Thermal Distribution Mapping and Its Role in Informing Fatigue Life Predictions of FRP Patrol Vessels

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Abstract. Fiberglass Reinforced Plastic (FRP) composites are extensively used in maritime applications due to their high strength-to-weight ratio, corrosion resistance, and adaptability to complex designs. However, the effects of operational thermal conditions on FRP's viscoelastic properties and fatigue life remain understudied, particularly in tropical environments. This study focuses on determining the temperature range for Dynamic Mechanical Analysis (DMA) testing by analyzing the thermal distribution of an FRP patrol vessel operating in Bangka Belitung waters. Thermal simulations using Ansys Steady State Thermal and Finite Element Analysis (FEA) identified critical zones on the vessel. The maximum temperature, approximately 70°C, was observed near the engine bulkhead in the stern area. However, this study focuses on load-bearing regions experiencing significant thermal and mechanical stresses, where temperatures range between 35°C to 45°C. These values were selected for DMA testing to evaluate FRP's viscoelastic behavior under operationally relevant conditions. The results highlight how localized thermal gradients affect FRP's structural performance and provide critical input parameters for future fatigue life studies. By integrating thermal analysis with the selection of operational temperature ranges, this study offers a robust framework to enhance the design and reliability of FRP patrol vessels in tropical maritime environments.

Keyword: Fiberglass Reinforced Plastic, Thermal Distribution, Dynamic Mechanical Analysis, Fatigue Life Prediction, Finite Element Simulation.

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1 Introduction

Fiberglass Reinforced Plastic (FRP) has become the primary material of choice in various maritime applications due to its superior mechanical properties, such as high strength-to-weight ratio, corrosion resistance, and the ability to be molded into complex designs [1].This material has been widely utilized in various structural elements of ships, such as hulls, decks, and bulkheads, as well as supporting components like propellers and machinery elements [2], [3]. In the context of modern ship design, FRP offers advantages in fuel efficiency and improved structural integrity, making it a competitive solution compared to conventional materials such as steel and aluminum [4].

However, the viscoelastic properties of FRP make it sensitive to thermal environmental effects, especially in tropical regions where ships often operate under extreme thermal conditions. Tropical regions, such as the waters of Bangka Belitung, exhibit atmospheric temperatures reaching up to 35°C and an average seawater temperature of 29°C[5]. The combination of atmospheric heat, solar radiation, and exhaust heat from ship engines creates significant temperature gradients within the ship structure, particularly in areas near heat sources such as the engine room. This phenomenon can affect the thermal stability of FRP material, ultimately impacting the structural integrity and reliability of ships in the long term[6].

Previous research has identified several challenges associated with the fatigue behavior of FRP materials, particularly in relation to temperature and environmental exposure. Increasing temperatures have been shown to degrade the elastic modulus and strength of FRP, leading to reduced structural performance[7]. Similarly, exposure to harsh marine environments accelerates the aging process of composite materials, further compromising their long-term durability[8]. However, many of these studies were conducted under controlled laboratory conditions, which do not fully account for the dynamic variability of operational temperatures, especially in tropical climates. Furthermore, conventional fatigue life prediction methods, such as S-N curves, often fail to capture the time- and temperature-dependent viscoelastic behavior of FRP materials, limiting their applicability to real-world scenarios.

In recent years, Dynamic Mechanical Analysis (DMA) has become an essential tool for evaluating the viscoelastic properties of FRP materials. DMA enables the analysis of storage modulus (G'), loss modulus (G''), and damping factor (Tan δ) across a wide range of temperatures, providing a deeper understanding of changes in the mechanical properties of materials due to thermal cycling and mechanical loading[9]. Nevertheless, the literature related to the application of DMA for FRP material characterization in tropical environments remains limited. Most studies focus only on room temperatures, while the effects of actual temperature distribution during ship operation remain poorly understood[10].

This research aims to address these gaps by analyzing the temperature distribution on FRP patrol vessels operating in tropical waters. The study employs Ansys Steady State Thermal software to model the temperature distribution across the ship structure based on realistic operational environmental parameters, including maximum air temperature, seawater temperature, and engine exhaust heat. This Finite Element Analysis (FEA) based approach is complemented by mesh validation to ensure high numerical accuracy, with thermal errors maintained below 2% [11]. The simulation results are used to determine the temperature range that will serve as input for DMA testing, focusing on the operational range between 35°C and 45°C.

Despite extensive utilization of Fiberglass Reinforced Plastic (FRP) in maritime applications, existing studies often rely on controlled laboratory conditions that fail to capture the dynamic and extreme thermal gradients encountered in tropical maritime environments. Furthermore, conventional fatigue life prediction methods inadequately address the viscoelastic behavior of FRP under combined thermal and mechanical stresses. This research aims to bridge these gaps by employing thermal distribution simulations that replicate operational conditions in tropical waters, particularly in the Bangka Belitung region. The study provides a systematic approach to identifying critical thermal zones and determining representative temperature ranges for Dynamic Mechanical Analysis (DMA) testing, with a focus on operationally relevant parameters. By integrating advanced finite element analysis and material characterization, this research contributes to the development of more robust fatigue life prediction models for FRP materials. The findings are anticipated to enhance the reliability and longevity of FRP patrol vessels operating under tropical conditions, setting a new benchmark for performance optimization in marine engineering.

