

AERO ENGINE TURBINE DISK MULTI DISCIPLINARY OPTIMIZATION

Delivering enhanced turbine disk efficiency and extended lifecycle, ensuring reliability and performance that elevate your operations.

CONTENTS

Abstract	3
Introduction	3
Objectives and Scope of Work	5
Parametric Model	5
Finite Element Model	6
Design Criteria	8
Baseline Analysis	9
Optimization	10
Optimization Results	11
Sensitivity Studies	14
Conclusion	15
References	16
About the Author	16
About Cyient	17

ABSTRACT

Turbine disks are critical components of aero-engines, ensuring aircraft safety by withstanding extreme operational conditions. These components are subjected to fatigue loading, due to high temperatures, immense centrifugal forces, and aerodynamic loads stresses, which significantly limit their service life. A key failure mode is rotor burst, where disks disintegrate at excessive speeds, posing catastrophic risks. To mitigate this, turbine disks are designed to resist low-cycle fatigue (LCF) failure and maintain stress levels within acceptable limits under thermal, centrifugal, and aerodynamic loads.

This study focuses on developing a minimum -weight turbine disk design while adhering to stringent safety and performance criteria. Using numerical methods in ANSYS Workbench, a parametric model with variables such as bore width, bore height, web width, and web height was developed. The optimization process ensures reduced disk weight while maintaining critical stress and burst margin thresholds. Sensitivity analyses further evaluate the impact of geometric parameters on performance guiding an efficient and safe disk design. The optimized design achieved up to 24% weight reduction without compromising safety, demonstrating a robust methodology for turbine disk optimization.

INTRODUCTION

Turbine disks are essential in aero-engines, securing rotating blades and transmitting circumferential forces through central shaft. Often employing a fir-tree root design, these assemblies ensure operational reliability. A schematic assembly view of turbine assembly is illustrated in Figure 1.

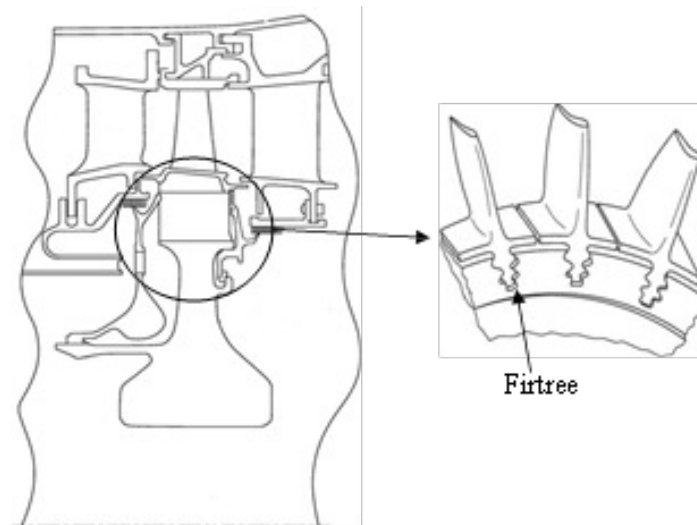
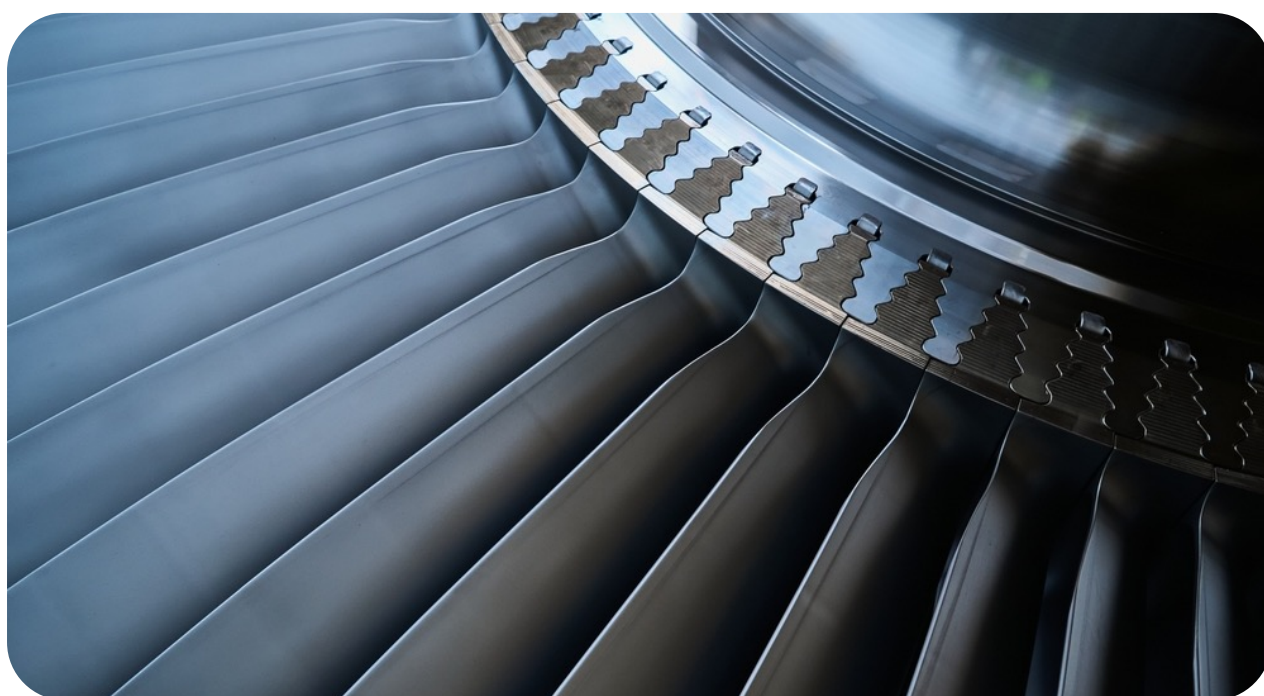


Figure 1: Turbine Disk Assembly

The structural integrity of turbine disks and the attached blades is critical for the safety and performance of aero-engines. Failures in turbine disk can occur due to various factors, including high-cycle and low-cycle fatigue, assembly errors, bearing failure, over temperature, over speed incidents and impacts caused by failures in adjoining components. These disks endure severe stresses caused by multiple loads, including significant centrifugal forces generated by rotation and the weight of attached blades. The blades themselves are subject to bending, twisting and vibratory loads which are transmitted to the disk rim. Moreover, the blade-disk assembly experiences substantial temperature gradients, resulting in high thermal stresses. The disk rim, web and disk bore are particularly prone to these stresses, often exceeding yield limits, necessitating robust safeguards against potential failures. Furthermore, the disk must maintain structural integrity under both operating and redline speeds to prevent catastrophic rotor bursts.

