Coupled Thermal And Structural Analysis Of Gas Turbine Blade

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Abstract: This study presents a comprehensive thermal and structural analysis of a gas turbine rotor blade utilizing ANSYS software. Gas turbine rotor blades are critical components in gas turbine engines, subjected to extreme thermal and mechanical loads during operation. Understanding their thermal behavior and structural integrity is crucial for optimizing performance and ensuring safe operation. The study employs both thermal and structural analyses, with results including temperature distribution and total heat flux obtained from the thermal analysis, and total deformation and equivalent stress from the structural analysis. The model is constructed using SolidWorks and then imported into Ansys for analysis.

Index Terms – **Gas Turbine Blade, Modelling, Thermal Analysis, Ansys**

I. INTRODUCTION-

Gas turbine rotor blades represent a critical component in gas turbine engines, where their performance directly influences engine efficiency, reliability, and longevity. The steady-state thermal and structural behaviors of these blades under operating conditions are paramount considerations in their design and optimization processes. ANSYS Workbench, a comprehensive simulation platform, offers a robust framework for conducting coupled thermal and structural analyses, providing insights into the complex interplay between thermal loads and mechanical stresses experienced by rotor blades.

In this study, we focus on the coupled thermal and structural analysis of gas turbine rotor blades using ANSYS Workbench. The steady-state thermal analysis investigates temperature distributions and heat transfer phenomena within the blade, employing boundary conditions such as root temperature and blade temperature. Solutions including temperature gradients and total heat flux enable the assessment of thermal performance and identification of critical areas prone to thermal stresses and fatigue.

Simultaneously, the structural analysis examines the mechanical response of the rotor blade to aerodynamic forces and thermal loading. Boundary conditions such as rotational velocity, fixed support, and imported body temperature simulate realistic operating conditions. Solutions such as total deformation and equivalent stress provide insights into blade deformation, stress distribution, and potential failure modes, crucial for ensuring structural integrity and reliability under operational loads.

By coupling thermal and structural analyses within ANSYS Workbench, engineers can comprehensively evaluate the thermal-mechanical behavior of gas turbine rotor blades. This integrated approach enables informed design decisions aimed at optimizing blade geometry, material selection, and cooling strategies to enhance performance, efficiency, and durability of gas turbine engines

II. WORKING OF GAS TURBINE-

1. Compressor: The compressor draws in ambient air and compresses it to high pressure before it enters the combustion chamber. The compression process increases the air temperature, preparing it for combustion.

2. Combustion Chamber: In the combustion chamber, the compressed air is mixed with fuel and ignited, creating a high-temperature, high-pressure gas mixture. This mixture expands rapidly, driving the turbine blades.

3. Turbine: The turbine consists of a series of blades mounted on a rotor. The high-velocity gas flow from the combustion chamber passes over the turbine blades, causing them to rotate. This rotation drives the compressor and any attached machinery, such as a generator or propeller.

4. Exhaust System: After passing through the turbine, the hot gases are expelled through the exhaust system, where they may be used for additional energy recovery or expelled into the atmosphere.
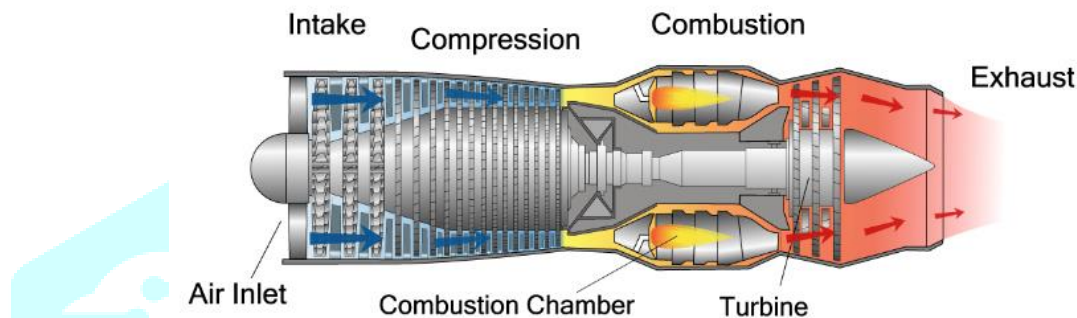

Fig.1 Components of Gas Turbine

III. Rotor Blade-

Gas turbine rotor blades are vital components within gas turbine engines, responsible for extracting energy from the high-velocity flow of hot gases and converting it into mechanical energy to drive the turbine. These blades typically operate under extreme conditions of temperature, pressure, and mechanical stress.

