

Finite Element-Based Structural Characterization and Material Selection for High-Durability Automotive Camshafts

N. V. S. Raju^{1*}, G. Suresh², Moodu Prasad², Thogiti Abhinay², K. N. Madhu Sudhan², Vanthadupula Pradeep²

¹Professor & Principal, ²UG Student, ^{1,2}Department of Mechanical Engineering
JNTUH College of Engineering Wanaparthy, Narsingaipalli, Gopalpet Rd, Wanaparthy, 509103,
Telangana

*Correspondence: N. V. S. Raju (enviousraju@jntuh.ac.in)

ABSTRACT

The camshaft is one of the most critical components in an internal combustion engine, responsible for controlling the opening and closing of the inlet and exhaust valves with precise timing. Proper valve operation is essential for ensuring efficient completion of the suction, compression, power, and exhaust strokes of the engine. Any deviation in camshaft performance can adversely affect engine efficiency, fuel consumption, power output, and overall reliability. Therefore, the design and material selection of the camshaft play a significant role in achieving optimal engine performance and durability. This project focuses on the design and static structural analysis of an automobile camshaft to evaluate its mechanical behavior under operating conditions. The camshaft dimensions are designed based on engine requirements, considering the power and suction stroke characteristics. A three-dimensional model of the camshaft is developed using Computer-Aided Three-Dimensional Interactive Application (CATIA), providing an accurate representation of its geometry and functional features. Subsequently, static analysis is performed using ANSYS Workbench to investigate the stress distribution, deformation, and structural integrity of the component under applied loading conditions. To identify the most suitable material for camshaft manufacturing, a comparative analysis is conducted using two commonly employed engineering materials, namely Cast Iron and Steel. The simulation results are evaluated based on their strength, stiffness, and resistance to deformation. The study provides valuable insights into the structural performance of the camshaft and assists in selecting the most appropriate material for enhanced durability, reliability, and

efficient engine operation in automotive applications.

Keywords: Automotive Camshaft, Finite Element Analysis, Static Structural Analysis, CATIA V5, ANSYS Workbench, Material Selection, Structural Steel

1. INTRODUCTION

A cam is a mechanical element used to convert rotary motion into reciprocating or oscillating motion through direct contact with a follower. As shown in fig 1 It is commonly incorporated into rotating shafts or wheels with specially designed profiles that impart a predetermined motion to the follower. The cam-follower mechanism is classified as a higher pair due to its line contact between mating surfaces. Owing to its ability to generate precise motion, the cam mechanism is widely used in various mechanical systems, particularly in internal combustion engines where accurate control of valve operation is essential. The cam acts as the driving member, while the follower serves as the driven component, translating the cam profile into the required motion.

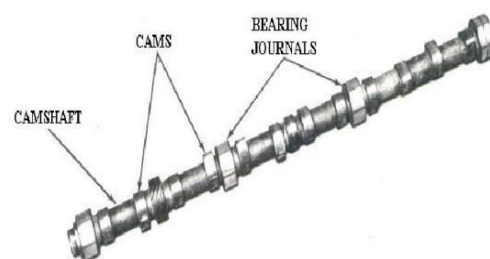


Fig 1. Cam and Cam shaft

The camshaft is a vital engine component that carries a series of cam lobes designed to operate the intake and exhaust valves. It is driven by the crankshaft through timing gears, chains, or belts, ensuring synchronization between piston movement and valve operation. This precise coordination enables the valves to open and close at the correct intervals during the engine cycle, thereby improving combustion

efficiency and engine performance. Depending on engine design, one or more camshafts may be employed to control intake valves, exhaust valves, and fuel injection systems. In multi-cylinder and V-type engines, separate camshafts are often provided for each cylinder bank to enhance performance and operational flexibility.

