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Review Article

Thermal and Structural Analyses of Aluminium Matrix Composite Reinforced with Palm Kernel Shell, Bamboo Fibre, Rice Husk and Groundnut Shell

Eboigbe, C. I[1]*, Ajitaadun, O. J[1]

[1]Department of Production Engineering, University of Benin, Nigeria

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***Corresponding author:** Eboigbe, C. I
Department of Production Engineering, University of Benin, Nigeria

Abstract

This research presents a comprehensive thermal and structural evaluation of a newly developed aluminium matrix composite reinforced with selected agricultural by-products—palm kernel shell, bamboo fibre, rice husk, and groundnut shell—using Finite Element Analysis (FEA) within the ANSYS 2025 environment. Aluminium scrap served as the matrix material in the composite fabrication. The experimental design followed a D-Optimal mixture approach, yielding twenty-five specimen combinations, each tested thrice, with mean values recorded. Specimen fabrication employed the stir casting technique. Optimization of process parameters and response outcomes was performed using Design Expert software. The composite model was developed using SOLIDWORKS for subsequent simulation analysis. Results from the thermal and structural simulations indicate a fatigue life of 1×10^6 cycles. The computed maximum and minimum total heat fluxes were 1.8122×10^6 W/m² and 1.515×10^6 W/m², respectively, while the fatigue damage factor reached 1000. The safety factor varied between 4.836 and 15. Temperature values ranged from 23.685°C to 170.000°C. The composite exhibited equivalent elastic strain values between 1.054×10^{-6} and 2.9051×10^{-5}. Directional deformation along the x-axis ranged from -2.5905×10^{-7} m to 2.5889×10^{-7} m. Equivalent (Von-Mises) stress was recorded between 1.3224×10^5 Pa and 5.8104×10^7 Pa, while total deformation ranged from 0.0000 m to 2.5912×10^{-7} m. These findings underscore the mechanical and thermal reliability of the developed composite material for engineering applications under variable thermal and mechanical loads.

Keywords: Aluminium Matrix, Agro-Waste Reinforcements, Palm Kernel Shell, Bamboo Fibre, Finite Element Analysis, Thermal Simulation.

1.0 INTRODUCTION

The increasing need for materials that are lightweight, mechanically robust, thermally stable, and economically viable has intensified research into advanced composite materials for engineering applications. Sectors such as automotive, aerospace, and manufacturing require materials that can effectively balance mechanical strength, thermal performance, wear resistance, and corrosion resistance without compromising cost-efficiency. Conventional materials often fall short in providing these multi-functional capabilities, thereby propelling interest in metal matrix composites (MMCs), particularly those with aluminium as the base matrix.

Aluminium matrix composites (AMCs) have gained considerable attention due to their favourable properties including high strength-to-weight ratio, thermal conductivity, and corrosion resistance. Integrating reinforcement from naturally derived or agro-waste materials further enhances their appeal, aligning with sustainable development goals by converting waste into valuable engineering inputs. Reinforcements such as palm kernel shell (PKS), bamboo fibre, rice husk, and groundnut shell offer not only environmental benefits but also significant potential for enhancing composite performance in structural and thermal applications.

This study explores the thermal and structural behaviour of a novel AMC reinforced with these agro-waste materials, using aluminium scrap as the matrix.

The incorporation of agricultural residues as reinforcements introduces a low-cost and sustainable alternative to synthetic fibres, potentially reducing environmental impact and production costs. The composite material was developed and analyzed using state-of-the-art computational tools to evaluate its viability in heat-intensive and mechanically demanding environments.

Finite Element Analysis (FEA) was employed through ANSYS 2025 software to investigate the thermal response and structural integrity of the developed composite under simulated operational conditions. The 3D model of the material was constructed using SOLIDWORKS to ensure geometrical precision for the simulations. Thermal analysis provided insights into temperature gradients, heat distribution, and flux across the material, while structural analysis examined deformation patterns, stress distribution, strain behaviour, fatigue performance, and safety factor under cyclic loading conditions.

This research builds upon earlier works that demonstrated the efficacy of numerical techniques in material and component analysis. For instance, Eboigbe and Achebo (2019) used FEA to optimize residual stresses in welded mild steel joints, highlighting the power of computational methods in stress modelling. Similarly, Ebhojiaye and Eboigbe (2022) applied FEA in the design and stress analysis of an 80cc spark ignition engine connecting rod, reinforcing its utility in assessing durability and performance of mechanical components. By employing similar tools and methodologies, this study aims to establish the suitability of the newly developed agro-waste-reinforced AMC for real-world engineering applications requiring reliable thermal and structural performance.

