iJRASET
International Journal For Research in
Applied Science and Engineering Technology

# INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: VI Month of publication: June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72762

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

# Lightweight Design and Structural Analysis of Air Intake Manifold Using Composites

Rajkumar[1], Gyanendra Singh Yadav[2]
[1]Research Scholar, [2]Professor, Vishveswarya Group of Institutions, Ghaziabad

***Abstract: This research presents a finite element analysis (FEA)-based investigation into the structural performance of an air intake manifold made from four different materials: Aluminum, Polyamide 6 (PA6), Polypropylene (PP), and Carbon Fiber Reinforced Polymer (CFRP). In response to the automotive industry's increasing demand for lightweight, fuel-efficient, and high-performance vehicles, the study explores alternative materials that can reduce component weight without compromising structural integrity. The air intake manifold was selected due to its significant impact on engine performance and efficiency. A 3D model of the manifold was developed using CATIA software and imported into ANSYS Workbench for simulation. Material properties were assigned, boundary conditions applied, and an internal pressure of 7 bar was used to simulate operating conditions. Fixed supports were applied at the mounting flanges. The analysis focused on key structural outputs: total deformation, equivalent (von Mises) stress, maximum principal stress, and factor of safety, allowing a comparative evaluation of each material's mechanical behavior. Results showed that Aluminium performed reliably with moderate deformation and adequate stress handling. PA6 exhibited slightly higher deformation but remained within acceptable limits, making it viable for medium-performance applications. PP, however, displayed excessive deformation and poor safety margins, suggesting its unsuitability for structural use. CFRP outperformed all other materials, demonstrating minimal deformation, low stress, and the highest safety factor, making it ideal for high-performance and weight-sensitive applications. This study confirms the utility of FEA in optimizing material selection during the early design stages of automotive components. It emphasizes the potential of composites like CFRP to meet modern performance and sustainability goals while offering insights for broader applications in lightweight vehicle design and advanced mechanical systems.***
***Keywords: FEM Analysis, CFRP, PP, PA6, Aluminium, Intake Manifold, IC Engine, and Ansys Workbench.***

## I. INTRODUCTION

The air intake manifold (AIM) plays a vital role in the operation of internal combustion engines by directing and distributing the intake air—or air-fuel mixture in carbureted systems, uniformly to each cylinder. This uniformity is essential for achieving efficient combustion, reducing emissions, and optimizing power output. In modern automotive design, AIMs have evolved from simple air routing components into highly integrated systems that affect engine performance, fuel efficiency, durability, and regulatory compliance. This evolution is driven in part by the growing emphasis on lightweight engineering, where composite materials offer significant advantages over traditional metals such as aluminum. Lightweight, high-strength polymers and fiber-reinforced composites are now widely used in the design and manufacture of AIMs, enabling reductions in overall vehicle weight, improvements in thermal efficiency, and new levels of structural and functional integration. Traditionally, air intake manifolds were manufactured from cast aluminum, valued for its durability, heat resistance, and machinability. However, these metal components contribute significant weight to the powertrain. With the increasing demand for lightweight vehicles to meet fuel efficiency and emission standards, composite materials such as glass-fiber-reinforced Polyamide (PA6) and Carbon Fiber Reinforced Polymer (CFRP) have gained prominence.

These composites offer high strength-to-weight ratios, resistance to chemical and thermal degradation, and the ability to mold complex shapes, making them ideal for manifold applications. Injection molding, resin transfer molding (RTM), and additive manufacturing are among the preferred production techniques for composite AIMs, offering precision, scalability, and integration of multiple functionalities in a single component. Air intake manifolds can be broadly classified into two main types: passive and active. Passive AIMs are characterized by fixed-length runners and a simple, static geometry. They are optimized to perform efficiently in a narrow engine speed range, typically the mid-RPM range. These manifolds are lightweight, cost-effective, and highly reliable due to the absence of moving parts. As a result, they are commonly used in small displacement engines and economy vehicles where simplicity, durability, and low cost are priorities. In contrast, active air intake manifolds feature variable geometry components such as electronically or vacuum-controlled flaps and valves that dynamically adjust the length or path of the runners based on engine load and RPM. Controlled by the Engine Control Unit (ECU), active systems enhance low-end torque with longer runners and maximize high-end power with shorter paths. This flexibility enables improved engine performance across a broader operating range.

Although active manifolds are more complex and potentially heavier, the use of composites offsets this weight gain while retaining structural integrity and enhancing performance adaptability. The working of an air intake manifold begins when ambient air is drawn through an air filter and passes through a Mass Air Flow (MAF) sensor, which measures airflow and provides data to the ECU. In turbocharged engines, the air is compressed and cooled through an intercooler before it reaches the throttle body. From there, the air enters the plenum chamber of the manifold, which serves as a buffer reservoir to stabilize airflow. The plenum distributes air into individual intake runners that connect to the engine's intake valves. The design of these runners, especially their length and diameter, affects volumetric efficiency and air velocity. Active intake manifolds further adjust these runner lengths using actuators to match performance needs in real time. At low engine speeds, longer runners increase air velocity and torque, while shorter runners at high speeds reduce resistance and support increased power output. This dynamic functionality is further enhanced by integrated sensors, such as the Manifold Absolute Pressure (MAP) and Intake Air Temperature (IAT) sensors, which provide feedback to optimize air-fuel mixture, ignition timing, and turbo boost control.

