

Finite Element Analysis of the Construction Strength of Semi-Submarine Glass-Bottom Catamaran

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ABSTRACT

Indonesia's extraordinary marine tourism potential requires innovation in how to enjoy it. This study discusses the innovative design of a semi-submarine glass-bottom ship for the development of marine tourism in Indonesia, which allows tourists to enjoy the beauty of the underwater world safely and comfortably. This catamaran is designed with two hulls that provide high stability and optimal deck area for tourism needs. The study focuses on analyzing the ship's frame structure using the finite element analysis method, especially on using sandwich panels that combine wood and carbon fiber materials to achieve the optimal combination of structural strength, weight, and cost efficiency. Finite element analysis shows that sandwich panels with 100% carbon fiber composition provide the best mechanical performance with a maximum stress of 615.41 MPa. The analysis shows that adding carbon fiber plays a significant role in reinforcement and is a more effective stress distributor than homogeneous materials. Although the 100% carbon fiber formulation provides the highest safety factor, the study recommends a combination of 70% wood and 30% carbon fiber, or 60% wood and 40% carbon fiber for the construction of the ship's hull frame as a more optimal solution in terms of technical and economic aspects. This ship design innovation is expected to become a new tourist attraction that introduces the beauty of Indonesia's underwater world to domestic and foreign tourists while encouraging the development of a sustainable marine tourism industry.

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Keywords: Carbon fiber, catamaran, finite element, sandwich panel, semi-submarine glass-bottom.

I. Introduction

Catamarans or double-hulled vessels are used as research vessels, crew vessels, tourist vessels, passenger ferries, survey vessels, rescue vessels, and patrol vessels. The configuration of two hulls with a separation distance that can be adjusted according to operational needs provides high catamaran stability. Optimization of the distance between the hulls affects the characteristics of wave resistance at various speeds and the significant moment of inertia of the water plane, which helps to increase the transverse stability of the vessel [1]. Additionally, catamarans have more deck space than monohull vessels of the same length. They are more stable in different sea conditions, so catamarans are great for use at sea. The semi-submarine bottom catamaran is a new type of vessel that helps marine tourism grow. It allows tourists to see the beauty of the ocean without diving, in a safe and comfortable way. The hull's bottom and walls are made of glass panels that can handle the pressure of water at the ship's operational depth. The two symmetrical hulls of the catamaran design allow tourists to be safe and comfortable on their trip without being bothered by the ship's movements.



The hull's design has a big impact on the ship's structure, stability, and hydrostatic pressure [1]. For planning the ship's structure, it's very important to know its surface area because it will change the cross-sectional mass, area, shape, and length. CAD (computer-aided design) is very useful because it lets designers test and model the hull of the ship over and over again. When making plans, it's important to think about things like the weight, the water pressure, and the materials to be used. A catamaran design was chosen because it is more stable than a single hull. Stable semi-submarine glass bottoms are also a good thing. In maritime engineering, design optimization based on simulation is now very important and has effects in many other fields. This method makes ships, underwater vehicles, offshore platforms, and offshore power systems work better, cost less, and be safer by using CAD software, optimization techniques, and numerical solutions [2].

The finite element method (FEM) is a very useful tool for designing ships these days, especially for testing the structure's strength and stability. A thorough understanding of the differences between finite element modeling and numerical simulation is necessary to use this method effectively. Finite element modeling preceded numerical simulation theory. It logically assembles beams, plates, shells, and solid elements [3]. Start with the ship's CAD geometry and use CAE geometry to simplify it. The finite element analysis (FEA) shows how stress, strain, deformation, and safety factors are distributed in the ship's hull structure [4]. Glass fiber composites are strong and light, making them ideal for marine applications [5]. This method has been successful for testing complex building parts mechanically. How the maritime industry uses computers, especially getting permission to use simulation and numerical analysis software, is still problematic [6]. This method is very helpful for the 5-meter-long semi-submarine glass-bottom catamaran because it informs how water pressure from the outside and forces from the inside change the shape of the hull. The study's goal is to find the highest stress value in the ship's frame design so that it stays strong until it breaks. It also wants to know how strong the link is between the hull and the glass panel.

The framework of the semi-submarine catamaran with a glass bottom for this project was built using sandwich panel technology because sandwich panels have walls that are not very thick but are still very strong, and they could be used as structural parts [7]. This is especially true in the modern part of the maritime industry. This new way of building uses a three-layered structure that is unlike any other. It gives the structure a strong but light quality. The inside layer is softer than the two outside layers. This mix gives a structure that is perfect for meeting the needs of complicated structures. Sandwich panels are a great choice for building strong marine structures because they are light and have design benefits.