Material Composition: Gas turbine rotor blades are typically constructed from advanced materials capable of withstanding high temperatures, mechanical stresses, and corrosion. Nickel-based superalloys are commonly used due to their excellent high-temperature strength, resistance to creep and oxidation, and thermal stability. Additionally, ceramic matrix composites (CMCs) are being increasingly utilized for their lightweight properties and high-temperature capabilities.

Aerodynamic Design: The aerodynamic design of gas turbine rotor blades is crucial for efficient energy extraction from the fluid flow. The blade geometry, including air foil shape, chord length, twist, and camber, is meticulously optimized through computational fluid dynamics (CFD) simulations and wind tunnel testing to achieve maximum lift and minimize drag. This optimization enhances turbine efficiency and performance.

Cooling Systems: Gas turbine rotor blades operate in extremely high-temperature environments, particularly in the turbine section where gas temperatures can exceed 1,000°C (1,832°F). To prevent overheating and material degradation, rotor blades often incorporate internal cooling passages or external film cooling arrangements. These cooling systems circulate cooler air from the compressor or bypass air around the blade surfaces, effectively dissipating heat and maintaining blade integrity.

Fig.2 Rotor Blade Design

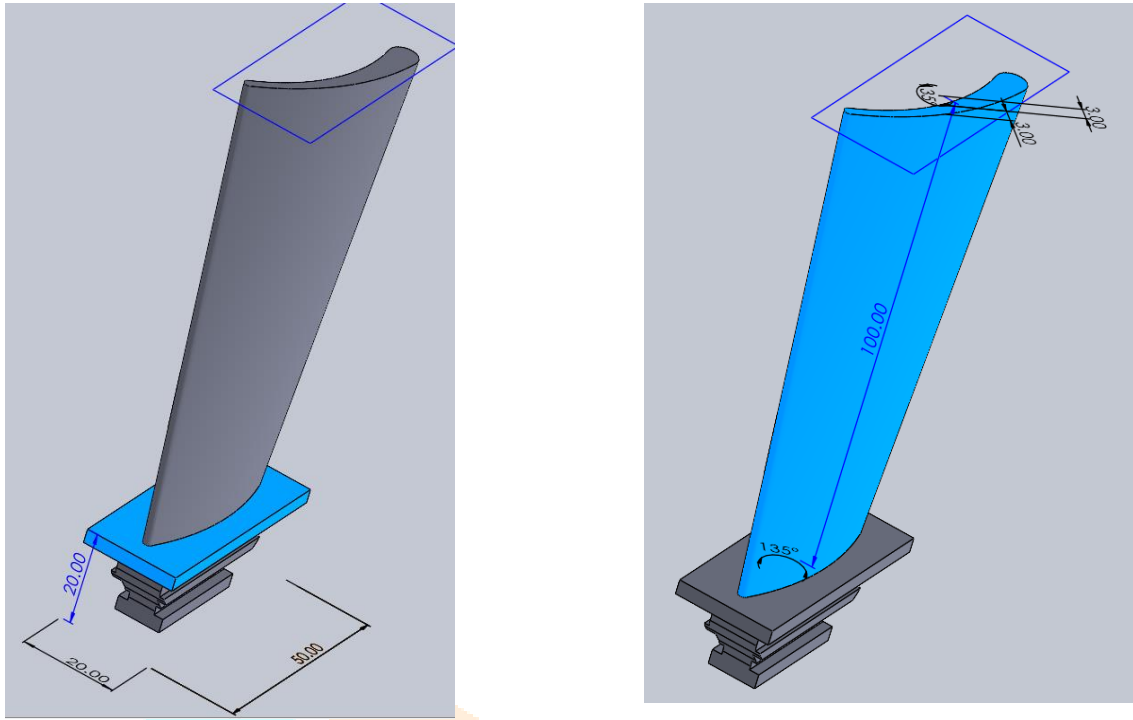**IV. SolidWorks Model of Gas Turbine Blade-**

Fig. 3 SolidWorks Model

V. MESHING-

The model is imported into ANSYS, tetrahedral meshing is conducted to discretize the geometry into finite elements.

