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Performance Evaluation of F1 Car Chassis Frame using Finite Element Analysis

Atif Ali Hashmi[1], B. G. Shukla[2]
[1]Research Scholar, [2]Assistant Professor, Oriental Institute of Science & Technology, Bhopal (M.P)

Abstract: This research evaluates the structural performance of the front part of a Formula One (F1) car chassis using Finite Element Analysis (FEA). A comparative study is conducted using four advanced materials: Carbon Fiber (Epoxy), Aluminum 7075-T6, Titanium Alloy (Ti-6Al-4V), and AISI 4130 Chromoly Steel. CATIA is employed for accurate 3D modeling, while ANSYS Workbench is used for static structural simulations. The study applies a 15,000 N frontal load to replicate crash conditions and examines key output parameters such as directional deformation, total deformation, and von Mises stress. The results indicate that Carbon Fiber offers the best balance of stiffness and low deformation, making it ideal for F1 chassis design. Titanium Alloy demonstrates excellent strength and ductility, while AISI 4130 provides superior rigidity at the cost of higher weight. Aluminum, though light, exhibits excessive deformation under load. The findings guide optimal material selection to improve safety and performance in high-speed automotive applications.
Keywords: FEA, Carbon Fiber, Titanium Alloy, Aluminum 7075, AISI 4130, CATIA, ANSYS, Formula One, Chassis, Structural Analysis

I. INTRODUCTION

In the world of high-performance motorsport, the chassis of a Formula One (F1) car plays a central role in determining the safety, speed, and overall efficiency of the vehicle. Acting as the structural backbone, the chassis supports essential components such as the engine, suspension, steering system, and aerodynamic body panels. It also serves as the first line of defense during collisions, particularly frontal impacts, where the front section of the chassis must absorb and dissipate crash energy to protect the driver and maintain the structural integrity of the vehicle. With the relentless advancement in motorsport engineering, the emphasis has shifted toward materials and structural configurations that optimize both performance and safety.

The challenge lies in striking the right balance between low weight, high stiffness, and excellent crashworthiness, without compromising the aerodynamic and mechanical integration required in competitive racing. As the demand for lightweight, crash-resistant structures increases, modern engineering has turned to simulation-driven design to meet performance and safety standards. Among these techniques, the Finite Element Method (FEM) has become an indispensable tool in structural analysis. FEM enables engineers to discretize a component into smaller elements, assign material properties, and apply loading and boundary conditions to predict how a structure will behave under different stress scenarios. This virtual testing capability minimizes the need for costly and time-consuming physical prototypes and allows for quick iterations during the design process. In motorsport environments like F1 where every millisecond and every gram matters such predictive capabilities provide a crucial advantage.

This study focuses on evaluating the structural behavior of the front part of an F1 car chassis using FEM-based tools. A static structural analysis is performed to simulate a frontal impact load on the chassis and investigate the mechanical performance of four high-performance materials: Carbon Fiber (Epoxy), Aluminum 7075-T6, Titanium Alloy (Ti-6Al-4V), and AISI 4130 Chromoly Steel. These materials are widely considered in motorsport and aerospace applications for their exceptional strength-to-weight ratios and mechanical robustness. The analysis is conducted using CATIA V5 for 3D modeling and ANSYS Workbench for simulation, forming a digital design pipeline that mirrors real-world crash scenarios. Key simulation outputs directional deformation, total deformation, and von Mises stress are used to quantify how each material responds under a standardized frontal load of 15,000 N.

This comparison is critical in identifying which material offers optimal crash energy absorption and stiffness without surpassing its yield limits. The study not only provides insights into material selection for Formula One applications but also delivers simulation-based design recommendations applicable to other high-performance fields, including aerospace, defense, and electric vehicles. F1 chassis are typically designed as monocoque structures, capable of withstanding extreme aerodynamic forces, engine vibrations, and collision loads. These monocoques integrate critical vehicle zones such as the suspension mounting points, steering linkages, cockpit safety cell, and front crush structures. Optimizing the performance of the front chassis section is essential for complying with FIA safety standards and maintaining a competitive edge.

This research, by leveraging the accuracy of FEM analysis, aims to contribute to the development of safer and lighter front chassis structures while reinforcing the use of advanced simulations in modern automotive design. In the high-stakes world of motorsports, the design and structural integrity of a Formula One (F1) car's chassis are critical determinants of vehicle safety, speed, stability, and competitive performance. The chassis, often referred to as the "spine" of the car, serves as the foundational support structure to which all other major components including the suspension system, engine, transmission, and bodywork are affixed. Among the various sections of the chassis, the front portion is particularly crucial as it is the primary point of contact during frontal collisions. Its ability to absorb and dissipate crash energy effectively is directly linked to driver safety and vehicle survivability. Therefore, selecting the optimal material and structural configuration for the front chassis is not just a matter of engineering efficiency, but also a regulatory and ethical imperative in motorsport.

Formula One, being the pinnacle of automotive performance, places extreme demands on every component of the vehicle. The design of the chassis must achieve a fine balance between conflicting requirements being lightweight to enhance speed and fuel efficiency, while simultaneously offering high stiffness and energy absorption capacity to withstand crash forces. Traditionally, the development of F1 chassis structures relied heavily on iterative prototyping and real-world testing. However, these methods are not only time-consuming and expensive, but they also expose teams to unnecessary risks and inefficiencies. With advancements in computational engineering, simulation-based techniques such as Finite Element Method (FEM) analysis have become indispensable tools in modern chassis design and validation.

FEM allows engineers to divide a complex structure into smaller, manageable finite elements and apply known material properties and boundary conditions to predict how the structure will behave under various types of loads. This numerical technique enables detailed insights into deformation patterns, stress concentrations, and potential failure zones all before a single physical prototype is built. For this study, FEM is executed using ANSYS Workbench, a leading platform in structural analysis and simulation. The chassis geometry is first developed in CATIA, a powerful CAD software widely used in the automotive and aerospace sectors for high-precision modeling. The seamless integration of CAD and FEM tools creates a digital pipeline that enables virtual crash testing with a high degree of reliability and repeatability.

II. REVIEW OF LITERATURE

The study of Formula One car chassis design has attracted considerable scholarly attention due to its implications for performance, safety, and material optimization in extreme conditions. Over the years, researchers have explored the dynamics of integrated vehicle systems, structural design principles, material behavior, and simulation technologies, all of which play critical roles in enhancing the overall integrity and responsiveness of high-performance racing vehicles. A significant portion of the literature highlights the increasing reliance on integrated control systems that merge steering, yaw, and suspension responses to improve stability. Active front steering (AFS) and direct yaw control (DYC), when coupled with intelligent braking and torque distribution systems, have shown remarkable improvements in cornering stability and lateral motion control. These advancements are particularly useful in dynamic racing conditions where instantaneous handling adjustments are crucial.

