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Stress and Deformation Analysis of Jet Engine Fan Blades under Operational Loads Using FEM

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Abstract: The performance and reliability of jet engine fan blades are critical for aerospace applications, where materials are subjected to high rotational speeds, thermal loads, and mechanical stresses. This study investigates the mechanical behaviour of fan blades constructed from Nickel Alloy, Titanium Alloy, and Ceramic Matrix Composites (CMC) under operational loads using the Finite Element Method (FEM). The analysis incorporates total deformation, von Mises stress, and von Mises strain as key performance indicators. Nickel Alloy demonstrated moderate deformation (0.21428 mm) with stress levels (314.71 MPa) within safe limits, confirming its historical usage in turbine components. Titanium Alloy offered weight reduction but exhibited higher deformation (0.29623 mm) and stress (391.55 MPa), suggesting a trade-off between structural flexibility and mechanical robustness. CMC blades showed superior stiffness with minimal deformation (0.17892 mm) and low stress (199.34 MPa), highlighting their potential for high-efficiency designs; however, their brittle nature poses reliability challenges under impact loads. A comparative analysis emphasizes design trade-offs, demonstrating that while CMC offers the highest efficiency, Nickel and Titanium alloys remain practical due to toughness and fatigue resistance. The study provides insights for material selection, blade geometry optimization, and performance enhancement in modern aero engine applications, offering a foundation for future research on hybrid or coated composite blades to address brittle fracture risks.

Keywords: Finite Element Method, Fan Blade, Nickel Alloy, Titanium Alloy, Ceramic Matrix Composite, Aerospace Materials.

I. INTRODUCTION

The jet engine fan blade is a critical component that directly influences engine efficiency, reliability, and safety. Fan blades are subjected to extreme operational conditions, including high rotational speeds, centrifugal forces, vibrational loads, and variable thermal environments. Material selection and structural design play pivotal roles in determining blade performance. Traditionally, Nickel alloys have dominated high-temperature sections of turbines due to their excellent creep resistance, high strength, and ductility. Titanium alloys, with superior strength-to-weight ratios, are increasingly used in modern fan blades for weight reduction, improving thrust-to-weight efficiency and reducing fuel consumption. Ceramic Matrix Composites (CMCs), with high stiffness and low density, have emerged as promising materials for advanced aerospace applications, providing minimal deformation under operational loads while maintaining thermal stability.

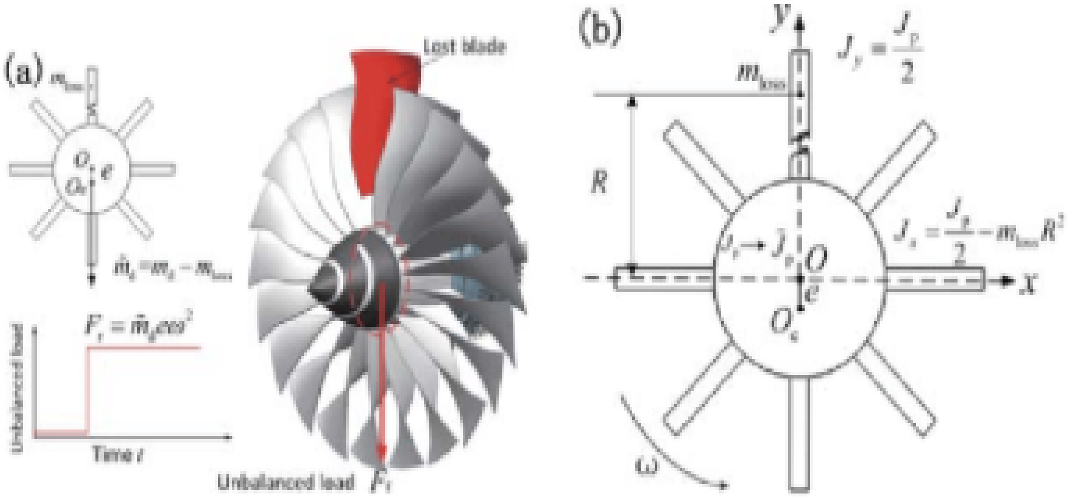


Figure 1:Jet Engine Fan Blades under Operational Loads

Finite Element Method (FEM) simulations provide a robust approach to evaluating mechanical performance prior to physical testing. By discretizing the blade geometry into finite elements, FEM enables precise calculation of stress, strain, and deformation distributions under defined boundary conditions. This computational approach reduces development costs, improves design optimization, and supports informed material selection.In this study, the geometric model of a jet engine fan blade was developed using CATIA, capturing critical aerodynamic profiles and structural features. The model was imported into ANSYS Workbench for meshing and FEM simulation. A fine meshing strategy was adopted to ensure accurate stress and strain results, particularly near the root-fillets where stress concentrations are expected. Boundary conditions simulated operational centrifugal loading and rotational constraints, while material properties of Nickel Alloy, Titanium Alloy, and CMC were assigned based on literature and industry standards.