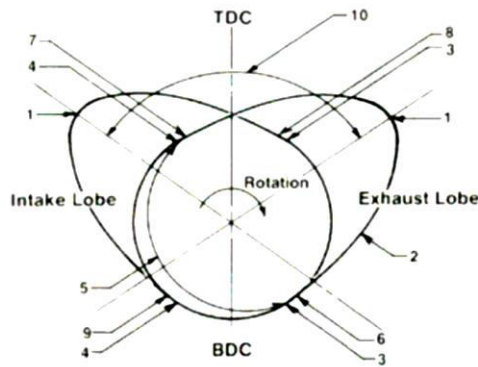


Fig 2. Rotation of cam shaft

The location and configuration of the camshaft vary according to engine type and design requirements. In modern engines, the camshaft may be positioned within the cylinder head or the engine block. In addition to controlling valve train operation, the camshaft influences engine firing order, air-fuel intake, exhaust processes, and the effective operating speed range of the engine. It also incorporates bearing journals and thrust surfaces to support rotation and prevent axial movement. As the central component governing valve timing and engine breathing, the camshaft plays a crucial role in determining engine efficiency, power output, reliability, and overall performance.

The automotive industry continues to experience steady growth due to increasing production capacity and rising global demand, making it one of the most significant contributors to the world economy. As one of the largest industrial sectors, the automotive field is closely connected with more than 300 supporting industries, including manufacturing, materials, electronics, and engineering services. Consequently, any failure or disruption in either the primary manufacturing process or its associated industries can directly affect the performance, reliability, and quality of vehicles. Therefore, ensuring the durability and proper functioning of automotive components is of

paramount importance. In this context, failure analysis has emerged as a critical area of study for both materials and mechanical engineers. It involves the systematic investigation of component failures to identify their root causes and evaluate their impact on performance. Through careful observation, testing, and analysis, engineers develop a deeper understanding of the relationship between material properties, structural characteristics, and operational behavior. Such knowledge contributes to the design of safer, more reliable, and higher-performing automotive systems while minimizing maintenance costs and preventing unexpected failures.

2. LITERATURE SURVEY

2.1 Optimization of Cam Mechanisms and Circuit Breaker Systems

The optimization of cam-based mechanisms has gained significant attention due to the increasing demand for high-performance and reliable mechanical systems. Jang et al. [1] presented a multibody dynamics (MBD)-based simulation approach for optimizing switch mechanisms in circuit breakers. Their study demonstrated that simulation-driven design methodologies can effectively improve operational reliability while reducing design iterations. Similarly, Liu et al. [2] investigated the dynamic optimization of cam structures used in Molded Case Circuit Breakers (MCCBs). The authors focused on improving motion characteristics and reducing operational losses through structural modifications. Their findings highlighted the importance of dynamic analysis in enhancing the efficiency and performance of cam-operated systems. Yu et al. [8] further examined the relationship between displacement characteristics and operating mechanisms in vacuum circuit breakers, emphasizing the influence of cam-driven motion on switching performance and operational stability.

2.2 Evolutionary Algorithms for Mechanism Synthesis and Design Optimization

Optimization algorithms have become essential tools in the synthesis and design of mechanical linkages and cam mechanisms. Storn and Price [3] introduced Differential Evolution (DE), a robust population-based optimization technique capable of solving complex engineering

optimization problems. Building on this concept, Acharyya and Mandal [4] evaluated the effectiveness of various Evolutionary Algorithms (EAs) for four-bar linkage synthesis and demonstrated their capability to obtain optimal mechanism dimensions. Lin [5] proposed a hybrid Genetic Algorithm-Differential Evolution (GA-DE) approach, combining the exploration capabilities of GA with the convergence efficiency of DE to achieve improved path synthesis solutions. Ortiz et al. [6] further enhanced the optimization process through an adaptive Differential Evolution algorithm featuring self-adjusting control parameters. More recently, Kang et al. [7] conducted a comparative analysis of multiple metaheuristic optimization algorithms for path-generating four-bar linkages and concluded that evolutionary optimization techniques provide superior design accuracy and convergence performance. These studies collectively demonstrate the effectiveness of advanced optimization algorithms in mechanical component design and dimensional synthesis.

2.3 Mechanical Design Principles and Kinematic Analysis of Cam-Follower Systems

The theoretical foundations of cam and linkage mechanism design are extensively documented in classical mechanical engineering literature. Yan and Wu [9] provided a comprehensive treatment of mechanism theory, including the kinematic analysis and synthesis of cam-follower systems. Their work serves as a valuable reference for understanding motion transmission, displacement characteristics, and mechanism behavior. The study emphasized the importance of accurate kinematic design in achieving smooth motion transfer and minimizing dynamic disturbances. These principles form the basis for the development of efficient camshaft designs used in modern automotive engines.

