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Design Optimization of Truck Chassis using Finite Element Analysis

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***Abstract:** The structural integrity and performance of a truck largely depend on the design and material selection of its chassis frame. This study focuses on the performance evaluation of truck chassis for heavy-duty commercial trucks using three distinct materials Structural Steel (AISI 1020), Aluminum Alloy (6061-T6), and Carbon Fiber Composite through Finite Element Analysis (FEA) conducted in ANSYS Workbench. A ladder frame chassis model was developed using CATIA and analyzed under a uniformly applied vertical load of 2500 N with fixed supports at suspension and rear axle mounting points. The primary parameters assessed included total deformation, equivalent (von Mises) stress, and strain distribution. Simulation results revealed that Structural Steel offered superior stiffness and the least deformation, making it suitable for high-strength applications, albeit at the cost of added weight. Aluminum Alloy exhibited the lowest stress and highest deformation, highlighting its effectiveness in lightweight truck design. Carbon Fiber Composite demonstrated a balanced performance, with moderate deformation and high strength, indicating its potential in high-performance automotive applications. The findings emphasize that material selection significantly influences chassis behavior and must be tailored according to performance, weight, and cost requirements. This research provides a comparative insight into material behavior, aiding engineers in selecting optimal materials for automotive chassis design. This research supports material selection and structural refinement in the design of truck chassis subjected to high-load and durability requirements typical of commercial applications.*
***Keywords:** Truck Chassis, Finite Element Analysis (FEA), Structural Steel (AISI 1020), Aluminum Alloy (6061-T6), Carbon Fiber Composite, Total Deformation, Von Mises Stress, Strain Distribution, Material Optimization, Commercial Vehicle Design*

I. INTRODUCTION

In the field of automotive and mechanical engineering, the chassis is one of the most critical structural components of a truck. It serves as the primary framework on which the entire truck is built, providing the essential support structure that bears the weight of several key subsystems including the engine, transmission, suspension, steering system, and body structure. The performance, safety, and efficiency of any truck largely depend on the design, geometry, and strength of its chassis. As the demands on modern trucks continue to increase whether for better fuel economy, higher safety standards, or enhanced performance the role of the chassis in achieving these objectives has become more significant than ever before. Traditionally, materials like mild steel have been extensively used in chassis manufacturing because of their strength, durability, availability, and ease of fabrication. While these materials have proven effective over many decades, they significantly contribute to the overall weight of the truck. This increased mass impacts key performance indicators, most notably fuel consumption and emissions, and places additional strain on powertrains and braking systems.

With growing global emphasis on reducing fuel consumption and environmental impact, manufacturers are now facing immense pressure to innovate and transition toward lighter, more efficient alternatives. Recent trends in material science and automotive design have led to the exploration of advanced materials such as aluminum alloys and carbon fiber composites in chassis manufacturing. These materials offer high strength-to-weight ratios and exhibit superior mechanical properties compared to conventional steel. For instance, aluminum alloys like 6061-T6 provide substantial weight savings along with resistance to corrosion, while carbon fiber composites demonstrate exceptional stiffness and strength, albeit at a higher cost and with more complex manufacturing requirements. The integration of such materials into truck design enables enhanced fuel efficiency, improved acceleration, and better handling all without compromising safety.

Moreover, advancements in design and simulation tools have revolutionized the way chassis development is approached in engineering practice. Computer-Aided Design (CAD) tools allow engineers to create highly detailed and accurate virtual models of truck components, while Finite Element Analysis (FEA) enables the simulation of real-world mechanical stresses and loads on these components without the need for extensive physical prototyping.

These simulation techniques significantly reduce development time and cost and allow for the iterative optimization of designs for maximum performance. ANSYS Workbench, a widely adopted FEA software, has become instrumental in evaluating stress distribution, strain response, and total deformation in truck structures.