Studies emphasize that incorporating such integrated systems demands a highly rigid and reliable chassis structure capable of enduring compounded forces transmitted from these control systems. In parallel, the use of Finite Element Method (FEM) simulation has become a cornerstone in the analysis and optimization of automotive chassis frames. FEM facilitates precise prediction of stress distribution, deformation zones, and potential failure points without the need for physical testing. Tools such as ANSYS Workbench and CATIA are widely employed in research and industrial applications to simulate crash conditions and refine material layouts. Several researchers have successfully demonstrated the advantages of FEM in evaluating and comparing the performance of different materials under standardized loading conditions.

These digital simulations not only save time and costs associated with physical prototyping but also offer high accuracy in predicting structural behavior under real-world conditions. FEM is particularly beneficial in F1 design, where minor adjustments in geometry or material can significantly influence race-day performance. The literature also reveals a strong emphasis on material selection as a critical factor in chassis performance. Traditional materials such as mild steel and basic aluminum alloys have gradually been replaced by advanced alternatives like carbon fiber composites, titanium alloys, and specialized steels such as AISI 4130 Chromoly. Each material presents its own set of advantages and limitations. Carbon fiber reinforced polymers are renowned for their exceptional strength-to-weight ratio and stiffness, making them ideal for minimizing chassis weight while maintaining structural integrity. However, their brittle nature and high production costs pose challenges.

On the other hand, titanium alloys, specifically Ti-6Al-4V, are praised for their high ductility, corrosion resistance, and mechanical reliability under dynamic loading, albeit at higher machining costs. Aluminum 7075-T6 is favored for its lightweight properties and good manufacturability but is less resistant to deformation during high-impact events. AISI 4130 Chromoly steel offers high tensile strength and fatigue resistance, making it suitable for safety-critical zones, although its relatively high density can be a disadvantage in weight-sensitive applications like Formula One. Numerous simulation-driven studies have been conducted to compare these materials under equivalent boundary and loading conditions, particularly for crash-prone areas such as the front chassis segment. These studies often evaluate key output metrics such as directional deformation, total displacement, and von Mises stress to determine a material's suitability.

While carbon fiber typically shows superior performance in reducing deformation and absorbing impact energy, titanium provides a better balance of strength and ductility. Steel, though heavier, has demonstrated excellent results in preserving structural integrity under severe conditions. Aluminum, although advantageous in terms of cost and ease of fabrication, tends to deform excessively, making it less viable for primary structural components in F1 applications. Most researchers agree that there is no universally perfect material, and that trade-offs must be considered based on the application zone within the chassis. In addition to materials and simulation tools, the structural layout and suspension integration have also been widely investigated. The transition from traditional ladder frames to monocoque designs has significantly enhanced chassis rigidity and crash energy absorption.

Monocoque chassis structures, commonly used in F1, allow better distribution of loads and improve aerodynamics. Independent suspension systems, often integrated with modern chassis designs, offer better ride quality and control during high-speed maneuvers. Studies have shown that suspension dynamics significantly influence stress distributions around attachment points, making it critical to simulate these interactions accurately during the design process. Such findings further underscore the importance of high-fidelity FEM modeling. Recent trends in chassis research have also been influenced by the growing shift toward electric and autonomous vehicles. The structural implications of large battery packs, changes in load distribution, and the need to accommodate electronic control systems have necessitated a rethinking of chassis architecture. Moreover, the sustainability of chassis materials is becoming a major consideration. The lifecycle impact of carbon composites, in particular, has driven research into recyclable materials and hybrid composite-metal structures.

Additive manufacturing, hydroforming, and topology optimization are being explored to reduce material usage and improve performance without compromising strength. These techniques have found early adoption in motorsport due to their ability to produce complex geometries with minimal waste. Validation of FEM-based results through physical testing remains a key component of many studies. The development of digital twins virtual replicas that integrate real-time sensor data with simulation models has enhanced the accuracy of crash simulations. By embedding sensors into physical prototypes, researchers are able to gather data on strain, displacement, and temperature, which is then used to fine-tune simulation parameters and improve model precision. This iterative feedback loop between virtual and physical testing enables continuous refinement of chassis designs, ultimately leading to safer and more efficient vehicles.Despite the considerable progress made, certain research gaps persist. There is still a scarcity of comparative studies focusing solely on the front chassis section of F1 cars under identical conditions.

Much of the existing literature centers on either full-body dynamics or individual component analysis, often under varying assumptions that hinder cross-comparison. Moreover, fatigue behavior under race-specific cyclic loading conditions remains underexplored, even though it is critical to long-term performance and driver safety. Another limitation is the lack of standardization in simulation protocols across studies, which creates challenges in replicating and benchmarking results. Therefore, there remains a compelling need for focused studies that examine multiple materials within a controlled simulation framework, particularly for critical sections like the F1 front chassis.

The reviewed literature provides a comprehensive foundation for the present study, which aims to address these gaps by systematically evaluating the structural response of four key materials Carbon Fiber (Epoxy), Aluminum 7075-T6, Titanium Alloy (Ti-6Al-4V), and AISI 4130 Chromoly Steel when subjected to a consistent frontal impact load. The findings of this research are expected to offer valuable insights for chassis engineers and motorsport designers, contributing to the development of safer, lighter, and more performance-optimized Formula One vehicles.

III. RESEARCH METHODOLOGY

This research utilizes a simulation-based approach to evaluate the structural performance of the front chassis section of a Formula One (F1) car. The methodology includes three phases: CAD modeling, Finite Element Analysis (FEA), and result extraction, implemented using CATIA V5 for geometry creation and ANSYS Workbench for simulation.

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The aim is to test four high-performance materials under identical conditions to identify the most suitable for crash resistance:

1) Carbon Fiber (Epoxy)
2) Aluminum 7075-T6
3) Titanium Alloy (Ti-6Al-4V)
4) AISI 4130 Chromoly Steel

A. *CAD Modeling*

The front chassis section of the F1 car was designed using CATIA V5. This section is crucial due to its role in absorbing frontal impacts. The model was geometrically accurate, dimensionally simplified, and prepared with necessary load surfaces and boundary constraint interfaces.

