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# DESIGN OF A MICRO WIND TURBINE

**[1]Dhanwin Mehta, [2]Dr. Prashant Kumar**
PG Student Department of Space Engineering M. Tech Aerospace Engineering[1], Associate Professor Department of Space Engineering[2]
E25m051099@adypu.edu.in[1], Prashant.kumar_visfac@adypu.edu.in[2]

## ABSTRACT

This study presents the design, aerodynamic evaluation, and structural analysis of a micro wind turbine based on the NACA 0018 airfoil. Aerodynamic analysis and rotor performance simulations were conducted using QBlade, where airfoil polars, blade element momentum (BEM) simulations, and lifting line theory (LLT) were employed to evaluate turbine behavior under realistic wind conditions. The turbine demonstrated stable aerodynamic performance with smooth stall characteristics and effective energy capture within the intended operating range. Structural analysis performed using ANSYS static structural analysis confirmed that the blade design withstands operational aerodynamic and rotational loads with minimal deformation and stress. The results indicate that the proposed micro wind turbine design is structurally robust and aerodynamically efficient, making it suitable for small-scale renewable energy applications.

## INTRODUCTION

Wind energy has emerged as one of the most important renewable energy resources in the global transition toward sustainable and low-carbon power generation. Continuous advancements in wind turbine technology have significantly improved energy conversion efficiency and reduced the cost of wind-generated electricity. Aerodynamic performance of wind turbine blades plays a decisive role in determining overall turbine efficiency, making airfoil selection, blade geometry optimization, and accurate performance prediction essential components of turbine design [1], [2]. As wind energy systems expand into decentralized and small-scale applications, the need for efficient and reliable micro wind turbines has gained increasing attention.

Micro wind turbines, typically rated below 5 kW, are designed for residential, rural, and small commercial applications where large-scale turbines are impractical or economically unfeasible. These systems operate predominantly at low Reynolds numbers and under highly variable wind conditions, particularly in urban and semi-urban environments [6]. Under such operating conditions, aerodynamic behavior becomes more sensitive to airfoil shape, angle of attack variations, turbulence, and stall characteristics. Consequently, airfoil selection and aerodynamic optimization are critical for ensuring stable operation and effective energy capture in micro wind turbine applications [4].

Several studies have demonstrated that airfoil geometry significantly influences turbine performance, especially at low to moderate wind speeds. Tira and Furqon [1] investigated the aerodynamic performance of the NACA 6409 airfoil using QBlade simulations and reported improved lift-to-drag characteristics and delayed stall behavior, leading to enhanced turbine efficiency at low wind speeds. Similarly, Rogowski et al. [4] conducted experimental investigations on the NACA 0018 airfoil at low Reynolds numbers and observed stable aerodynamic characteristics with reduced sensitivity to wind direction changes. Their results highlighted the suitability of symmetric airfoils for small-scale wind turbines operating in turbulent environments.

Computational tools have become indispensable in modern wind turbine design and analysis. QBlade, which integrates Blade Element Momentum (BEM) theory with XFOIL-based airfoil analysis, has been widely adopted for aerodynamic performance prediction and rotor optimization [2]. Alaskari et al. [2] demonstrated that QBlade provides reliable performance estimation while allowing efficient parametric studies on blade geometry, tip-speed ratio, and operating conditions. However, while BEM-based approaches are computationally efficient, they often require accurate airfoil polar data and validation against more detailed flow physics.

To address limitations associated with simplified aerodynamic models, several researchers have employed Computational Fluid Dynamics (CFD) to analyze wind turbine blade performance under varying angles of attack and Reynolds numbers. Patil and Thakre [3] used CFD to investigate stall behavior, vortex formation, and flow separation on turbine blades, revealing complex aerodynamic phenomena that significantly affect performance under unsteady operating conditions. Such studies emphasize the importance of understanding both steady and unsteady aerodynamic effects, particularly for micro wind turbines exposed to gusty and turbulent wind fields.