Figure 1 illustrates the 3D representation of the developed composite material model used in the simulation analyses.

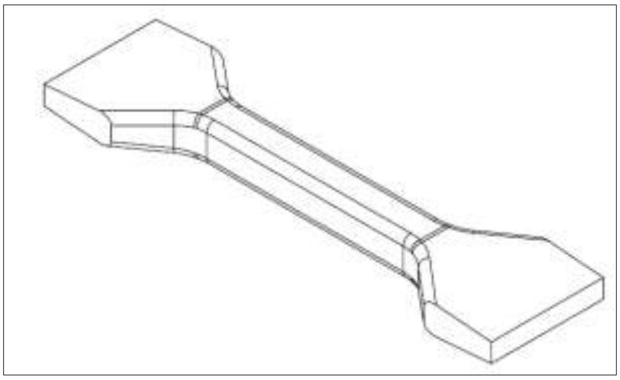

Figure 1: 3D Model of the developed Composite Material

2.0 THERMAL ANALYSIS

Thermal analysis is a critical tool in engineering for evaluating how materials respond to temperature variations over time. It provides essential insights into thermal gradients, heat transfer characteristics, temperature distributions, and heat flux within a system. These thermal parameters are fundamental for determining the suitability of materials in high-temperature environments and applications where thermal stability is vital.

Oghoghorie *et al*., (2022) emphasized the importance of thermal characterization in their investigation of a locally developed internal combustion engine cylinder head using Finite Element Analysis (FEA). Similarly, Farooq Omar (2024) noted that Computational Fluid Dynamics (CFD) and FEA are now widely adopted to study thermal behaviour in composite systems, particularly where heterogeneous materials such as agro-waste reinforcements are involved. These numerical methods allow for detailed, non-destructive simulation of thermal performance under different operating conditions.

Moreover, thermal simulations have become indispensable in the design and optimization of modern engineering components such as engine parts, turbine blades, heat exchangers, pipeline systems, and electronic packaging (Reddy *et al*., 2016). The capacity of a material to maintain structural integrity under thermal loading is paramount in these contexts. Hence, thermal evaluation is a prerequisite for material selection and system reliability in thermally active environments.

In this study, thermal simulations were conducted using ANSYS 2025 to determine the response of the developed aluminium matrix composite when subjected to varying thermal conditions. The analysis followed a structured approach comprising preprocessing (geometry import and material assignment), simulation setup (application of thermal loads), and post-processing (interpretation of output data), in line with the framework proposed by Roylance (2011).

2.1 Mesh

To ensured that fine sizes are employed in the analysis to get accurate results, meshing should be done according to *Rahman et al., 2008.* The mesh generated is shown in figure 2.

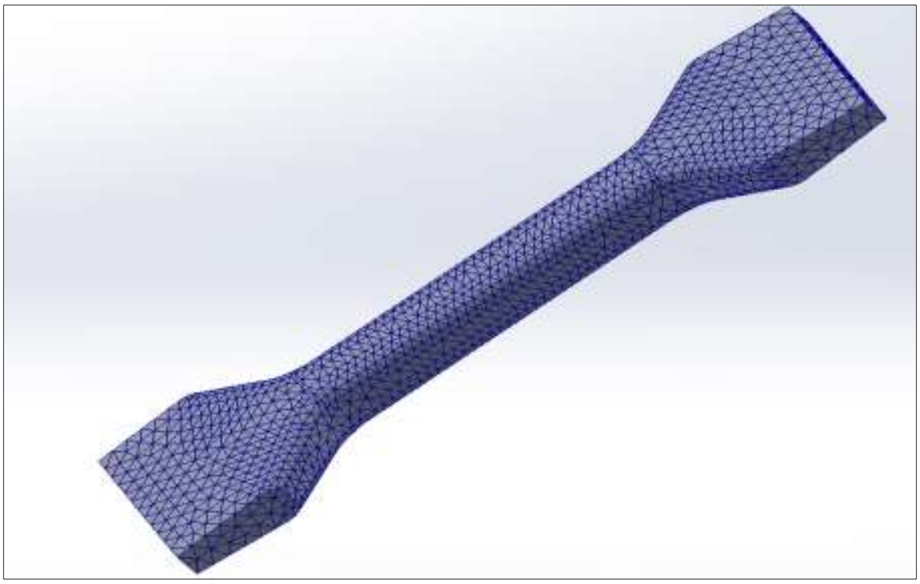

Figure 2: Generated Mesh

2.2 Temperature

Table 1 shows the temperature load on the material at different points in time.