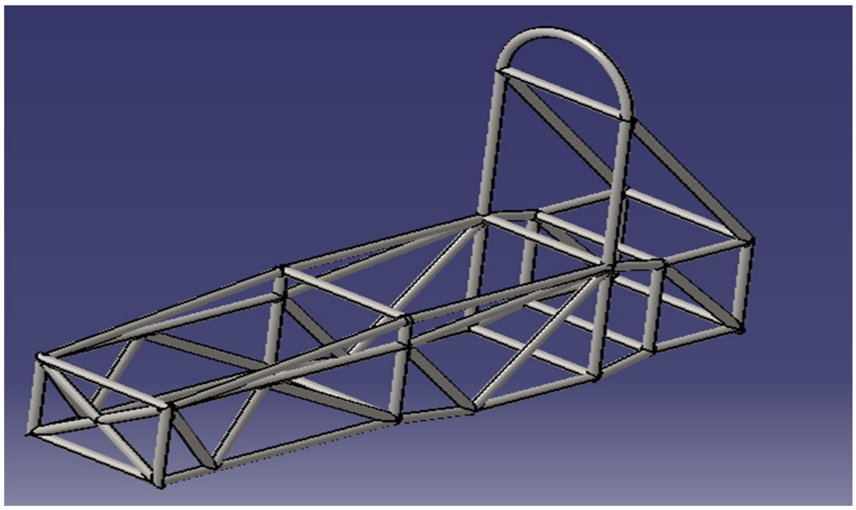

Figure 3.1: 3D Model of Front Chassis Section in CATIA

B. *Meshing*

The chassis was imported into ANSYS Workbench. Mesh generation was performed using tetrahedral elements, with refined mesh (~5 mm) in stress-concentrated areas and coarser mesh (~15 mm) elsewhere.

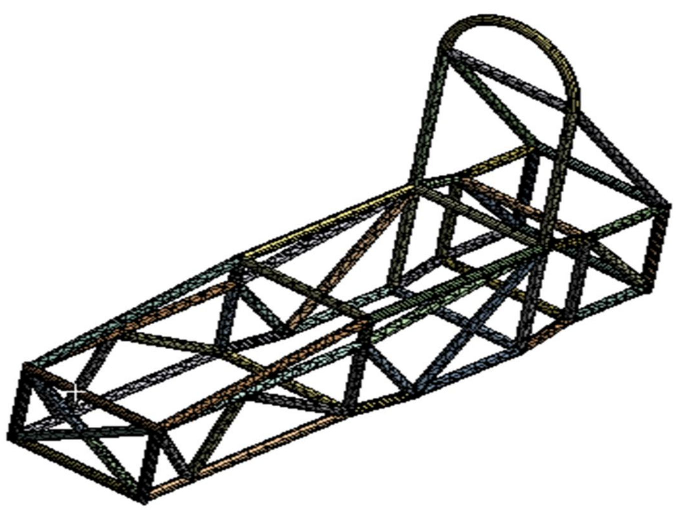

Figure 3.2: Meshing of the Front Chassis Section

C. *Boundary Conditions and Load Application*

The rear end of the chassis was constrained using fixed support, while a frontal load of 15,000 N was applied at the nose cone to simulate a crash.

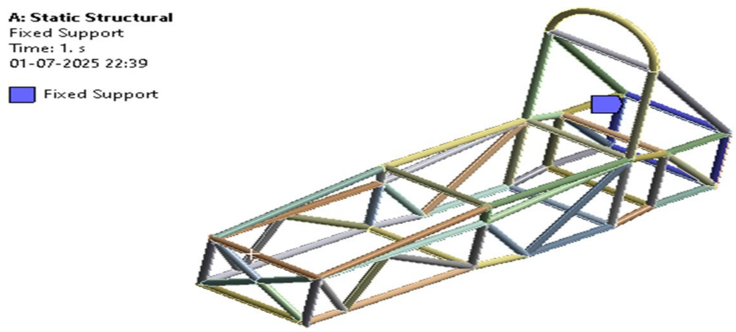

Figure 3.3: Fixed Support at the Back End of the Chassis

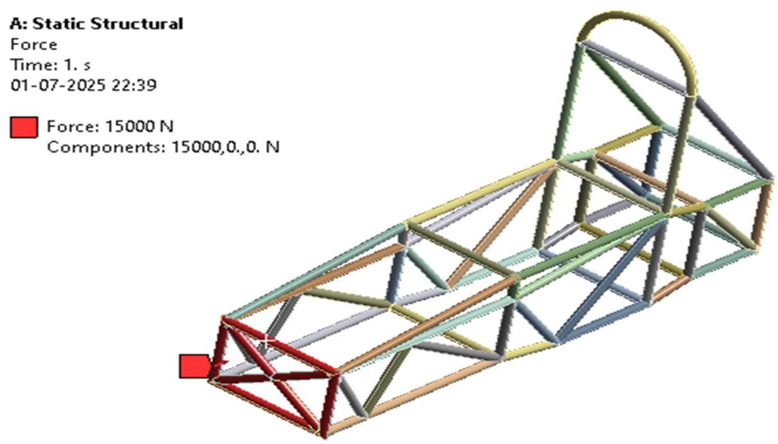

Figure 3.4: Force of 15,000 N Applied at the Frontal Part of Chassis

D. Material Selection

Each material was selected based on its known use in motorsport and aerospace for high-performance applications. Tables below summarize the mechanical properties of the selected materials:

Table 3.1: Mechanical Properties of Carbon Fiber (Epoxy)

Property	Value
Density (kg/m³)	1600
Young’s Modulus (GPa)	135
Poisson’s Ratio	0.30
Yield Strength (MPa)	600
Ultimate Strength (MPa)	900

Table 3.2: Mechanical Properties of Aluminum 7075-T6

Property	Value
Density (kg/m³)	2810
Young’s Modulus (GPa)	71.7
Poisson’s Ratio	0.33
Yield Strength (MPa)	503
Ultimate Strength (MPa)	572

Table 3.3: Mechanical Properties of Titanium Alloy (Ti-6Al-4V)

Property	Value
Density (kg/m³)	4420
Young's Modulus (GPa)	113.8
Poisson's Ratio	0.34
Yield Strength (MPa)	880
Ultimate Strength (MPa)	950

Table 3.4: Mechanical Properties of AISI 4130 Chromoly Steel

Property	Value
Density (kg/m³)	7850
Young's Modulus (GPa)	205
Poisson's Ratio	0.29
Yield Strength (MPa)	460
Ultimate Strength (MPa)	670

E. *Simulation Execution*

Each material was assigned in ANSYS separately while keeping mesh size, boundary conditions, and loading consistent across all simulations. The solver used was a static structural solver to evaluate chassis response to steady frontal loading.