This research aims to determine how sandwich panel thickness affects semi-submarine glass-bottom catamaran loading. Glass is used in the hull to withstand water pressure and protect people. FEA for stress analysis looks at the most important parts of the hull to see how the loads and materials are spread out. The goal is to keep the structure from falling apart. Building and testing the catamaran hull showed that it keeps passengers safer, makes it less likely to capsize, and makes it easier to see underwater [8].

There is limited research on semi-submarine glass-bottom tourist boats in Indonesia, but they have the potential to significantly enhance the tourism industry. To develop new ship designs, engineers must conduct extensive research, particularly to identify the best sandwich panel materials, determine the passenger capacity, and establish the thickness and placement of the glass. Given Indonesia's diverse maritime conditions, adaptable designs are crucial. This new facility is anticipated to attract both domestic and international tourists, thereby supporting the tourism sector by facilitating underwater viewing experiences.

II. Material and Methods

1. Ship Design

Geometry modification based on geometric modeling includes CAD techniques that can perform global and local deformations and control volume changes before and after deformation [9]. Ship design semi-submarine glass-bottom catamaran is illustrated in Figure 1. This technology has profoundly impacted the ship design process in the maritime industry, as evidenced by the development of comprehensive CAD systems that have profoundly impacted design, leading to a paradigm shift in the field. It is imperative to consider not only the phase but also the production and delivery processes. The functionality of CAD systems in contemporary use extends beyond rudimentary design instruments, encompassing centralized databases.

These databases facilitate direct data exchange, enable real-time feedback, and reduce the probability of errors during the design process. Consequently, this increases productivity, accelerates production timelines, and enhances vessel market value [10]. Additionally, with the advancement of CAD technology, the feature-based approach has become increasingly prominent in CAE. This approach is superior to others because features are more critical modeling elements than points, lines, or surfaces, providing more meaningful and relevant analysis outcomes. This study employs a feature-based approach, as equipment suppliers utilize mechanical CAD systems to produce 3D assembly data [10].

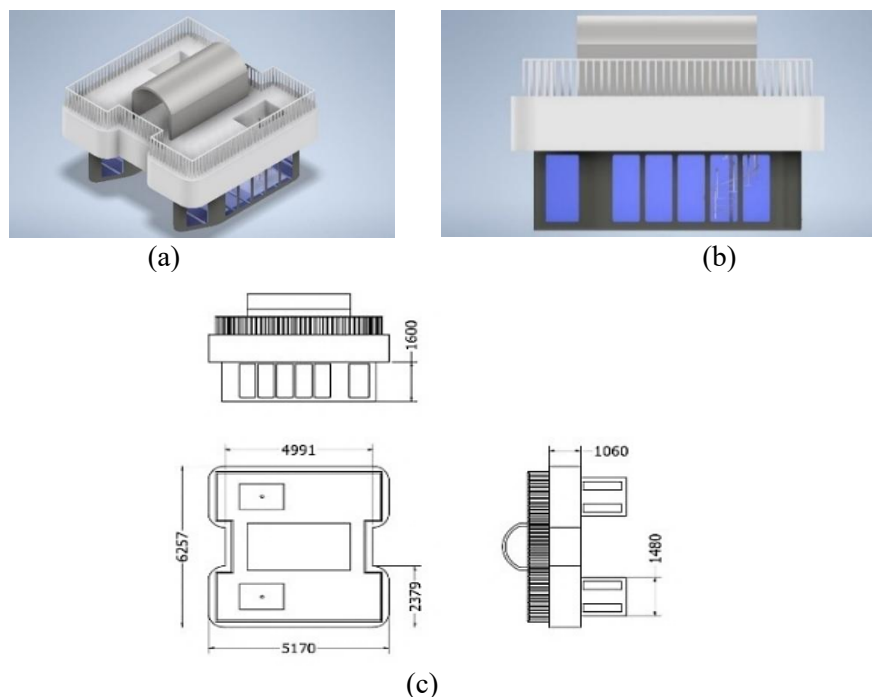


Fig. 1. Design 2D semi-submarine glass-bottom catamaran; (a) Isometric view, (b) Side view, (c) Engineering drawing

2. 3D Geometry and Principal Dimensions

In this study, the 3D geometry of the semi-submarine glass-bottom catamaran was designed using 3D CAD technology and analyzed through FEA to accurately represent the vessel's innovative structure, including the catamaran hull, transparent glass bottom, and semi-submarine configuration. As illustrated in Figure 1 and specified in Table 1, the vessel's primary dimensions, including length, width, draft, and displacement, were

meticulously delineated to enhance hydrodynamic performance. This design offers tourists a unique opportunity to observe underwater ecosystems while promoting innovation in Indonesian marine technology through a feature-based 3D modeling approach.