Beyond air distribution, AIMs perform multiple crucial functions including sealing and fixation, gas initiation, fuel delivery, airflow manipulation, and charge air cooling. Sealing is critical for maintaining air pressure and preventing leaks, particularly at high temperatures and mechanical loads. Composite manifolds rely on gaskets, O-rings, and compression limiters to achieve airtight and durable sealing. Gas initiation involves the controlled introduction of blow-by gases, EGR (Exhaust Gas Recirculation), and evaporative fuel vapors into the intake stream, which helps reduce emissions. Components such as EGR valves, auxiliary inlets, and heating elements are integrated into the manifold to facilitate this process. In engines equipped with Port Fuel Injection (PFI), the manifold houses fuel rails and injectors positioned to ensure

## II. REVIEW OF LITERATURE

The need for lightweight materials in the automotive industry has become paramount due to the increasing demand for fuel-efficient and high-performance vehicles. Among various components of an engine, the air intake manifold plays a crucial role in engine efficiency, requiring materials that are both strong and lightweight. The shift towards composite materials for these applications has garnered significant attention, owing to their superior strength-to- weight ratio, durability, and potential for reducing overall vehicle weight. This literature review explores the evolution of lightweight design principles, the role of composite materials in enhancing performance, and the latest developments in structural analysis of air intake manifolds. Bates et al. (2004) explored the application of vibration welding for air intake manifolds made from reinforced nylon 66, nylon 6, and polypropylene. The study demonstrated how vibration welding could be effectively used to join thermoplastic materials, ensuring strong, durable connections while also enabling weight reduction in automotive components. The authors found that these materials, particularly when reinforced, provided excellent mechanical properties that are critical for the high-stress environments of automotive applications. Their findings emphasized the potential of vibration welding to enhance the performance of air intake manifolds, offering a viable solution for reducing the overall weight of vehicle components without compromising on strength or durability. This work plays a significant role in advancing lightweighting strategies in automotive design, with a focus on both structural integrity and material efficiency. Battistoni et al. (2006) investigated the effect of structural design on the noise, vibration, and harshness (NVH) performance of plastic air intake manifolds. Their study revealed that the geometric features and material properties of intake manifolds had a significant impact on NVH characteristics, which are critical for improving engine acoustics. By optimizing structural design elements like wall thickness and ribbing, they demonstrated that it is possible to balance light weighting goals with the need for effective NVH performance.

Their study played a pivotal role in advancing hybrid material systems, providing a foundation for future research into the use of thermoplastics in critical engine components. Capitani et al. (1998) introduced a methodology to analyze the dynamic behavior of car engine components made from plastic materials, particularly focusing on the vibrational characteristics of plastic intake manifolds. They developed a practical approach for evaluating how plastic manifolds respond to dynamic loads, ensuring that these components can perform reliably under the stresses of engine operation. Their work also addressed the challenges of using plastics in critical automotive systems, offering a method for validating the performance of these materials in real-world conditions. This study was instrumental in establishing testing standards for plastic intake manifolds, enabling the automotive industry to confidently incorporate plastic materials into engine systems without compromising on performance or safety. Capitani et al. (1999) further extended their research by detailing a validation testing method for polyamide-based engine components. This method focused on assessing the performance of polyamides under various conditions, including thermal and mechanical stresses that intake manifolds typically face. Their research underscored the importance of conducting thorough validation tests to ensure that polyamide materials could withstand the high demands of engine systems.

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By providing a structured approach for testing polyamide components, their work contributed to the growing acceptance of plastic materials in automotive applications, offering a reliable alternative to traditional metal components. Capitani et al. (2000) continued their exploration of polyamide-based engine components by introducing testing methods for assessing the shock and vibration resistance of these materials.

## III. RESEARCH METHODOLOGY

This study investigates the lightweight design and structural performance of an air-intake manifold manufactured from aluminum alloy, polyamide-6 (PA6), polypropylene (PP), and carbon-fiber-reinforced polymer (CFRP) through a combined CAD-based modeling and finite-element analysis (FEA) approach. Beginning with a parametric CAD model, the Key-Topology Feature Optimization (KTFO) process generated an organic, skeleton-like internal architecture by defining design and non-design domains such as inlet runners, plenum volume, and mounting flanges and subjecting the volume to topology optimization under prescribed load and support conditions.

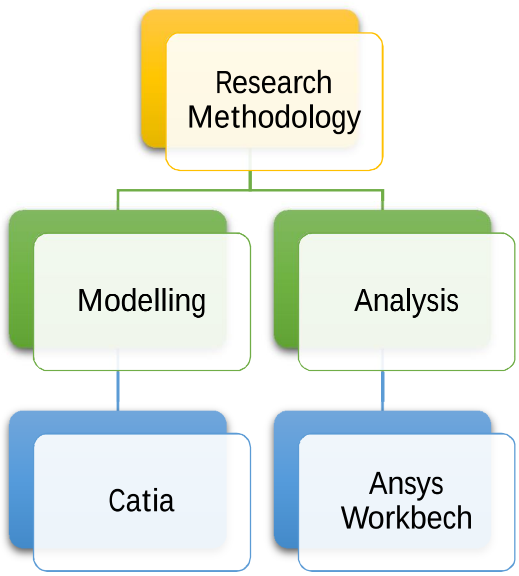


Figure 1 A systematic approach of Research Methodology

This optimized shape was then translated into manufacturable features (ribs, fillets, and smooth shell surfaces) to yield the final geometry. Each material characterized by its density, Young's modulus, yield strength, and Poisson's ratio, with CFRP's effective longitudinal modulus derived via the rule-of-mixtures was assigned to the identical geometry in ANSYS Workbench. A high-quality tetrahedral mesh, refined at fillet and junction regions, ensured accurate stress and deformation predictions without excessive computational cost. Static structural analyses applied a uniform 7 bar internal pressure to all internal surfaces while fully constraining the flange mounting faces at the cylinder-head interface; ambient thermal effects at 23 °C were assumed negligible.