The present study focuses on designing and analyzing a truck chassis using three different materials: Structural Steel (AISI 1020), Aluminum Alloy (6061-T6), and Carbon Fiber Composite. The primary goal is to investigate the performance of each material under identical loading conditions, thereby enabling a comparative assessment. The key mechanical responses evaluated include total deformation, equivalent (von Mises) stress, and strain distribution, which are critical factors in determining the durability and safety of the chassis. By comparing these parameters, the research aims to identify the most suitable material for automotive chassis applications, based on structural performance, weight efficiency, and economic feasibility. The background of this study is deeply rooted in the ongoing shift within the automotive industry toward lightweight, high-performance materials that can meet the dual objectives of enhanced truck dynamics and regulatory compliance. As governments across the globe continue to impose stringent emission and safety standards, the need to reduce truck mass without compromising structural integrity has become more urgent. Material optimization, therefore, plays a central role in meeting these modern requirements. The challenge lies in achieving a careful balance between weight reduction, mechanical strength, crashworthiness, manufacturability, and cost-effectiveness. The significance of the chassis in the overall performance of a truck cannot be overstated. It is not merely a passive structure but an active contributor to various critical functions, including ride quality, crash energy absorption, and load distribution.

II. REVIEW OF LITERATURE

The field of integrated truck dynamics control has witnessed significant growth and innovation due to the increasing emphasis on truck safety, performance, and passenger comfort. At the heart of this field lies the objective of optimizing and synchronizing various vehicular subsystems such as braking, steering, and suspension, in order to achieve enhanced stability and maneuverability under a range of driving conditions. With advancements in automotive engineering, the idea of integrated chassis control has evolved as a vital framework for delivering a cohesive and responsive driving experience. A prominent area of research within this framework is the integrated control of Active Front Steering (AFS) and Direct Yaw Control (DYC), both of which aim to elevate truck agility and safety. AFS is designed to independently regulate the steering angles of the front wheels. This enables better truck maneuverability, especially during sharp cornering or obstacle avoidance scenarios. In contrast, DYC is utilized to manage the truck's yaw motion through the strategic application of differential braking or torque vectoring.

This ensures the truck follows the intended path, even in challenging conditions such as high-speed cornering or driving on slippery surfaces. Traditionally, these systems functioned independently; however, research has demonstrated that integrating AFS and DYC yields significant improvements in truck stability and agility. One of the longstanding dilemmas in truck dynamics is the trade-off between stability and agility. Enhancing stability often comes at the expense of agility, and vice versa. The integrated control of AFS and DYC offers a promising solution by balancing lateral and longitudinal forces, thus achieving both stability and maneuverability. Studies have confirmed that such integration improves cornering capability and stability during sudden lane changes, effectively reducing the risk of truck rollovers and skidding. Incorporating active suspension systems further complements this integration. Active suspension dynamically adjusts suspension stiffness and damping in real time, adapting to both road conditions and truck dynamics.

When used in conjunction with AFS and DYC, active suspension plays a vital role in distributing load during braking or cornering, which enhances traction and ensures better control. This synergy of systems is crucial in tailoring the truck response for varied driving environments. Model Predictive Control (MPC) has emerged as a favored methodology for implementing these integrated systems. MPC can predict future truck states based on current dynamics, allowing the control system to proactively adjust inputs in real time. The application of MPC in integrated truck dynamics has yielded significant gains in stability and performance, particularly in extreme driving scenarios. Torque vectoring represents another critical component in integrated truck dynamics. It enhances yaw control by intelligently distributing torque among the wheels, especially during high-speed cornering and evasive maneuvers.

The combined use of torque vectoring with AFS and DYC leads to more precise truck handling and notable reductions in understeer and oversteer. Truck Stability Control (VSC) systems, which constantly monitor and adjust braking and torque based on sensor inputs, also integrate well with AFS and DYC to create a robust safety net for drivers in adverse conditions. The rise of electric trucks (EVs) has expanded the scope of integrated control systems. EVs, free from traditional mechanical linkages, offer more flexibility in implementing control strategies.

This allows for seamless integration of AFS, DYC, and torque vectoring, facilitating highly precise control of truck dynamics. Furthermore, regenerative braking systems in EVs can be synchronized with VSC, optimizing both braking performance and energy efficiency.

Driver Assistance Systems (DAS) such as Adaptive Cruise Control (ACC), Lane Keeping Assist (LKA), and Automatic Emergency Braking (AEB) are increasingly becoming part of the integrated truck control ecosystem. These systems provide real-time environmental feedback and work alongside AFS and DYC to deliver a safer, more comfortable driving experience. The effectiveness of these systems is enhanced through their integration into the truck's dynamic control architecture. A key focus in integrated truck dynamics is optimizing tire-road interaction. The forces at the tire-road interface are pivotal in determining truck handling and stability. Advanced control systems now use algorithms to estimate tire-road friction coefficients in real time, allowing adjustments to be made for changing conditions such as wet or icy roads. Artificial Intelligence (AI) and Machine Learning (ML) have further improved this process by analyzing sensor data to predict future states and improve control decisions.