Table 1. Principal dimension of the ship

Symbol	Model	Unit
LOA	5170	mm
Beam	1480	mm
Draft	1600	mm
Displacement	12548.624	kg
Block coefficient	0.999	-

4. Meshing

To ensure the accuracy of FEA, the element network must be of high quality. It is essential to assess the quality of the mesh [14]. According to research, a coarse mesh size of 50 mm is the best because it strikes the best balance between speed and accuracy. Taking into account computational limits, this mesh size accurately shows how stress is spread out and how shapes change on the ship's structure. The meshing method works well for macrostructural analysis, which doesn't care about details. This method considers real-world situations such as the duration of the analysis, the available hardware, and the research objectives. It provides a comprehensive method to achieve substantial and beneficial outcomes.

5. Boundary Conditions

For FEA calculations, it is important to verify that the boundary conditions are correct. Due to these conditions, the model's parts can talk to and work with each other. The results can't be trusted without the right boundary conditions because the simulations won't accurately show how things work in the real world. There were three support structures in this study: one on the front of the hull skin and two on the back. This method allows us to check how well the ship's structure worked. Various methods were used to figure out the boundary conditions at the rigid ends of the vessel, since each support point limits a certain number of geometric degrees of freedom. These constraints and their lack of mathematical perfection allow researchers to study how the structure reacts to different types of loading. Researchers can achieve results that are quite similar to real-life circumstances by using structural stiffness.

6. Engineering Data

After modeling and meshing, a significant portion of the ship design process involves incorporating construction materials into the model according to engineering data standards. Engineering data is defined as "a set of facts or figures relevant to the field of engineering" [16]. It is essential for tracking the locations and distribution of items. In this project, both wood and carbon fiber were utilized to build the ship's frame. The thickness of the sandwich panels was varied to assess the strength comparison between the two materials. Design standards specify that the glass portion of the ship's hull must consist of conventional glass materials to ensure both clarity and strength. Carbon fiber, known for being strong and lightweight, is employed in constructing the ship's exterior shell, referred to as the "hull skin".

7. Frame Material

Sandwich panel structures with ordinary wood cores and fiber-reinforced composite layers are becoming increasingly popular in the transportation industry due to their several advantages. This material has high flexural strength and stiffness but is lightweight, with good damping properties and effective insulation [13]. From a sustainability perspective, using wood as a focal point helps reduce carbon emissions because wood is a renewable material. Studies have shown that the orientation of wood fibers significantly impacts their energy absorption capacity and resistance to impact loads. Although there has been little concrete research on the use of ordinary wood as the core of sandwich panels, this material has suitable properties at a relatively low cost, so it can be used in applications that require impact energy absorption and impact resistance, promising in the transportation sector [13]. This study analyzes sandwich panels with wood cores and carbon fiber outer layers for ship hull frame construction using FEA to evaluate the impact of thickness variations on structural performance. The goal is to determine the optimal composition for safe and cost-effective strength, providing insight into stress distribution, deformation, and mechanical behavior. However, wood selection for maritime use must consider factors such as strength, hardness, sea air resistance, and protection against organisms like teredo. Some types of wood commonly used in ship construction include teak, gopala, balau, bulgur, and bangkirai, which are selected based on their durability, strength, and dimensional stability [14].

Despite its benefits, wood has limitations, such as higher weight than composites, structural weakening from multiple joints, and susceptibility to fungal or insect damage if untreated. Integrating carbon fiber in sandwich panels mitigates these issues: carbon fiber improves tensile strength and impact resistance, while the wood core provides flexibility and vibration damping. Theoretical support for these results can be found in [16], discussing how adding fibers with a high elastic modulus to a matrix with a lower modulus increases the overall stiffness and strength of the composite material. Figure 2 shows the relationship between fiber volume fraction and the effective modulus of composite material, which supports the simulation result that increasing fiber content increases the material's stiffness. In addition, Rosid *et al.* [16] discusses how fiber orientation and fiber volume fraction percentage affect composite material's tensile and compressive strength. The graph illustrates that higher fiber content in composites increases the material's ability to withstand stress and deformation before failure, supporting the simulation results that greater fiber percentages enhance stress tolerance. Figure 2 highlights how matrix particles influence stress distribution, relevant to this study, as the wood-fiber combination forms a composite structure with fiber as reinforcement and wood as the matrix. These findings align with Gibson's theory, confirming that adding fiber improves stiffness, strength, and load-bearing capacity, making fiber-based composites superior to pure wood materials.