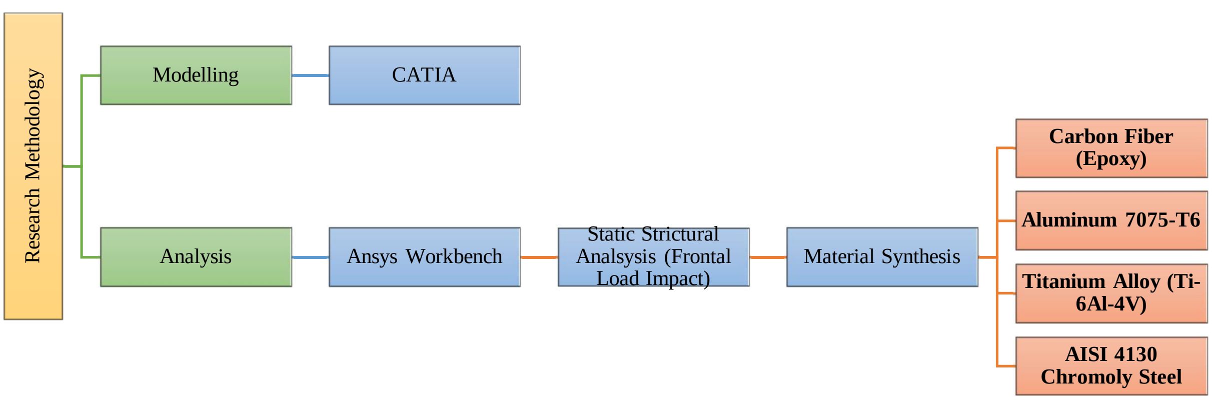

Figure 3.5: Flow Diagram Representing Research Steps

F. *Output Parameters and Post-processing*

Three main results were extracted from each simulation:

- Directional Deformation: Measures displacement along the X-axis (load direction)
- Total Deformation: Measures net displacement magnitude in 3D
- Equivalent (von Mises) Stress: Used to predict material yielding under multi-axial loading

These results were used to compare each material's performance in absorbing crash loads without exceeding yield strength. All results were exported using ANSYS's result processing module and plotted using contour visualization.

IV. RESULTS AND DISCUSSION

This section presents the outcomes of the static structural simulations conducted in ANSYS Workbench for the front chassis section of a Formula One (F1) car. The objective was to compare the structural performance of four different materials Carbon Fiber (Epoxy), Aluminum 7075-T6, Titanium Alloy (Ti-6Al-4V), and AISI 4130 Chromoly Steel under an identical frontal load of 15,000 N. The key parameters extracted from each simulation were directional deformation, total deformation, and von Mises stress. These metrics help evaluate each material's ability to resist bending, compressive force, and structural failure under realistic crash conditions. The results are presented using a combination of simulation images (figures) and comparative data tables. Each figure highlights a specific type of response deformation or stress and is paired with explanatory text. This structured approach helps interpret the performance of each material clearly and consistently.

A. Carbon Fiber (Epoxy)

Carbon Fiber demonstrated excellent performance in terms of stiffness and moderate stress distribution. The directional deformation in the load axis was found to be 0.5749 mm, which indicates a strong resistance to compression. The total deformation, representing the overall displacement of the chassis, was 1.11791 mm. The von Mises stress was calculated at 330.75 MPa, remaining below the material's yield strength.

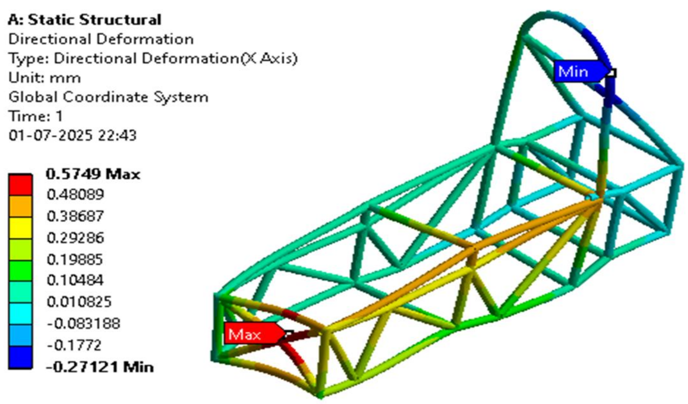

Figure 4.1: Directional Deformation in Carbon Fiber (Epoxy)
Maximum displacement along X-axis: 0.5749 mm

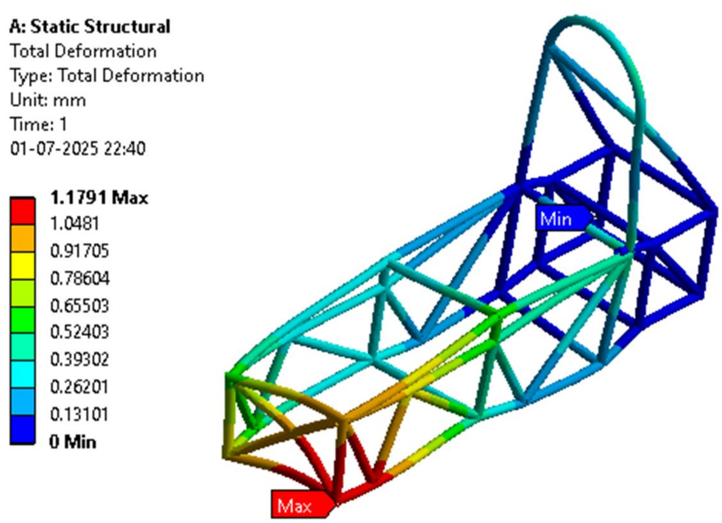

Figure 4.2: Total Deformation in Carbon Fiber
Maximum 3D displacement: 1.11791 mm

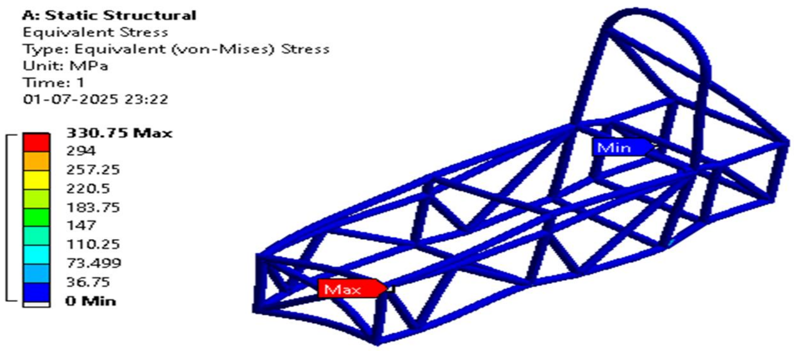

Figure 4.3: Von Mises Stress Distribution in Carbon Fiber
Peak stress: 330.75 MPa

B. Aluminum 7075-T6

Aluminum 7075-T6, though lightweight and cost-effective, showed excessive deformation under load. Directional deformation was 1.0809 mm, nearly twice that of Carbon Fiber. Total deformation measured 2.2209 mm, suggesting reduced stiffness and potential instability in crash conditions. The von Mises stress was slightly lower at 323.36 MPa, but deformation values may compromise safety in critical zones.