The evolution of design techniques, especially the Finite Element Method (FEM), has significantly enhanced the ability to develop mechanical components like turbine disks. In parallel, advancements in optimization algorithms have facilitated the resolution of complex mathematical programming problems. Together, FEM and Optimization techniques have paved the way for structural optimization, which involves achieving the best feasible design by modifying geometry, material properties and topological parameters while satisfying defined constraints.

Reducing the weight of turbine disks offers numerous advantages, including a decrease in gyroscopic forces and kinetic energies, which in turn reduces the weight of associated components such as bearings, shafts, casings, and frames. Even a minor reduction in disk weight can lead to significant overall weight and material savings for the engine. This study explores a comprehensive approach to turbine disk design, emphasizing weight optimization while ensuring safety and operational efficiency.



OBJECTIVES AND SCOPE OF WORK

The primary objective of this study is to develop a parametric turbine disk model and optimize it for weight reduction while meeting stress and burst margin constraints. Design parameters, including bore, web and neck are used as variables. Sensitivity analyses explore the influence of geometric parameters on stress and burst margin, providing a foundation for an efficient design.

PARAMETRIC MODEL

A representative turbine disk model was developed based on publicly available data . The turbine assembly in this study includes 54 blades, which is a typical configuration for such applications. The parametric Computer-Aided Design (CAD) model was created using Design modeler application in ANSYS Workbench, a parametric feature-based solid modeling tool tailored for engineering analysis preprocessing.

The developed model is a 2D cross-section of the turbine disk, incorporating key parameters such as bore width, bore height, web width, and web height. Each parameter was assigned appropriate upper and lower bounds, ensuring the design remains within feasible operational limits. Figure 2 illustrates the parametric turbine disk cross-section, highlighting the labeled parameters and their constraints. A detailed study was conducted to determine the recommended parameter ranges for each variable. This parametric approach ensures flexibility in assessing the impact of design changes on disk performance, providing a robust foundation for optimization.

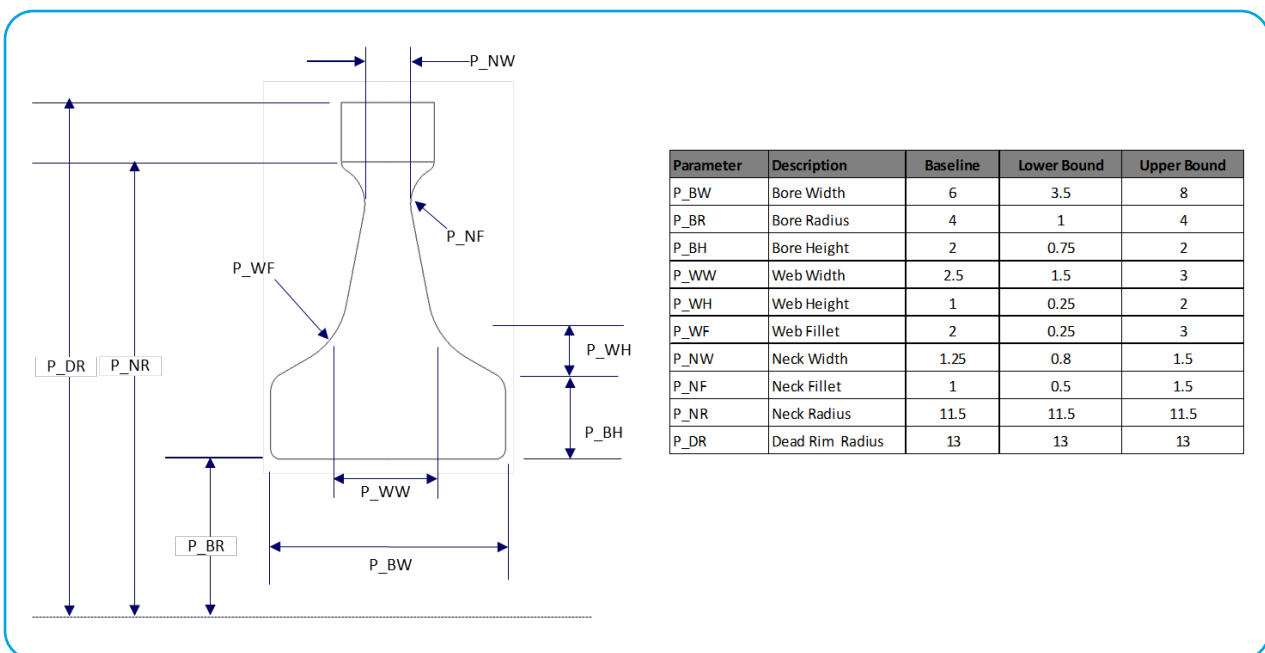


Figure 2: Disk Parametric Model

FINITE ELEMENT MODEL

This study utilized a 2D axisymmetry model for conceptual design analysis. The disc was modeled using PLANE 182 elements, with the live rim represented by axisymmetric elements and the blade attachment region by plane stress elements. An APDL (Ansys Parametric Design Language) macro was employed to calculate and assign appropriate thickness values to each element in the blade attachment region.

To avoid rigid body motion, a node at the bore center was constrained in the axial direction. The turbine assembly consisting of 54 blades was modeled by assigning the total blade assembly weight to MASS 21 elements positioned at the BladeCG (Center of Gravity) location. Additional MASS 21 elements were placed at the center of pressure to apply aero loads.

The FE model, Loads and boundary conditions applied on the disc are shown in Figure 3.