Each node in the mesh is assigned three degrees of freedom, enabling the simulation to capture the complex behavior of the blade under thermal and structural loading conditions.
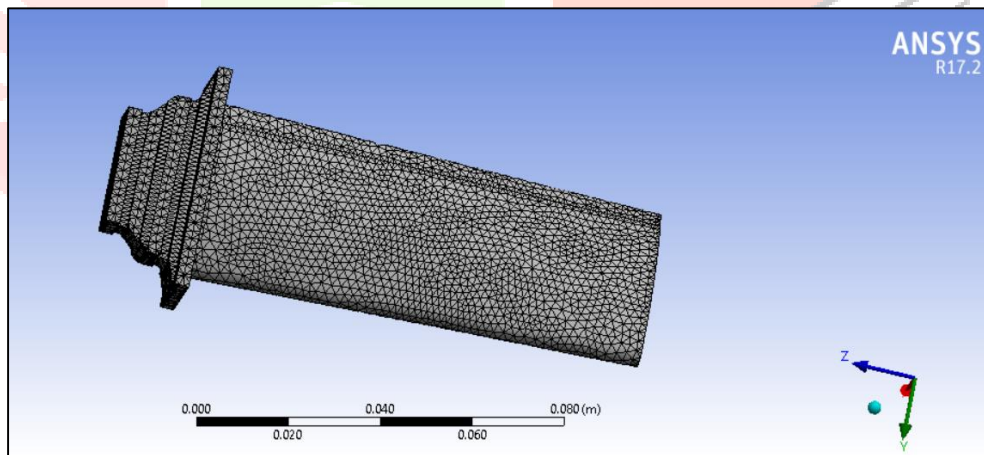

Fig.4 Meshing

Statistics	
Nodes	43624
Elements	24449

VI. MATERIAL DATA-

- Material: Structural steel

- Compressive Yield Strength Pa: 2.5e+008

Structural Steel > Strain-Life Parameters

Strength Coefficient Pa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient Pa	Cyclic Strain Hardening Exponent
9.2e+008	-0.106	0.213	-0.47	1.e+009	0.2

Structural Steel > Isotropic Elasticity

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	2.e+011	0.3	1.6667e+011	7.6923e+010

Structural Steel > Constants

|	
Density	7850 kg m^-3
Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat	434 J kg^-1 C^-1
Thermal Conductivity	60.5 W m^-1 C^-1
Resistivity	1.7e-007 ohm m

VII. THERMAL ANALYSIS-

The thermal analysis focused on understanding how the temperature distribution within the rotor blade influenced its behavior under operating conditions. The boundary conditions set, with a root temperature of 800°C and a blade temperature of 1000°C, represented the extreme thermal environment experienced during gas turbine operation. By simulating these conditions using ANSYS software, the study aimed to evaluate heat transfer mechanisms within the blade and identify potential hotspots or areas of thermal stress concentration. The analysis also involved calculating the total heat flux, providing insights into the overall heat transfer characteristics of the blade. This thermal analysis was crucial for assessing how thermal gradients influenced material properties, such as thermal expansion and conductivity, which are vital factors affecting structural integrity.