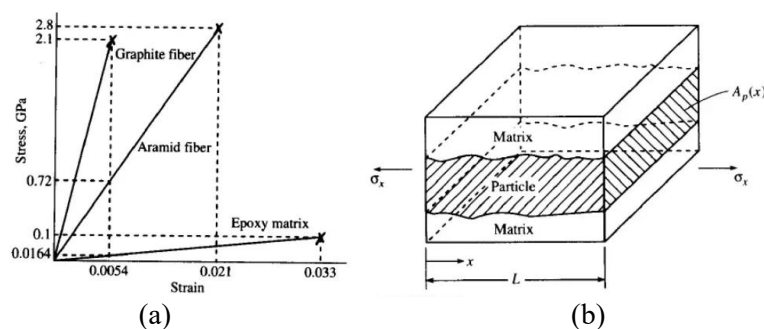


Fig. 2. (a) Effective modulus vs. fiber volume fraction; (b) Matrix particle effects on stress distribution.

8. Frame Geometry

The geometry of the ship frame structure consists of two outer layers: a bottom layer made of carbon fiber (g) and a middle layer made of wood (h), as illustrated in Figure 3. The upper and lower carbon fibers function as laminates, strengthening the structure. Concurrently, the middle wood core maintains the distance between the two fiberglass layers, thereby ensuring optimal stiffness and strength properties with relatively low weight.

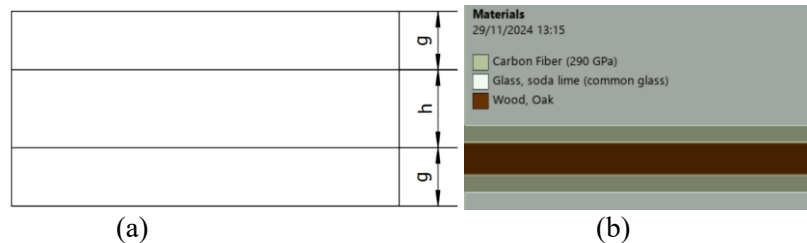


Fig. 3. Geometry of sandwich panel construction frame material; (a) 2D CAD; (b) 3D CAE

9. Frame Material Variations

Testing different thickness configurations on sandwich panels aims to ascertain the optimal combination of structural strength, design weight, and cost efficiency. This approach enables the assessment of the performance of composite materials under diverse environmental conditions and ship operational loads. The range of materials utilized in the fabrication of sandwich panels is enumerated in Table 2. The results of this study are expected to provide insight into the development of innovative and efficient ship designs that utilize the advantages of wood and fiberglass-based sandwich construction.

Table 2. Variation of frame material thickness

Variation	Carbon fiber (mm)	Wood (mm)	Carbon fiber (mm)
100% Wood	-	50	-
90% Wood & 10% Fiber	2.5	45	2.5
80% Wood & 20% Fiber	5	40	5
70% Wood & 30% Fiber	7.5	35	7.5
60% Wood & 40% Fiber	10	30	10
50% Wood & 50% Fiber	12.5	25	12.5
100% Fiber	25	-	25

10. Ship Weight Calculation

Table 3 shows the weights used in this study, with the gross weight of 3554.061 kg.