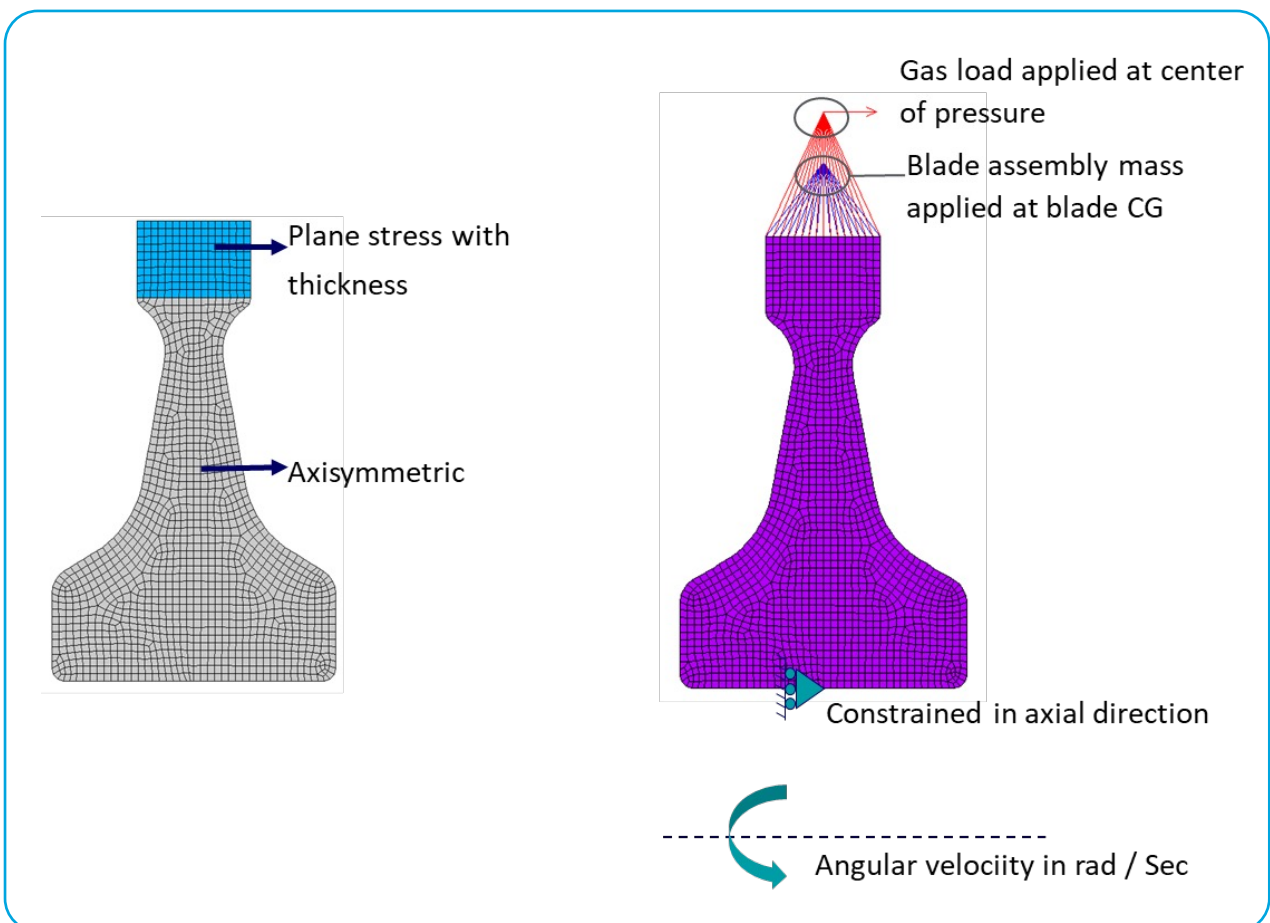


Figure 3: FE Model boundary condition

The engine flight cycle, depicted in Figure 4, illustrates inlet Mach number, turbine inlet temperature, and engine speed against flight time. During the end take-off phase, the disk experiences maximum operating speed, high temperatures, and significant thermal gradient. These extreme loadings cause high stress levels within the disk.

The turbine disk was analyzed and optimized for this critical end take-off condition. Additionally, the disk was evaluated under redline conditions to determine its burst margin, ensuring it meets safety and performance standards.

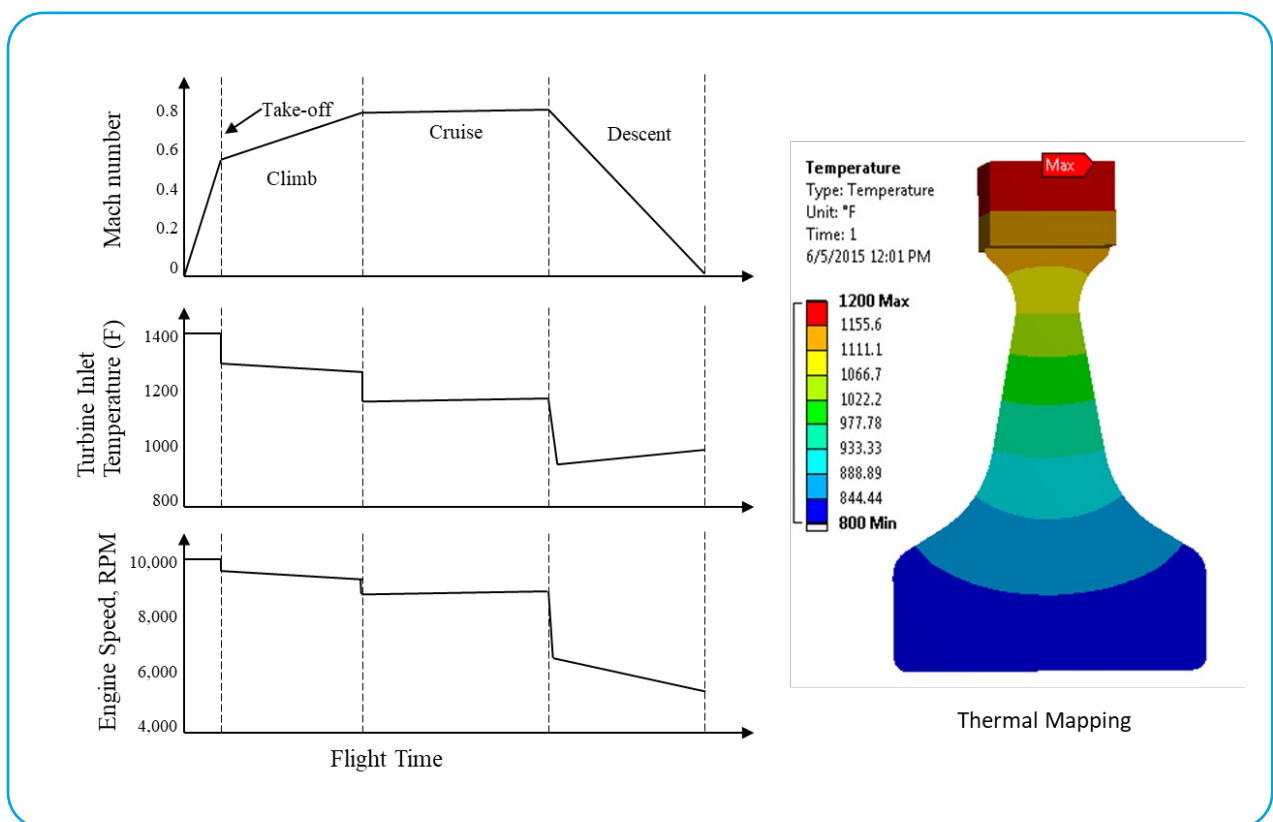
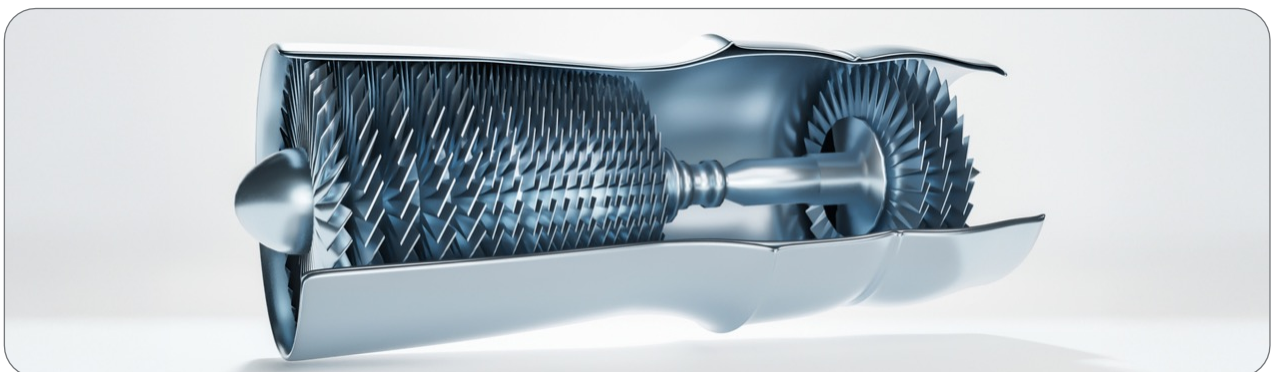