These technologies provide adaptive learning capabilities, allowing trucks to "learn" from past experiences and refine control strategies accordingly. The role of the chassis in this context is indispensable. As the fundamental structure upon which all other systems are mounted, the chassis must be designed to accommodate these integrated control components. Over the years, the chassis itself has undergone substantial evolution, both in terms of design and materials. Early chassis were predominantly constructed using steel due to its strength and durability. However, modern demands for fuel efficiency and performance have driven the adoption of lightweight materials such as aluminum, carbon fiber, and composites. These materials offer strength with significantly reduced weight, thus improving fuel economy and handling.

Chassis designs have also evolved from traditional ladder frames to more advanced monocoque structures. Monocoque designs improve weight distribution and structural rigidity, making them ideal for passenger trucks. Advances in welding, bonding, and manufacturing techniques have enabled the integration of multiple materials into a cohesive chassis design. Suspension systems, which are crucial for maintaining tire contact and ride comfort, have also seen considerable innovation. Independent suspension systems provide enhanced ride quality and are now common in modern trucks. The integration of suspension control with steering and braking systems is essential for holistic truck dynamics control. Steering systems have transitioned from manual to hydraulic and now to electric power steering. This progression has facilitated more precise steering inputs and paved the way for advanced features such as lane-keeping and autonomous steering.

III. RESEARCH METHODOLOGY

The research methodology adopted in this study was carefully structured to ensure an accurate, comparative, and meaningful analysis of truck chassis performance using different engineering materials. A ladder-type chassis was designed in CATIA, commonly used in light to heavy-duty trucks.

The methodology integrates computer-aided design (CAD), finite element analysis (FEA), and mechanical simulation tools to investigate how three different materials Structural Steel (AISI 1020), Aluminum Alloy (6061-T6), and Carbon Fiber Composite perform under identical loading and boundary conditions. The objective is to evaluate and compare each material's mechanical behavior with respect to total deformation, equivalent stress (von Mises stress), and strain, thereby identifying the most suitable material for optimal chassis design. The analysis considered loading conditions representative of commercial vehicle usage, including a 2500 N static load applied to simulate real-world operational stress.

A. Chassis Design and Modeling

The foundation of this research lies in the geometric modeling of a standard truck chassis. A custom ladder frame configuration was developed using CATIA, a professional CAD software widely used in the automotive industry. The ladder frame is favored for its high strength and efficient load distribution, especially in commercial and utility trucks. The chassis model was designed to incorporate key structural features such as longitudinal beams, transverse cross-members, mounting points, and clearances necessary for suspension and axle installation. Design parameters such as length, width, height, and cross-sectional thickness were selected based on standard automotive engineering practices and optimized to balance strength and weight. All three material cases shared the same chassis geometry. This consistency ensured that observed differences in mechanical performance could be attributed solely to the materials' inherent properties, rather than geometrical inconsistencies.

Figure 3.1: A systematic approach of the Research Methodology (CATIA modeling and ANSYS simulation flow)

B. Materials Used and Property Assignment

To achieve a comprehensive comparative analysis, three materials with distinct mechanical profiles were selected:

- Structural Steel (AISI 1020): Known for its toughness, durability, and cost-effectiveness. It has high strength and stiffness but comes with significant weight, which can affect fuel efficiency.
- Aluminum Alloy (6061-T6): A heat-treated alloy with a favorable strength-to-weight ratio. It is lighter than steel and resistant to corrosion, making it ideal for lightweight applications.
- Carbon Fiber Composite: Offers superior strength-to-weight ratio and excellent fatigue resistance. Despite being costly and more complex to manufacture, it is widely used in high-performance applications.