Table 1: Temperature load on the material at different points in time

Steps	Time [s]	Temperature [°C]
1	0.0	20.0
	1.0	52.0
2	2.0	84.0
3	3.0	116.0
4	4.0	138.0
5	5.0	170.0

Figure 3 shows the graph of the temperature load applied to the composite material faces against time.

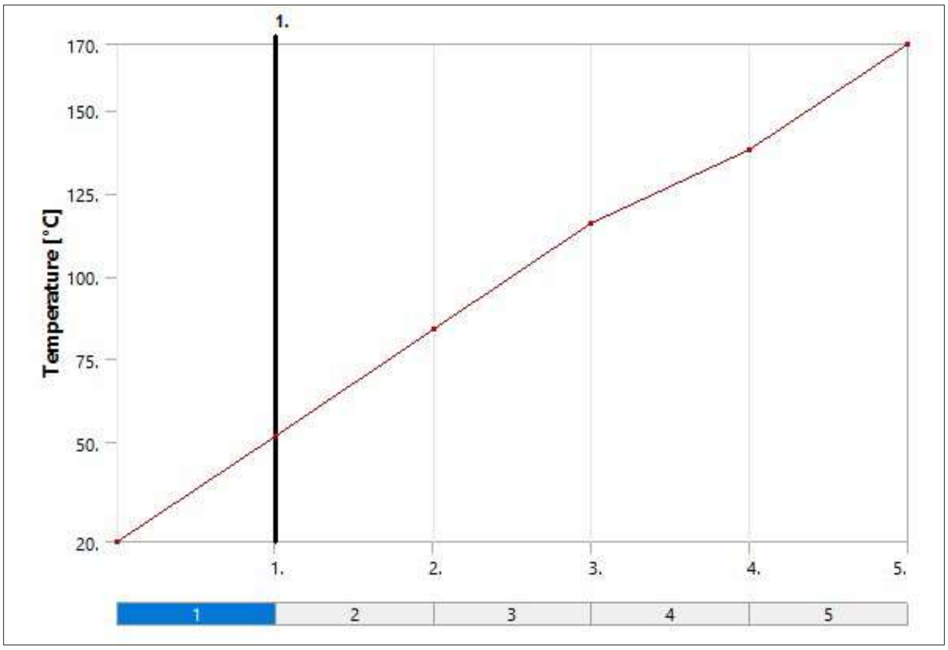

Figure 3: Graph of the temperature load applied to the composite material faces against time

Figure 4 shows the graph of temperature distribution at different intervals.

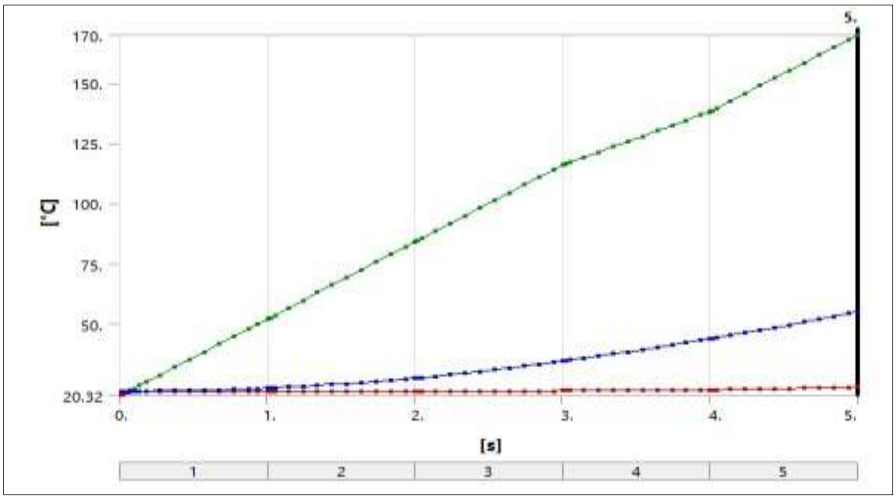

Figure 4: Graph of Temperature Distribution at Different Intervals

Figure 5 shows the temperature distribution throughout the Material at different intervals.

