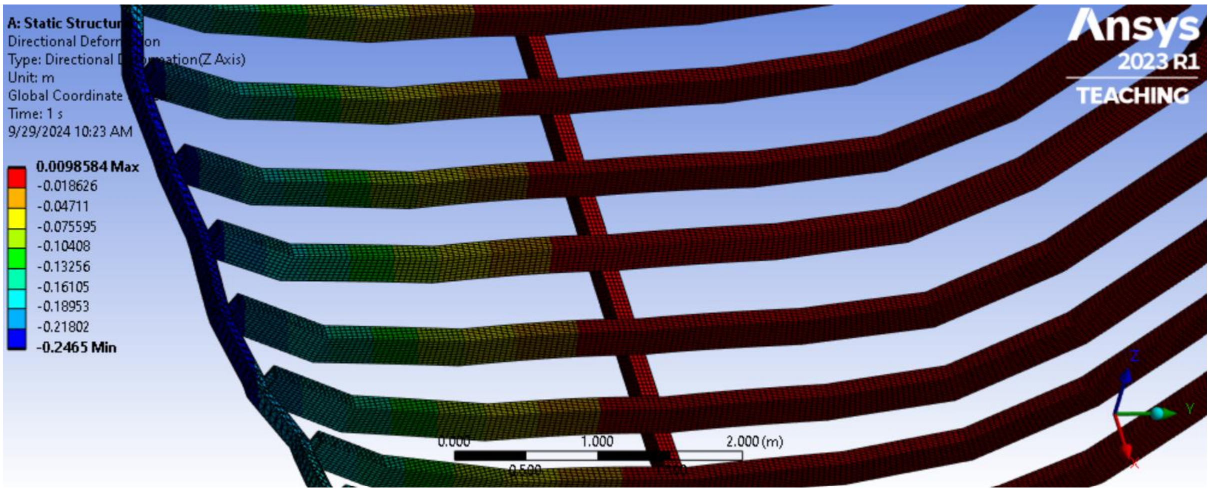

Figure 17 Deflection for the revised section of 230x120x20 mm

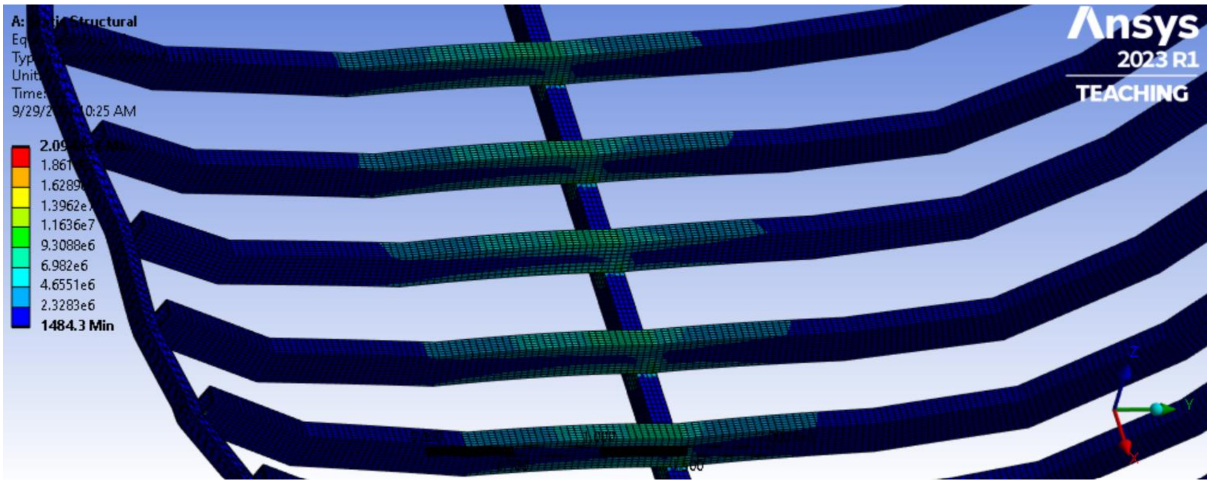

Figure 18 Von Mises stress for the revised section with the maximum value of 20.9MPa

Table 6 Reaction forces on both supports (Keel and Horizontal)