In addition to aerodynamic efficiency, structural reliability is a critical requirement for wind turbine blades. Turbine blades are subjected to cyclic aerodynamic loads, centrifugal forces, and environmental effects that can lead to fatigue, excessive deformation, or structural failure if not properly designed. Abbas et al. [6] highlighted the importance of optimizing blade geometry and material selection to balance aerodynamic performance with mechanical strength in micro wind turbines intended for domestic applications. Their findings demonstrated that structurally optimized blades can significantly improve durability while maintaining Control strategies and operational stability also influence wind turbine performance and longevity. Elkodama et al. [5] reviewed modern control methods for horizontal axis wind turbines and emphasized the role of pitch control, stall regulation, and adaptive strategies in maintaining power output while limiting structural loads. Although many advanced control techniques are developed for large-scale turbines, their principles remain relevant for micro wind turbines, especially in regulating loads under high wind conditions.

Despite extensive research on wind turbine aerodynamics and control, several gaps remain in the integrated aerodynamic–structural design of micro wind turbines. Many studies focus primarily on aerodynamic optimization without sufficient consideration of structural integrity under operational loads [6], [7]. Additionally, while advanced materials and manufacturing techniques have been explored, their combined influence on aerodynamic performance and structural response is not yet fully addressed in small-scale turbine design [8]. The lack of standardized benchmarking datasets further complicates the comparison and validation of proposed designs across different studies [7]. acceptable energy output.

Therefore, there is a clear need for an integrated design approach that combines aerodynamic performance evaluation with structural validation to ensure both efficiency and reliability of micro wind turbines. The present study addresses this need by designing a micro wind turbine blade using the NACA 0018 airfoil and performing a comprehensive aerodynamic analysis using QBlade, followed by structural assessment using ANSYS. By combining BEM simulations, lifting line theory, and finite element analysis, this work aims to demonstrate a practical and validated design methodology suitable for real-world micro wind turbine applications.

## LITERATURE SURVEY

Wind turbine performance and reliability are strongly influenced by aerodynamic design, airfoil selection, structural integrity, and control strategies. As wind energy technology has evolved, extensive research has been conducted on improving turbine efficiency across a wide range of operating conditions. This literature survey reviews key research contributions related to wind turbine aerodynamics, simulation tools, control methods, micro wind turbine design, and structural considerations, with emphasis on studies relevant to small-scale and micro wind turbines.

Airfoil selection is a fundamental aspect of wind turbine blade design, particularly for turbines operating at low Reynolds numbers. Tira and Furqon [1] conducted a detailed aerodynamic study using QBlade to evaluate the performance of the NACA 6409 airfoil for low to moderate wind speeds. Their simulation results demonstrated improved lift-to-drag ratios and delayed stall characteristics, leading to enhanced power coefficients. The study highlighted the importance of selecting airfoils tailored to specific wind regimes to maximize energy capture efficiency.

Experimental investigations have further validated the performance of symmetric airfoils in small wind turbine applications. Rogowski et al. [4] analyzed the aerodynamic behavior of the NACA 0018 airfoil in a low-turbulence wind tunnel at low Reynolds numbers. Their findings indicated that the NACA 0018 airfoil exhibits stable lift characteristics, smooth stall behavior, and reduced sensitivity to changes in wind direction. The study also examined pressure distribution and laminar separation bubbles, providing valuable insights into flow behavior relevant to predictive aerodynamic modeling for micro wind turbine.

Simulation tools play a critical role in modern wind turbine analysis and optimization. Alaskari et al. [2] investigated the application of QBlade software for wind turbine performance analysis. Their work demonstrated that QBlade, which integrates Blade Element Momentum (BEM) theory with XFOIL-based airfoil analysis, enables efficient blade geometry optimization and performance prediction. The study emphasized QBlade's effectiveness in conducting parametric studies while maintaining reasonable agreement with experimental data, making it suitable for both educational and research applications.

While BEM-based tools offer computational efficiency, they often simplify complex flow physics. To address this limitation, Patil and Thakre [3] employed Computational Fluid Dynamics (CFD) to analyze wind turbine blade performance under varying angles of attack and Reynolds numbers. Their CFD results revealed important aerodynamic phenomena such as flow separation, vortex shedding, and stall behavior that significantly influence turbine efficiency. This work highlighted the necessity of incorporating detailed aerodynamic analysis when designing blades for unsteady and turbulent wind conditions.