2 Methodology

2.1. Vessel Design and Operational Parameters

The patrol vessel constructed from Fiberglass Reinforced Plastic (FRP) in this study was designed by the Hydrodynamic National Research and Innovation Agency. This design addresses the critical need for lightweight, durable, and corrosion-resistant materials in maritime applications, especially under the challenging operational conditions prevalent in tropical coastal regions such as the Bangka Belitung waters. E-glass FRP was chosen due to its high strength-to-weight ratio, tensile strength of approximately 3448 MPa, and low thermal conductivity of 0.3–0.4 W/m·K, which are essential for minimizing thermal stresses in marine environments [12].

The Bangka Belitung waters are characterized by distinct tropical environmental factors, including air temperatures reaching up to 35°C during the day and average seawater temperatures of 29°C. These conditions, combined with heat emissions from the propulsion system specifically exhaust gases from the generator reaching 70°C create a significant thermal gradient across the vessel's structure [13], [14]. This gradient is further intensified by direct solar radiation, which contributes to localized heating, especially in areas near the engine room and exhaust channels. Such thermal loads exacerbate the risk of thermo-mechanical degradation, a phenomenon where prolonged exposure to elevated temperatures reduces the material's mechanical integrity and viscoelastic performance [15].

To address these challenges, this study began with a comprehensive literature review of FRP material properties, including their thermal resistance, mechanical behavior, and long-term performance under hygrothermal conditions. Particular attention was given to how UV exposure and moisture absorption influence the aging process of FRP composites. For example, while short-term UV exposure may increase material stiffness, prolonged exposure can cause resin embrittlement, reducing the material's lifespan [13]. Additionally, studies on the hygrothermal aging of epoxy resins highlight reversible yet critical changes in mechanical properties that must be accounted for in vessel design [15].

The study further incorporates advanced simulation techniques using Ansys Steady-State Thermal software to analyze the temperature distribution across the vessel's structure under real-world conditions. This simulation integrates environmental parameters such as air and seawater temperatures and heat flux from internal machinery, ensuring an accurate representation of operational scenarios [14]. Numerical modeling techniques, including mesh convergence analysis, were employed to ensure that thermal errors remain below 2%, enhancing the reliability of the results and identifying critical thermal zones requiring further evaluation [16].

By combining material characterization, environmental analysis, and numerical simulation, this research provides a robust framework for assessing the thermo-mechanical performance of FRP patrol vessels in tropical maritime environments. The findings contribute to a deeper understanding of material behavior under thermal loads and offer practical insights into optimizing patrol vessel design for enhanced durability and operational efficiency.

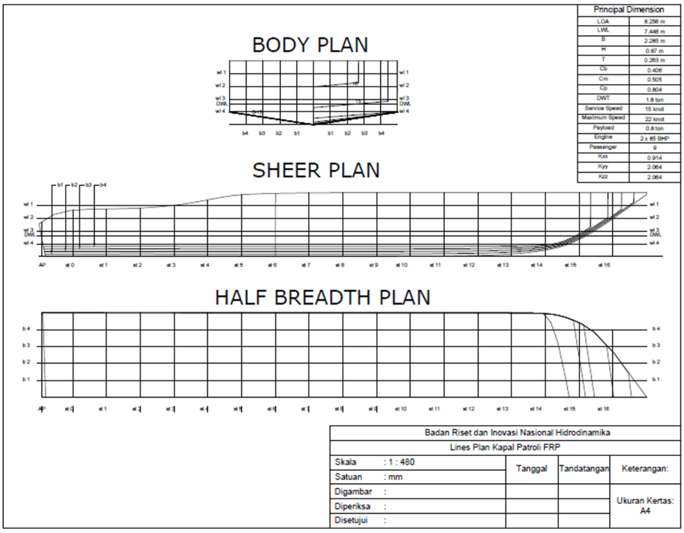
2.2 Hull Modelling

The data collection phase ensures the numerical model accurately represents the physical structure and operational characteristics of the FRP patrol vessel. Key inputs include the vessel's lines plan, general arrangement drawings, and the FRP material's mechanical and thermal properties, such as elastic modulus and thermal expansion coefficient, to simulate its thermal behavior under operational conditions. Focused on a patrol vessel operating in Bangka Belitung waters, this study uses its principal dimensions and specifications, as outlined in Table 1, to precisely replicate the actual design for simulation.