➢ **Boundary Conditions**
  1. Root temperature is 800°C
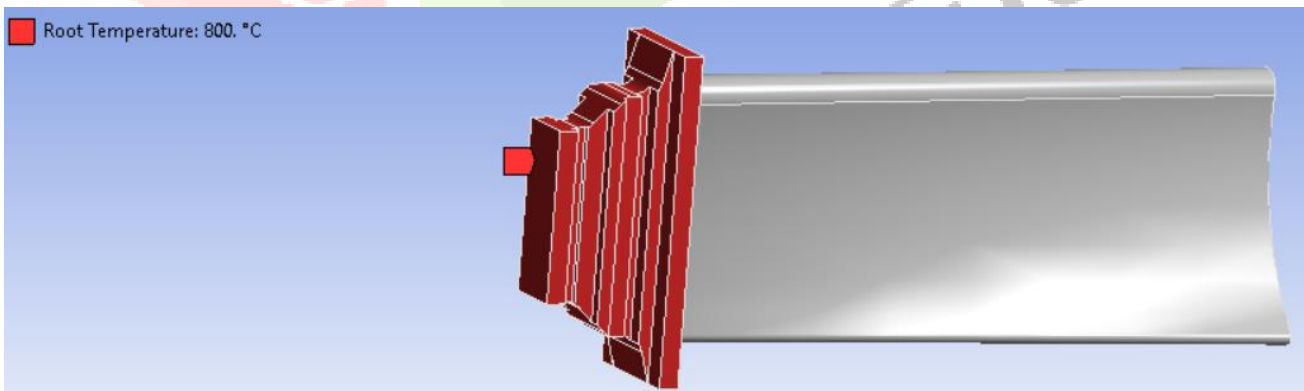
2. Blade temperature is 1000°C
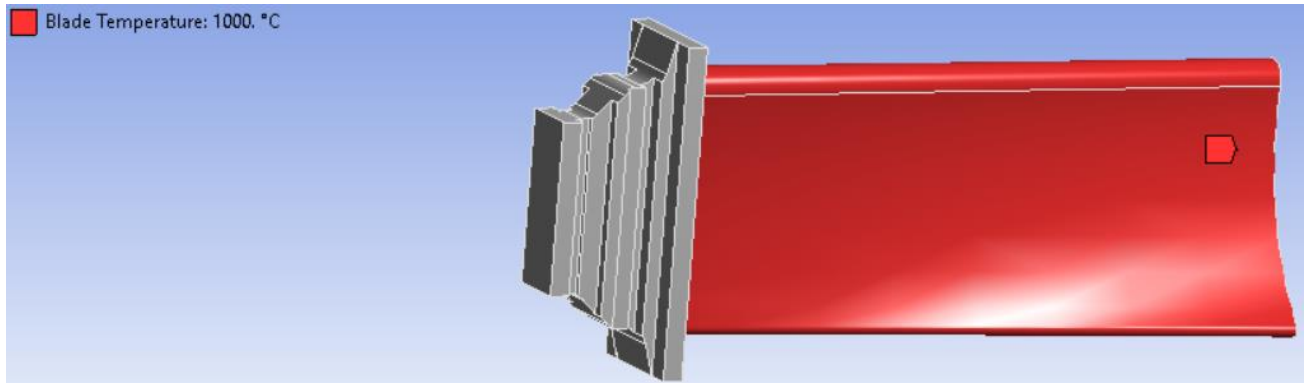
> **Results-**

1. Temperature Distribution:

Maximum temperature was observed at the blade surface, reaching 1000°C, consistent with the specified boundary condition.

Minimum temperature was recorded at the root of the blade, with a value of 800°C.

This temperature distribution indicates that the blade experiences significant thermal gradients from the root to the tip, which can influence material properties and structural behavior.
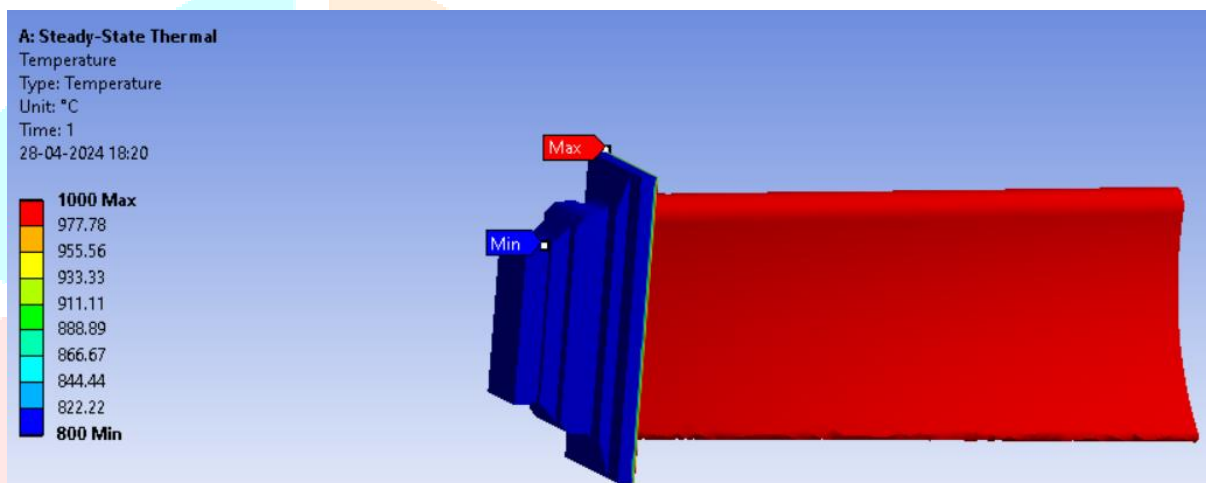

2. Total Heat Flux:

Maximum heat flux was observed at the root of the blade, where thermal energy input is highest due to the proximity to the engine combustion chamber.