Control strategies are essential for maximizing energy extraction while ensuring operational safety. Elkodama et al. [5] presented a comprehensive review of control methods for horizontal axis wind turbines, including pitch control, stall control, and hybrid control strategies. Their review emphasized that advanced control systems play a vital role in regulating aerodynamic loads, maintaining power output, and enhancing turbine lifespan. Although much of the focus was on large-scale turbines, the principles discussed are equally applicable to micro wind turbines operating under fluctuating wind conditions.

Research focusing specifically on micro wind turbine applications has highlighted the importance of design optimization tailored to domestic and small-scale use. Abbas et al. [6] conducted a design optimization and performance investigation of a micro wind turbine intended for residential applications. Their study examined rotor configuration, tip-speed ratio selection, and blade profile optimization, demonstrating that appropriately designed micro turbines can effectively supplement grid electricity and support decentralized energy systems.

Historical and foundational research continues to provide valuable context for contemporary wind turbine design. Pippin and Wang [9] presented a comprehensive overview of wind turbine research and development, discussing early aerodynamic theories, simulation techniques, and material advancements. Their work underscored how fundamental aerodynamic principles remain relevant despite significant technological advancements**.**

Recent reviews have emphasized the growing role of optimization techniques and advanced simulation methods in wind turbine design. ShourangizHaghighi et al. [7] reviewed state-of-the-art CFD-based optimization methods for wind turbine performance enhancement, highlighting the potential of numerical simulations to improve aerodynamic efficiency. Similarly, Jeong et al. [8] investigated blade shape optimization to reduce unsteady aerodynamic loads in turbulent wind, demonstrating that optimized blade geometries can significantly reduce load fluctuations and improve structural durability.

Despite extensive research in wind turbine aerodynamics and optimization, several gaps remain. Many studies focus primarily on aerodynamic performance without fully integrating structural analysis into the design process [6], [8]. Additionally, limited research addresses the combined effects of emerging composite materials and manufacturing techniques on both aerodynamic efficiency and structural response [7]. The lack of standardized datasets and benchmarking frameworks further limits direct comparison between proposed designs [7].

## METHODOLOGY

### Airfoil Selection

The selection of an appropriate airfoil is a critical step in the design of a micro wind turbine blade. For this study, the NACA 0018 airfoil was chosen due to its favorable aerodynamic characteristics at low Reynolds numbers, which are typical operating conditions for micro wind turbines. NACA 0018 is a symmetric airfoil with an 18% thickness-to-chord ratio, providing a balance between aerodynamic performance and structural strength.