Table 3.1: Mechanical Properties of Selected Materials

Property	Structural Steel (AISI 1020)	Aluminum Alloy (6061-T6)	Carbon Fiber Composite
Young's Modulus (E)	200 GPa	69 GPa	70–130 GPa (fiber-dependent)
Poisson's Ratio (ν)	0.3	0.33	0.27–0.35
Density (ρ)	7850 kg/m³	2700 kg/m³	1600 kg/m³
Yield Strength (σ_y)	250 MPa	276 MPa	500–900 MPa
Ultimate Strength (σ_u)	400–500 MPa	310 MPa	600–1500 MPa

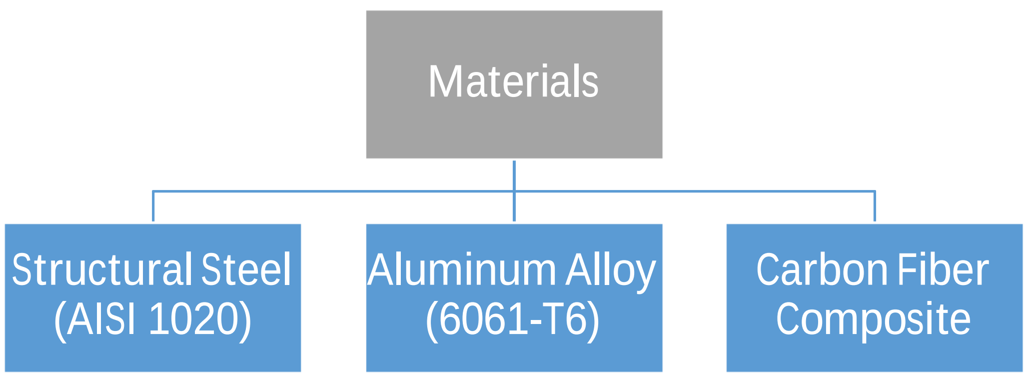

Figure 3.2: Materials used for the proposed simulation

C. Simulation Environment Setup

The structural simulations were carried out using ANSYS Workbench, which provides an integrated platform for importing CAD models, defining boundary conditions, applying loads, and conducting FEA. The primary goal of the simulation phase was to analyze how the three materials respond under identical load and support conditions.

1) Meshing Strategy

Each material required a unique meshing strategy based on its material behavior and geometry.

- For Aluminum AL-6061-T6, hexahedral elements (C3D8) were used wherever possible due to their accuracy and computational efficiency. Fine meshes were applied to stress-concentration zones such as suspension mounts and axle supports.
- For Carbon Fiber Composite, both shell (S4R) and solid 3D elements were considered. Mesh orientation aligned with fiber direction was critical for capturing anisotropic behavior accurately. A layered mesh strategy was used to model the lamination effect of carbon fibers.
- For Structural Steel AISI 1020, a uniform structured hexahedral mesh was applied. High-stress areas were refined, and less critical regions had a coarser mesh to save computational time.

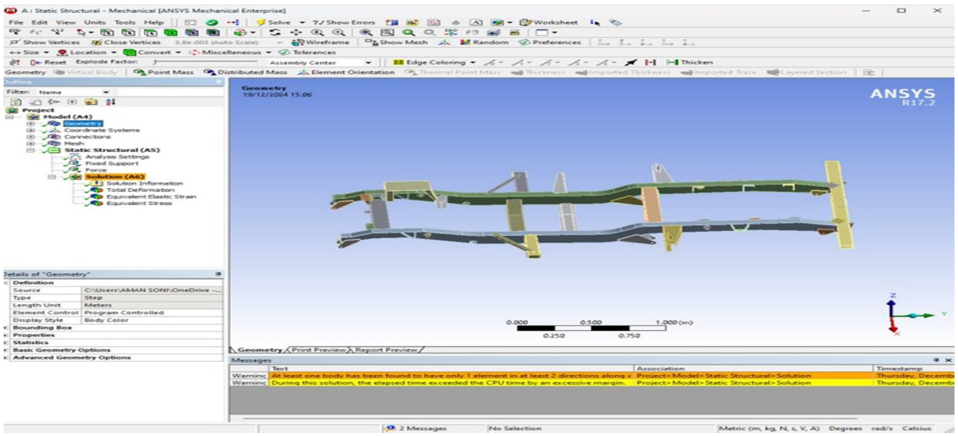

Figure 3.3: Meshing Strategy – Aluminum Alloy (6061-T6)