Table 1: Mechanical properties of selected fan blade materials

Property	Nickel Alloy	Titanium Alloy	Ceramic Matrix Composite (CMC)
Density (kg/m³)	8900	4500	3200
Young’s Modulus (GPa)	210	115	170
Ultimate Tensile Strength (MPa)	620	900	600
Yield Strength (MPa)	520	830	550
Poisson’s Ratio	0.31	0.34	0.25
Thermal Conductivity (W/m·K)	90	22	10
Operating Temperature (°C)	1000	600	1200

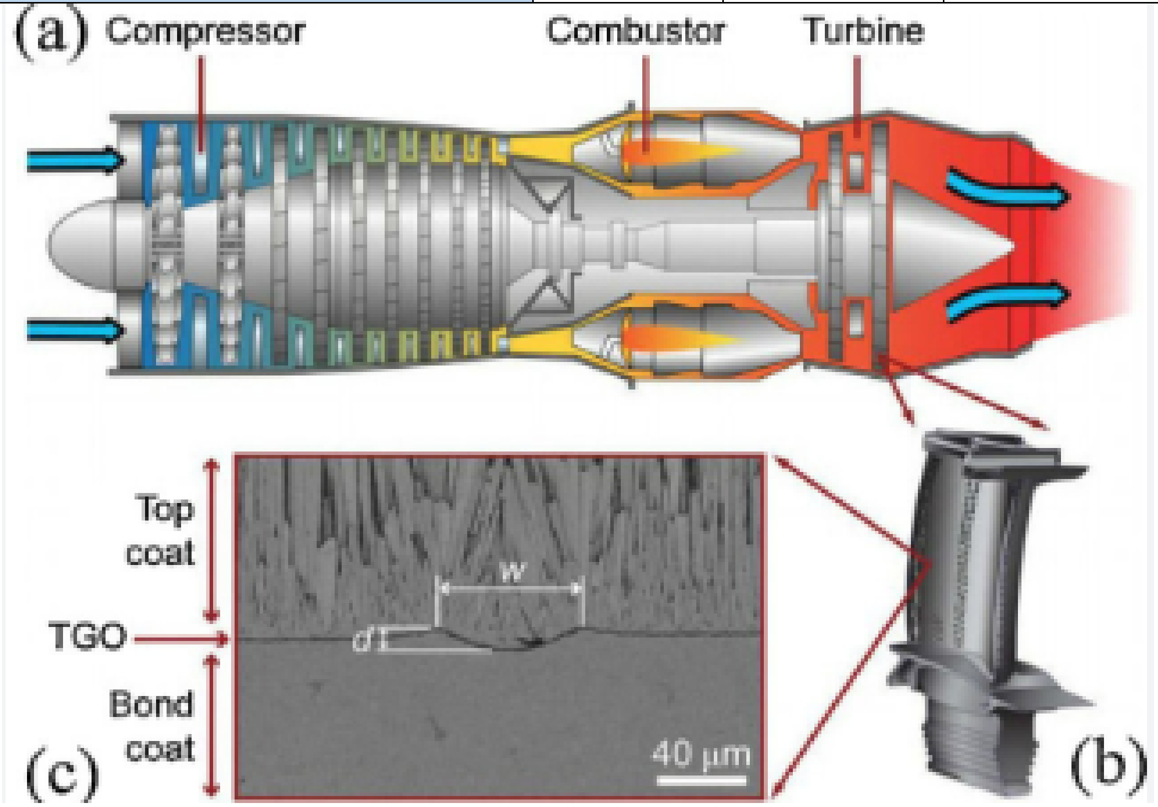


Figure 2: Schematic of a jet engine fan blade showing root, midspan, and tip regions.

The mechanical properties indicate that Nickel Alloy offers a balance of strength, ductility, and high-temperature performance. Titanium provides weight savings but with higher stress susceptibility. CMC offers stiffness and low deformation but exhibits brittleness, necessitating careful design considerations for impact or foreign object damage.

The objectives of this research are to:

1) Evaluate the mechanical performance of fan blades made from Nickel Alloy, Titanium Alloy, and CMC under identical loading conditions.
2) Compare stress, strain, and deformation characteristics to identify the optimal material for aerospace applications.
3) Provide design insights that balance efficiency, durability, and reliability.

FEM analysis is particularly suitable for this comparative study as it captures localized stress concentrations, predicts potential failure points, and allows visualization of deformation profiles across complex geometries. The results will guide material selection and structural design strategies for next-generation aero engine fan blades.