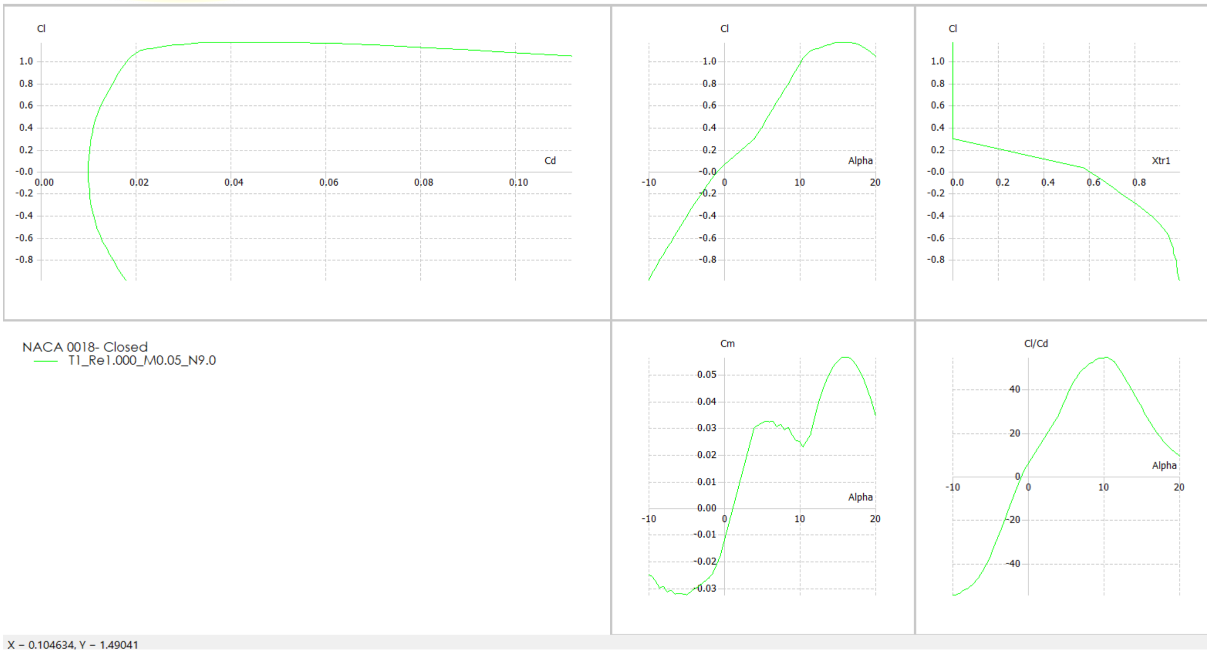


Figure 3.1 Performance Parameters using NACA 0018 Airfoil

The symmetric nature of the airfoil ensures stable aerodynamic behavior and reduced sensitivity to wind direction changes. The relatively thick profile contributes to higher bending stiffness, allowing the blade to withstand aerodynamic and centrifugal loads without excessive deformation. Additionally, the airfoil exhibits smooth stall characteristics, which reduce sudden load fluctuations and improve fatigue performance under turbulent wind conditions. The NACA 0018 airfoil is also less sensitive to surface roughness and manufacturing imperfections, enhancing its suitability for real-world micro wind turbine applications.

## Aerodynamic Analysis Using QBlade

QBlade software was used to perform aerodynamic analysis of the airfoil and rotor. The airfoil geometry was generated within QBlade, and aerodynamic polars were computed using XFOIL for a range of angles of attack from −10° to +20°. These polars provided lift coefficient, drag coefficient, pitching moment coefficient, and lift-to-drag ratio data, which are essential for Blade Element Momentum analysis.

To capture the complete aerodynamic behavior of the airfoil under dynamic operating conditions, 360° polar data were generated. This full-range polar data allowed the simulation of post-stall behavior, reverse flow conditions, and dynamic stall effects that occur during gusts, yaw misalignment, and transient operating states. These data are particularly important for micro wind turbines operating in turbulent environments.