Figure 4: Engine Flight Cycle



DESIGN CRITERIA

The disk design adhered to established industry criteria

Disk Stresses:

The stresses in disk should be within the yield strength of material

$$\sigma_{\text{Disk}} < \frac{\sigma_{\text{Yield}}}{1.1} = 113\text{ksi}$$

σ_{Disk} = Stresses in Bore, Web and Rim

σ_{Yield} = Material Yield Strength

Burst Margin:

The maximum permissible rotor speeds should be 120% of redline speed. The disk burst margin is expressed as the ratio of strength to the applied load. The burst margin is specifying as:

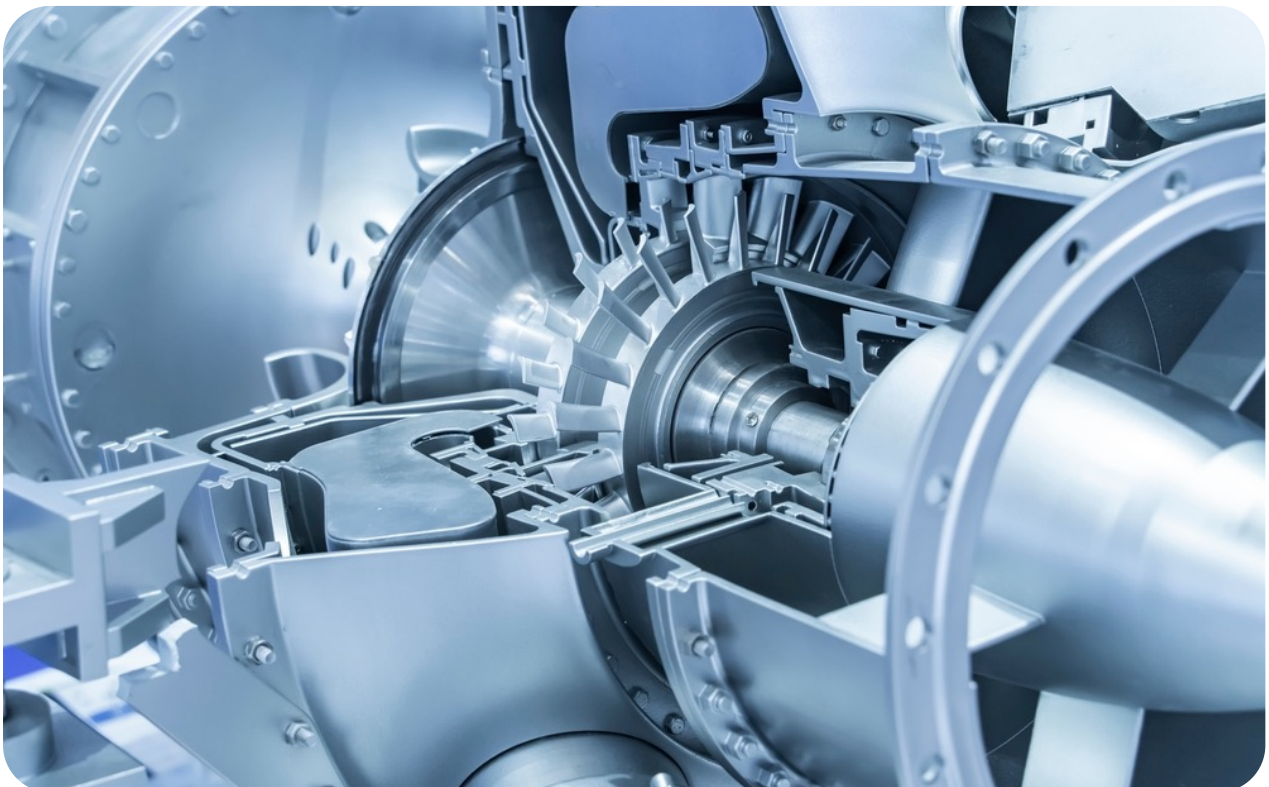
$$M_B = \sqrt{\frac{F \sigma_{\text{Ulti}}}{\sigma_{\text{HAvg}}}}$$

M_B = Burst Margin

F = Material Utilization Factor

σ_{Ulti} = Material Ultimate Tensile Strength

σ_{HAvg} = Disk Average Hoop Stress



BASELINE ANALYSIS

The baseline model was analyzed under take-off conditions, considering angular velocity, thermal gradients and aero loads. This loading condition was critical for extracting the key stress metrics in the disk. Figure 5 illustrates the von Mises stress, maximum principal stress and minimum principal stress distributions for the disk under these conditions.