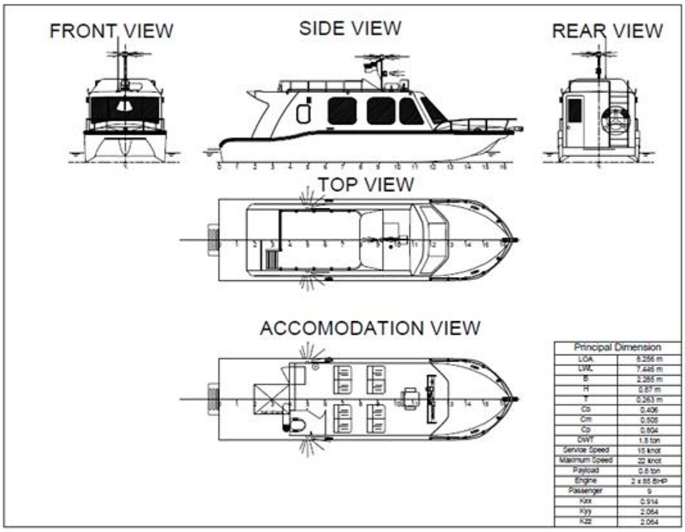
Table 1. Principal Dimension of FRP Patrol Vessel

Principal Dimension			
LOA	=	8.256	m
LWL	=	7.446	m
B	=	2.285	m
H	=	0.87	m
T	=	0.263	m
Cb	=	0.406	
Cm	=	0.505	
Cp	=	0.804	
DWT	=	1.8	ton
Service speed	=	20	knot
Maximum speed	=	30	knot
Payload	=	0.8	ton
Propulsion	=	2 x 85	BHP
Passengers	=	9	persons
Kxx	=	0.914	m
Kyy	=	2.064	m
Kzz	=	2.064	m

The patrol vessel is specifically designed to endure the dynamic conditions of coastal waters, characterized by variable wave directions and heights. To achieve this, careful consideration is given to the ship's structural configuration, geometric profile, and material selection. The modeling process involves compiling critical parameters such as the primary dimensions, weight distribution coefficients (Kxx, Kyy, Kzz), and detailed material properties. The lines plan and general arrangement, which serve as essential references for the structural and geometric design, are illustrated in Fig. 1.



(a). Lines Plan of FRP Patrol Vessel



(b). General Arrangement of FRP Patrol Vessel

Fig 1. (a) Lines Plan and (b) General Arrangement as part of the FRP Patrol Vessel design

The lines plan and general arrangement obtained serve as the primary references for the development of the patrol vessel's 3D model. The presentation of this data provides an accurate geometric and structural foundation for the modeling process, ensuring a detailed representation of each vessel component. This patrol vessel is designed using E-type Fiberglass Reinforced Plastic (FRP) [17], known for its high mechanical strength and corrosion resistance. The resin utilized is Yukalac 157, which possesses excellent thermal and mechanical properties, as detailed in Table 2.

Table 2. Material Properties of FRP Patrol Vessel

Mechanical and Thermal Properties of E-Type FRP with Yukalac 157 Resin		
Density	1.39	g/cm^3
Young Modulus	3200	Mpa
Poisson's Ratio	0.3	
Bulk Modulus	2666.7	MPa
Shear Modulus	1230.8	MPa
Tensile Yield Strength	190	MPa
Tensile Ultimate Stength	105	MPa
Thermal Conductivity	0.3	W/m.K
Specific Heat Capacity	384.5	J/kg.K
Coefficient of Thermal Expansion	10-3x10^{-6}	1/°C

Table 2 presents the mechanical and thermal properties of E-type Fiberglass Reinforced Plastic (FRP) with Yukalac 157 resin, which serve as the primary input for the temperature distribution simulation. This data ensures that the numerical analysis results accurately reflect the material characteristics under tropical operational conditions. Once the patrol vessel's FRP material properties are identified, the next step involves determining the patrol vessel's detailed construction dimensions. This information is a critical element for developing the numerical model and conducting the thermal distribution simulation. The primary dimensions of the patrol vessel's FRP construction used in this study are summarized in Table 3 below.

Table 3. Construction Dimensions of the FRP Patrol Vessel

Table of Dimensions for FRP Patrol Vessel Construction		
Description	Dimension	Unit
Longitudinal Deck Beams	40 x 30 x 4	mm
Main Frame	30 x 30 x 4	mm
Bottom Thickness	10	mm
Side Thickness	8	mm
Main Deck Thickness	4	mm
Deck Beam	60 x 60 x 12	mm

2.3 Thermal Distribution Simulation

Following the collection of essential data including material properties, construction dimensions, and environmental parameters the FRP patrol vessel model was developed using

Ansys SpaceClaim. This software enables high-fidelity 3D visualizations, ensuring accurate representation of the patrol vessel's geometry and structure. Ansys also supports steady-state thermal simulations, providing a reliable framework for analyzing heat transfer and thermal behavior in composite structures. Such simulations are critical in marine applications to optimize design and ensure structural reliability under varying operational conditions [18]. Figure 3 illustrates the digital model, which forms the basis for thermal analysis, replicating real-world structural and environmental conditions.