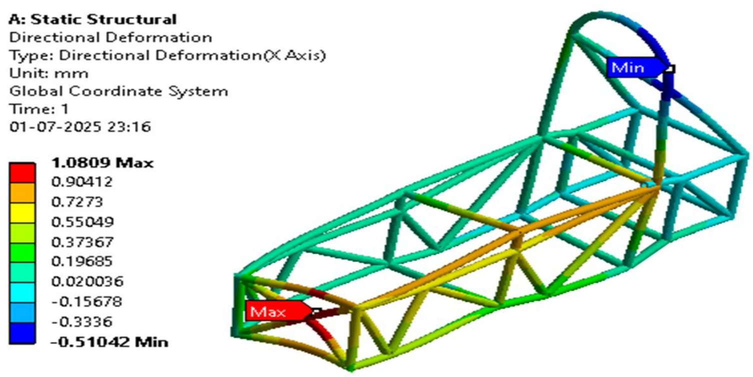

Figure 4.4: Directional Deformation in Aluminum 7075-T6
Maximum X-displacement: 1.0809 mm

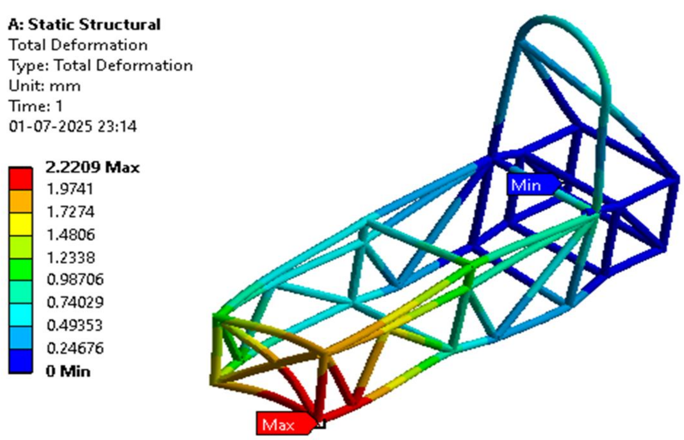

Figure 4.5: Total Deformation in Aluminum
Total deformation: 2.2209 mm

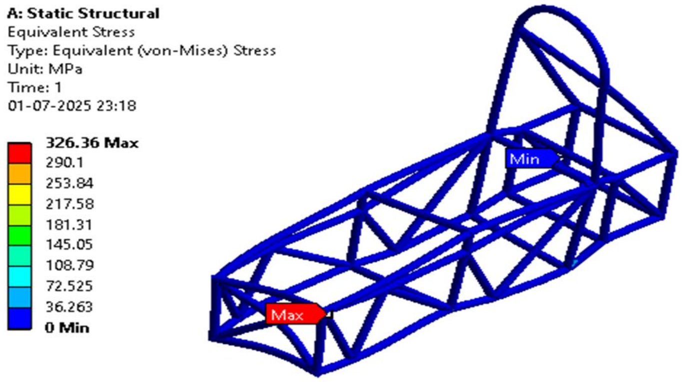

Figure 4.6: Von Mises Stress Distribution in Aluminum
Stress level: 323.36 MPa

C. Titanium Alloy (Ti-6Al-4V)

Titanium Alloy demonstrated a good balance between stiffness and energy absorption. It recorded a directional deformation of 0.68061 mm, total deformation of 1.3988 mm, and a von Mises stress of 324.85 MPa. The stress was evenly distributed, indicating favorable structural behavior under load.

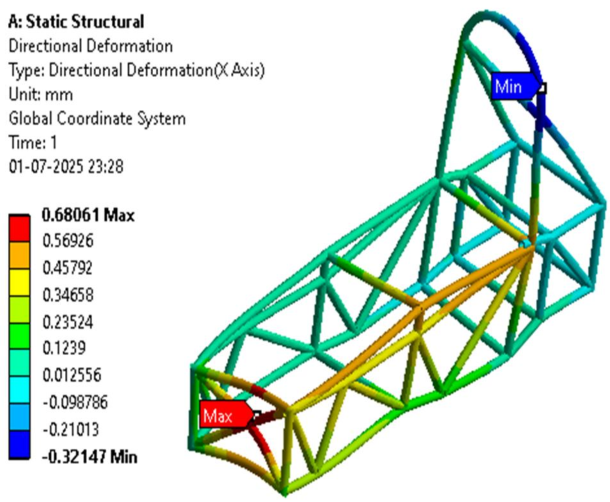

Figure 4.7: Directional Deformation in Titanium Alloy
X-axis deformation: 0.68061 mm

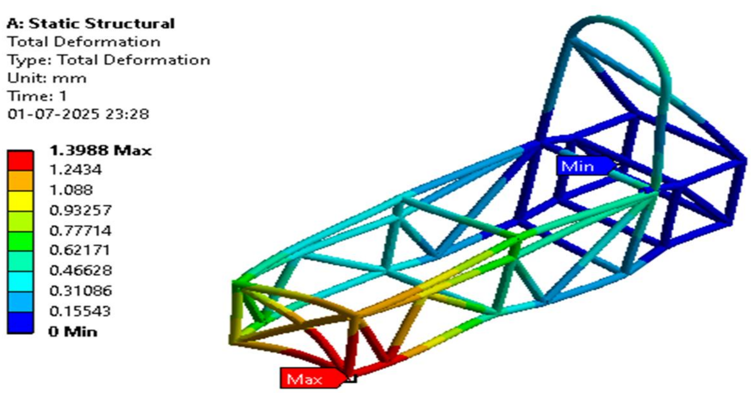

Figure 4.8: Total Deformation in Titanium Alloy
Overall deformation: 1.3988 mm

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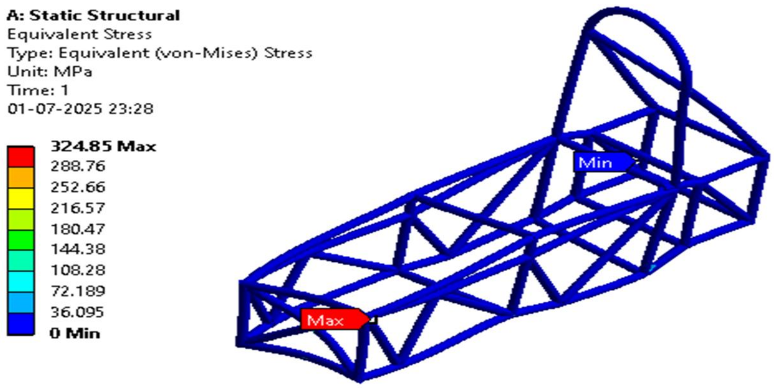