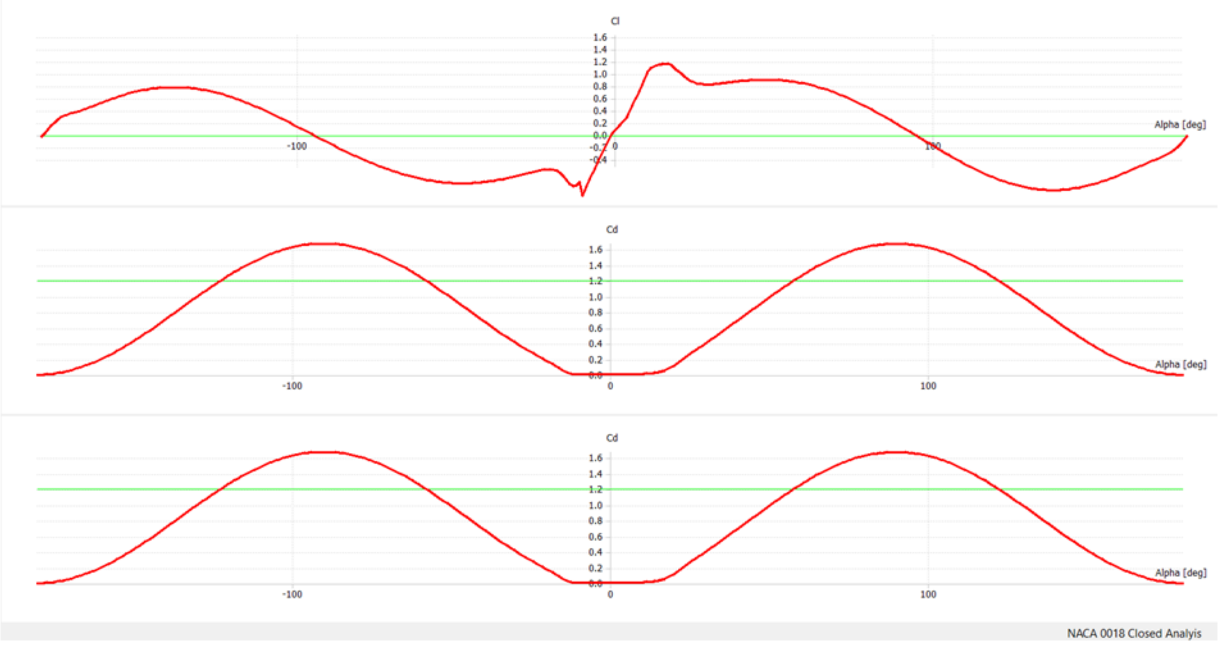


Figure 3.2 360 degree Polar of the Airfoil

## Blade Geometry Design

A rotor blade with a radius of 2.5 m was designed to balance power generation capability with structural feasibility. The blade was divided into 28 spanwise sections, each defined by specific chord lengths, twist angles, and airfoil profiles. A circular airfoil section was used near the root to facilitate attachment to the hub, while NACA 0018 sections were used along the remaining span.

The chord length gradually decreased from root to tip, and the twist angle was reduced along the blade span to ensure optimal angle of attack distribution during operation. This configuration allows the blade to extract energy efficiently across its entire span while minimizing aerodynamic losses near the tip.

Rotor performance simulations were conducted using QBlade's Blade Element Momentum model. Power coefficient (Cp), thrust coefficient (Ct), torque, and axial induction factor were evaluated over a range of tip-speed ratios. Multiparameter simulations were performed to analyse the effects of rotational speed, wind speed, and pitch angle on turbine performance.

Turbine-level simulations were carried out to generate power curves and thrust curves from cut-in to cut-out wind speeds. The turbine exhibited cut-in at approximately 3 m/s and achieved rated power of 2.5 kW at wind speeds of 14–15 m/s. Pitch regulation was employed to maintain constant power output beyond the rated wind speed.

Wake behavior was analyzed using non-linear lifting line theory, which provided three-dimensional visualization of trailing and shed vortices. These simulations helped assess aerodynamic loading, wake stability, and rotor performance under dynamic operating conditions.

Figure 3.3 Final Wind Tunnel Assembly

## Structural Analysis Using ANSYS

Structural analysis of the optimized blade was performed using ANSYS static structural analysis. The blade geometry was imported into ANSYS, and the root section was fixed to simulate hub attachment. Aerodynamic loading corresponding to a wind speed of 12 m/s was applied along the blade.

The analysis evaluated total deformation, strain energy, von Mises stress, and shear stress distributions. These results were used to assess structural integrity, load distribution, and safety margins under operational conditions.