Minimum heat flux was recorded at the blade surface, away from the heat source, indicating dissipation of thermal energy as it travels along the blade.

Understanding heat flux distribution is crucial for assessing heat transfer mechanisms and thermal management strategies to prevent overheating and thermal fatigue.
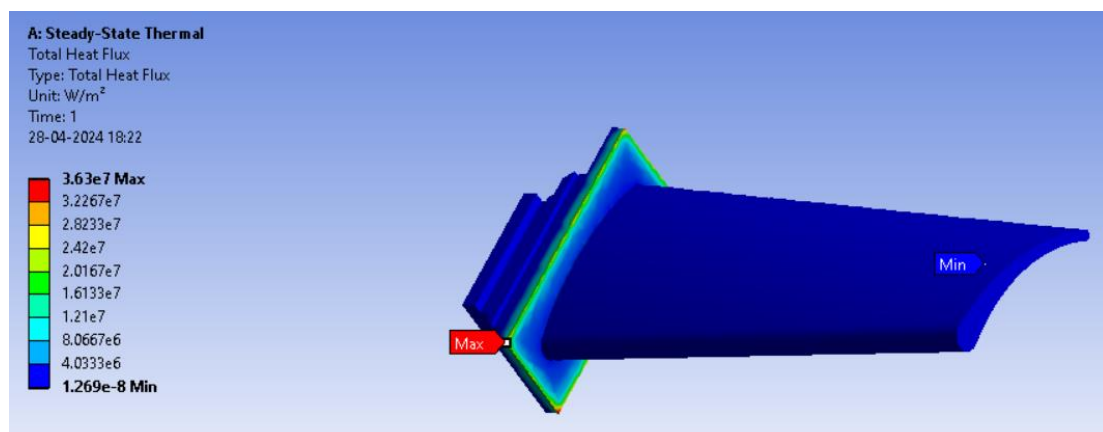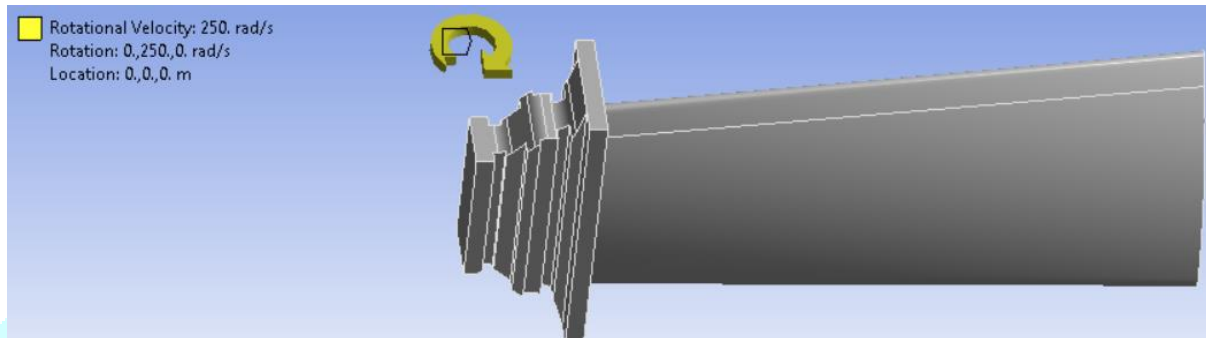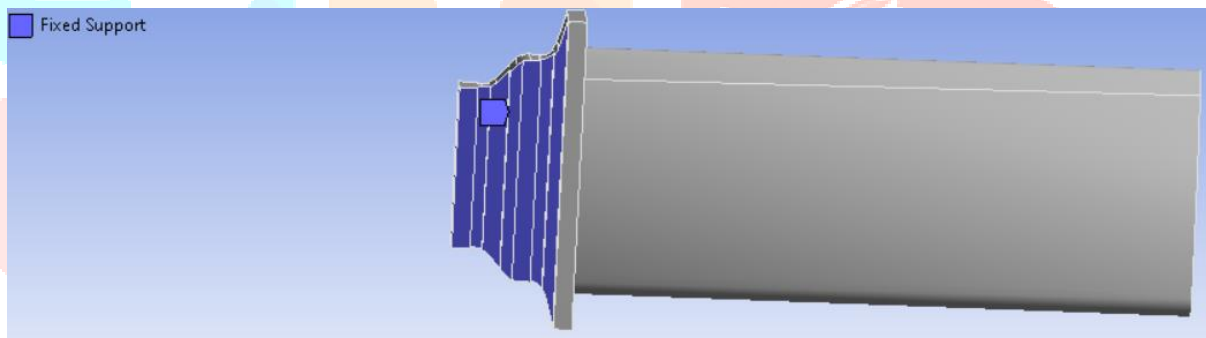
VIII. STRUCTURAL ANALYSIS-