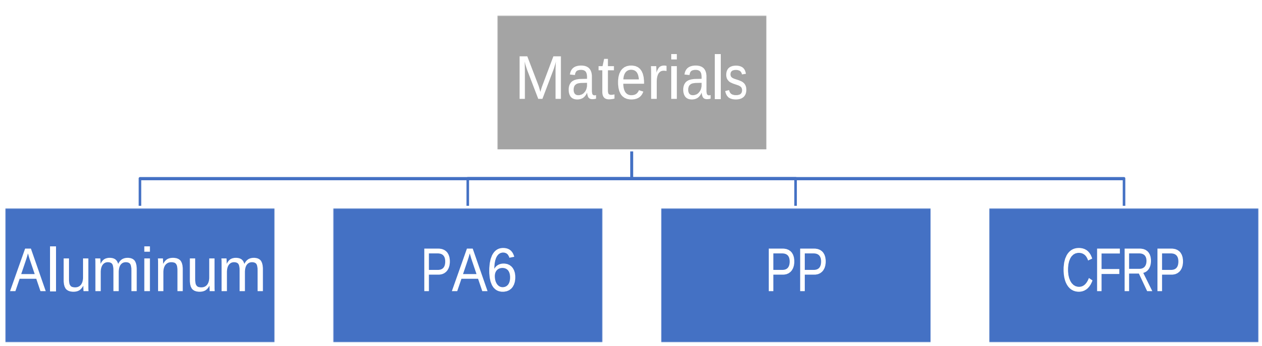


Figure 2 Materials used for the proposed simulation

Four key performance metrics were extracted: maximum total deformation (mm), peak equivalent (von Mises) stress (N/mm²), maximum principal strain, and factor of safety (computed as yield strength divided by maximum stress). To validate the FEA results, closed-form calculations were performed on a representative straight segment: axial deformation via Hooke's law ($\delta = FL/AE$), nominal hoop stress under internal pressure ($\sigma = pr/t$), principal-strain evaluation using plane-stress relations, and safety-factor estimation by comparing analytical stress to yield strength. These hand-calculated values, along with weight estimations from volume × density, provided cross-checks on mesh convergence and material modeling assumptions. Finally, the combined simulation and analytical data were tabulated to compare stiffness-to-weight ratios, deformation limits, stress margins, and safety-factor margins across materials, enabling identification of the optimal balance between lightweight design and structural integrity for potential use in advanced composite or hybrid manifold constructions.