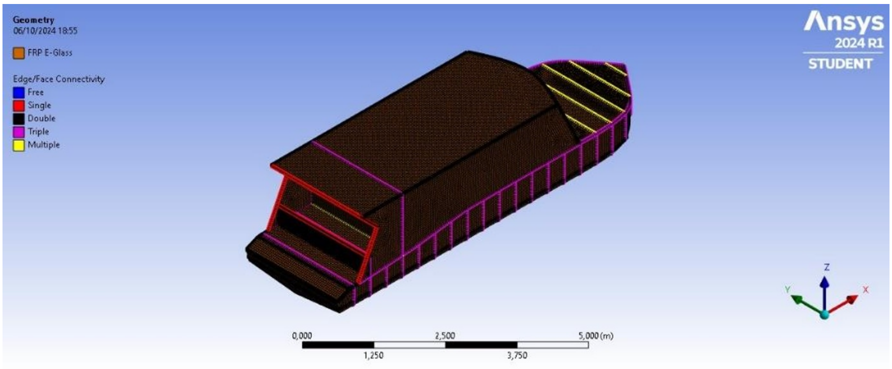


Fig 3. FRP Patrol Vessel Model

This patrol vessel model is designed to operate in the coastal waters of Bangka Belitung, which has a tropical environment characterized by an average sea water temperature of 29°C and a maximum air temperature of 35°C. These conditions create significant thermal challenges for Fiberglass Reinforced Plastic (FRP) composite ship structures, especially due to the material's sensitivity to temperature gradients and continuous heat exposure. The combination of heat from atmospheric and aquatic mediums, plus thermal emissions from the ship's engine systems, demands a comprehensive thermal distribution analysis to understand the impact of these conditions on material behavior.

Once the operational parameters were comprehensively established, the ship geometry model was transferred to Ansys Steady State Thermal software to perform the thermal distribution analysis. This analysis begins with the mesh discretization process, which is an important step in Finite Element Method-based simulations. Discretization is performed using the grid independence method to validate the mesh used, ensuring that the simulation results are independent of the mesh size. This grid validation is applied incrementally, with the thermal error deviation kept within a tolerance of less than 2% [11]. This aims to improve numerical accuracy while minimizing bias due to non-optimal discretization.

2.4 Numerical Model Validation and Convergence

Validasi Validation and convergence of numerical parameters are performed to ensure the stability and accuracy of thermal simulation results on FRP-based ship structures. In this process, convergence criteria are strictly applied. First, the monitor point imbalances are kept below 0.5% to ensure local stability in critical areas. Secondly, the global imbalances in the system are kept not to exceed 1%, so that the overall thermal energy distribution is within acceptable tolerance. Third, the temperature variation between iterations is kept less than 0.1°C, ensuring that the difference in temperature values between iterations is close to the numerical equilibrium condition. This approach provides assurance that the thermal simulations performed are not only stable but also precise enough to be used in further analysis.

The mesh validation process is essential for ensuring the accuracy of analyses based on the Finite Element Method. This validation involves assessing the convergence of simulation results across varying mesh sizes until further refinement no longer influences the outcomes. Such an approach aligns with methods outlined in previous studies, which demonstrate that mesh quality can be enhanced through the application of Jacobian techniques, ensuring compliance with validity criteria and enabling reliable simulation results in Ansys software [19].

In another study, it was highlighted that in steady-state thermal analysis, the application of certain temperatures on the inner and outer surfaces of the analyzed structure is essential to represent the thermal distribution of the material under operational conditions[20]. This approach is used in this study by applying an average seawater temperature of 29°C and a maximum air temperature of 35°C as external thermal boundaries. Meanwhile, the engine zone receives thermal input from the generator exhaust heat that reaches 70°C, creating a significant thermal gradient in the ship structure.

The importance of mesh configuration is crucial in thermal simulations, as it directly influences both the accuracy of the results and computational efficiency. To ensure reliable outcomes, mesh validation was performed through iterative refinement, particularly in regions with high thermal gradients, guaranteeing results that are independent of mesh size. This approach produced realistic temperature distributions, supporting the analysis of critical thermal zones and determining the temperature range for Dynamic Mechanical Analysis (DMA) testing[21].

The obtained temperature distribution analysis results then become the empirical basis in determining the temperature range for material characterization through Dynamic Mechanical Analyzer (DMA) testing. This approach ensures that the investigated temperature intervals have a direct relevance and correlation with the thermal profile of the ship's operational environment, resulting in applicable and reliable material characteristic data for the evaluation of the structural performance of patrol vessels under ship operational environmental conditions.

3. Result and Discussion

3.1 Temperature Distribution on Ship Structure

Through numerical simulations using Ansys Steady State Thermal software, the temperature distribution on a Fiberglass Reinforced Plastic (FRP) patrol vessel structure has been modeled in detail and thoroughly. The simulation adopts a Finite Element Analysis (FEA) approach to map the heat transfer mechanism under steady state thermodynamic equilibrium conditions that directly represent the operational scenario of the ship in a tropical environment.

The modeling process begins with the definition of FRP material parameters, including thermal conductivity, specific heat capacity, and thermal expansion coefficient, followed by the integration of thermal constraints that represent realistic operational conditions. The simulation results reveal a pronounced thermal gradient, with the engine room bulkhead identified as a critical zone where the maximum temperature reaches 45°C due to exhaust heat generated by the ship's engine system. Similar observations were made in a study that identified engine-adjacent areas as critical thermal zones in foam-core sandwich composite ships, emphasizing the impact of localized heat sources, such as engines, in inducing elevated thermal gradients and compromising the structural integrity of composite materials [22].