Table 3. Calculation of ship weight

Weight type	Weight	Unit
Machine	538	kg
Outfit	47.745	kg
Fuel	8.5	kg
Passenger	1200	kg
Hull	1759.816	kg
Total	3554.061	kg

Converting the gross weight to Newton (N) is important in determining the external load in an FEA simulation, using Eq. (1) [15].

$$F = m \cdot g \quad \dots\dots\dots (1)$$

Where: $F = \text{force (N)}$; $m = \text{massa (kg)}$; $g = \text{gravitational acceleration (m/s}^2\text{)}$

Using equation (1), the external force on the ship's hull frame structure can be calculated:

$$F = m \cdot g = 3554.061 \text{ kg} \cdot 9,81 \frac{\text{m}}{\text{s}^2} = 34856.34 \text{ N}$$

9. Von Mises Stress Validation

FEA von-Mises stress is an equivalent stress value used to determine whether a particular material will begin to yield during the maximum von Mises stress value [17]. Manual calculations are performed using formulas based on material and structural mechanics theories, essential for obtaining von Mises stress estimates on a particular object. A comparison was made between the simulation results and manual calculations, with the former being derived from the latter. If the discrepancy between the two is less than 5%, the simulation model and manual calculations are both accurate, consistent, and can be trusted.

For example, manual calculation of von Mises stress with a von Mises stress value of 600.06 MPa is carried out on materials with 50% wood and 50% carbon fiber variations using a mesh size of 50 mm. The calculation results will be carried out using Eq. (2).

$$\sigma_{vm} = \sqrt{\frac{1}{2}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)} \quad \dots\dots\dots (2)$$

Where: $\sigma_1 = \text{maximum principal (650.13 MPa)}$; $\sigma_2 = \text{middle principal (117.52 MPa)}$; $\sigma_3 = \text{minimum principal (15.884 MPa)}$

$$\sigma_{vm} = \sqrt{\frac{1}{2}((650.13 - 117.52)^2 + (117.52 - 15.884)^2 + (15.884 - 650.13)^2)} = 590.03 \text{ MPa}$$

The difference between the calculated von Mises stress result (590.03 MPa) and the equivalent stress value mentioned (600.06 MPa) is about 1.67%. Since this difference is below 5%, the result can be considered accurate and valid.

10. Finite Element Validation

To further emphasize the validity of the results, manual calculations (analytical method) will be carried out at specific points on the object, as was done in studies [18] and [19]. In a study [18], manual calculations were carried out by considering shear stress and everyday stress, while in the study [19], manual calculations also considered mesh variations on the object being analyzed.

The present study validates von Mises stress at points of maximum stress by employing different mesh sizes. This approach is used to assess the impact of mesh variation on simulation accuracy and to ensure the model's validity. Analytical calculations of total von Mises stress for a 50% wood and 50% carbon fiber composition are performed using Eq. (2). The validation process emphasizes critical points that exhibit the highest stress levels, as illustrated in Figure 4. Point 1 serves as the primary reference due to its maximum stress value. Points 2, 3, and 4 are also evaluated for their significant stress levels in key structural areas. This methodological approach ensures simulation accuracy while enhancing the understanding of stress distribution and structural performance.

Table 4 and Figure 5 indicate that there is minimal difference between the results of manual calculations and simulation. This similarity suggests that the simulation's modeling method, material parameter selections, and boundary conditions are grounded in assumptions derived from analytical calculations. The close alignment of the two outcomes demonstrates that the simulation effectively predicts the behavior of the parts or structures under study. The 50 mm mesh size was selected due to its lowest error value compared to other mesh sizes, indicating that the simulation is likely to be quite accurate. Therefore, the validation results obtained have met the desired reliability standards. The amalgamation of manual calculations and simulations provides a robust foundation for concluding that the model and analysis have been adequately validated. This is in line with previous research [20], which shows that simulation results with the FEM can be validated analytically with an error below 5% so that the reliability of the numerical approach in predicting stress and structural behavior is valid.

Table 4. Comparison of manual calculation and simulation results

Point	Mesh size	Manual calculation (MPa)	Simulation calculation (MPa)	Error
1	49	614.19	604.75	1.56%
	50	590.03	600.06	1.67%
	51	581.44	592.27	1.86%
2	49	546.54	548.02	0.27%
	50	567.28	568.7	0.25%
	51	535.8	537.33	0.29%
3	49	559.85	556.21	0.65%
	50	546.62	550.05	0.62%
	51	540.99	545.95	0.91%
4	49	523.3	526.47	0.60%
	50	541.8	543.52	0.32%
	51	486.44	489.49	0.62%