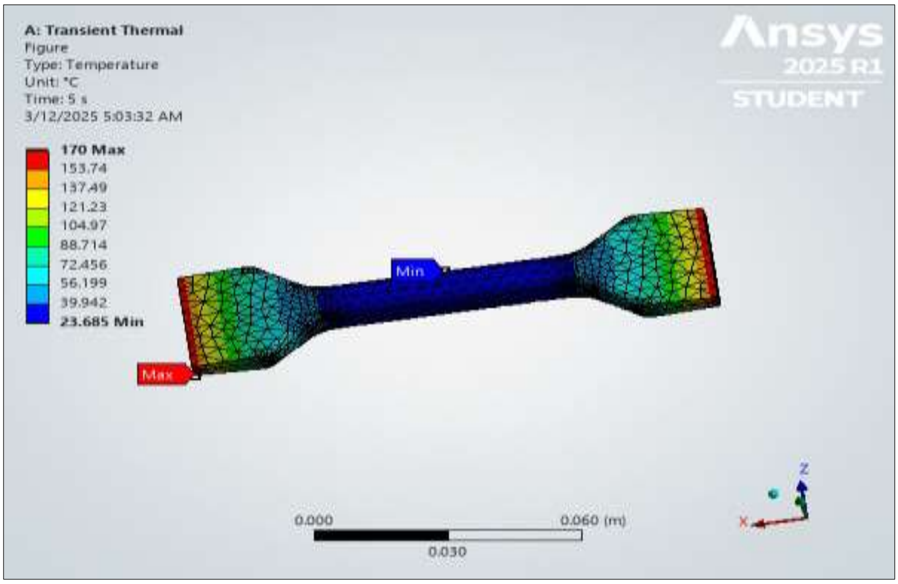

Figure 5: Shows the temperature distribution throughout the Material

From the contour plot of temperature distribution in the material in figure 5, the red portion has the maximum temperature of 170.00^{0}C and the blue portion shows the area with lowest temperature of 23.69^{0}C.

2.3: Total Heat Flux

Heat flux represents the rate at which thermal energy is transferred per unit area, typically expressed in watts per square meter (W/m²). It is a fundamental parameter in thermal analysis as it indicates how efficiently heat is conducted through a material or across a surface. Understanding the heat flux distribution is essential for evaluating the thermal performance and identifying potential regions of thermal stress or failure in engineering components.

In this study, the total heat flux within the developed aluminium matrix composite was assessed through finite element simulations in ANSYS 2025. The simulation results were presented as a contour plot illustrating the spatial distribution of heat flux throughout the material. As depicted in Figure 6, regions highlighted in red correspond to the highest thermal activity, with a maximum recorded value of 1.8122×10^6 W/m², indicating areas of intense heat transfer. Conversely, the areas shown in blue represent zones with the lowest heat flux, measuring 1.515×10^6 W/m², suggesting relatively limited thermal conduction.

The variation in heat flux across the composite can be attributed to differences in thermal conductivity between the aluminium matrix and the reinforcing agro-waste particles. These differences influence how heat propagates through the material structure, making such analyses crucial for predicting thermal performance under real-world operating conditions.

To complement the visual data, a graph was generated to show the heat flux values at various time intervals, as illustrated in Figure 7. This temporal plot aids in understanding how heat transfer rates evolve over time under the applied thermal load, providing valuable insights for design optimization and thermal management strategies.