Conversely, other structural regions of the ship, including the bow and stern plating, exhibit relatively lower and more moderate temperature distributions, ranging between 29°C and 35°C. This pattern is consistent with findings that areas farther from primary heat sources in reinforced composite structures tend to experience reduced thermal gradients, thereby mitigating susceptibility to thermal-induced degradation over time [23]. A detailed representation of the ship's temperature distribution is presented in Table 4, while the spatial visualization of thermal gradients is illustrated in Figure 4.

Table 4. Temperature Distribution Critical Areas of The SEP-HULL Patrol Vessel

Ship Construction	Minimum Temperature (°C)	Maximum Temperature (°C)
Bulkhead	35	70
Frame	35	45
Bow Plating	29	31
Stern Plating	29	31
Plating Midship	32	35

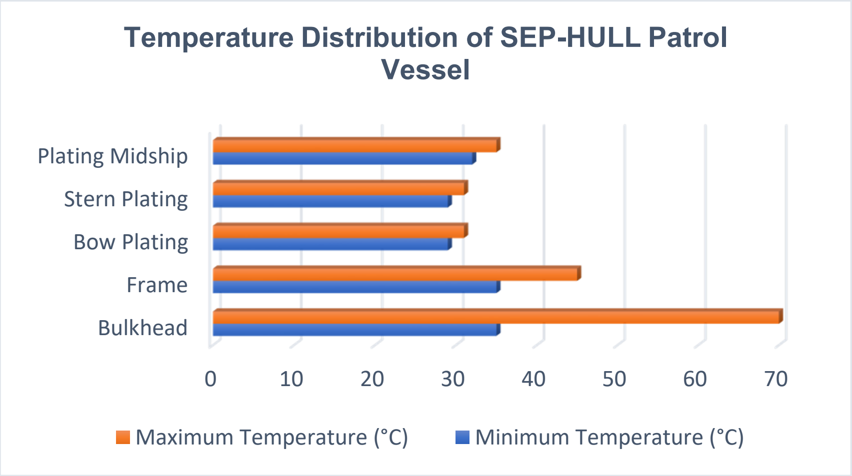


Fig 4. Graphical Representation Temperature Distribution in Various Structural Zones of the SEP-HULL Patrol Vessel

Thermal simulation simulation results presented in Table 3 and Figure 4 highlight critical temperature distributions across structural zones of the SEP-HULL patrol vessel, emphasizing the influence of thermal gradients on structural integrity. The engine room bulkhead exhibits the highest thermal concentration, reaching approximately 70°C, primarily due to localized exhaust heat. This elevated temperature accelerates thermal degradation and significantly impacts the viscoelastic properties of the FRP material. Structural frames, with peak temperatures of 45°C, experience moderate yet noteworthy thermal exposure, especially considering their critical role as load-bearing components and their proximity to heat sources. These thermal conditions are pivotal, as they induce thermal stresses in load-bearing zones, altering the FRP's storage modulus, loss modulus, and damping factor. Consequently, this compromises the mechanical reliability and long-term performance of the vessel under operational conditions.

Localized heating from engine systems and solar radiation significantly contributes to thermal gradients within FRP structures. Solar radiation creates non-uniform heating that induces thermal stresses, a phenomenon commonly observed in maritime applications [24]. This thermal disparity can result in material softening under cyclic loads, thereby accelerating degradation [25]. Additionally, differential thermal expansion between FRP and adjacent components, such as bulkheads, exacerbates stress concentrations in critical areas, increasing the likelihood of mechanical failure.

In contrast, regions such as the bow and stern plating exhibit moderate thermal ranges (29°C–35°C), attributed to their distance from primary heat sources. These zones are less prone to thermal-induced degradation, yet they are vital for the vessel's structural integrity [23]. The variations in temperature distribution necessitate defining operationally realistic thermal inputs for Dynamic Mechanical Analysis (DMA) testing. Critical temperatures of 35°C, 40°C, and 45°C, representative of load-bearing zones, are selected to evaluate FRP's viscoelastic response under realistic conditions, bridging the gap between simulation and experimental material characterization.

The observed thermal behavior underscores the interplay of conduction and convection as dominant heat transfer mechanisms. Conduction governs internal heat flow due to FRP's low thermal conductivity, while convection impacts external surfaces exposed to tropical environments. The resulting gradients accelerate mechanical property degradation under thermal cycling, highlighting the need for precise thermal management strategies [26]. This integrative approach ensures robust predictions of FRP performance under combined thermal and mechanical stresses The observed thermal behavior underscores the interplay of conduction and convection as dominant heat transfer mechanisms. Conduction governs internal heat flow due to FRP's low thermal conductivity, while convection impacts external surfaces exposed to tropical environments. The resulting gradients accelerate mechanical property degradation under thermal cycling, highlighting the need for precise thermal management strategies [26]. This integrative approach ensures robust predictions of FRP performance under combined thermal and mechanical stresses.