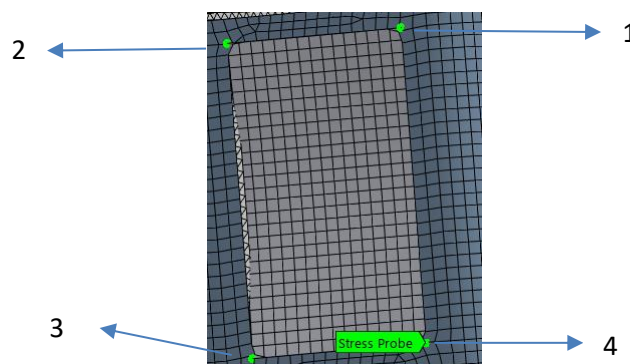


Fig. 4. Analysis points for von Mises stress validation

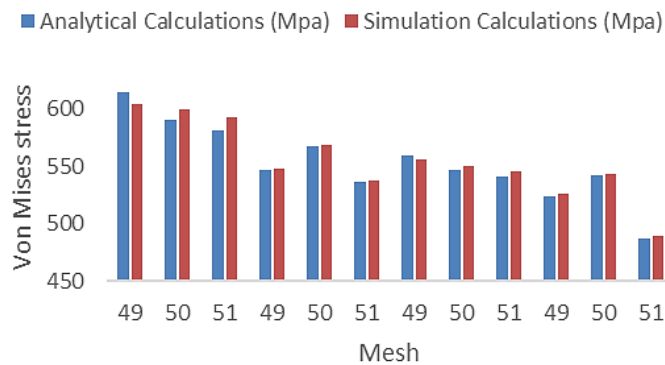


Fig. 5. Validation results “Analytical (equation approach) vs simulation (FEM)”

11. Safety Factor

Safety factor is Allowable Material Stress (equivalent stress generated during simulation with ANSYS structural statics) [17]. Calculating the safety factor of a 100% Fiber sandwich panel using Eq. (3):

$$SF = \frac{\sigma_{maks}}{\sigma_{actual}} \dots\dots\dots (3)$$

$$SF = \frac{2900 \text{ MPa}}{615.41 \text{ MPa}} = 4.71$$

The Safety Factor (SF) calculation for different material combinations can also be done analytically, as has been done in research [21]. Calculation of the safety margin of the design was conducted using the formula Eq. (3). By entering the yield stress of each material, such as wood and carbon fiber, in the sandwich panel, it obtain the analytical Safety Factor results that reflect how much structural strength reserves are facing the workload that occurs.

Each material possesses unique mechanical properties, making yield stress a critical factor in establishing design safety limits. To accurately represent each material's contribution to structural strength, it is essential to highlight that wood has a lower yield stress than carbon fiber. This study presents the safety factor and identifies structural vulnerabilities, which can be leveraged to improve both technical and economic efficiency. Numerical simulations, such as FEA, can confirm the validity of these analytical conclusions. This process ensures the reliability of estimates based on the yield stress of each material. The findings demonstrate that the sandwich panel frame of the semi-submarine glass-bottom catamaran meets the safety standards outlined in SOLAS Chapter II-1, confirming that the vessel can support operational loads.

III. Results and Discussions

1. Finite Element Simulation Analysis

To determine the strength and rigidity of a vessel, it is essential to utilize computer-aided engineering, particularly FEM analysis. FEM facilitates the fragmentation of geometry, which simplifies the analysis of ship hulls. CAD creates virtual prototypes that enhance this analysis. This study employs FEA to investigate how variations in the thickness of sandwich panels influence load distribution within a ship frame using actual material properties, boundary conditions, and stress factors to ensure that our analyses are accurate at a 1:1 scale. This methodology strengthens the ship's structure and materials prior to construction.

CAE Geometry

This study's 3D CAE geometry is designed to facilitate the collection of samples from one of the hulls for further research. The 3D CAE geometry of the ship's hull is a crucial task that must be executed systematically and thoroughly, especially for the semi-submarine glass-bottom vehicle. The model's geometry is initially generated using CAD and subsequently transformed into CAE geometry. This process of simplification allows FEA to clarify the structure's stress, strain, deformation, and safety factors.

Meshing

For this study, the coarse mesh network could only have elements that were no bigger than fifty millimeters. It has been carefully designed to make global mesh studies more useful, especially in places where microstructural features aren't as significant as they are in other situations. This technique is more user-friendly because it has lesser computing requirements. It allows for the simulation of complicated systems with minimal resources. To gain this advantage, one must strike a balance between the importance of analytical reliability and the precision of geometric measurements.