2.4 Structural Analysis and Elastic Behavior of Mechanical Components

Structural integrity is a critical consideration in the design of automotive camshafts due to the cyclic loads experienced during engine operation. Timoshenko and Goodier [10] established the fundamental principles of

elasticity and stress analysis, providing analytical methods for evaluating deformation, stress distribution, and material behavior under loading conditions. Their work remains a cornerstone in understanding the elastic response of machine elements subjected to static and dynamic forces. These theoretical concepts are widely applied in Finite Element Analysis (FEA) tools such as ANSYS for assessing the structural performance of mechanical components.

2.5 Material Selection and Design Considerations for Automotive Components

Material selection plays a vital role in determining the durability, strength, and reliability of camshafts and other automotive components. Budynas and Nisbett [11] discussed comprehensive mechanical design methodologies, including material selection criteria, fatigue analysis, stress concentration effects, and safety factor considerations. Their work provides essential guidelines for evaluating engineering materials such as cast iron and steel based on mechanical performance requirements. The authors emphasized that appropriate material selection, combined with proper structural design, significantly improves component life and operational efficiency. These principles are directly applicable to the present study, which compares the structural behavior of cast iron and steel camshafts through static analysis.

2.6 Research Gap

A review of the existing literature indicates that considerable research has been conducted on cam mechanism optimization, linkage synthesis, dynamic performance evaluation, and evolutionary design methodologies. Furthermore, extensive theoretical studies have addressed elasticity, stress analysis, and material selection for mechanical components. However, limited research has focused on the comparative static structural analysis of automotive camshafts using different engineering materials under identical loading conditions. In particular, studies evaluating the deformation and stress characteristics of cast iron and steel camshafts through Finite Element Analysis are relatively scarce. Therefore, the present work aims to bridge this gap by designing a camshaft model in CATIA and

performing static structural analysis in ANSYS Workbench to identify the most suitable material based on stress distribution, deformation behavior, and overall structural performance.

3. PROPOSED SYSTEM

The proposed system focuses on the design and static structural analysis of an automotive camshaft using advanced CAD and CAE tools. The three-dimensional geometric model of the camshaft is developed using CATIA, a leading engineering software widely utilized in the aerospace, automotive, shipbuilding, and manufacturing industries. CATIA provides a comprehensive environment for creating precise 3D models, mechanical components, assemblies, and complex engineering structures. Its powerful modeling capabilities enable the accurate representation of cam lobes, bearing journals, and shaft geometry, ensuring that the designed camshaft meets functional and dimensional requirements. The software also supports product lifecycle development by integrating design, engineering, and manufacturing processes within a unified platform.

After the completion of the CAD model, the camshaft is imported into ANSYS Workbench for static structural analysis. The analysis is performed to evaluate critical performance parameters such as total deformation, equivalent stress, strain distribution, and structural stability under applied loading conditions. To determine the most suitable material for automotive applications, the camshaft model is analyzed using different engineering materials, namely Cast Iron and Steel. Comparative assessment of the simulation results helps identify the material that offers superior strength, stiffness, and durability while minimizing deformation and stress concentration. The proposed methodology combines advanced modeling and simulation techniques to optimize camshaft performance, improve reliability, and support effective material selection for enhanced engine efficiency and long-term operational stability.

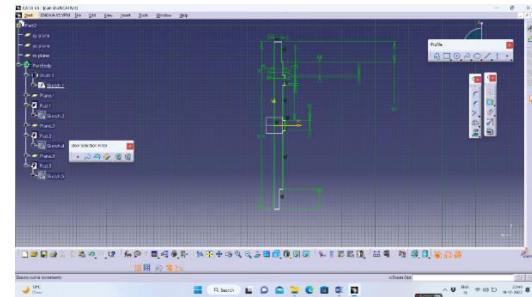


Fig 2. 2D sketch of cam shaft using Catia v5 interface

As shown in fig 2 the geometric model of the camshaft was developed using CATIA V5 by creating a detailed two-dimensional sketch based on the required design dimensions. Initially, reference planes were established, and the shaft profile was generated using lines, arcs, and dimensional constraints to accurately define the geometry of the camshaft. Critical dimensions such as shaft length, journal diameter, cam lobe dimensions, and spacing between components were incorporated into the sketch to ensure design accuracy. Parametric constraints were applied to maintain dimensional consistency and facilitate future modifications.