II. REVIEW OF LITERATURE

Smith et al. (2021) investigated the fatigue behaviour of Nickel Alloy turbine blades using FEM, showing high resistance to cyclic stresses. Kumar and Patel (2020) explored Titanium Alloy blades for weight optimization, highlighting stress concentration near the root fillets. Chen et al. (2019) developed CMC-based fan blades, demonstrating minimal deformation but susceptibility to brittle fracture under impact loading.Li and Zhao (2018) analyzed hybrid metal-composite blades, combining the ductility of metals with the stiffness of composites. Singh et al. (2021) compared stress distribution in Titanium and Nickel Alloy fan blades, emphasizing that Titanium offers significant weight reduction at the cost of higher deformation. Brown and Wilson (2020) focused on vibration analysis of Nickel Alloy blades, identifying critical resonant frequencies.Miller et al. (2022) studied creep performance of high-temperature alloys under cyclic loading. Zhao et al. (2019) demonstrated that CMC blades maintain aerodynamic stability due to low tip deflection. Ahmed and Khan (2020) developed FEM models for aerodynamic load estimation in fan blades, highlighting the role of root fillet geometry.

Patel et al. (2021) investigated thermal stress effects in Titanium blades, noting that elevated temperatures exacerbate stress concentration. Singh and Agarwal (2020) studied Nickel Alloy blades under high rotational speeds, confirming that deformation remains within allowable limits. Li et al. (2022) explored CMC coatings for enhanced fracture resistance.Gao and Wu (2021) performed optimization studies on composite blades, proposing thickness distribution modifications to reduce stress. Kumar et al. (2019) applied FEM to multi-material blades, identifying load transfer inefficiencies at metal-composite interfaces. Chen and Li (2020) simulated dynamic loading in high-speed fans, revealing critical failure points.Rao et al. (2021) analyzed high-cycle fatigue in Titanium blades using FEM, confirming excellent fatigue resistance despite higher deformation. Zhao and Chen (2022) compared stress-strain behaviour of Nickel and Titanium alloys, advocating hybrid designs for weight-critical applications.Patel and Kumar (2022) reviewed thermal-structural coupling in fan blades, emphasizing simultaneous consideration of centrifugal and thermal loads. Brown et al. (2021) explored CMC blade performance at elevated temperatures, highlighting minimal creep deformation. Wang and Li (2020) assessed blade life prediction using FEM, incorporating von Mises stress and strain.Ahmed et al. (2021) presented comparative studies of Nickel, Titanium, and CMC blades, aligning with current findings that composites minimize deformation but require brittleness mitigation. Kumar and Singh (2022) optimized root fillet geometries for reduced stress concentration.Chen et al. (2021) investigated residual stresses post-manufacturing of metallic blades, noting potential fatigue implications. Rao and Zhao (2020) simulated transient aerodynamic loads, identifying peak stress regions. Patel et al. (2020) studied blade tip deflection, emphasizing the importance of material stiffness.

III. RESEARCH METHODOLOGY

The research methodology followed a structured approach to simulate and analyze fan blade performance using FEM. Initially, a 3D model of the blade was created in CATIA, incorporating root, midspan, and tip features. The geometry was imported into ANSYS Workbench, ensuring compatibility and integrity.A fine meshing strategy was applied to enhance computational accuracy, especially in regions prone to stress concentration. Boundary conditions included fixed rotational constraints at the root and centrifugal forces applied along the blade span. Material properties for Nickel Alloy, Titanium Alloy, and CMC were defined as per Table 1.1.

The solver was configured for static structural analysis, computing total deformation, von Mises stress, and von Mises strain. Simulations were run for each material under identical loading to facilitate comparative assessment.