Boundary Conditions

This study utilizes boundary conditions by strategically placing three support structures at specific locations to limit the model's movement. One support is situated on the front hull skin, while the other is located at the rear, as depicted in Figure 6. These placement choices simulate the vessel's loading and support conditions, accurately representing the stress distribution and deformation. The boundary conditions preclude translation or rotation at these points, thereby simulating the real-world constraints that the structure would encounter under operational conditions. In analogous applications, axial and rotational displacements are constrained along the centerline of the impacted vessel. In contrast, the striking ship is restricted axially along the x- and z-axes. This allows movement only in the transverse direction, ensuring that the model's behavior closely reflects the forces and motions the vessel undergoes during actual use or collision scenarios [22].

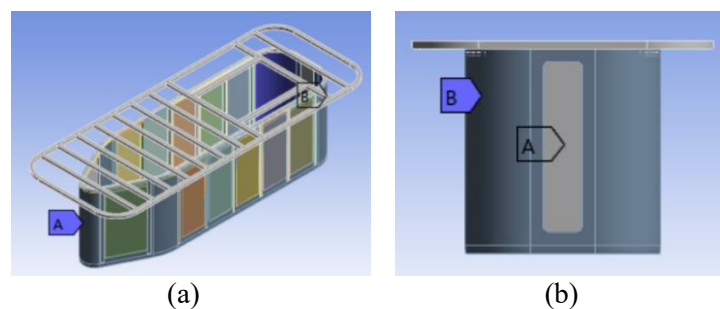


Fig. 6. Boundary conditions in CAE; (a) Front point, (b) Back point

Pressure and Force Distribution

The force value uses the results from equation (1), which is 34856.34 N. The pressure value is obtained from the draft size in Table 1, which is 1600 mm or 1.6 m. The hydrostatic pressure value in seawater can be calculated using Eq. (4).

$$P = \rho \cdot g \cdot h \dots\dots\dots (4)$$

Where: P = hydrostatic pressure; ρ = seawater density = 1025 kg/m³; g = gravitational acceleration = 9.81 m/s²; h = depth = 1.6m

Using Eq. (4), the pressure or hydrostatic pressure on the ship's hull frame structure can be calculated:

$$P = \rho \cdot g \cdot h = 16072.8 \text{ Pa} = 0.0161 \text{ MPa}$$

The calculated pressure and force values are input into the FEA as shown in Figure 7.

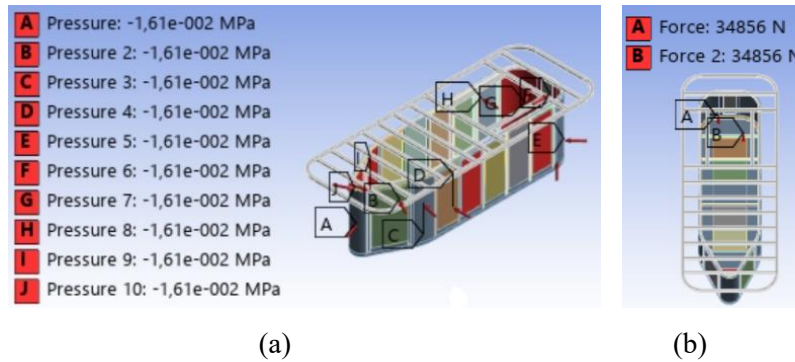


Fig. 7. Distribution points: (a) pressure, (b) force

2. Finite element analysis (FEA) results

In this study, the researchers found that the mechanical characteristics of sandwich panels with variations in the composition of wood and carbon fiber materials significantly affect the structural performance of the material. The primary focus of FEA is the maximum stress value, also known as von Mises stress. The findings of the FEA depicted in Figure 8 and Table 5 reveal that the 100% carbon fiber sandwich panel exhibits optimal mechanical performance, with a maximum tensile strength of 615.41 MPa.

Table 5. Finite element analysis result

Variation	Von Mises Stress (MPa)
100% wood	595.66
90% wood & 10% fiber	600.97
80% wood & 20% fiber	600.82
70% wood & 30% fiber	600.93
60%wood & 40% fiber	600.05
50% wood & 50% fiber	600.06
100% fiber	615.41