The structural analysis focused on evaluating how mechanical loads, particularly those induced by rotational motion, affected the integrity and deformation of the rotor blade. With a rotational velocity of 250 rad/sec and fixed support applied to 21 faces of the geometry, the study simulated the dynamic forces exerted on the blade during operation. The structural analysis aimed to predict the total deformation and equivalent stress experienced by the blade under these mechanical loads. By coupling thermal and structural analyses, the study aimed to provide a holistic understanding of how thermal gradients interacted with mechanical loads to influence the structural integrity of the rotor blade. This approach enabled the identification of potential failure points or areas susceptible to fatigue, guiding optimization efforts to enhance the durability and reliability of the blade under real-world operating conditions.
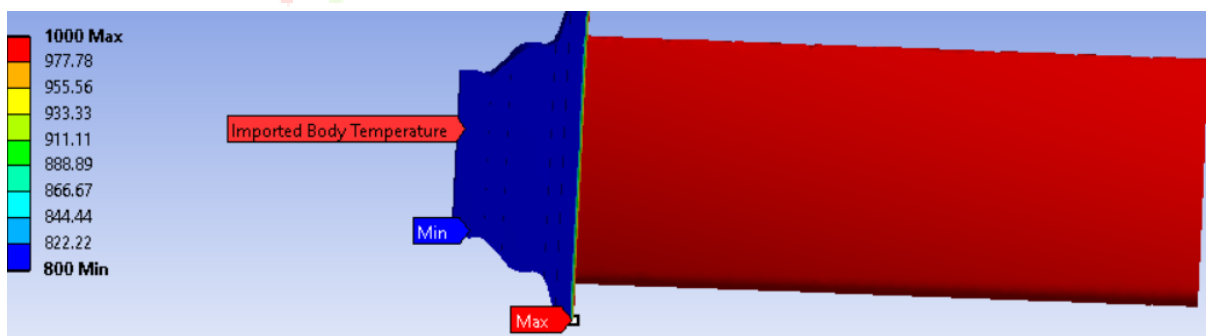
➢ **Boundary conditions-**

1. Rotational velocity is 250 rad/sec.

2. Fixed Support: 21 faces geometry

3. Imported load: imported body temperature from steady state thermal analysis.

➢ **Results-**

1. Total deformation-

The structural analysis revealed deformation patterns within the blade under the influence of mechanical loads, primarily rotational motion.

Total deformation was observed to be higher at the blade tips compared to the root, indicating greater mechanical stress accumulation towards the extremities.

This deformation pattern highlights the importance of considering both thermal and mechanical loads in assessing structural integrity and fatigue life of the blade.
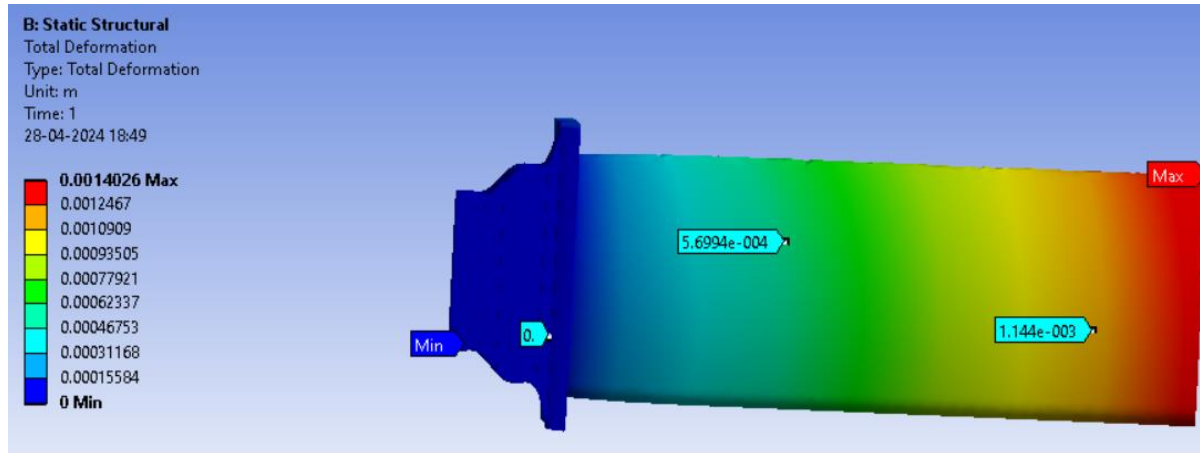