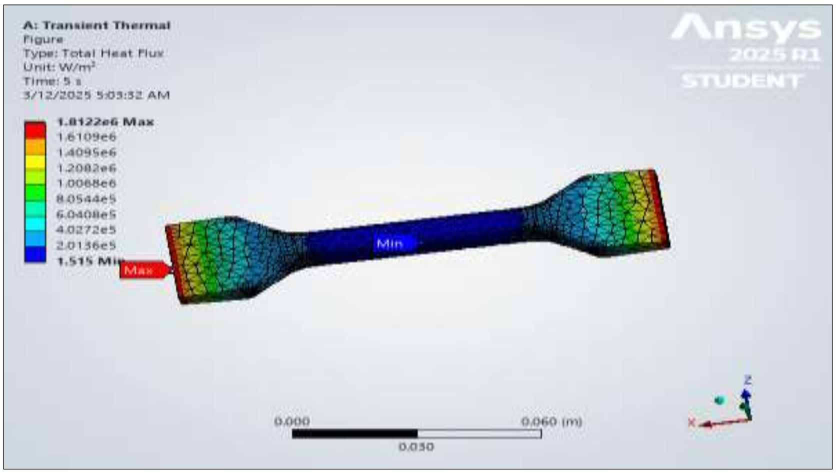

Figure 6: Contour plot of total heat flux

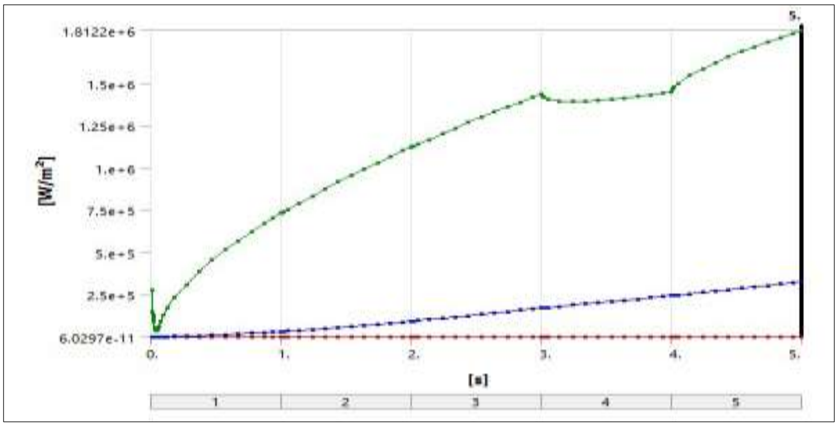

Figure 7: Graph of Total Heat Flux at Different Intervals

2.4 Equivalent Elastic Strain

Figure 8 shows the contour plot for the Equivalent Elastic Strain.

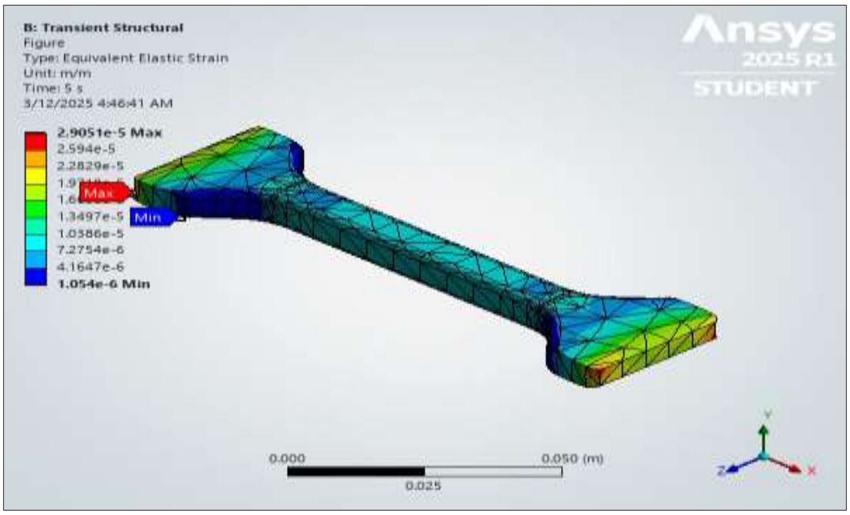

Figure 8: Contour plot for the Equivalent Elastic Strain

The contour plot in figure 8 shows that the red portion has a maximum Equivalent Elastic Strain of 2.9051 x 10^{-5} while the blue portion has the minimum Equivalent Elastic Strain of 1.054 x 10^{-6}

2.5: Directional Deformation (x – axis)

Figure 9 shows the Directional Deformation along x – axis.

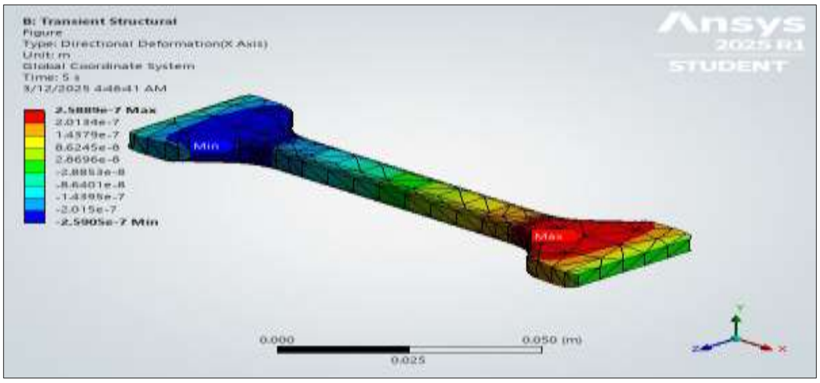

Figure 9: Contour plot for Directional Deformation Along X – axis

The maximum Directional Deformation in the x – axis is seen in the red portion with a value of 2.5889 x 10^{-7} m and the blue portion shows the minimum Directional Deformation in the x – axis with a value of – 2.5905 x 10^{-7} m as shown is figure 9.