The model was further analyzed under redline conditions, encompassing angular velocity, thermal gradients and aero loads, to evaluate burst margin. The baseline configuration demonstrated a burst margin of 1.46 at the redline speed, meeting the required safety standards.

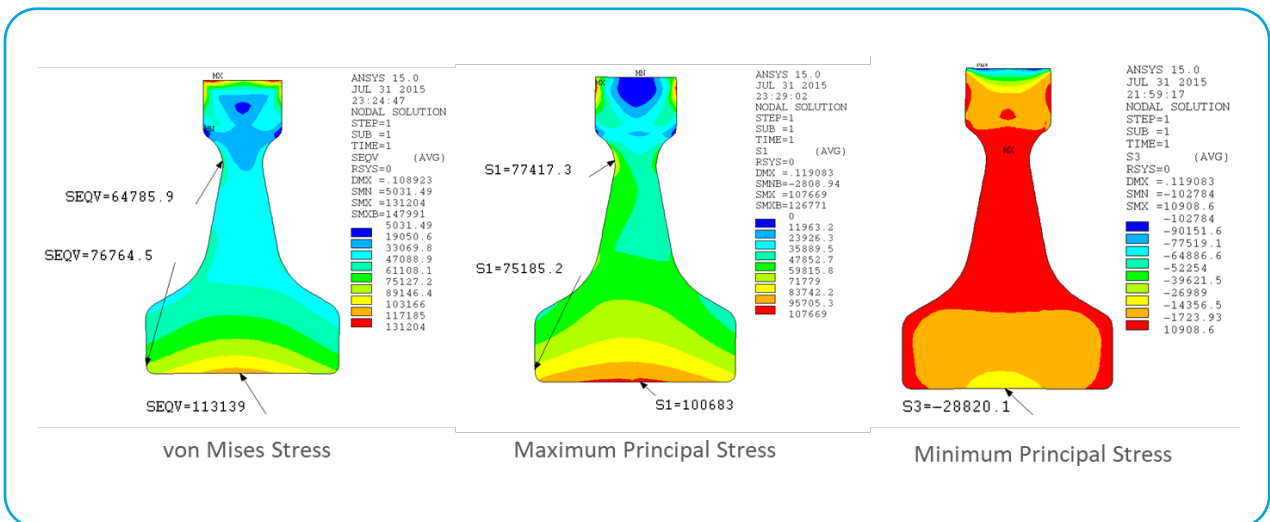


Figure 5: Stresses in Turbine disk



OPTIMIZATION

Optimization techniques are used to modify the current design and enhance structural margins in line with design requirements. For any mechanical system, multiple feasible designs can exist, each meeting the defined objectives and constraints. The design objectives often include minimizing cost, maximizing reliability or maximizing strength, among others.

These techniques enable the identification of the best possible design configuration while adhering to performance and safety constraints.

A general optimization problem can be written as follows:

Minimize / Maximize $f(\bar{x})$

$$f(\bar{x}); \quad \bar{x} = [x_1, x_2, x_3, \dots, x_N]^T$$

$$g_j(\bar{x}) \geq 0 \quad j = 1, 2, 3, \dots, J$$

$$h_k(\bar{x}) = 0 \quad k = 1, 2, 3, \dots, K$$

$$x_i^{(L)} \leq x_i \leq x_i^{(U)} \quad i = 1, 2, 3, \dots, N$$

$\bar{x}$: a column vector of design variables, $x_1, x_2, x_3, \dots, x_N$; where N is the number of design variables.

$f(\bar{x})$: Nonlinear scalar function of the design variables called the objective function.

$g_j(\bar{x})$: K nonlinear inequality constraint functions.

$h_k(\bar{x})$: L nonlinear equality constraint functions.

Goal Driven Optimization (GDO) in ANSYS Workbench is a constrained, multi-objective optimization technique used to identify the "best" possible designs from a sample set, based on the objectives defined for the output parameters. The GDO process enables the evaluation of input parameters' effects on achieving the specific objectives for the output parameters.

In this study, since the baseline showed sufficient burst margins and stresses (other than bore location), the optimization focused on minimizing the weight. Disk weight was defined as the objective function while the disk stresses and burst margin served as constraint functions. Stresses in the disk were limited to 113 ksi, incorporating a safety factor of 1.1 of the yield stresses. The burst margin was minimized, with a threshold of 1.3 set as the minimum acceptable requirement. Table 1 outlines the objectives and constraints used in the optimization.

Parameter	Objective	Constraints
Weight	Minimize	No constraint
Bore Stress	Minimize	≤ 113 ksi
Web Stress	Maximize	≤ 113 ksi
Neck Stress	Maximize	≤ 113 ksi
Burst Factor	Minimize	≥ 1.3

Table 1: Optimization objectives and constraints



OPTIMIZATION RESULTS

Six optimal feasible design configurations were identified through the optimization process. Figure 6 shows the baseline and optimized profiles of the turbine disk. Weight reduction was achieved in all design points, with the maximum reduction of 24% observed in Design Point 2. All other design points also achieved weight reductions exceeding 10%. A comparison of weight reductions across all optimized design points is shown in Figure 7.

The disk stresses in all optimized design points remained within the limiting stress of 113 ksi. However, no significant reduction in bore stresses was observed across the design points. Instead, stresses in the neck and web locations increased significantly. As the baseline model provides a sufficient margin, these stresses were optimized to achieve weight reduction. A comparison of the disk stresses for all optimized design points is shown in Figure 8.

All six design points met burst margin criterion of 1.3. The burst margin for Design Point 2 is matched the baseline model at 1.46, while other designs exhibited a marginal decrease in burst margins. A detailed comparison of burst margins across all optimum design points is provided in Figure 9.