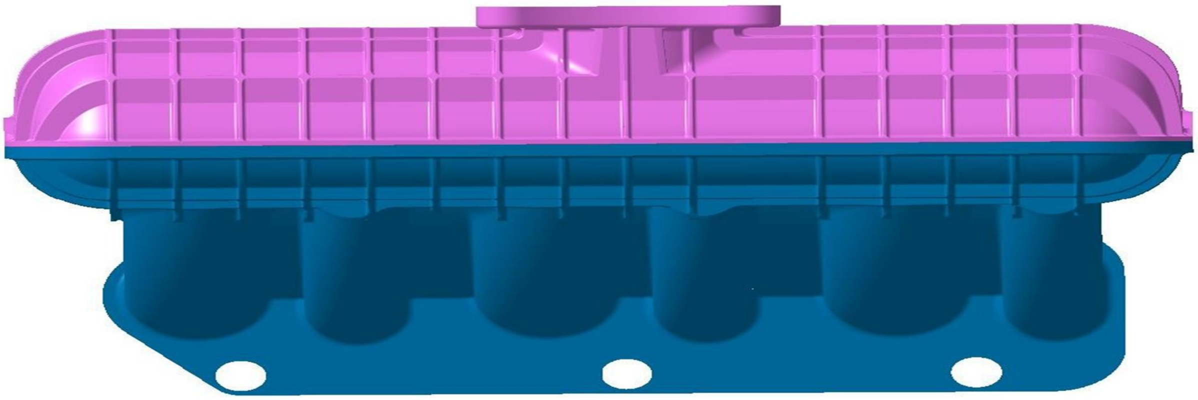

Figure 3 Modelling View of Intake Manifold

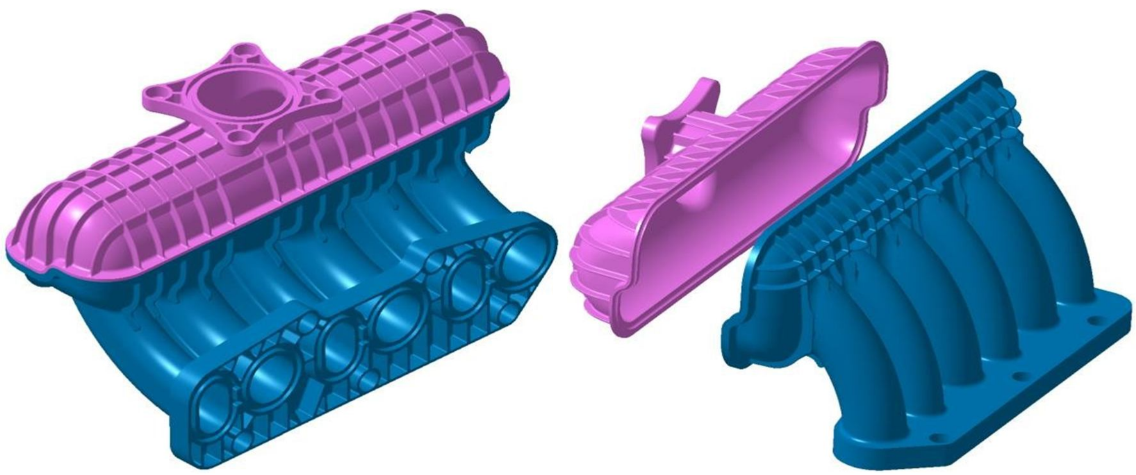

Figure 4 Isometric and Exploded View of Intake Manifold

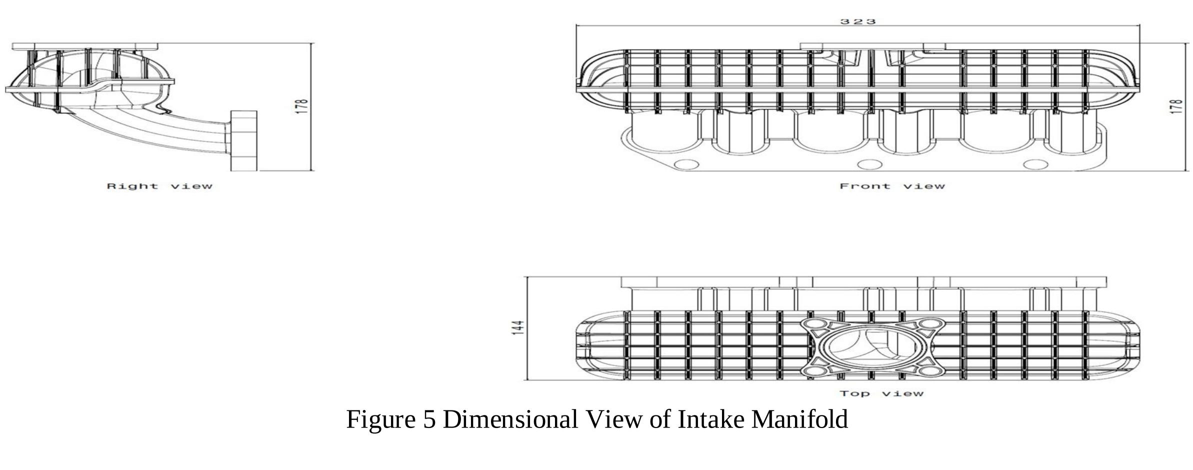


Figure 5 Dimensional View of Intake Manifold

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Figure 6 Meshing view of Intake Manifold (Side)