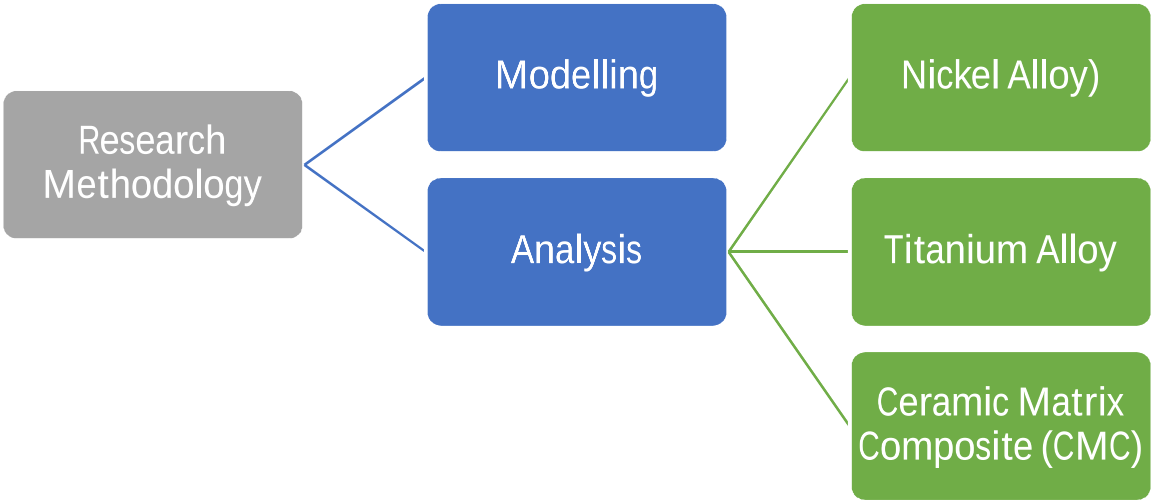
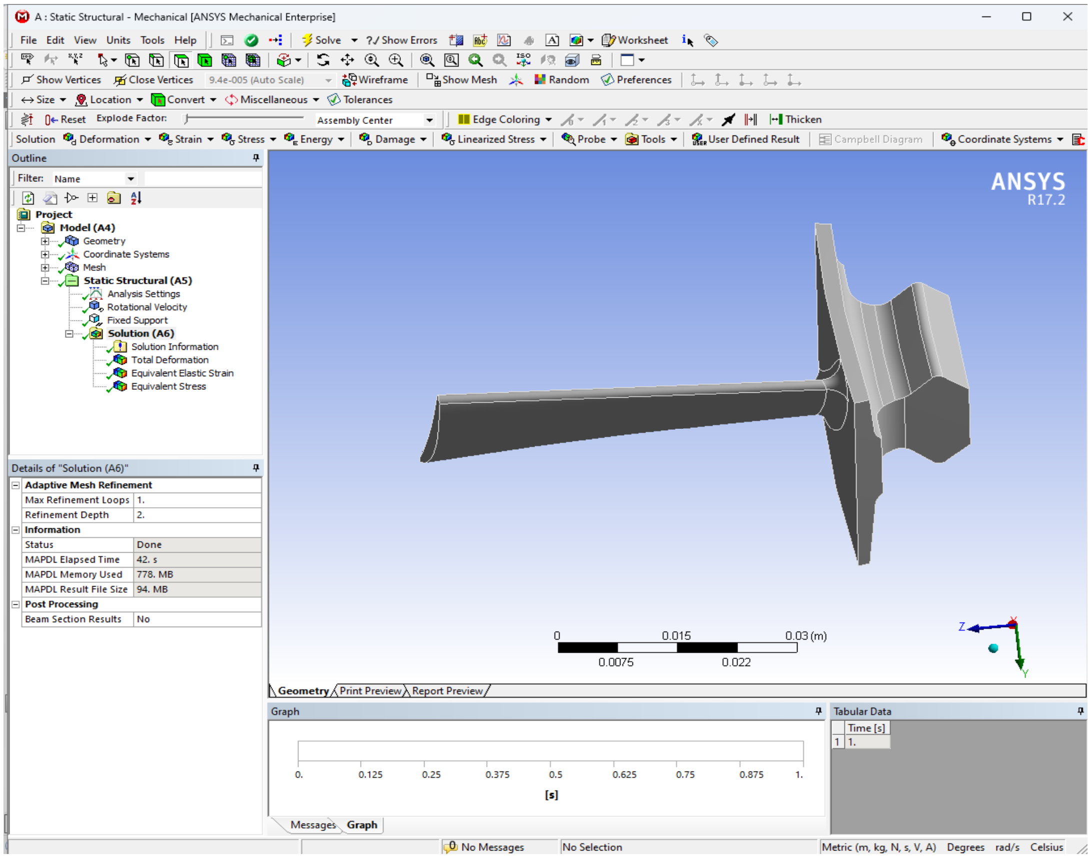