After completing the sketch, CATIA's Part Design workbench was utilized to convert the 2D profile into a three-dimensional solid model using pad and extrusion operations. Additional features such as cam lobes, bearing journals, and support sections were subsequently created to obtain the final camshaft geometry. The completed CAD model serves as the foundation for further structural evaluation and static analysis in ANSYS Workbench, enabling the assessment of deformation, stress distribution, and material performance under applied loading conditions.

CATIA V5 R20 offers numerous advantages that make it one of the most widely used CAD software packages in engineering design and product development. It provides a fast, efficient, and highly accurate modeling environment for creating complex mechanical components and assemblies. Once the design process is completed, both two-dimensional (2D) drawings and three-dimensional (3D) models can be generated quickly, improving design visualization and documentation. The software allows modifications to be incorporated even during the later stages of

product development without significantly affecting the overall design process. CATIA delivers precise geometric representations by accurately defining dimensions, tolerances, and hidden features within the model. It supports both solid and surface modeling techniques, offering greater flexibility for designers working on complex structures. Furthermore, its user-friendly interface enables efficient model creation, while its advanced visualization capabilities help engineers better understand product geometry and functionality. The flexibility to implement design changes, coupled with high accuracy and powerful modeling tools, makes CATIA V5 R20 an ideal platform for modern engineering applications.

4. RESULT ANALYSIS.

Fig 3 illustrates the process of importing the camshaft CAD model created in CATIA into ANSYS Workbench for structural analysis. Using the Geometry module within the Static Structural analysis system, the previously developed CATIA model is imported in IGES format. This step establishes the link between the CAD design and the simulation environment, enabling further operations such as material assignment, meshing, application of loads and boundary conditions, and evaluation of stress and deformation characteristics during static analysis.

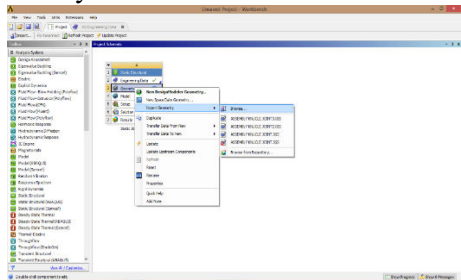


Fig 3. Importing Catia Camshaft Geometry into ANSYS Workbench

Fig 4 illustrates the finite element meshing of the camshaft model in ANSYS Workbench prior to structural analysis. Meshing is a critical preprocessing step in which the geometry is discretized into a large number of smaller finite elements and nodes. The generated mesh accurately captures the complex profile of the cam lobes and shaft surfaces, enabling precise evaluation of stress, strain, and deformation under applied loading conditions. A well-defined mesh improves the accuracy and

reliability of simulation results while ensuring efficient computational performance during static structural analysis

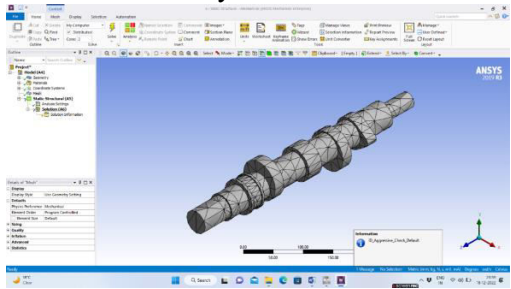


Fig 4. Finite Element Meshing of the Camshaft Model in ANSYS Workbench.

Fig 5 presents the summary of static structural analysis results obtained for the camshaft modeled with Structural Steel. The analysis indicates a maximum total deformation of 2.4046×10^{-3} mm, demonstrating excellent dimensional stability under the applied loading conditions. The maximum equivalent (von Mises) stress recorded is 8.4374 MPa, which is significantly lower than the yield strength of structural steel, confirming the structural safety of the design. Additionally, the maximum equivalent elastic strain is 4.3892×10^{-5} mm/mm, indicating minimal material deformation and elastic behavior throughout the component. These results demonstrate that the structural steel camshaft possesses sufficient strength, rigidity, and load-carrying capability, making it suitable for reliable operation in automotive engine applications.