2.6 Total Deformation

Figure 10 shows the contour plot for Total Deformation on the material.

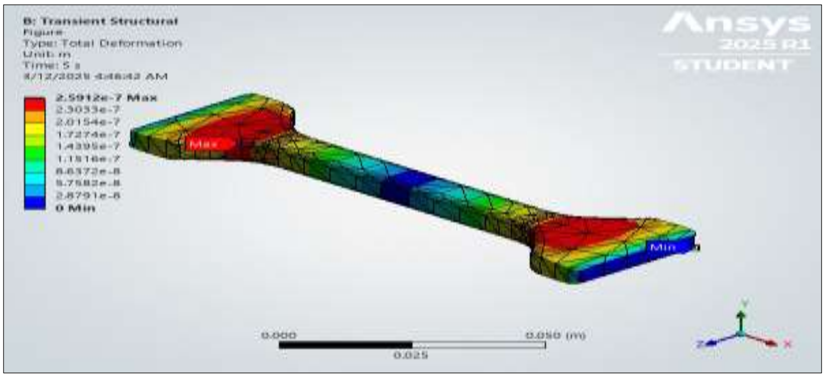

Figure 10: Contour plot for Total Deformation on the material

From the contour plot of Total Deformation on the material in Figure 10, the red portion has a maximum value of 2.5912 x 10^{-7} m while the blue portion has the least Total Deformation.

2.7 Equivalent (Von-Mises) Stress

Figure 11 shows the Equivalent (Von-Mises) Stress on the material. The red portion has the maximum value 5.8104 x 10^{7} Pa. while the blue part has a minimum value of 1.3224 x 10^{5} Pa.

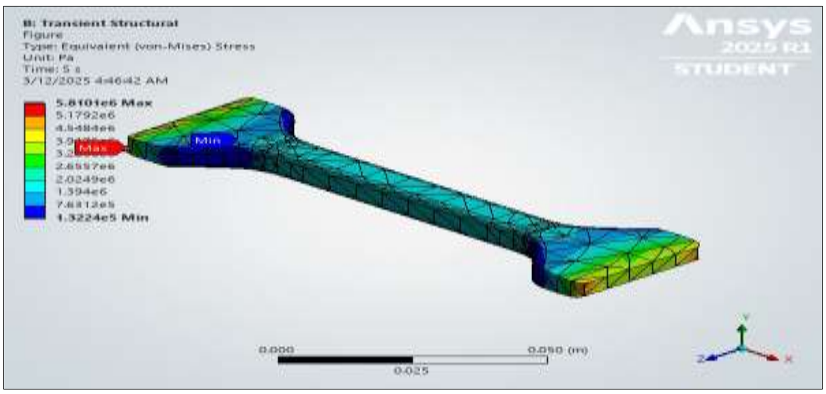

Figure 11: Equivalent (Von-Mises) Stress on the material

2.9 Safety Factor

From the contour plot of the Safety Factor in Figure 12, the maximum and the minimum values of the Safety Factors are 15.000 and 4.836 respectively and the only colour seen is blue which show that the material is safe.

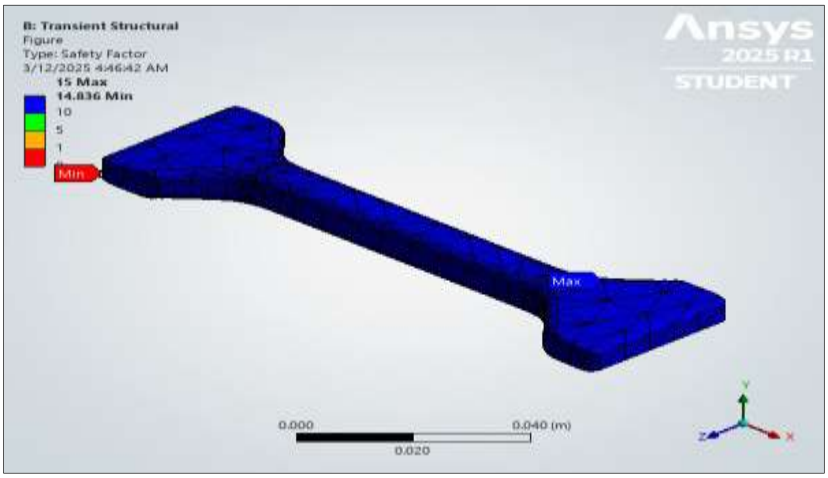

Figure 12: Contour plot of the safety factor

3.0 FATIGUE ANALYSIS OF THE DEVELOPED COMPOSITE

Evaluating the expected lifespan of a material under operational conditions is a crucial aspect of engineering design. This evaluation relies on design assumptions, the material's inherent properties, and the specific loading conditions it will experience. Fatigue, a process involving the initiation and propagation of cracks under cyclic loading, is a primary cause of failure in structural components. Köksal *et al*., (2013) highlighted that fatigue is a common failure mechanism, progressing through crack initiation, crack growth, and ultimately, fracture. Cyclic loading can induce cracking within a material, potentially leading to damage. Therefore, fatigue analysis is an essential step in assessing the material's suitability for cyclic loading applications and preventing premature failure.