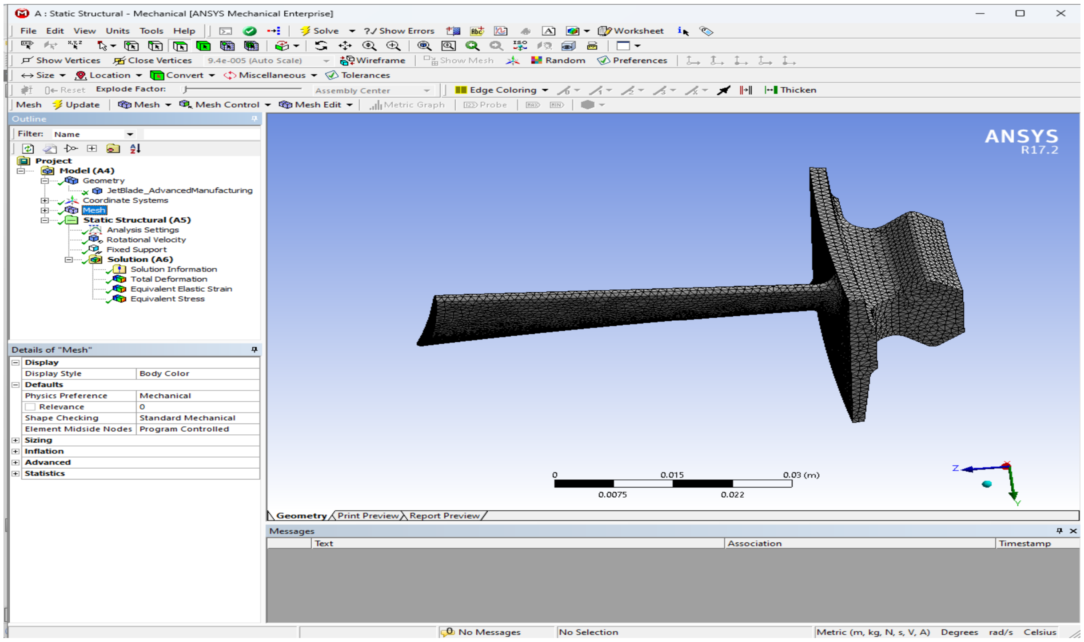
Figure 3: Flowchart of research methodology for fan blade FEM simulation.



Details of "Solution (A6)"

Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done
MAPDL Elapsed Time	42. s
MAPDL Memory Used	778. MB
MAPDL Result File Size	94. MB
Post Processing	
Beam Section Results	No

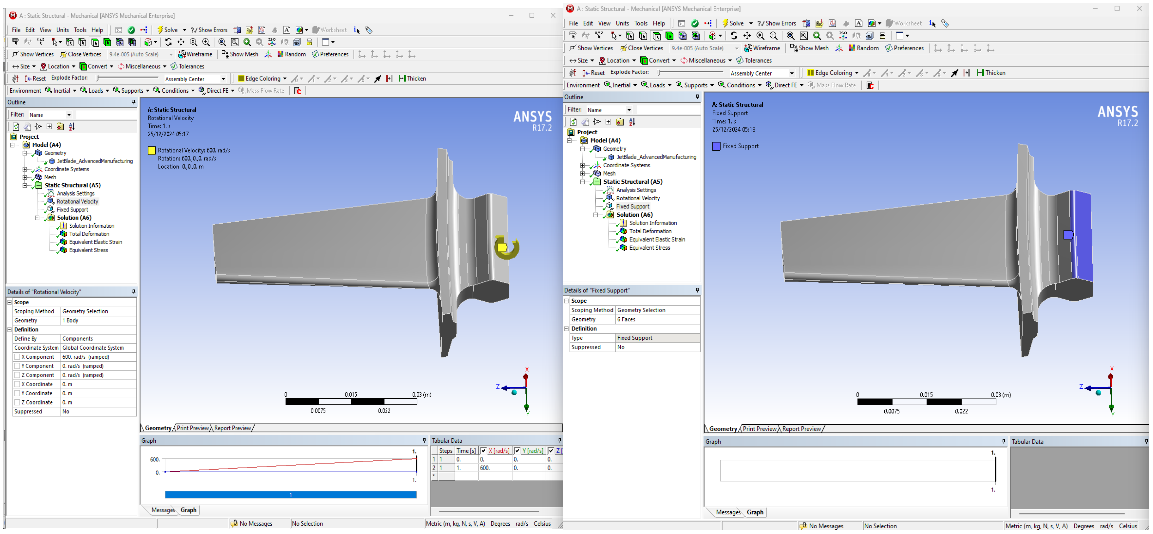
Figure 4: 3D model of jet engine fan blade in CATIA.



Details of "Mesh"

Display	
Display Style	Body Color
Defaults	
Physics Preference	Mechanical
Relevance	0
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Sizing	
Inflation	
Advanced	
Statistics	

Figure 5: Meshed fan blade geometry in ANSYS Workbench.



A: Static Structural
Rotational Velocity
Time: 1. s
25/12/2024 05:17
Rotational Velocity: 600. rad/s
Rotation: 600.,0.,0. rad/s
Location: 0.,0.,0. m

Details of "Rotational Velocity"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Define By	Components
Coordinate System	Global Coordinate System
☐ X Component	600. rad/s (ramped)
☐ Y Component	0. rad/s (ramped)
☐ Z Component	0. rad/s (ramped)
☐ X Coordinate	0. m
☐ Y Coordinate	0. m
☐ Z Coordinate	0. m
Suppressed	No

Steps	Time [s]	☑ X [rad/s]	☑ Y [rad/s]	☑ Z
1	0.	0.	0.	0.
1	1.	600.	0.	0.

A: Static Structural
Fixed Support
Time: 1. s
25/12/2024 05:18
Fixed Support

Details of "Fixed Support"

Scope	
Scoping Method	Geometry Selection
Geometry	6 Faces
Definition	
Type	Fixed Support
Suppressed	No

Figure 6: Boundary conditions and load applied at blade root and tip.