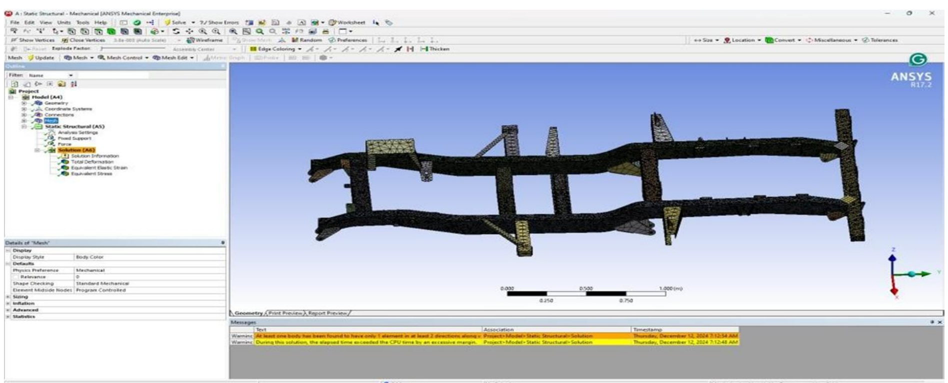

Figure 3.4: Meshing Strategy – Carbon Fiber Composite

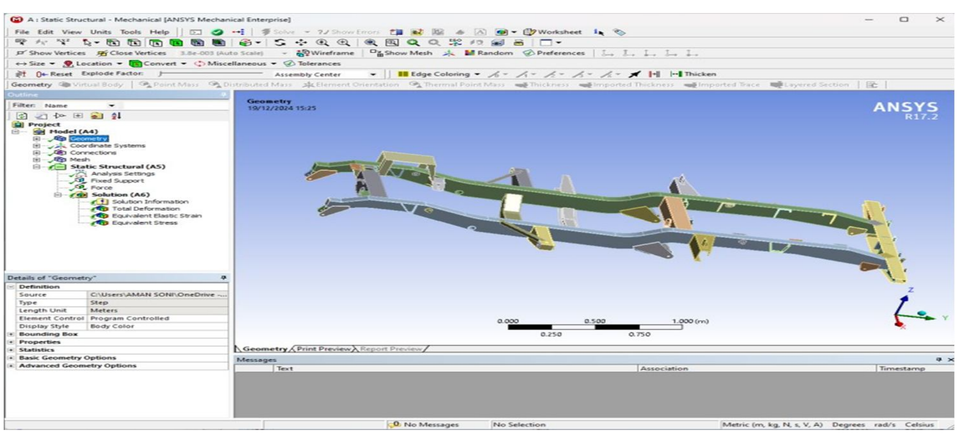

Figure 3.5: Meshing Strategy – Structural Steel AISI 1020

D. Boundary Conditions and Loading

The chassis was subjected to realistic operational constraints to ensure meaningful simulation results:

- Fixed Supports: Applied at the suspension mounting points and rear axle mounts to replicate physical constraints and eliminate rigid body motion.
- Symmetry Conditions: When applicable, symmetry was applied to reduce the model size and improve computation efficiency.
- Loading: A vertical force of 2500 N was uniformly applied to simulate static loading conditions due to passengers, engine, and body weight. This force distribution was kept consistent across all three material simulations to ensure comparability.

Table 3.2: Boundary Conditions Applied in All Simulations

Condition	Description
Fixed Supports	Applied at suspension and rear axle mounting points
Symmetry (if applicable)	Applied along vertical mid-plane
Applied Load	2500 N vertical load distributed over chassis frame