Maximum Value Over Time	
X Axis	0. N
Y Axis	15003 N
Z Axis	39935 N
Total	42660 N

Maximum Value Over Time	
X Axis	-2.1512e-008 N
Y Axis	-15003 N
Z Axis	72504 N
Total	74040 N

9.4.2 Case 2: Structural Frames in every empty space between the wooden frames

In the current design of the structural frames, utilizing a rectangular section with dimensions of 200x100x10 mm, the analysis reveals a significant discrepancy in deflection and stress performance. On the port side, the maximum deflection observed is 16 mm, which remains well within the allowable deflection limits. However, on the starboard side, the deflection reaches an alarming value of 311 mm Figure19 , which far exceeds the acceptable threshold. This considerable deviation indicates a critical imbalance in structural stiffness and load distribution.

Furthermore, the stress analysis using the Von Mises criterion shows that certain nodes are experiencing a maximum stress of 26.537 MPa (Figure 20) , surpassing the material's yield strength. While this overstress is observed only in localized regions, it nonetheless highlights the inadequacy of the current section's capacity to withstand the applied loads without yielding.

In light of these findings, it is evident that the selected section is insufficient for ensuring structural integrity and stability. The excessive deflection on the starboard side, coupled with localized overstress, necessitates a revision of the section dimensions. An increase in both the depth and thickness of the section would likely be required to enhance its stiffness and load-bearing capacity, thereby ensuring compliance with deflection and stress limits.

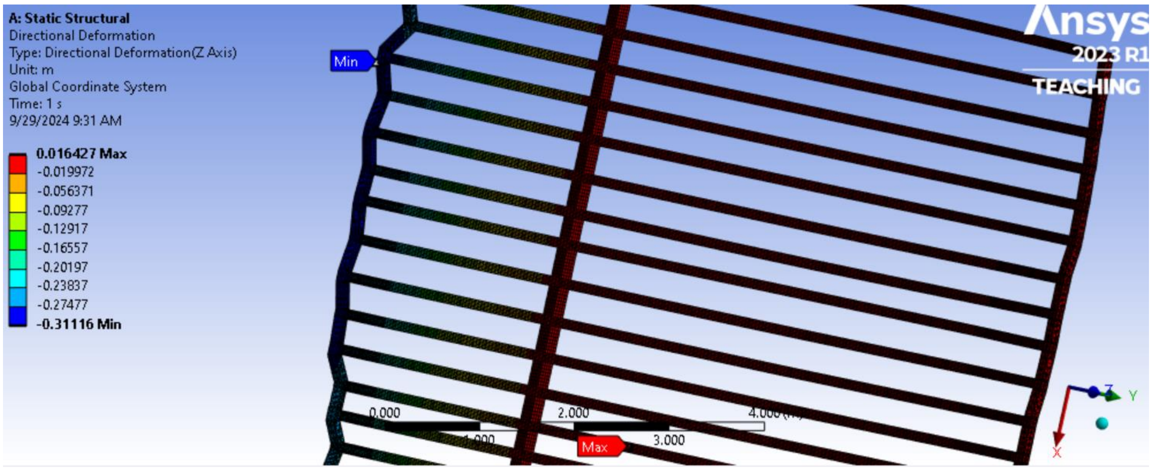

Figure 19 Deflections of the support system for the more densesupport system with the section of Case 2 200x100x10mm