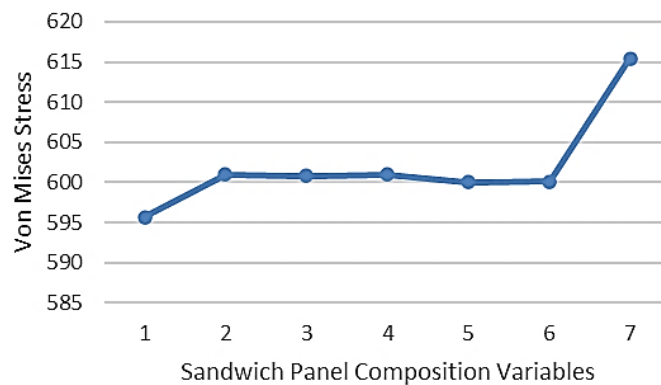


Fig. 8. Graph of finite element analysis results

In comparison, the 90% wood and 10% carbon fiber composite, with its composition of 90% wood and 10% carbon fiber, demonstrates a maximum tensile strength of 600.97 MPa. As illustrated in Figure 8, the results of the FEA for each sandwich panel composition demonstrate the impact of varying material configurations on structural strength. The findings demonstrate that laminating wood with carbon fiber and incorporating a regulated quantity of sandwich panels can enhance the strength and toughness of the hull frame structure of a semi-submersible glass-bottom catamaran.

Conversely, if the 100% wood material does not provide optimal strength and toughness, it may not be a viable option. The material's 100% composition yielded a stress value of 595.66. This finding indicates that pure wood material has inherent limitations in its capacity to resist internal and external loads. The phenomenon can be explained through the material strengthening mechanism. Fiber is a reinforcing agent, endowing the material with enhanced structural integrity and stress distribution capabilities surpassing traditional wood. In addition to exhibiting superior tensile strength and load-bearing capacity, the 90% wood and 10% carbon fiber sandwich panels demonstrate notable economic superiority. Employing limited carbon fiber enables superior material performance without substantially escalating production costs. Consequently, this variety of sandwich panels offers a balanced solution between technical performance and economic efficiency.

3. Safety Factor Calculation

The results of the safety factor calculation are presented in Table 6. As demonstrated in Table 6, which details the safety factor calculation data, it can be concluded that an increase in the percentage of carbon fiber lamination on the sandwich panel corresponds to an increase in the resulting safety factor value. This finding indicates that incorporating carbon fiber lamination into the sandwich panel configuration can enhance the system's structural integrity under load. It has been demonstrated that, when composed entirely of carbon fiber, the safety factor exhibits its maximum value of 4.71. However, when a sandwich panel composed of 90% wood and 10% carbon fiber is employed, the safety factor experiences a substantial decline to only 0.46. It has been demonstrated that an increase in the percentage of carbon fiber in sandwich panels is directly proportional to an increase in the safety factor value. This phenomenon is attributable to the inherent properties of carbon fiber, which possesses higher tensile strength and stiffness than wood. Consequently, incorporating carbon fiber in a more substantial percentage can serve as a solution to enhance the safety and durability of ship frame construction structures.

Table 6. Safety factor results of sandwich panels

Variation	Safety Factor
100% wood	0.08
90% wood & 10% fiber	0.46
80% wood & 20% fiber	1.02
70% wood & 30% fiber	1.50
60% wood & 40% fiber	1.98
50% wood & 50% fiber	2.45
100% fiber	4.71

IV. Conclusions

The analysis indicates that the optimal solution for constructing the semi-submarine glass-bottom catamaran hull frame is wood and carbon fiber sandwich panels. FEA has revealed that sandwich panels composed of 90% wood and 10% carbon fiber exhibit optimal mechanical performance, with a maximum stress of 600.97 MPa being attained. However, the material composition of 100% carbon fiber still produces a higher maximum stress. Consequently, in this study, sandwich panels were strategically implemented to achieve a mechanically optimal structure while offering a more economical solution.

Incorporating fiber within the sandwich panel structure functions as a reinforcing element, facilitating more effective stress distribution compared to homogeneous materials. The findings of the safety factor calculation demonstrate a direct proportionality between the percentage of carbon fiber and the safety factor value. Notably, a composition of 100% carbon fiber attains the maximum value of 4.71, signifying a heightened level of safety. Integrating wood and carbon fiber materials in sandwich panels has yielded optimal structural strength for constructing the semi-submarine glass-bottom catamaran hull frame. Furthermore, it is imperative to prioritize the safety factor of the sandwich panel combination. A combination of 70% wood and 30% carbon fiber, as well as 60% wood and 40% carbon fiber, is recommended for constructing the hull frame, considering both factors. The tensile strength of the composition, safety factor, and economic value are the parameters by which this phenomenon is measured. The development of the semi-submarine glass-bottom catamaran tourist ship in Indonesia is poised to significantly impact the marine tourism sector, offering a novel attraction for both domestic and international visitors.

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