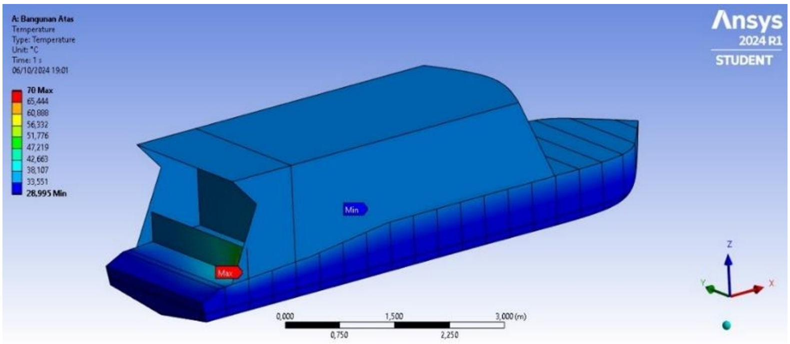


Fig 5. Temperature Distribution on The SEP-HULL Patrol Vessel Structure

Heat transfer in FRP materials is primarily governed by conduction, influenced by key thermal properties such as heat conductivity and specific heat capacity, which shape the temperature distribution. Externally, convection drives energy exchange between the vessel's surface and the surrounding air, fluctuating in a tropical environment with an average temperature of 35°C. Solar radiation further complicates heat transfer, particularly at the ship’s surface, which experiences higher temperatures than internal areas.

The numerical model incorporates boundary conditions that replicate real operational scenarios. Thermal loads from the engine, reaching 70°C in the engine room, combined with ambient heat and solar radiation, create a non-uniform temperature distribution across the ship's structure. To ensure accuracy, a mesh sensitivity analysis was performed, refining areas with steep temperature gradients. Refined mesh validation has been shown to substantially improve the precision of thermal simulations in composite structures under complex environmental conditions, as demonstrated in prior research [27]. These findings emphasize the importance of mesh optimization to ensure reliable thermal gradient predictions. This approach guarantees that simulation results are independent of computational domain discretization, thereby accurately representing the ship's realistic thermal profile.

The simulation results reveal a temperature distribution pattern that illustrates the formation of isothermal contours within the ship's structure. The bulkhead zone, located at the afterbody, is identified as the region with the highest heat concentration, reaching a maximum temperature of 70°C, as shown in Figure 6. In contrast, areas such as the bow and stern exhibit lower temperature profiles, ranging between 29°C and 31°C, while the midship region demonstrates a more stable thermal gradient, with temperatures between 32°C and 35°C. This non-uniform thermal distribution indicates the presence of thermal stress phenomena, which could potentially impact the long-term structural stability of the vessel.

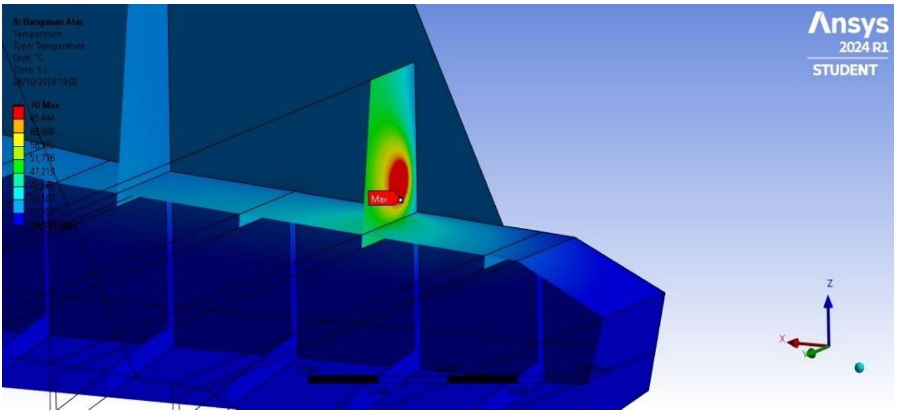


Fig 6. Temperature Maximum

As part of this preliminary analysis, these findings provide a crucial foundation for further discussion of critical zones within the ship's structure, particularly the bulkhead area. Emphasis on this region is essential due to the significant thermal exposure, which can accelerate material degradation, induce internal stress, and increase the risk of material fatigue. A detailed discussion regarding the thermal distribution's influence on critical areas and its implications for structural performance is elaborated in Section 3.2.

3.2 FRP Patrol Vessel Critical Area Analysis

Based on the thermal simulation results, the critical area in the FRP ship structure is identified at the frame located within the hull. This frame serves as a primary load-bearing element that significantly contributes to the structural rigidity of the ship; however, it is also susceptible to material degradation due to prolonged exposure to elevated temperatures during operation. The thermal distribution reveals maximum heat concentration in areas adjacent to heat sources, such as the engine room and propulsion system, resulting in significant temperature gradients within the structure, as illustrated in Figure 7.