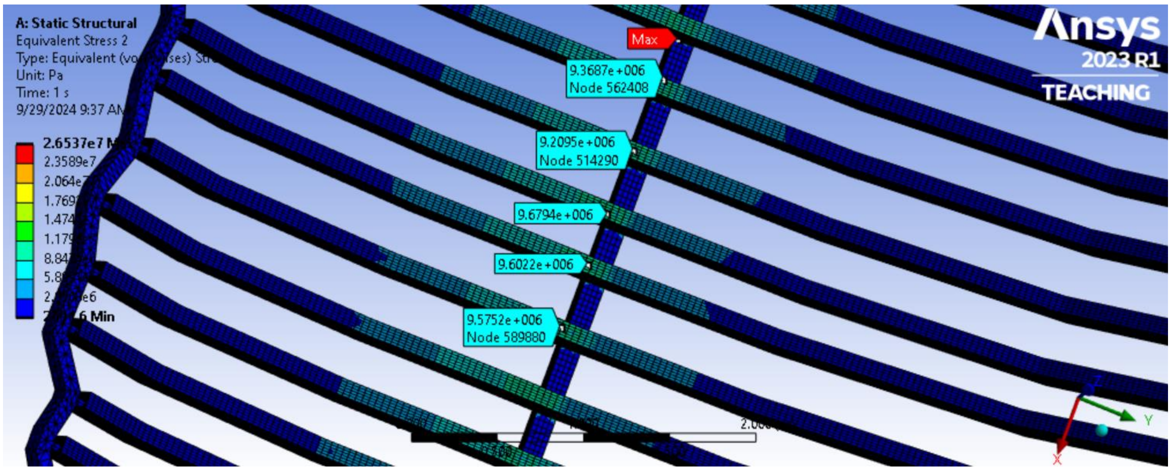

Figure 20 VonMises stress distribution on the frames with maximum distribution near to the keel For Case 2(200x100x10mm)

Table 7 The Reaction Forces on Horizontal

Maximum Value Over Time	
X Axis	0. N
Y Axis	12121 N
Z Axis	34077 N
Total	36169 N

For the revised of 230x100x20 mm the maximum deflection on the portside is 144 mm (Figure 21) which is still larger than the allowable limit. The VonMises stress is 11Mpa (Figure 22) which is below than the maximum yield strength of HDPE