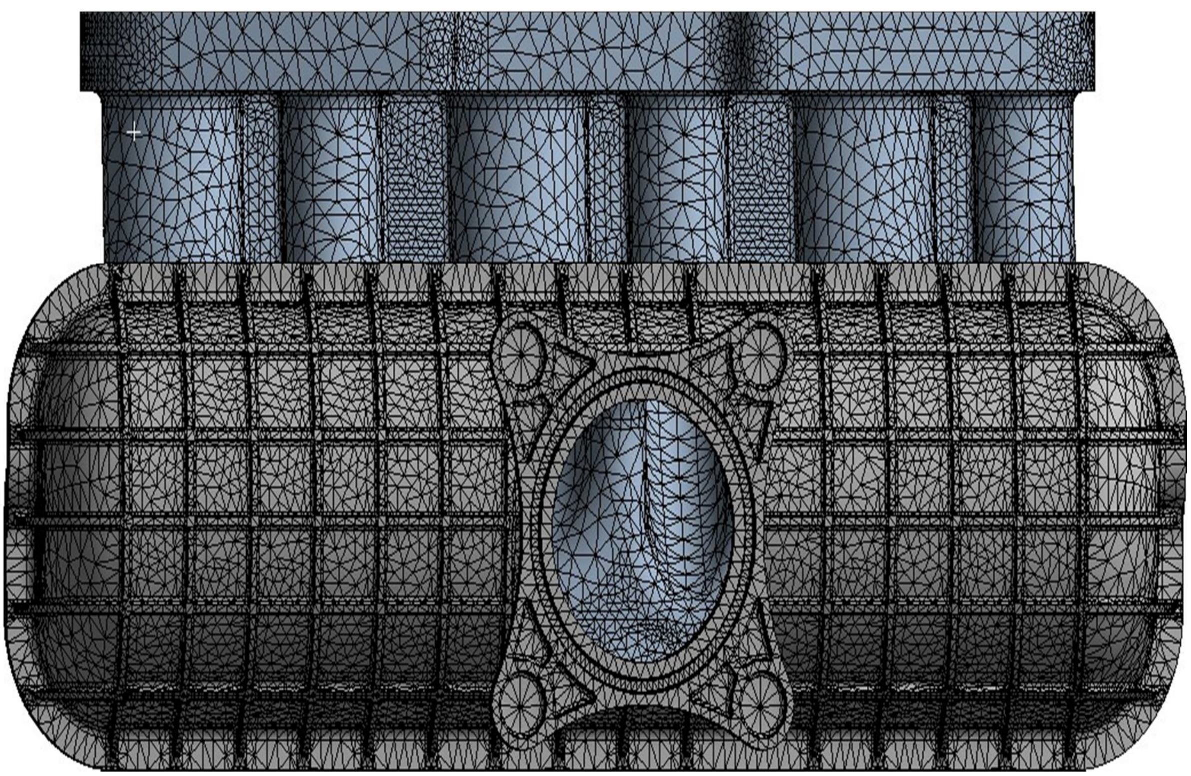

Figure 7 Meshing view of Intake Manifold (Front)