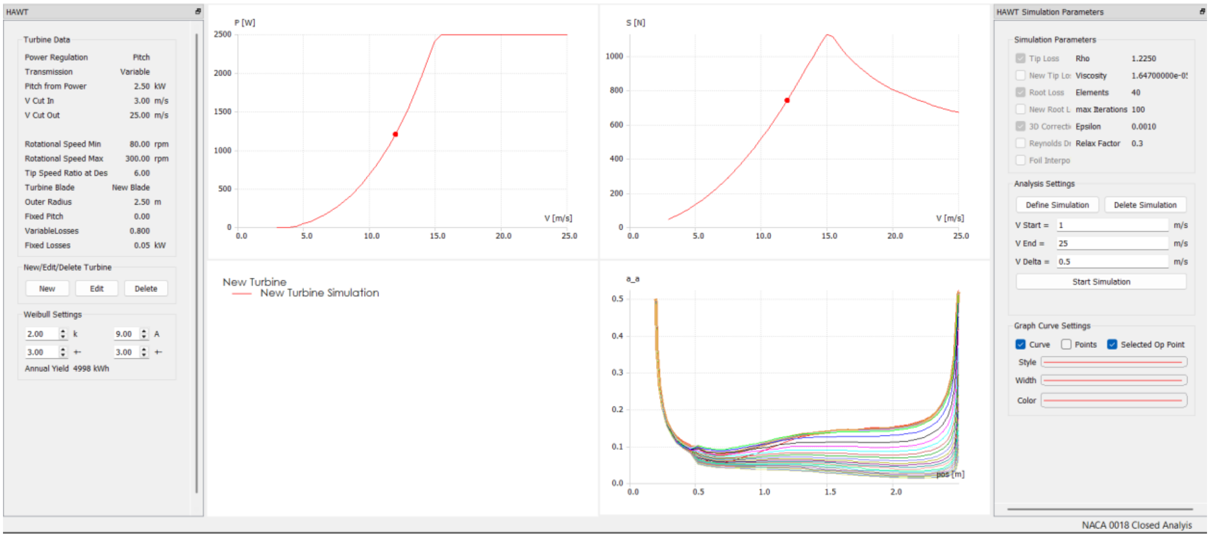
## CONCLUSIONS

The integrated aerodynamic and structural analysis conducted in this study demonstrates that the micro wind turbine blade designed using the NACA 0018 airfoil is both aerodynamically efficient and structurally robust. Aerodynamic simulations using QBlade showed that the airfoil exhibits stable performance with smooth stall behavior and a high lift-to-drag ratio in the optimal angle-of-attack range. The rotor achieved maximum aerodynamic efficiency at a tip-speed ratio of approximately 6–7, with a power coefficient in the range of 0.29–0.31.

Turbine-level simulations confirmed that the designed micro wind turbine reaches its rated power of 2.5 kW at wind speeds of approximately 14–15 m/s, with stable operation across the entire operating range. Wake visualization using lifting line theory indicated smooth vortex shedding and balanced aerodynamic loading, confirming stable rotor behavior under dynamic conditions.

Structural analysis using ANSYS validated the mechanical reliability of the blade design. The maximum deformation was extremely small, approximately 3.9 × $10^{-5}$ m, indicating high structural stiffness. Von Mises and shear stress levels were several orders of magnitude below the allowable limits of GRP composite materials, resulting in a high factor of safety. Strain energy distribution confirmed cantilever behavior, with maximum energy concentration near the blade root, as expected.

Overall, the results confirm that the combined aerodynamic and structural design approach produces a micro wind turbine blade suitable for small-scale renewable energy generation. The turbine demonstrates reliable performance, high safety margins, and effective energy capture, supporting its application in decentralized and distributed energy systems.


HAWT

Turbine Data

| | |
|---|---|
| Power Regulation | Pitch |
| Transmission | Variable |
| Pitch from Power | 2.50 kW |
| V Cut In | 3.00 m/s |
| V Cut Out | 25.00 m/s |
| Rotational Speed Min | 80.00 rpm |
| Rotational Speed Max | 300.00 rpm |
| Tip Speed Ratio at Des | 6.00 |
| Turbine Blade | New Blade |
| Outer Radius | 2.50 m |
| Fixed Pitch | 0.00 |
| VariableLosses | 0.800 |
| Fixed Losses | 0.05 kW |

Weibull Settings

2.00 k 9.00 A
3.00 +- 3.00 +-
Annual Yield 4998 kWh

New Turbine
New Turbine Simulation

HAWT Simulation Parameters

Simulation Parameters

☑ Tip Loss Rho 1.2250
☐ New Tip Lo: Viscosity 1.64700000e-0!
☑ Root Loss Elements 40
☐ New Root L max Iterations 100
☑ 3D Correcti Epsilon 0.0010
☐ Reynolds Di Relax Factor 0.3
☐ Foil Interpo