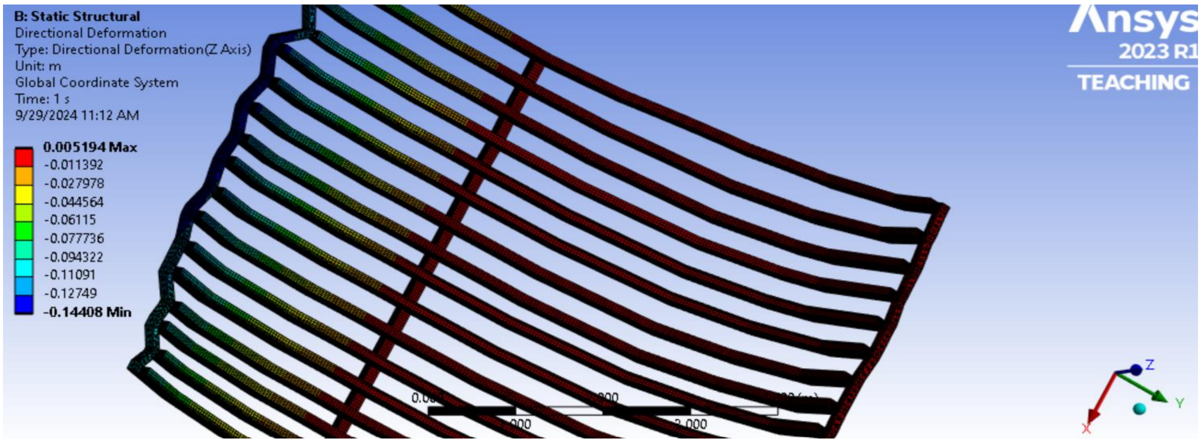

Figure 21 Deflection for the modified section of Case 2

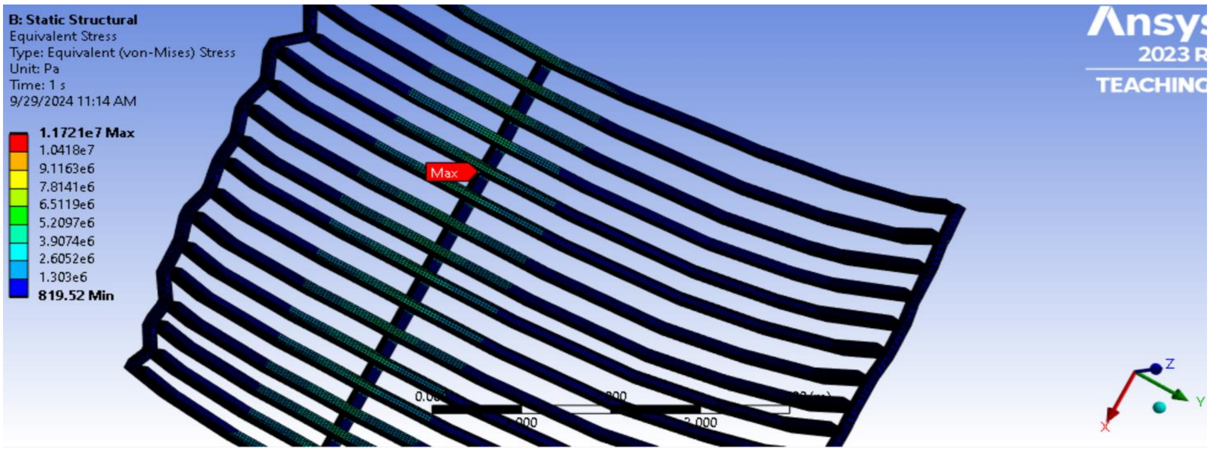

Figure 22 Distribution of VonMisses in the Support System

Table 8 Reaction forces on the keel and horizontal forces

Maximum Value Over Time		Minimum Value Over Time	
X Axis	0. N	X Axis	-3.1303e-007 N
Y Axis	15276 N	Y Axis	-15276 N
Z Axis	39379 N	Z Axis	66967 N
Total	42238 N	Total	68688 N

9.4.3 *Summary of Reaction Forces on the Horizontal Support*

In the Case 1 the length used of ship was 7.2 m and for Case 2 used length of the ship was 6.2 m.So, the load per unit in both horizontal and vertical are in the Table 9

Table 9 Distribution of force in y and z direction of horizontal support

Column1	Cross -Section (mm)	Load in y-direction(KN/m)	Load in Z-sirection(KN/m)
Case 1	200x120x10	1.6	4.9
	230x120x20	2.1	5.6
Case 2	200x100x10	2.0	4.7
	230x100x20	2.5	6.4

10 CONCLUSION AND RECOMMENDATION

The analysis of HDPE as a support system for the Medieval Newport Ship was carried out in two phases, focusing on the effect of spacing between wooden frames of the ship. In the first case, support frames were placed with alternating empty spaces between them, leaving gaps between the supports. Using a section of 200x120x10 mm, the analysis indicated failure under both the Von Mises yield criterion and the allowable deflection criterion. A revised section of 230x120x20 mm was able to meet the Von Mises stress requirement but still failed in terms of deflection, particularly on the port side. This indicated that simply increasing the section size was not sufficient to address the issue of excessive deflection.

In the second case, the spacing between the support frames was reduced, utilizing every available empty space between the wooden frames. While both the 200x120x10 mm and 230x120x20 mm sections passed the Von Mises yield criterion in this scenario, deflection remained a critical issue, especially on the port side. The deflection far exceeded the allowable limits, suggesting that the primary failure criterion for this design is the deflection on the port side. This shows that the selected section sizes and the current three-point support system are inadequate for providing the necessary stability and load-bearing capacity when using HDPE as the support material.

The analysis strongly suggests that a new approach is needed to design the support system using HDPE. One potential solution is to modify the existing three-point support system by providing additional supports on the port side, similar to the configuration used on the starboard side. Preliminary trials, as outlined in the Appendix, showed that this adjustment resulted in a significant reduction in deflection, offering a promising direction for further refinement.

In conclusion, while HDPE has potential as a material for the ship's support system, the current design is insufficient. A more robust support strategy, including additional supports on both the port and starboard sides, is recommended to improve load distribution and meet both stress and deflection criteria. Further design iterations and analysis will be required to finalize an optimal solution.