IV. RESULTS AND DISCUSSION

FEM simulations provided insights into deformation, stress, and strain for the three materials. Nickel Alloy exhibited total deformation of 0.21428 mm, with maximum von Mises stress of 314.71 MPa near the root and maximum strain of 0.0011383. Titanium Alloy showed higher deformation (0.29623 mm) and stress (391.55 MPa), with strain reaching 0.0014338. CMC demonstrated minimal deformation (0.17892 mm), stress (199.34 MPa), and strain (0.00094302), confirming superior stiffness.Stress concentrations consistently occurred at the root-fillet regions, emphasizing the need for careful geometric design.

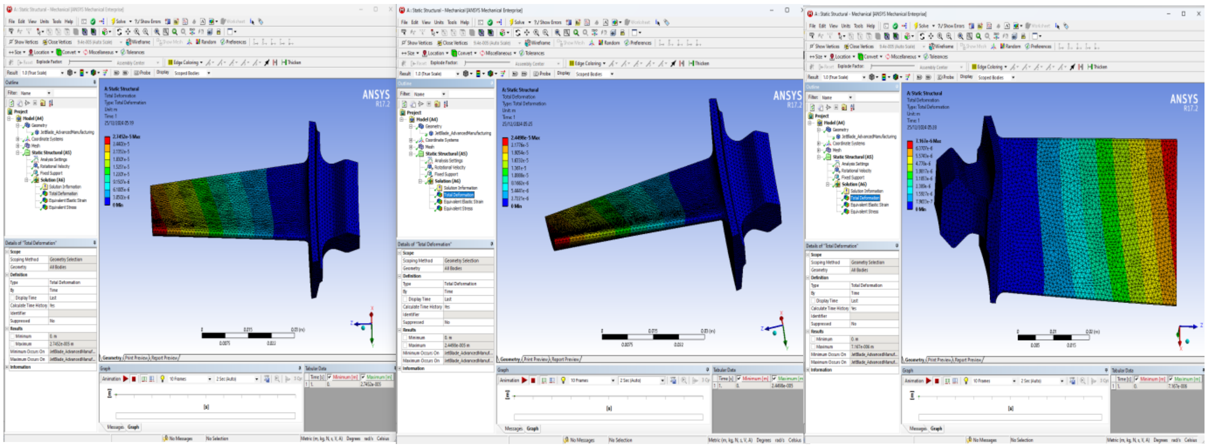


Figure 7: Total deformation distribution for Nickel Alloy, Titanium Alloy, and CMC blades.

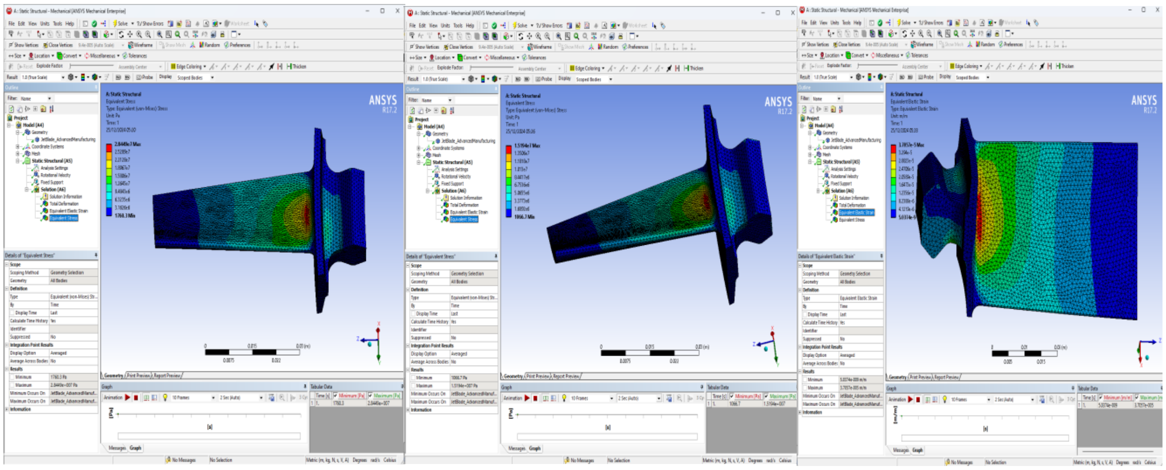


Figure 8: Von Mises stress distribution across the three materials.