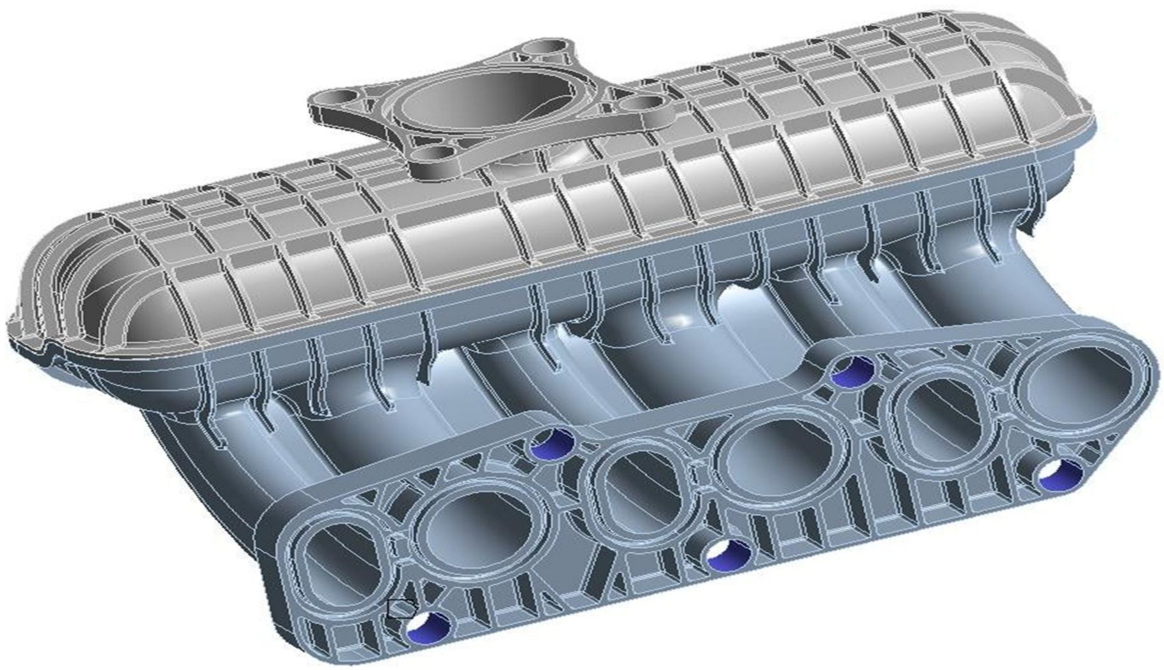

Figure 8 Boundary Conditions applied at the flange mountings

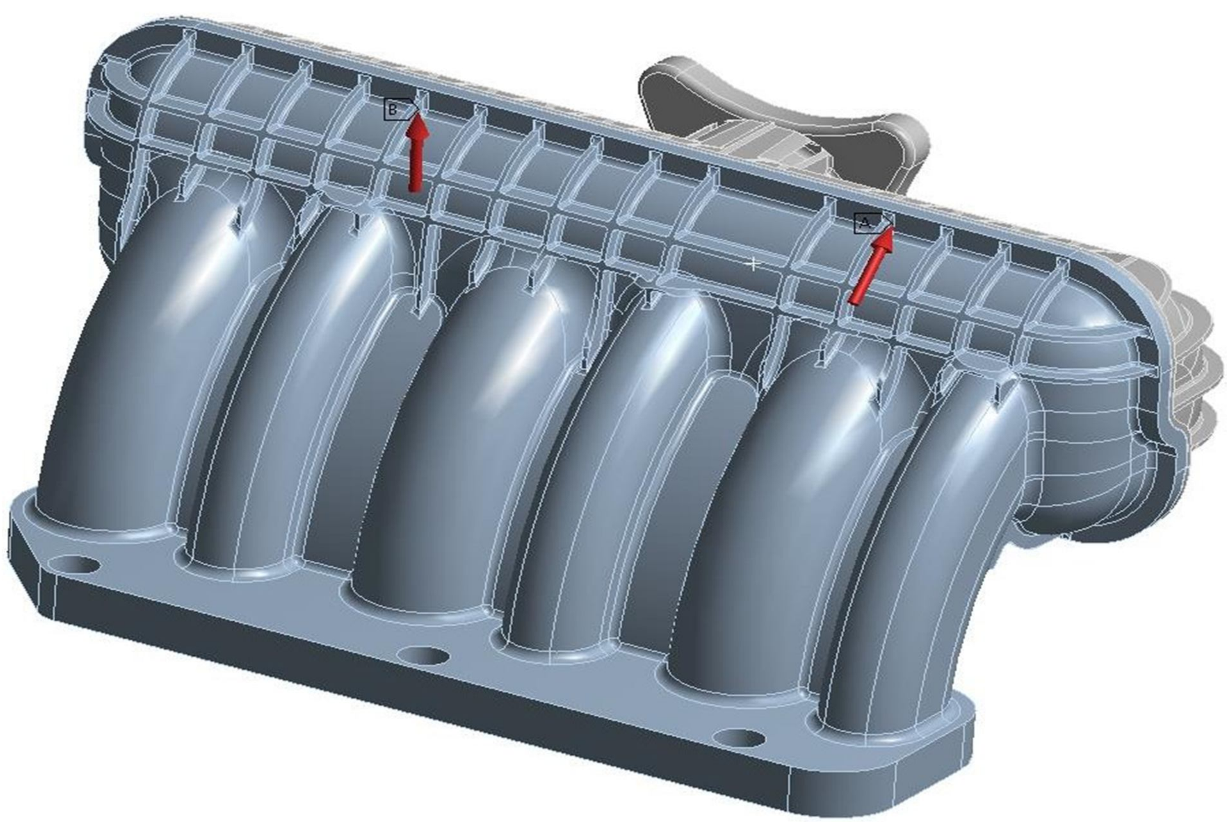

Figure 9 Load (Pressure at 7bar) applied

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## IV. RESULTS AND DISCUSSION

Table no 1 Performance evaluation of proposed materials

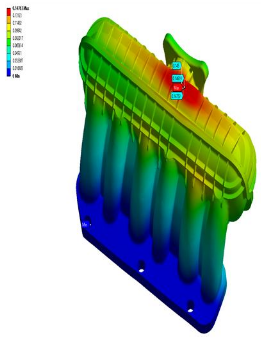
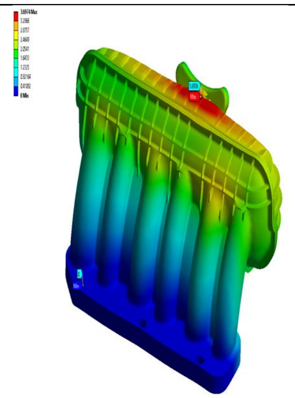
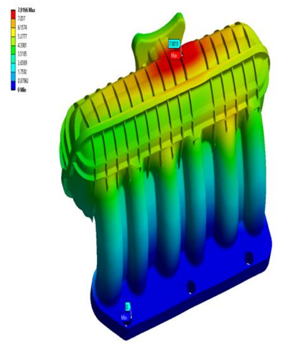
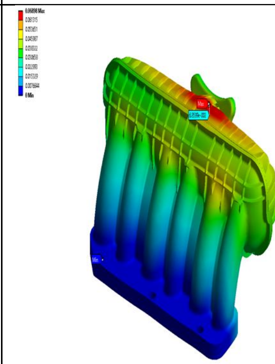
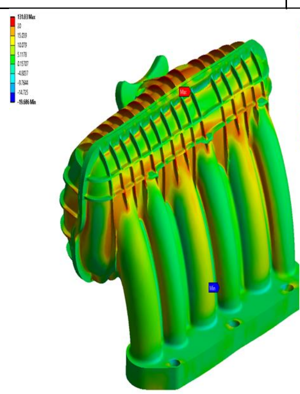
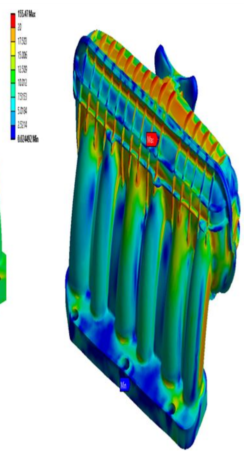
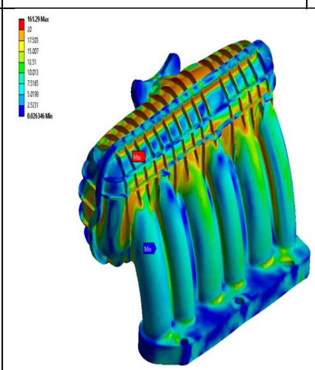
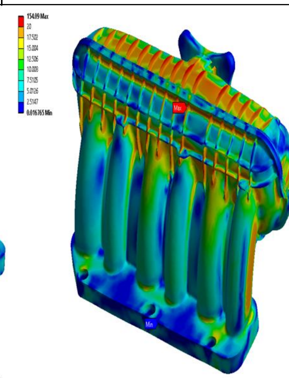
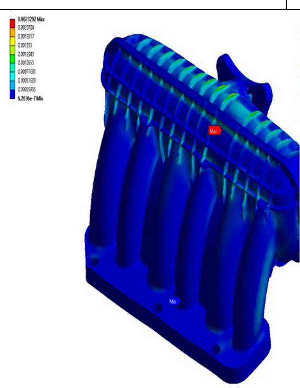
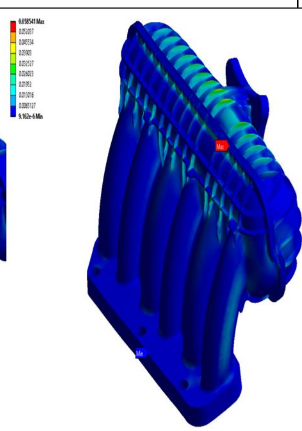
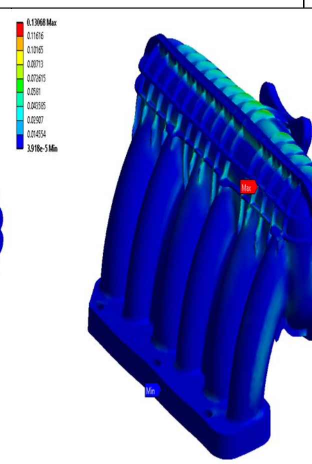
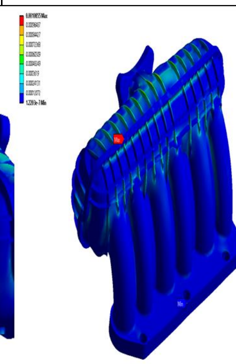
| Materials | Aluminum | PA6 | PP | CFRP |
|---|---|---|---|---|
| Total Deformation(mm) |  |  |  |  |
| Equivalent Stress ($N/mm^2$) |  |  |  |  |
| Max Principal Elastic Strain |  |  |  |  |