Result Summary

Results	Minimum	Maximum	Units	Time (s)
Total Deformation	0	2.4046e-003	mm	1.
Equivalent Stress	1.8607e-006	8.4374	MPa	1.
Equivalent Elastic Strain	9.3037e-012	4.3892e-005	mm/mm	1.

Fig 5. Static Structural Analysis Results of the Camshaft Using Structural Steel.

Fig 6 presents the static structural analysis results of the camshaft when Titanium Alloy is used as the material. The simulation results show a maximum total deformation of 4.7728×10^{-3} mm, indicating a very small displacement under the applied loading conditions. The maximum equivalent (von Mises) stress developed in the camshaft is 8.7795 MPa, while the maximum equivalent elastic strain is 9.3577×10^{-5} mm/mm. These values indicate that the stresses and strains generated are well within the allowable limits of titanium alloy, ensuring safe and reliable operation. Owing to its high

strength-to-weight ratio, excellent corrosion resistance, and superior mechanical properties, titanium alloy offers enhanced durability and performance for automotive camshaft applications. The analysis confirms that the camshaft maintains structural integrity and exhibits stable behavior under static loading conditions.

● Result Summa

Results	Minimum	Maximum
Total Deformation	0.	4.7728e
Equivalent Stress	1.6305e-006	8.7795
Equivalent Elastic Strain	1.6985e-011	9.3577e

Fig 6. Structural Analysis Results of the Camshaft Using Titanium Alloy.

● Result Summary

Results	Minimum	Maximum	Units	Time (s)
Total Deformation	0.	4.4272e-003	mm	1.
Equivalent Stress	1.8217e-006	8.4445	MPa	1.
Equivalent Elastic Strain	1.6561e-011	7.997e-005	mm/mm	1.

Fig 7 shows the result summary of the static structural analysis performed on the camshaft using Grey Cast Iron as the material. The analysis reveals a maximum total deformation of 4.4272×10^{-3} mm, indicating that the camshaft experiences only a small displacement under the applied loading conditions. The maximum equivalent (von Mises) stress is found to be 8.4445 MPa, while the maximum equivalent elastic strain is 7.997×10^{-5} mm/mm. These values demonstrate that the stresses and strains developed within the camshaft are within the permissible limits of Grey Cast Iron, ensuring safe structural performance. Due to its good wear resistance, vibration damping characteristics, and cost-effectiveness, Grey Cast Iron remains a widely used material for camshaft manufacturing. The simulation results confirm that the camshaft maintains adequate strength and structural stability during operation, making Grey Cast Iron a suitable material for automotive engine applications.

5. CONCLUSION

The research successfully carried out the design, modeling, and static structural analysis of an automotive camshaft using CATIA and ANSYS Workbench. The camshaft model was developed in CATIA by accurately

incorporating the geometric features of the cam profile, including the inlet and exhaust cam lobes, to ensure proper valve timing and efficient engine operation. The generated three-dimensional model was subsequently imported into ANSYS for finite element analysis to evaluate its structural performance under applied loading conditions. The analysis focused on determining critical parameters such as total deformation, equivalent stress, and equivalent elastic strain, which are essential for assessing the strength, stiffness, and reliability of the camshaft. To identify the most suitable material for automotive applications, a comparative study was conducted using Structural Steel, Titanium Alloy, and Grey Cast Iron. The simulation results demonstrated that all three materials were capable of withstanding the applied loads within safe stress limits; however, noticeable differences were observed in their deformation and strain characteristics. Structural Steel exhibited the lowest deformation and strain values while maintaining acceptable stress levels, indicating superior rigidity and load-carrying capability compared to the other materials. Titanium Alloy provided excellent strength-to-weight characteristics, whereas Grey Cast Iron offered good wear resistance and vibration damping properties. Based on the comparative evaluation of stress distribution, deformation behavior, structural stability, manufacturability, and overall performance, Structural Steel was identified as the most suitable material for the camshaft. The study confirms that proper material selection combined with advanced CAD modeling and finite element analysis significantly enhances component reliability, durability, and engine performance in automotive applications.

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