3.1 Fatigue Damage

Fatigue damage is a critical concern, particularly in the design of structures like ships and offshore platforms. Dong *et al*., (2022) emphasized the significance of fatigue damage as a failure mode in these applications. To mitigate the risk of catastrophic failures due to fatigue, design practices incorporate fatigue damage assessment, and structures undergo inspection, maintenance, and repair. A fatigue damage value greater than 1 generally indicates that the material is predicted to withstand the applied cyclic loading without failure. The fatigue damage results are shown in Figure 13.

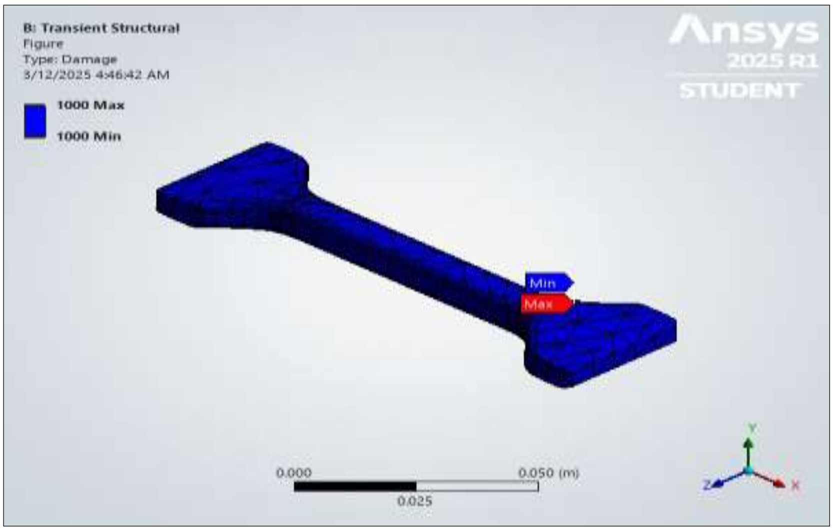

Figure 13 shows the Fatigue Damage

From Figure 13, the value of the Fatigue Damage is 1000 and this is greater than 1 and every area is blue which shows that the material is safe.

3.2 Fatigue Life

This helps to determine how the material is affected by cyclic loading. Figure 14 shows the available life (cycles) of the material if the load is repeatedly applied.

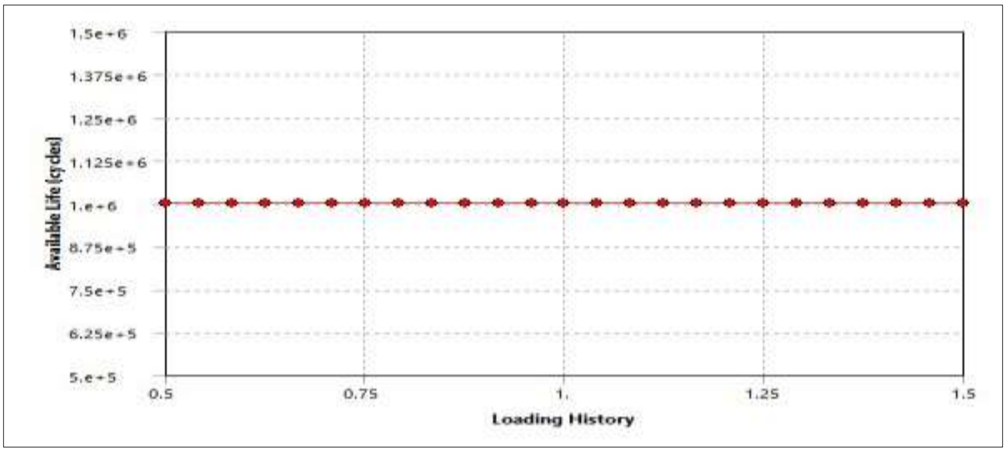

Figure 14: Available life (cycles) of the material if the load is repeatedly applied

The contour plot for the Fatigue Life of the material is shown in figure 15.