Figure 4.9: Von Mises Stress in Titanium Alloy
Equivalent stress: 324.85 MPa

D. AISI 4130 Chromoly Steel

AISI 4130 Steel showed the least deformation among all materials, confirming its structural rigidity. Directional deformation was only 0.37871 mm, and total deformation reached 0.77606 mm. The von Mises stress peaked at 332.16 MPa, slightly higher than others, but still within safe operational limits.

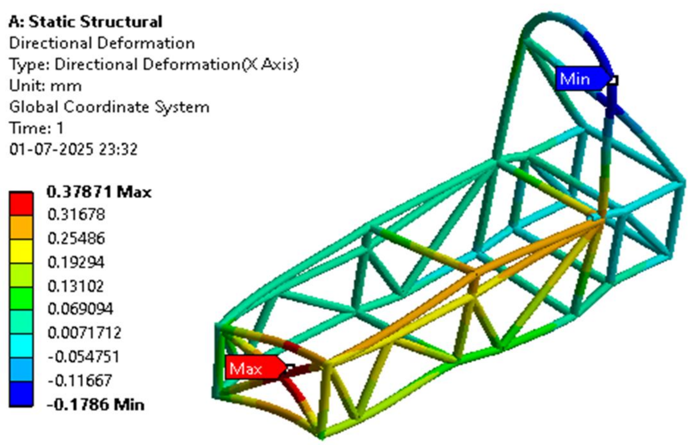

Figure 4.10: Directional Deformation in AISI 4130 Steel
Minimum directional deformation: 0.37871 mm

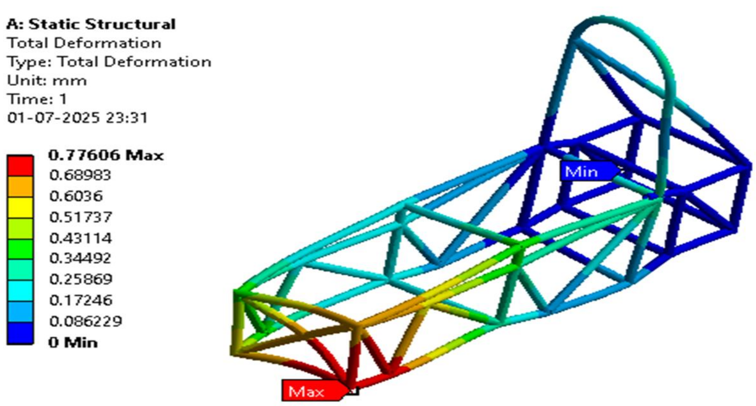

Figure 4.11: Total Deformation in AISI 4130 Steel
Smallest overall displacement: 0.77606 mm

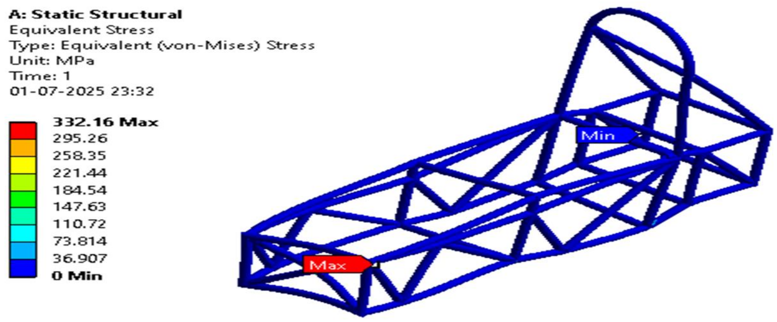

Figure 4.12: Von Mises Stress in AISI 4130 Steel
Peak stress: 332.16 MPa

E. Comparative Data Summary

To enable a direct comparison of all materials, the following tables summarize key deformation and stress values.

Table 4.1: Summary of Simulation Results

Material	Directional Deformation (mm)	Total Deformation (mm)	Equivalent Stress (MPa)
Carbon Fiber (Epoxy)	0.5749	1.11791	330.75
Aluminum 7075-T6	1.0809	2.2209	323.36
Titanium Alloy	0.68061	1.3988	324.85
AISI 4130 Steel	0.37871	0.77606	332.16

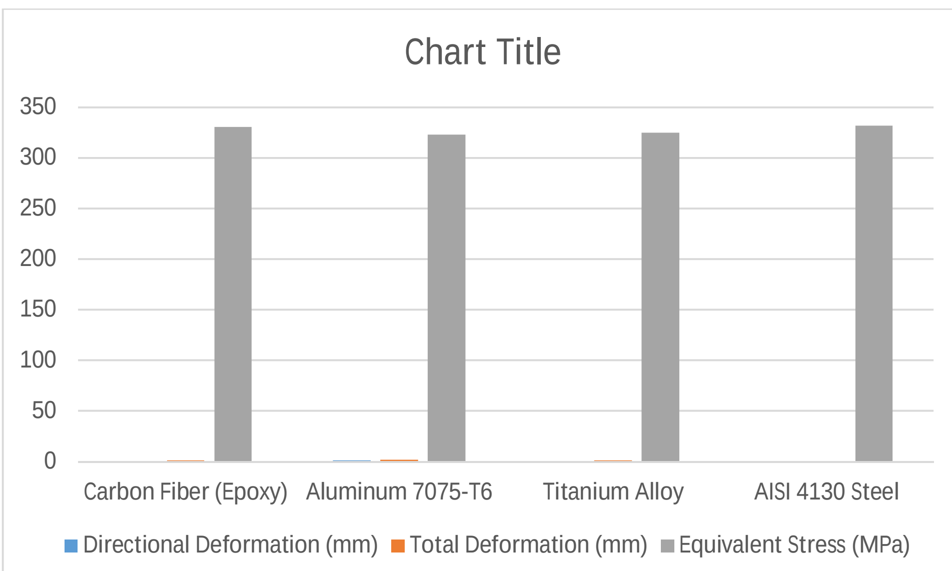

Figure 4.13 - Bar graph comparing all three parameters across materials

Table 4.2: Directional Deformation Comparison

Material	Directional Deformation (mm)
Carbon Fiber (Epoxy)	0.5749
Aluminum 7075-T6	1.0809
Titanium Alloy	0.68061
AISI 4130 Steel	0.37871