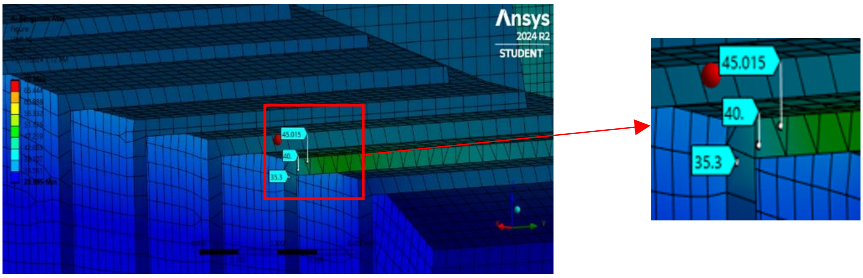


Fig 7. FRP Patrol Vessel Critical Area

The thermal distribution illustrated in Figure 7 is in line with the findings of other studies emphasizing that the bulkhead area often appears as a critical zone in thermal analysis. The study explained that the thermal response at the bulkhead remained consistent despite changes in mesh size, highlighting the importance of the design of this component in mitigating heat propagation[28]. In addition, Wulandari emphasized that non-optimal frame or bulkhead design can increase the risk of structural failure due to prolonged exposure to heat[29]. Therefore, the thermal design of the frame not only supports structural integrity but also acts as a barrier to heat accumulation in certain areas.

Significant temperature fluctuations in the frame area can cause material temperatures to exceed the glass transition temperature (Tg) of FRP, impacting viscoelastic properties by reducing the elastic modulus and increasing thermal deformation [10]. Elevated temperatures may transition the polymer resin from a glassy to a rubbery state, causing mechanical degradation and stress concentrations in critical zones, accelerating material deterioration. Thermal mismatches between the fiber and matrix further generate residual stress during heating and cooling, reducing resistance to cyclic loading, especially in areas subjected to repeated thermal and mechanical stresses [30]. Thermal aging of FRP composites affects storage and loss modulus, leading to long-term performance decline [31]. Adaptive design strategies, such as adjusting DMA test temperature ranges, can improve the evaluation of material performance under thermal exposure. Selecting FRP materials with higher thermal resistance, adding insulation layers, and optimizing cooling systems can mitigate thermal damage [32]. Thermal analysis of critical zones, such as bulkheads and trusses, enhances the durability of FRP structures and reduces heat-induced degradation risks [33]

These findings highlight the importance of prioritizing frame areas in thermal analysis to ensure the structural integrity and reliability of FRP patrol vessels. A data-driven design approach, considering thermal distribution effects, can significantly improve vessel safety and performance under operational conditions.

3.3 Convergence and Validation of Thermal Simulation

Validation of simulation results is a crucial step to ensure that the numerical model is able to accurately represent the temperature distribution in FRP ship structures. The validation process is carried out through two main approaches: mesh element convergence analysis and average thermal error evaluation, which aim to assess the stability and reliability of the simulation results.

3.3.1 Mesh convergence

The simulation process uses the Finite Element Method (FEM) approach, which is highly dependent on the quality and density of the mesh. To ensure that the simulation results are not affected by the number of mesh elements, a convergence test was conducted by gradually increasing the number of elements. The graph in Figure 8 illustrates that the average thermal error decreases exponentially with an increase in the number of mesh elements.

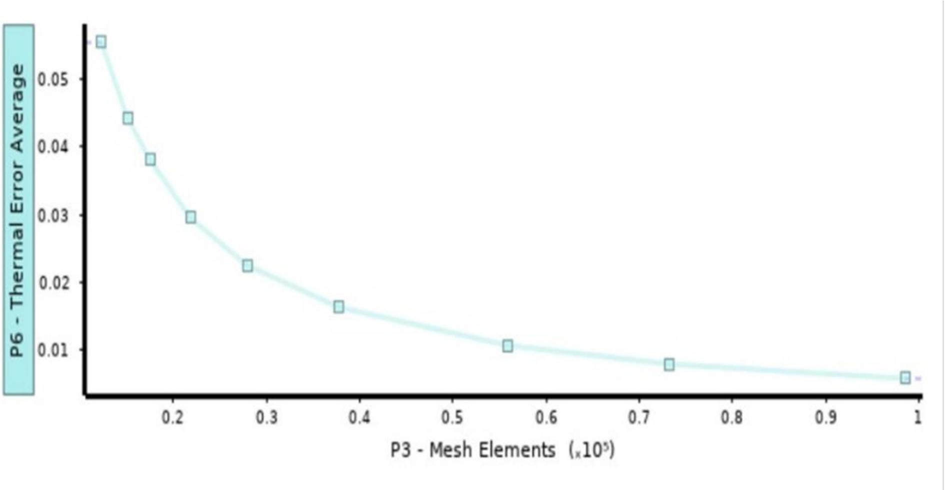


Fig 8. Trend Thermal Error

At a mesh density of about 106 elements, the average thermal error value has reached a stable minimum value, which is less than 0.01. This indicates that the model has reached a numerical convergence condition, so the mesh distribution used can be considered valid for further analysis without the risk of bias due to numerical discretization.

3.3.2 Evaluasi Thermal Error

The average thermal error is calculated as an indicator of the difference between the simulation results and the reference value assumed to be the baseline. This analysis aims to measure the simulation's ability to represent thermal distributions that are close to field conditions.