2. Equivalent stress-

Maximum equivalent stress was typically observed at critical points such as blade roots or regions experiencing high mechanical loading.

Minimum equivalent stress was generally found at regions farther away from the root and experiencing lower mechanical loads.

Identifying areas of high equivalent stress is essential for predicting potential failure points and guiding design optimization efforts to enhance blade durability and reliability.
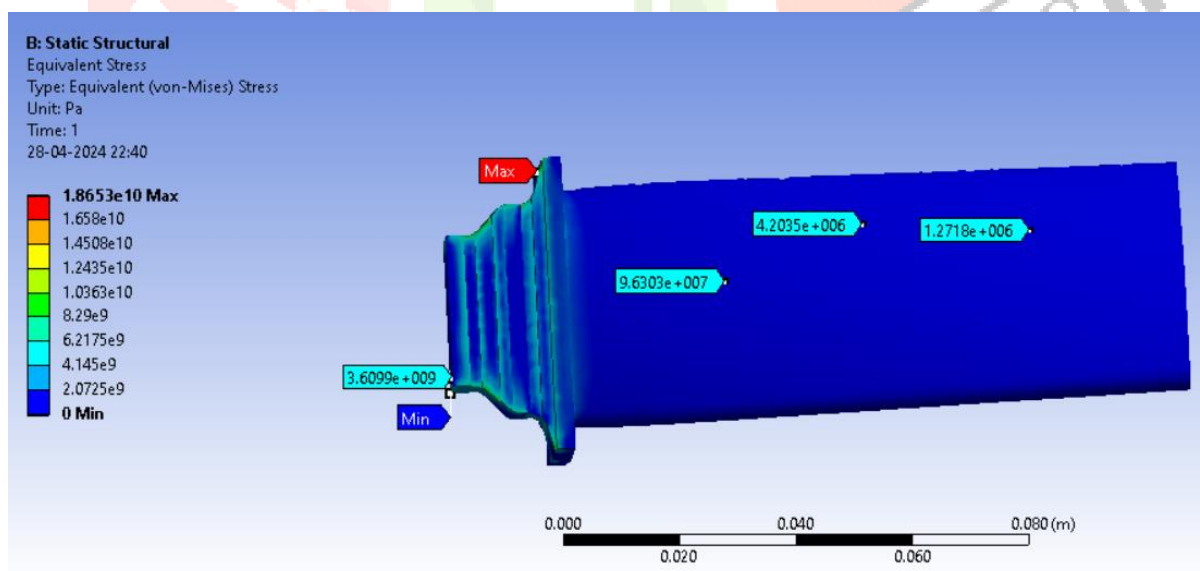
IX. COMPARISON WITH TITANIUM ALLOY-

(Titanium alloy data taken from "Structural and modal analysis of gas turbine blade using ansys" by Hrushikesh Paricharak and S.K. Tiwari)

	Density (Kg/m3)	Young's Modulus (GPa)	Thermal Conductivity (W/mk)	Poisson's Ratio	Max. stress	Total deformation
Structural steel	7850	200	60.5	0.3	1.8653e10	1.4026 mm
Titanium Alloy	4540	110	7.1	0.33	0.6439e10	1.9199mm

X. CONCLUSION

Titanium alloy offers several advantages over structural steel. It has a lower density, making it lighter and potentially more suitable for applications where weight reduction is critical, such as aerospace. Additionally, titanium alloy indicates greater stiffness and resistance to deformation under load. This characteristic is advantageous in maintaining the integrity and performance of turbine blades, especially in high-temperature environments. Moreover, titanium alloy typically exhibits better thermal conductivity compared to structural steel, facilitating efficient heat dissipation and minimizing thermal stresses.

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