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Table no 2 Comparison of Total Deformation, Weight, and Cost for Different Materials

| Material | Total Deformation(mm) | Weight(g) | Cost(Rupees) |
|---|---|---|---|
| Aluminum | 0.14 | 1587 | 412.62 |
| PA6 | 3.6 | 664.5 | 119.61 |
| PP | 7.91 | 529 | 51.313 |
| CFRP | 0.06 | 911 | 2277.5 |


Figure 10 Comparison of Total Deformation, Weight, and Cost for Different Materials

## V. CONCLUSION

This research focused on the structural evaluation of an air intake manifold using a lightweight design approach with four different materials: Aluminium, Polyamide 6 (PA6), Polypropylene (PP), and Carbon Fiber Reinforced Polymer (CFRP). The main objective was to compare the structural behavior of these materials under identical operating conditions, using simulation-based finite element analysis (FEA) to determine their suitability for automotive applications. The manifold was first modeled in CATIA software to accurately reflect real-world geometry and then analyzed in ANSYS Workbench under standardized conditions, including a fixed support at the cylinder head flange and an internal pressure of 7 bar to simulate engine working conditions. The structural analysis used four critical evaluation metrics: total deformation, equivalent (von Mises) stress, maximum principal strain, and factor of safety. These parameters helped assess each material's stiffness, strength, and mechanical performance. The results revealed distinct performance characteristics for each material. Aluminium exhibited balanced performance with moderate deformation, low strain, and an adequate safety factor, making it a reliable and traditional choice with a good balance between weight and mechanical integrity.

PA6 demonstrated higher deformation and strain compared to Aluminium but remained within acceptable limits. It was identified as a lightweight and cost-effective option suitable for medium-load applications, offering a good compromise between weight savings and mechanical performance. On the other hand, Polypropylene showed excessive deformation and low structural resistance, resulting in the lowest factor of safety. This suggests PP is not suitable for high-stress applications like intake manifolds in internal combustion engines, though it may be viable for non-structural, low-load components where cost reduction is prioritized. CFRP significantly outperformed all other materials, showing minimal deformation, very low stress and strain levels, and the highest factor of safety.

This indicates its superior mechanical efficiency and validates it as the most suitable material for high-performance or weight-sensitive automotive applications. Despite its higher production costs and complex manufacturing requirements, the advantages offered by CFRP, particularly in racing or performance vehicles, justify its use where weight reduction and high strength are crucial. The study also highlighted the effectiveness of the Finite Element Method (FEM) as a simulation tool for evaluating the structural integrity of automotive components. FEM enabled detailed analysis through pre-processing (mesh generation and boundary condition setup), solution computation, and post-processing of results. It allowed for early detection of high-stress regions, design optimization, and rapid material comparison without the need for extensive physical prototyping. This virtual testing approach is especially valuable in accelerating the development process and reducing production costs. This study underscores the critical role of material selection in the structural design of automotive components. Aluminium remains dependable but heavier; PA6 offers moderate performance benefits; PP is limited to non-critical uses; and CFRP emerges as the most advanced material for future-ready, high-performance applications. With the support of robust simulation tools like FEM, lightweight and high-strength composite designs can be successfully developed to meet the evolving demands of the automotive industry.

### *A. Future Scope*

- Explore hybrid composite materials combining CFRP with thermoplastics to reduce cost and enhance process ability.
- Evaluate the thermal performance of the selected materials under real-time temperature variations to consider thermal expansion and heat resistance.
- Implement topology optimization techniques to further reduce weight while maintaining structural integrity.
- Consider additive manufacturing techniques for prototyping with composite materials to reduce lead time.
- Investigate noise, vibration, and harshness (NVH) performance of each material to improve cabin comfort.
- Study fatigue life and long-term creep behavior of PA6 and PP under cyclic loading.
- Experiment with coating technologies to enhance surface durability and chemical resistance of PP and PA6.
- Perform multi-objective optimization that considers not only mechanical but also environmental and cost aspects.
- Extend the study to include dynamic loading conditions such as engine vibrations and pressure pulsations.
- Collaborate with automotive OEMs to validate the simulation results with real-world prototype testing.