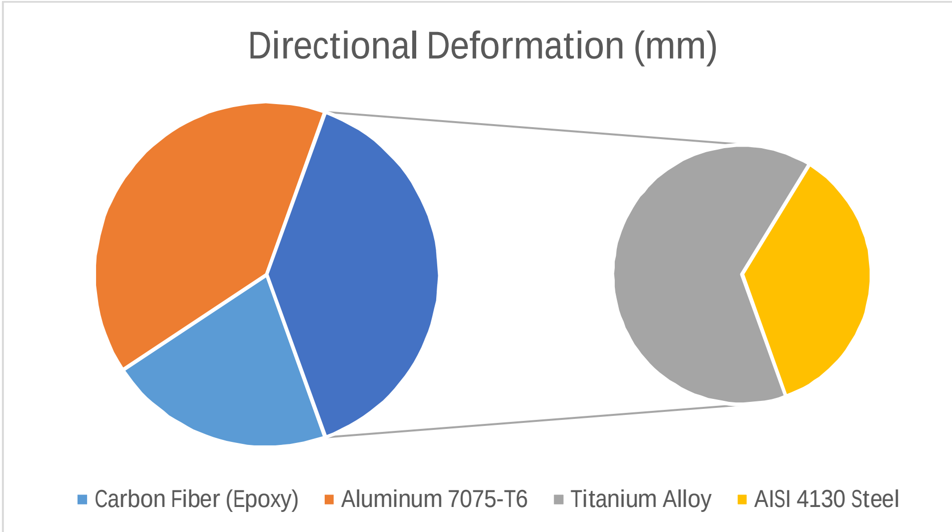

Figure 4.14 - Bar graph comparing directional deformation values

Table 4.3: Total Deformation Comparison

Material	Total Deformation (mm)
Carbon Fiber (Epoxy)	1.11791
Aluminum 7075-T6	2.2209
Titanium Alloy	1.3988
AISI 4130 Steel	0.77606

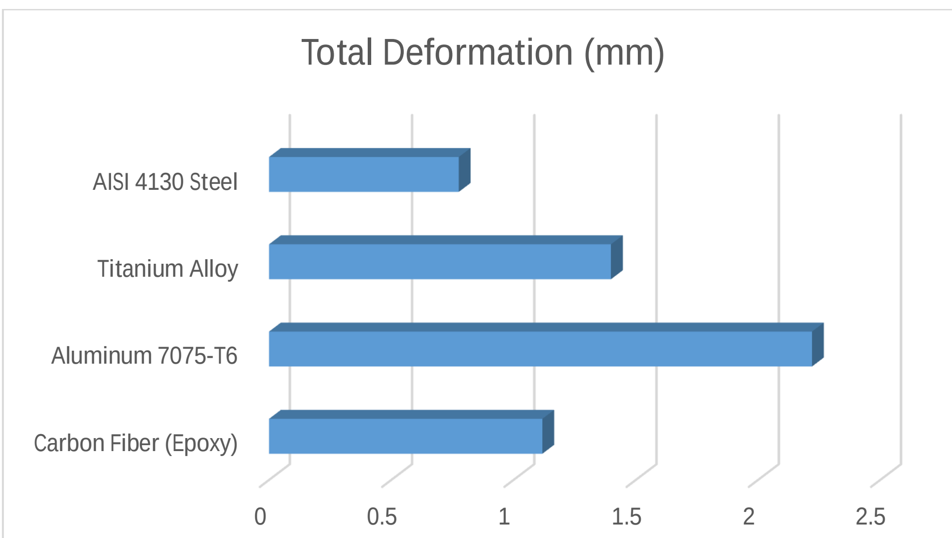

Figure 4.15 - Bar graph comparing total deformation values

Table 4.4: Equivalent Stress Comparison

Material	Equivalent Stress (MPa)
Carbon Fiber (Epoxy)	330.75
Aluminum 7075-T6	323.36
Titanium Alloy	324.85
AISI 4130 Steel	332.16

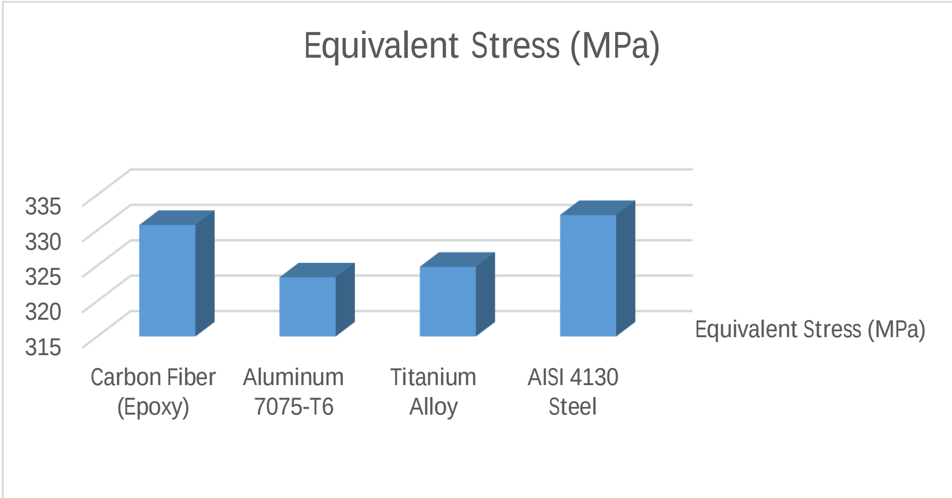

Figure 4.16 - Bar graph comparing von Mises stress values

F. Discussion

The results demonstrate that Carbon Fiber (Epoxy) offers an ideal balance between structural stiffness and weight, making it highly suitable for the front section of an F1 car chassis. While AISI 4130 Steel performs best in terms of minimum deformation, its high density can negatively affect the car's speed and fuel efficiency. Titanium Alloy provides moderate deformation and the most uniform stress distribution, but its high cost and difficulty in machining limit its practical use. Aluminum 7075-T6, though widely used in lightweight structures, exhibits high deformation, reducing its effectiveness in primary impact zones. These findings, supported by ANSYS simulations and visualized in Figures 4.1 to 4.12 and summarized in Tables 4.1 to 4.4, clearly demonstrate how each material responds under crash-like loads. This comparative analysis forms the foundation for the selection of optimal materials in future F1 front chassis development, where safety, rigidity, and weight savings are paramou