Design Point 2 emerged as the most optimal design configuration, achieving a 24% weight reduction. The von Mises stress in the bore was 109 ksi, slightly below the limiting stress. The von Mises stresses in the web and neck were 83.5 ksi and 89.6 ksi, respectively. A comparison of von Mises stress plots between the baseline and optimum design is presented in Figure 10. The burst margin was optimized design remained at 1.46, ensuring compliance with safety standards.

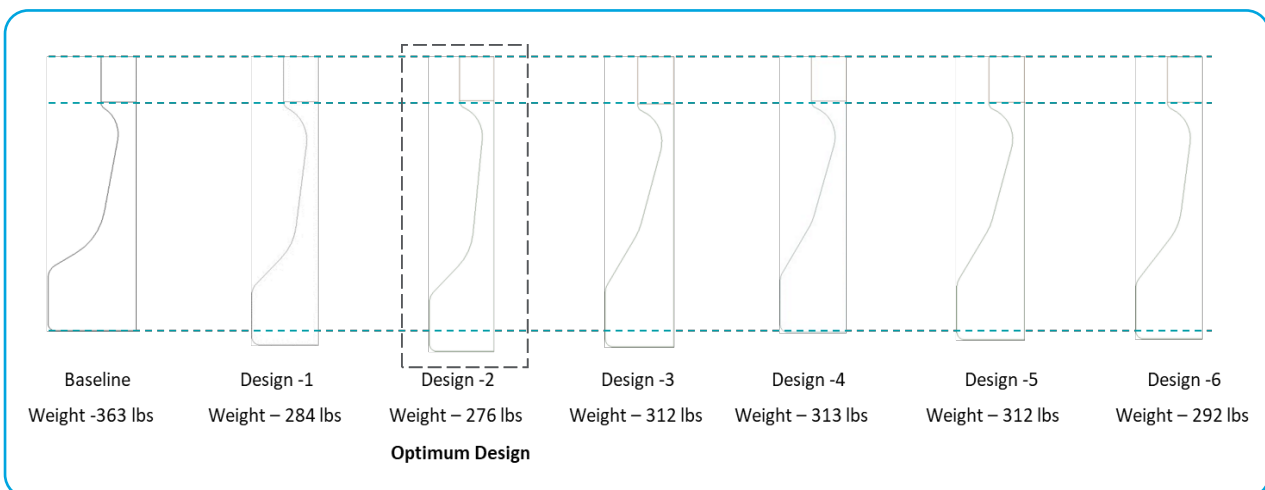


Figure 6: Baseline and Optimum Design points

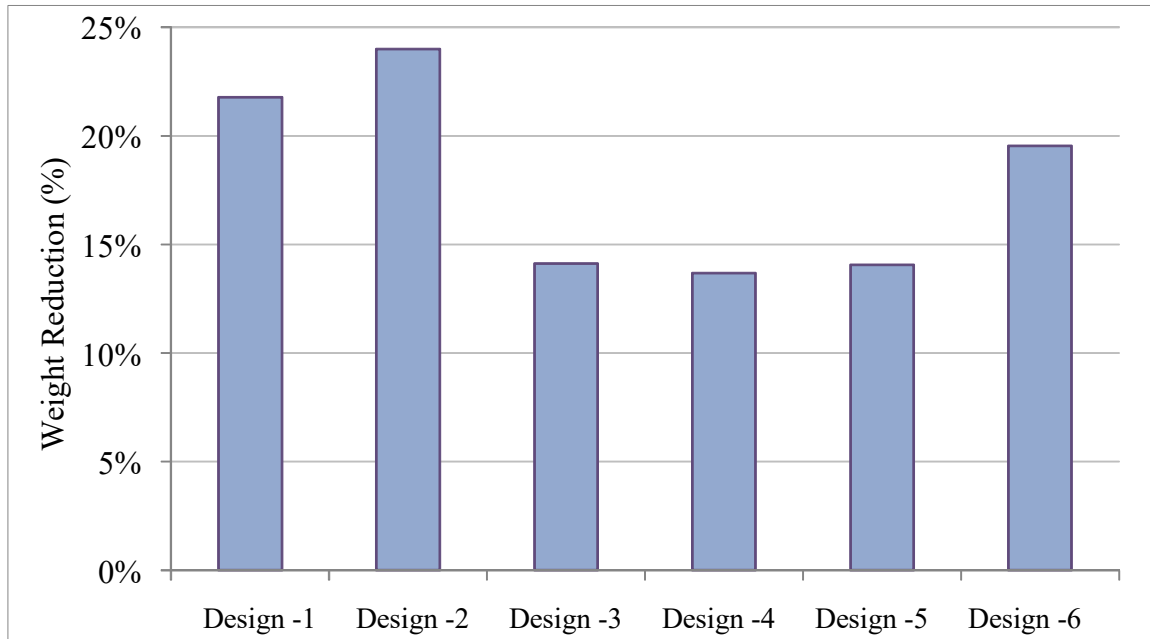


Figure 7: Weight reduction of optimum Design points

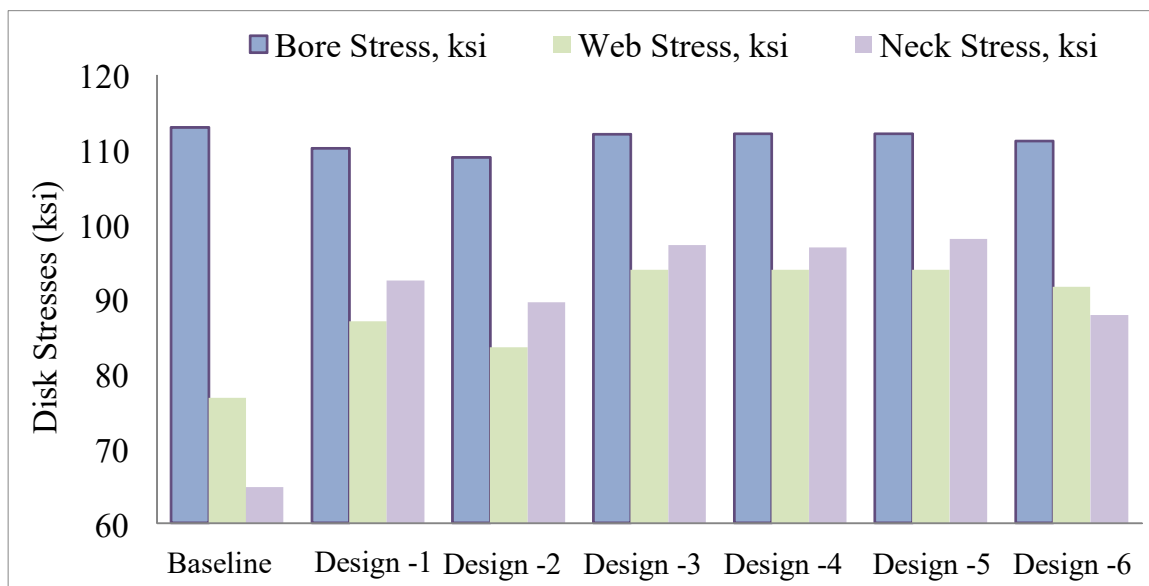


Figure 8: Stresses in Baseline and optimum Design points

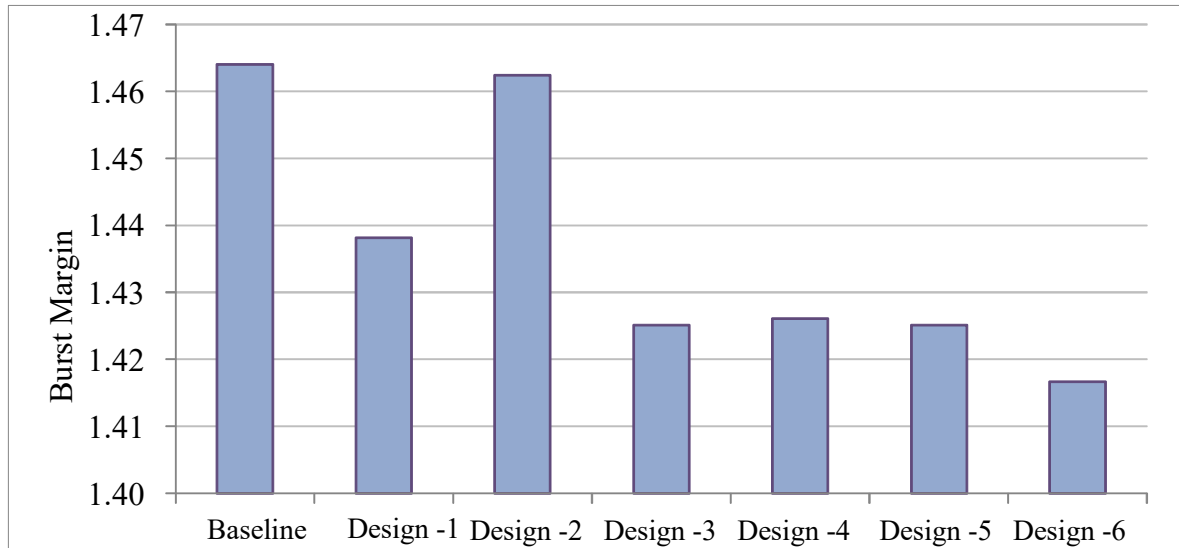
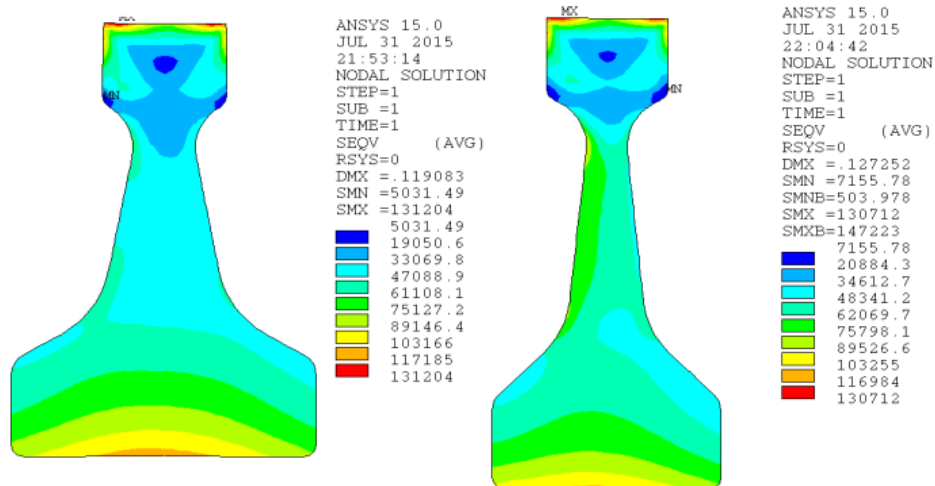


Figure 9: Burst margin in Baseline and optimum Design points

**Baseline Model**

Bore Stress, ksi	113.0
Web Stress, ksi	76.8
Neck Stress, ksi	64.8

Design-2