### *B. Recommendations*

- Aluminium can be considered in future models with geometry optimized for material usage and weight reduction.
- CFRP must be explored further using different weaves and orientations to maximize stiffness in critical directions.
- PP should be used only in components with negligible mechanical stress to prevent early failure.
- PA6 may be reinforced with glass or carbon fibers to improve its performance without increasing cost significantly.
- Future simulations should include thermal analysis to account for operating temperature effects on mechanical properties.
- Real-time stress testing under engine operating conditions should be conducted to validate simulation accuracy.
- Consideration should be given to manufacturability and tooling requirements for CFRP- based designs.
- Research should explore recycling and environmental impact of composite materials used.
- Apply Machine Learning techniques to predict material performance trends based on input parameters.
- Extend the analysis to include vibration modes to assess resonance and potential fatigue zones.
- Examine impact resistance to account for mechanical shocks during vehicle operation.
- Use life cycle assessment (LCA) to understand long-term sustainability of materials selected.
- Integrate experimental modal analysis with FEM results for better vibration behavior understanding.
- Include detailed contact and assembly simulation for full manifold system.
- Standardize a decision-making framework for material selection based on simulation data.

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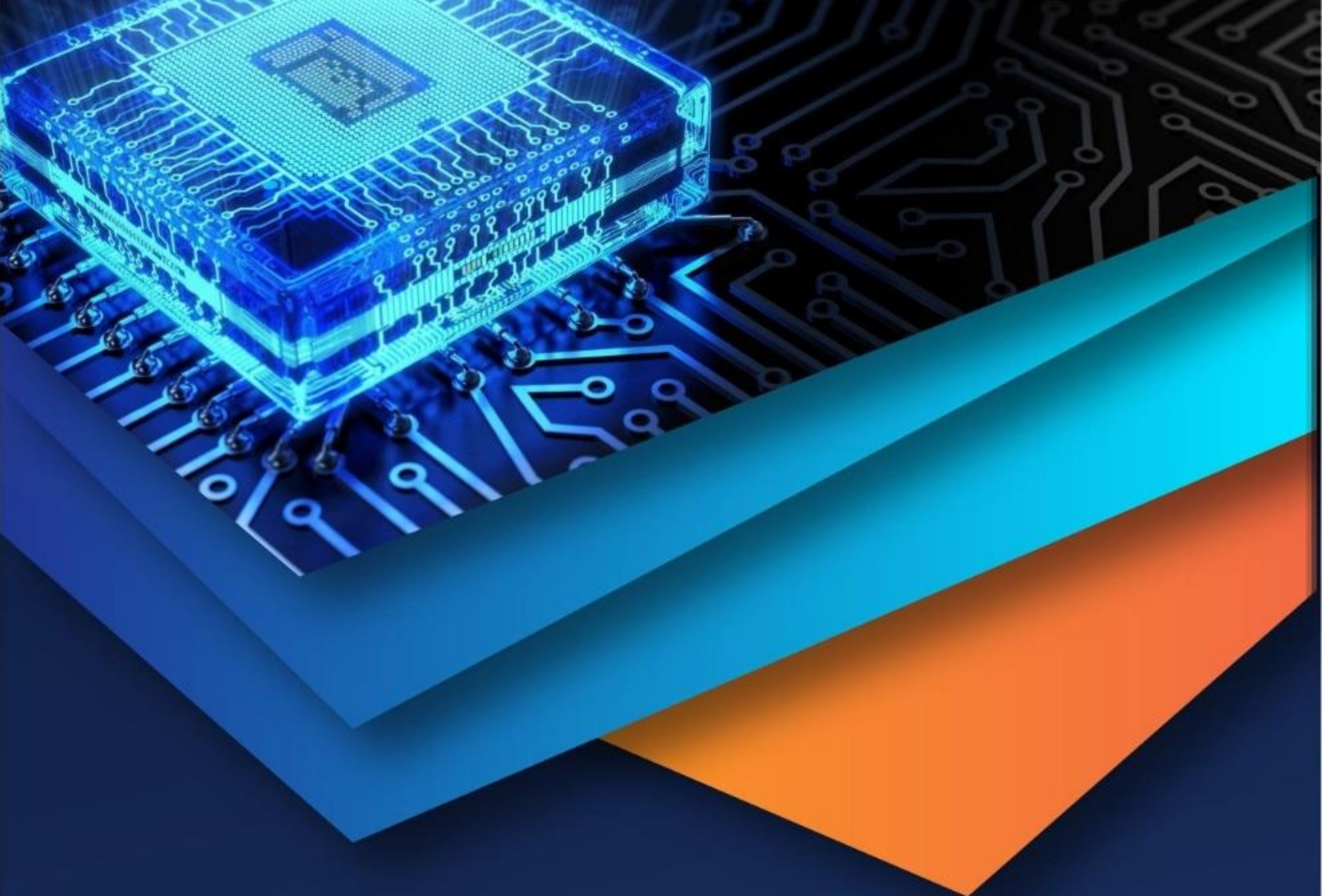


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