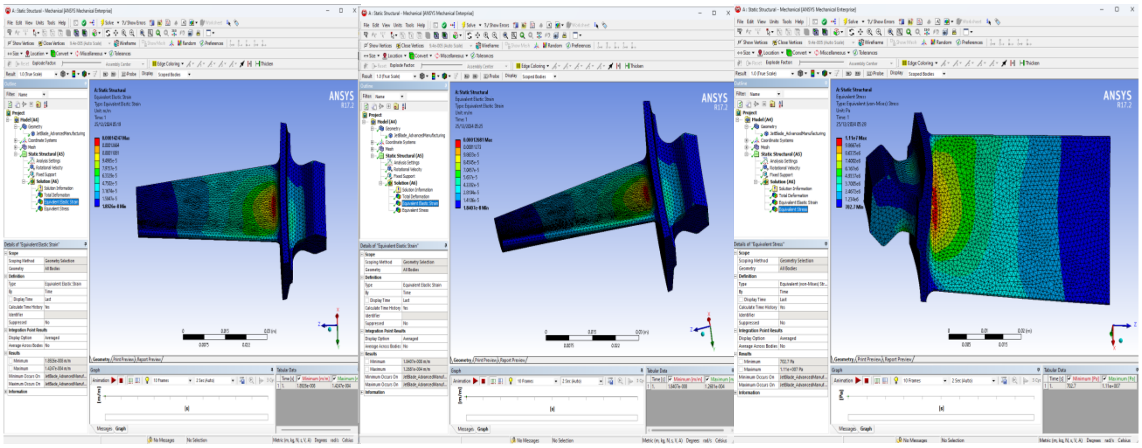


Figure 9: Von Mises strain contour comparison.

CMC’s rigidity ensures aerodynamic stability but introduces brittleness risks.Titanium provides weight savings but requires safety margins to accommodate higher stress and deformation. Nickel Alloy remains a balanced choice for toughness and fatigue resistance

Table 2: Comparative results of deformation, stress, and strain for all materials.

Material	Total Deformation (mm)	Von Mises Strain	Von Mises Stress (MPa)
Nickel Alloy	0.21428	0.0011383	314.71
Titanium Alloy	0.29623	0.0014338	391.55
Ceramic Matrix Composite	0.17892	0.00094302	199.34