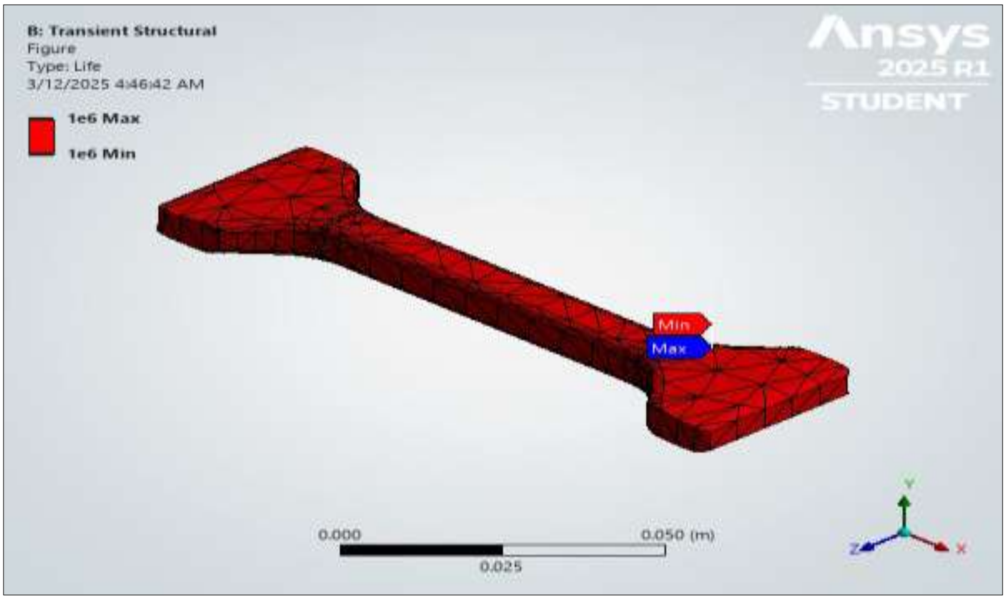

Figure 15: Contour plot for the Fatigue Life of the material

From the plot in Figure 15 and the contour plot in Figure 13, it is shown that the available life of the material is 1 x 10^6 cycles.

Figure 16 shows the graph of constant amplitude load fully reversed**.**

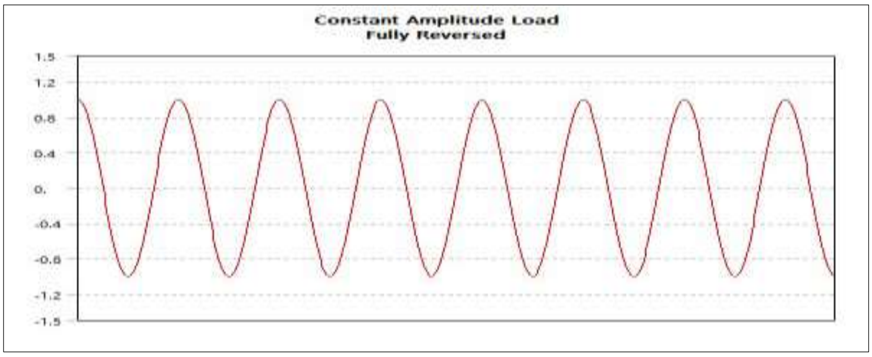

Figure 16: Graph of Constant Amplitude Load Fully Reversed

Table 2 shows the summary of the results obtained in the difference analyses.

Table 2: Summary of the results obtained in the difference analyses

Type	**Maximum**	**Minimum**
Temperature	170.000^{0}C	23.685^{0}C
Total heat flux	1.8122 x 10^6 W/m^2	1.515 x 10^6W/m^2
Equivalent Elastic Strain	2.9051 x 10^{-5}	1.054x10^{-6}
Directional Deformation along x – axis	2.5889 x 10^{-7} m	– 2.5905 x 10^{-7} m
Total Deformation	2.5912 x 10^{-7} m	0.0000m
Equivalent (Von-Mises) Stress	5.8104 x 10^7 Pa	1.3224 x 10^5 Pa.
Safety Factors	15.000	4.836
Fatigue Damage	1000	1000
Fatigue Life	1 x 10^6 cycles	1 x 10^6 cycles

4.0 CONCLUSION

Finite Element Analysis (FEA) ANSYS has been used successfully used to carry out the thermal and structural analyses on the developed composite material and the summary of the results obtained are shown in table 2.

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