Bore Stress, ksi	109.0
Web Stress, ksi	83.5
Neck Stress, ksi	89.6

Figure 10: von-Mises stress plots of Baseline and Optimum design

SENSITIVITY STUDIES

Burst Margin

The burst margin is highly sensitive to the design parameters of bore width and bore radius. An increase in bore width leads to an increase in the burst margin, while an increase in bore radius results in a decrease in the margin. The sensitivity curves for burst margin are shown in Figure 11. The upper and lower bounds of both parameters yield burst margin greater than 1.3, ensuring compliance with design criteria.

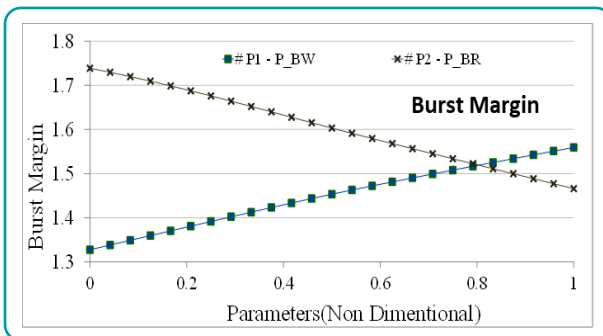


Figure 11: Burst Margin Sensitive Curves

Web Stresses

Web stress is sensitive to bore width and web width. Increasing web width reduces web stress significantly. Additionally, increasing bore width decreases web stress up to 50% of the parameter range, beyond which the change becomes minimal. Figure 13 illustrates the sensitivity of web stress to these parameters.