Analysis Settings

V Start = 1 m/s
V End = 25 m/s
V Delta = 0.5 m/s

Graph Curve Settings

☑ Curve ☐ Points ☑ Selected Op Point

NACA 0018 Closed Analyis

Figure 4.1 Turbine Simulation

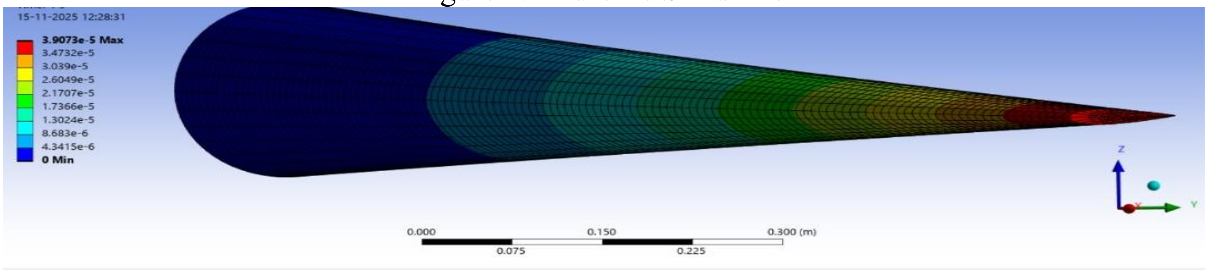


Figure 4.2 Total Deformation

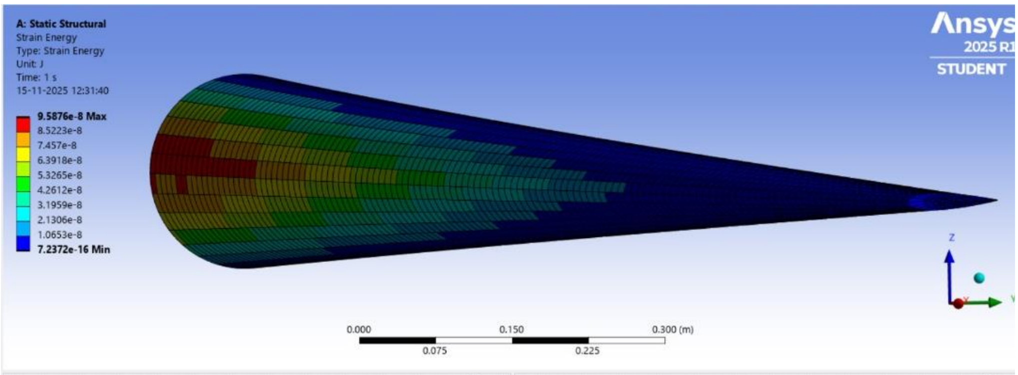


Figure 4.3 Strain Energy

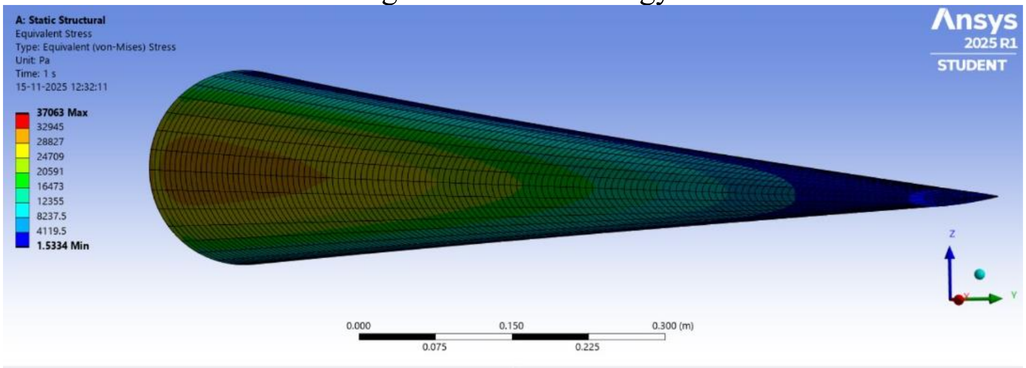


Figure 4.4 Equivalent Stress

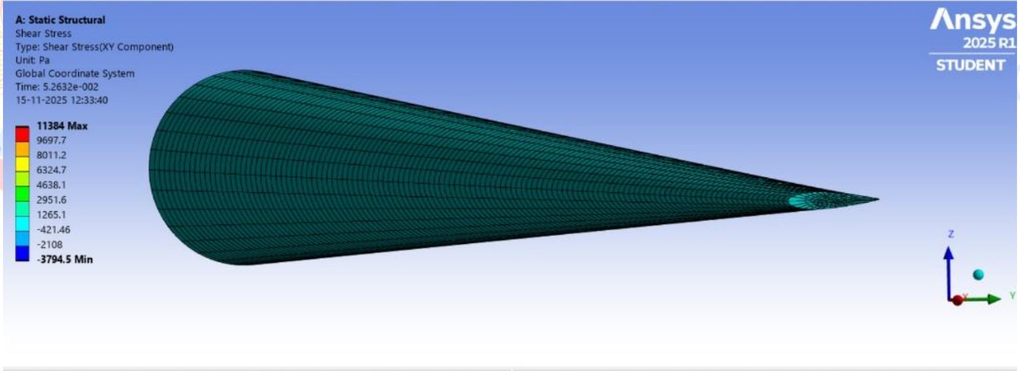


Figure 4.5 Shear Stress

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