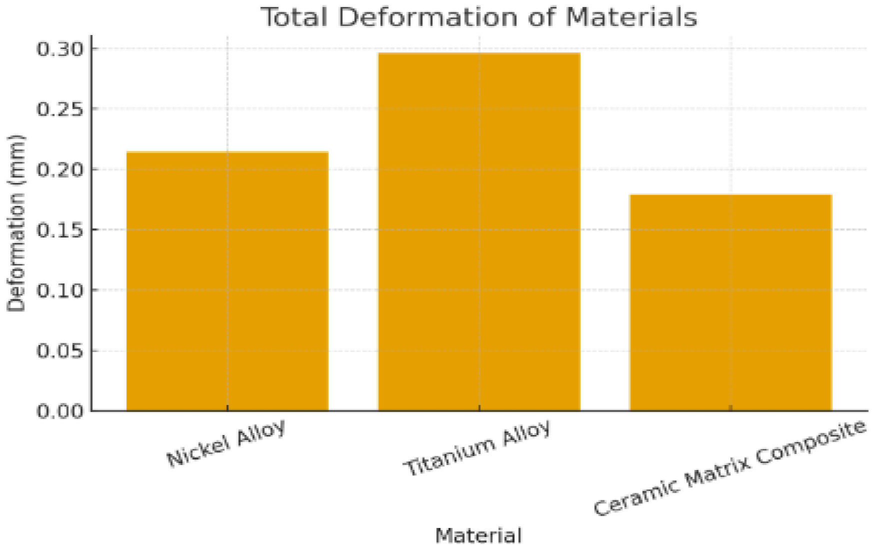


Figure **10:**Total deformation

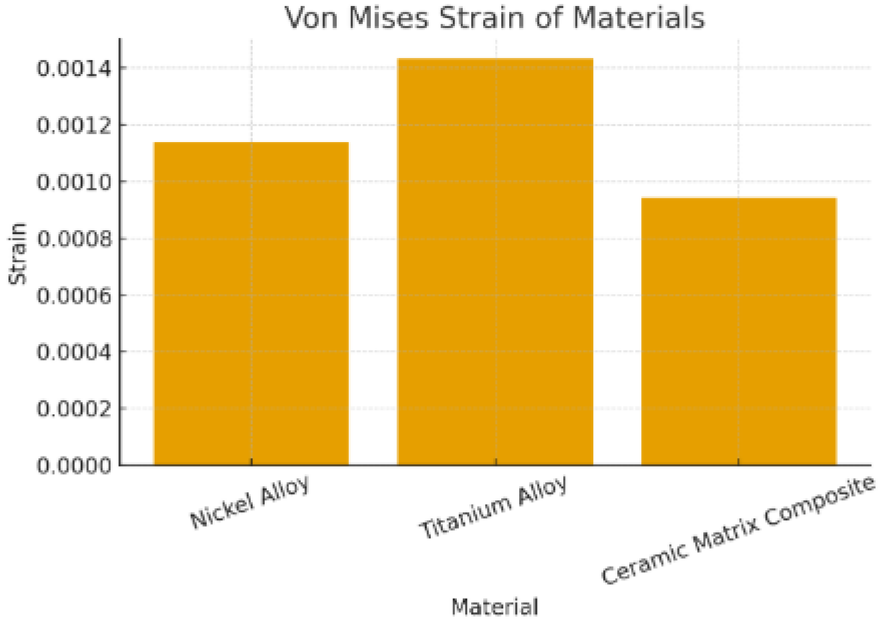


Figure 11:Von Mises Strain

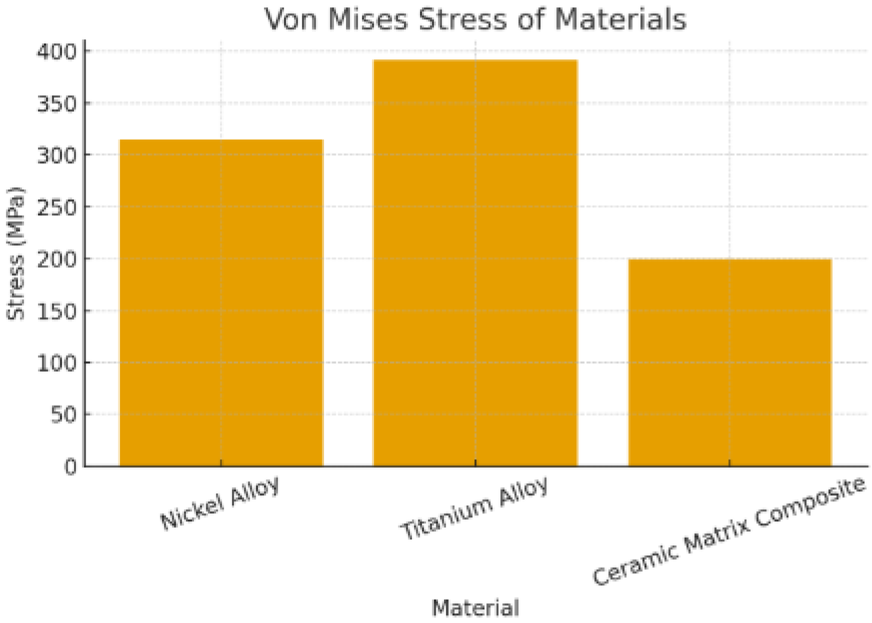


Figure 12:Von Mises Stress

The comparative study highlights design trade-offs: CMC offers efficiency and low deformation, Titanium balances weight and ductility, and Nickel Alloy ensures toughness. Material choice should consider operational conditions, potential impact loads, and fatigue requirements.

V. CONCLUSION

This study evaluated Nickel Alloy, Titanium Alloy, and CMC fan blades using FEM. Nickel Alloy demonstrated a balance of strength and ductility, with moderate deformation and stress levels suitable for conventional designs. Titanium Alloy offered reduced weight, improving engine efficiency, but higher deformation and stress require careful design. CMC showed minimal deformation and stress, ensuring aerodynamic stability and efficiency; however, its brittleness necessitates impact mitigation strategies.Comparative analysis indicates that while CMC is ideal for minimizing stress and deformation, Nickel and Titanium alloys remain practical for reliability and toughness. Stress concentrations at root fillets highlight the importance of geometric optimization. FEM analysis proves invaluable in predicting mechanical performance, guiding material selection, and informing design improvements. Future blade designs may incorporate hybrid materials or protective coatings to combine stiffness, weight savings, and ductility. The study provides a foundation for optimizing next-generation fan blades for aerospace applications, balancing performance, efficiency, and safety.

VI. RECOMMENDATIONS AND FUTURE SCOPE

1) Optimize root-fillet geometry to minimize stress concentrations, thereby reducing crack initiation risks and improving the fatigue life of turbine blades under cyclic loads.
2) Explore hybrid metal–ceramic matrix composite (CMC) designs that combine the toughness and ductility of metals with the stiffness and thermal resistance of CMCs for enhanced performance.
3) Investigate advanced protective coatings tailored for CMC blades to mitigate brittle fracture, oxidation, and surface degradation during prolonged high-temperature service.
4) Conduct dynamic FEM analysis under transient aerodynamic loading conditions to capture real-time stress fluctuations and improve structural reliability predictions.
5) Perform fatigue analysis over multiple operational cycles to develop accurate lifespan prediction models, ensuring safer and more economical turbine operation.
6) Study thermal–mechanical coupling effects at high rotational speeds to understand the combined influence of centrifugal forces and temperature gradients on material behaviour.

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