V. CONCLUSION

This research aimed to evaluate and compare the performance of four materials Carbon Fiber (Epoxy), Aluminum 7075-T6, Titanium Alloy (Ti-6Al-4V), and AISI 4130 Chromoly Steel used in the front chassis section of a Formula One car. Through simulation using Finite Element Analysis (FEA) in ANSYS Workbench, the study analyzed each material's directional deformation, total deformation, and von Mises stress under a simulated frontal impact load of 15,000 N. The simulation was grounded in high-precision CAD modeling performed in CATIA to ensure that real-world geometry and boundary conditions were accurately represented. The results clearly show that Carbon Fiber (Epoxy) offers an outstanding balance of low deformation and stress absorption within safety limits, validating its extensive application in F1 monocoque structures. While its brittle failure nature requires consideration, particularly in physical crash scenarios, the material's high stiffness-to-weight ratio makes it the leading candidate for performance-sensitive applications. Aluminum 7075-T6, on the other hand, presented the highest deformation values, indicating low stiffness and reduced suitability for high-impact applications. Despite staying within stress limits, the amount of bending could jeopardize structural alignment during a crash, confining its use to secondary or non-critical parts. Titanium Alloy offered a well-balanced performance with moderate deformation and superior ductility, making it an ideal backup for zones requiring high damage tolerance. However, its high cost and machining complexity remain practical limitations. AISI 4130 Steel proved the most rigid among all materials tested, with the lowest deformation under load, but its high density and resulting weight make it less suitable for F1 where every gram matters. Nevertheless, it remains valuable for safety-critical components where structural integrity takes precedence over weight reduction. Overall, this comparative study reinforces the importance of simulation-driven material evaluation in modern motorsport design. It highlights that no single material is universally superior; instead, each has context-specific strengths and trade-offs. Carbon Fiber stands out for weight-sensitive, performance-critical areas; Titanium Alloy serves as a reliable choice for durable yet expensive applications; Aluminum offers affordability where flexibility is acceptable; and Steel is best reserved for robust structural applications with minimal weight sensitivity. The insights gained through this research offer a valuable foundation for engineers seeking to optimize chassis design in Formula One and beyond, using digital tools to enhance both safety and performance in high-speed vehicle structures.

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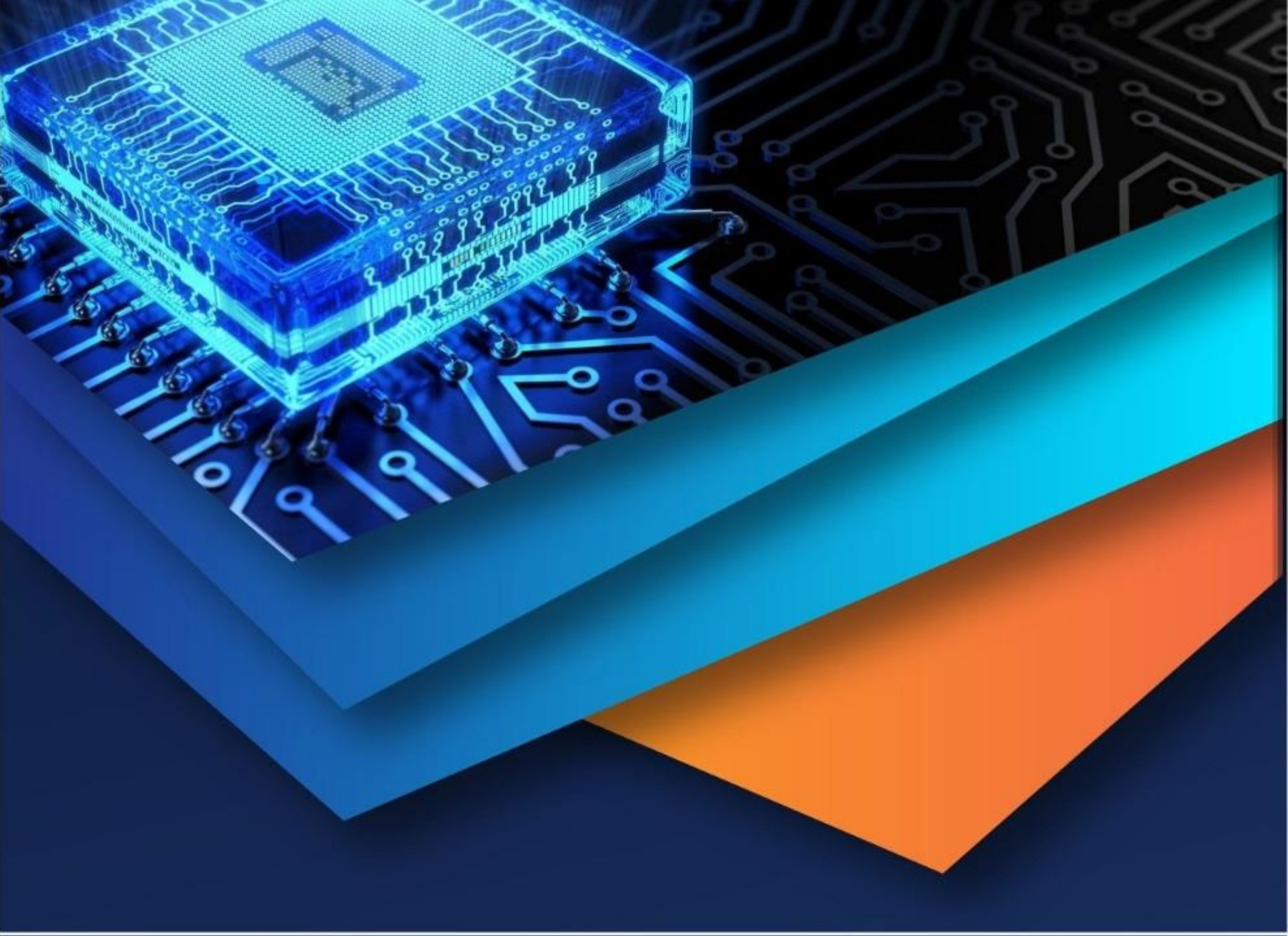

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