Table 5. Thermal Error Data Based on Mesh Element Density

Name	**P2 - Mesh Element Size**	**P1 - Temperature Average**	**P3 - Mesh Elements**	**P4 - Temperature Maximum**	**P5 - Temperature Minimum**	**P6 - Thermal Error Average**
Units	mm	C		C	C	%
DP 8	100	34.44	12270	70	29.00	0.055
DP 7	90	34.14	15083	70	29.00	0.044
DP 6	80	34.03	17487	70	29.00	0.038
DP 5	70	33.83	21835	70	29.00	0.029
DP 4	60	33.68	27873	70	29.00	0.023
DP 3	50	33.51	37745	70	29.00	0.016
DP 0 (Current)	40	33.35	55902	70	28.99	0.011
DP 1	35	33.27	73204	70	29.00	0.008
DP 2	30	33.25	98487	70	29.00	0.006

The evaluation results show an exponential relationship between increasing mesh density and decreasing thermal error values. As the number of elements increases up to the maximum density (106 elements), the error value decreases significantly to below 2% [11]. This decrease is in line with the principle of numerical convergence in the finite element method which asserts that simulation results approach the exact solution with an increase in the number of mesh elements. This level of accuracy is considered excellent for thermal simulation applications on FRP-based structures, where accurate temperature distribution is a critical aspect in ensuring the reliability of numerical analysis results[34].

3.3.3 Implications of Validation Results

These validation results strengthen the reliability of the numerical model in analyzing thermal distribution in FRP-based ship structures. The mesh convergence process ensures that geometric and thermal parameters do not produce numerical biases due to discretization inaccuracies. With low and stable thermal errors, the model meets the accuracy standards required to support the identification of thermal critical areas as discussed in 3.2.

3.4 Recommended Temperature Range for DMA Test

Determining the right temperature range for Dynamic Mechanical Analysis (DMA) testing is a crucial step in understanding the viscoelastic properties of glass fiber composite (FRP) materials, especially for applications in FRP-based ship structures. The recommended temperature range should reflect the operational conditions of the material so that the analysis results can accurately represent the characteristics of the material in the real environment. DMA testing allows the evaluation of storage modulus and loss modulus, which are strongly influenced by temperature, especially in the temperature range approaching or exceeding the glass transition temperature (Tg) of the material [9].

The temperature ranges selected in the DMA test were 35°C, 40°C, and 45°C. This selection was based on the need to reflect the thermal exposure conditions in critical areas with a high degree of representation of the actual operational situation. This approach is in line with the findings in another study which confirmed that temperature has a significant influence on the viscoelastic properties of materials, especially around the glass transition temperature. The study showed that viscoelastic properties, such as dynamic modulus, undergo significant changes when the material is in the critical operational temperature range[9].

By focusing on this range, DMA testing is expected to provide comprehensive information regarding changes in the mechanical properties of FRP due to thermal exposure. This data is critical for identifying potential material degradation, especially in areas of highest stress, as well as supporting the development of more reliable and durable vessel designs in the face of dynamic operating environments. The selected temperature range allows for a more precise analysis of the effects of thermal fluctuations on the viscoelastic behavior of FRP, such as a decrease in save modulus or an increase in loss modulus, which directly affects the reliability of the vessel structure.

4. Conclusion

This study highlights the influence of thermal distribution on the structural performance and reliability of Fiberglass Reinforced Plastic (FRP) patrol vessels operating in tropical maritime environments. Numerical simulations using Ansys Steady State Thermal identified critical thermal zones, with the highest temperature reaching 70°C near the engine room bulkhead. This extreme temperature is primarily attributed to exhaust heat generated by the ship's generator, combined with solar radiation and ambient tropical conditions. These findings emphasize the importance of localized thermal gradients, which significantly impact the viscoelastic properties of FRP materials, including reductions in modulus and potential material degradation over time.

The primary objective of this research was to establish a representative temperature range for Dynamic Mechanical Analysis (DMA) testing, reflecting the actual operational conditions of the vessel. Based on the simulation results, critical temperatures of 35°C, 40°C, and 45°C were selected to evaluate the viscoelastic response of FRP materials under operationally relevant conditions. This approach bridges the gap between thermal simulations and experimental material characterization, providing a robust framework for predicting fatigue life and optimizing the structural design of FRP vessels.

The incorporation of mesh convergence validation, achieving thermal error rates below 2%, ensures the reliability and accuracy of the numerical model. The study also highlights the dominance of conduction within the material's internal layers, governed by its low thermal conductivity, and convection at the ship's surface exposed to tropical air. These dual mechanisms underscore the necessity of detailed thermal modeling to understand FRP behavior under combined thermal and mechanical loads.

In conclusion, this research provides valuable insights into the thermal behavior of FRP patrol vessels in real-world operational environments. By integrating thermal distribution analysis with DMA testing, the study offers practical guidelines for enhancing the durability, safety, and reliability of FRP vessels in tropical maritime applications. These findings establish a foundation for future studies aimed at refining fatigue life prediction models and improving the structural performance of FRP in marine engineering.

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