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12 APPENDIX

Modified Support System

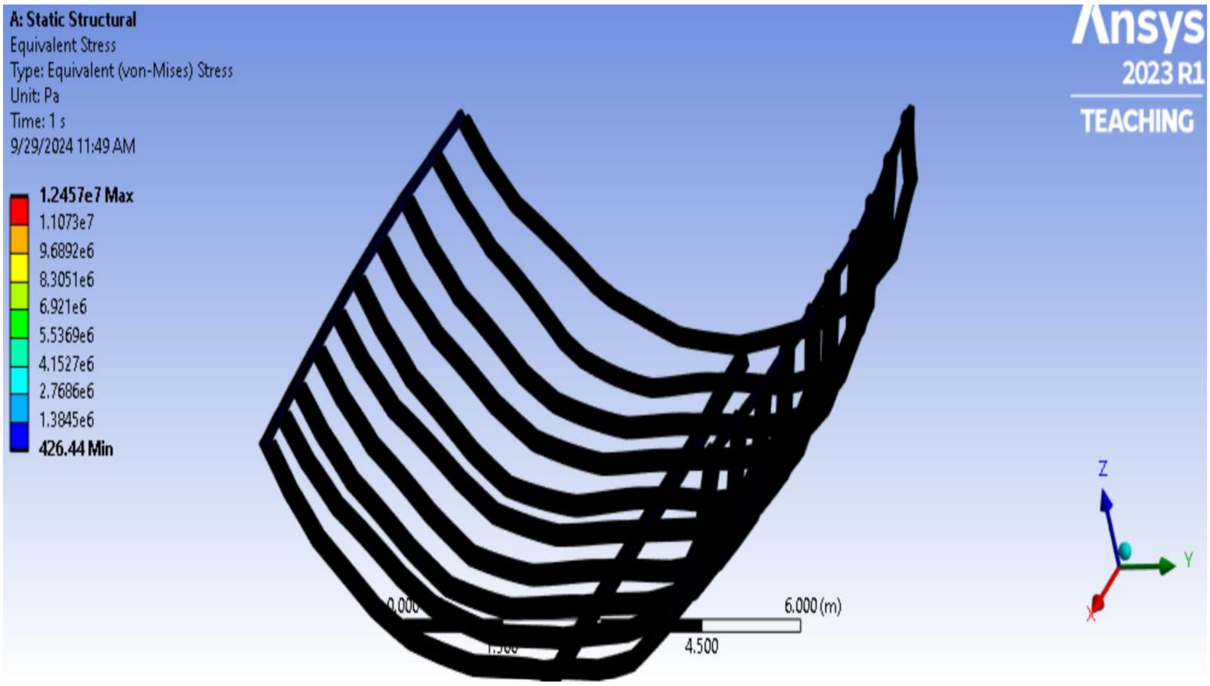

Figure 23 Von Misses stress distribution for the section 200x120x10 mm

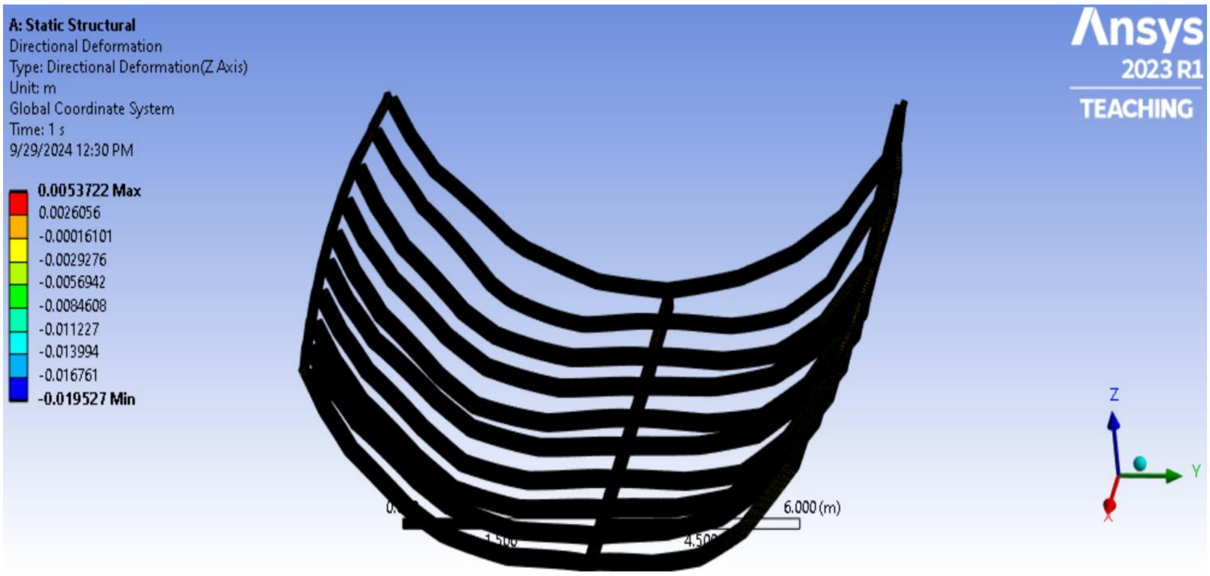

Figure 24 Maximum deflection on the portside is 19.52 mm