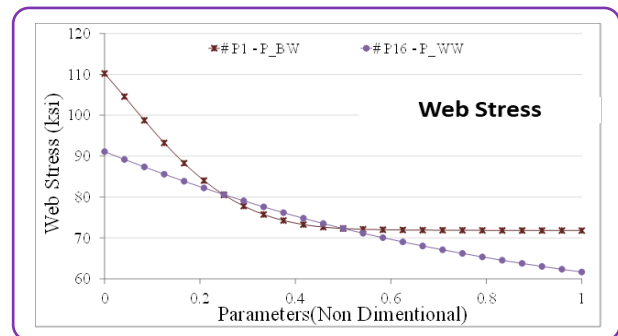


Figure 13: Web Stress Sensitive Curves

Bore Stresses

Bore stress is particularly sensitive to the design parameters of bore width and bore height. Maximizing these dimensions significantly reduces bore stresses. The sensitivity curves for bore stress are presented in Figure 12, demonstrating that bore stress can be limited to 113 ksi by optimizing these parameters.

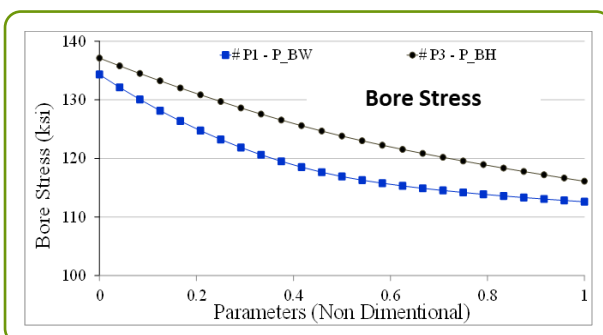


Figure 12: Bore Stress Sensitive Curves

Neck Stresses

Neck stress is strongly influenced by neck width and web width. Increasing either parameter effectively decreases neck stress. The sensitivity curves for neck stress are shown in Figure 14, highlighting how these parameters can be optimized for improved performance.

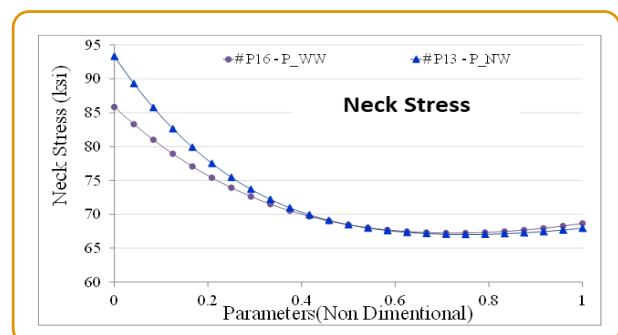


Figure 14: Neck Stress Sensitive Curves

CONCLUSION

The engine design process is inherently iterative, complex and multidisciplinary. The success of an engine depends on a design that optimally integrates various engineering disciplines such as aerodynamics, thermal management and structural integrity, along with lifecycle considerations like cost, manufacturability, serviceability and supportability. An integrated Multidisciplinary Design Optimization (MDO) system is most beneficial at the conceptual design stage, where it has the greatest influence on the final engine configuration.

This paper presented a Multi-disciplinary Optimization approach for turbine disk design using parametric modeling and optimization techniques in ANSYS workbench. The baseline model exhibited high stress at the bore location, exceeding the allowable stress limit, though it demonstrated a robust burst margin of 1.46 stresses at the web and neck locations were well within the acceptable limits. Optimization results revealed that a total weight reduction of up to 24% could be achieved without compromising disk stresses or burst margin.

Key parameters, including bore width, bore radius, bore height, web width, and neck width, were found to significantly influence output parameters such as burst margin and disk stresses:

- Increasing bore width improves burst margin and reduces disk stresses.
- Bore radius is highly sensitive to burst margin; increasing the bore radius decreases the burst margin.
- Bore height positively impacts bore stresses but has limited influence on other regions.
- Increasing neck width reduces neck stresses effectively.

Future work should explore the effects of transient thermal conditions on the optimized disk. Detailed 3D analyses, incorporating blades and blade attachments, are necessary to validate the optimized design further. Additionally, studies focusing on the blade attachment region could provide deeper insights and refinement opportunities.



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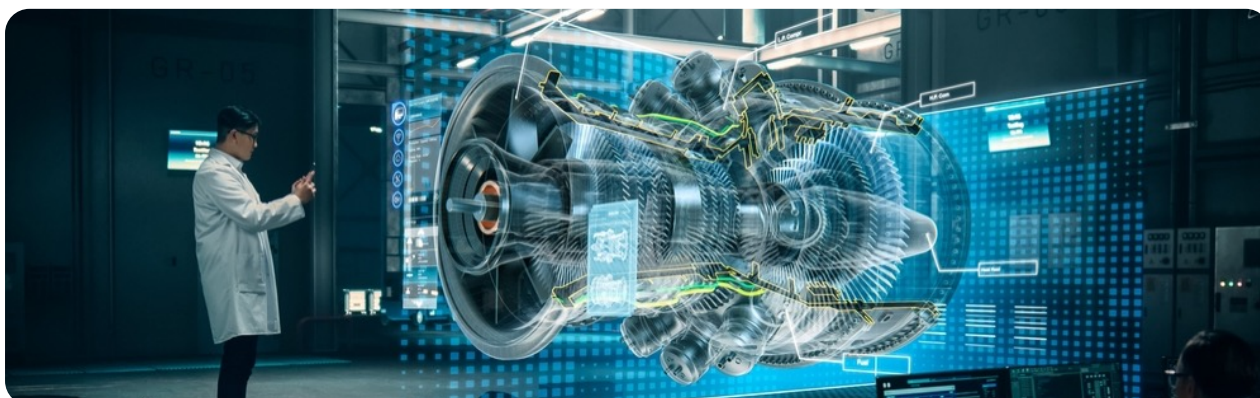
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ABOUT THE AUTHOR



Lakshman Kasina, an M.Tech graduate from IIT Madras, brings over 22 years of extensive experience in design, analysis, and simulation across various engineering domains. His expertise spans Stress Analysis, Impact Dynamics, Engineering Vibrations, and Composite Modeling. He is highly proficient in Low-Cycle Fatigue (LCF) and High-Cycle Fatigue (HCF), and Multidisciplinary Optimization.

Lakshman has made significant contributions to the field through his research and has authored over 10 papers presented at national and international conferences. His vast knowledge and hands-on experience make him a recognized authority in the areas of structural design and optimization.



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