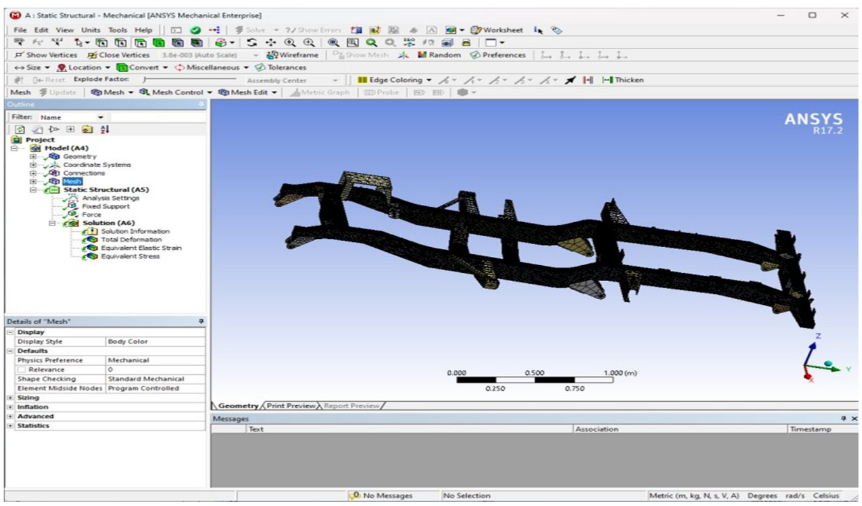

Figure 3.6: Chassis Model with Boundary and Loading Conditions

E. Types of Analysis Conducted

Three structural analyses were conducted to comprehensively evaluate material performance:

1) Total Deformation Analysis: Quantified the extent to which the chassis deforms under the given load, highlighting stiffness and flexibility.

2) Equivalent (von Mises) Stress Analysis: Assessed stress distribution to determine whether the material stays within safe yield limits under loading.

3) Strain Distribution Analysis: Measured how much strain the material experienced, providing insights into ductility and structural response.

By using the same chassis geometry, loading scenarios, and boundary conditions, the study ensures an unbiased and fair evaluation of how material properties influence chassis performance. The results from this phase form the basis for the comparative discussion in the following chapters.

IV. RESULTS AND DISCUSSION

This section presents the results obtained from structural simulations conducted in ANSYS Workbench on a truck chassis modeled using CATIA. The chassis was analyzed under a uniform vertical load of 2500 N applied at critical mounting points, with constraints at the suspension and rear axle regions. The aim was to compare the structural performance of three materials Structural Steel (AISI 1020), Aluminum Alloy (6061-T6), and Carbon Fiber Composite with respect to:

- Total Deformation
- Equivalent (von Mises) Stress
- Strain Distribution

A. *Total Deformation*

Total deformation measures how much the chassis structure displaces under the applied load. A higher deformation indicates less stiffness.

Table 4.1: Total Deformation of Materials under Load

Material	Total Deformation (mm)
Structural Steel (AISI 1020)	2.1743
Aluminum Alloy (6061-T6)	3.8451
Carbon Fiber Composite	2.8477

Analysis:

- Aluminum Alloy (6061-T6) experienced the maximum deformation of 3.8451 mm, indicating lower stiffness due to its lower Young's Modulus.
- Carbon Fiber Composite showed 2.8477 mm deformation, demonstrating a balance between weight and stiffness.
- Structural Steel (AISI 1020) exhibited the least deformation at 2.1743 mm, confirming its superior structural rigidity.

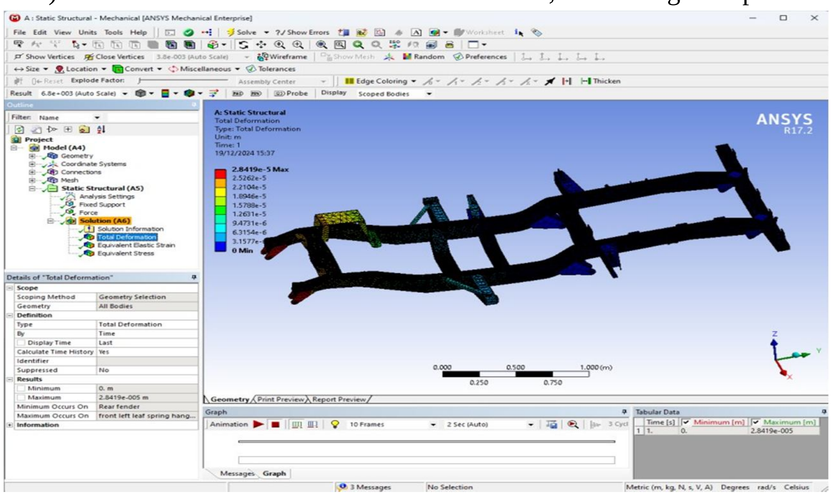

Figure 4.1: Total Deformation – Structural Steel (AISI 1020)

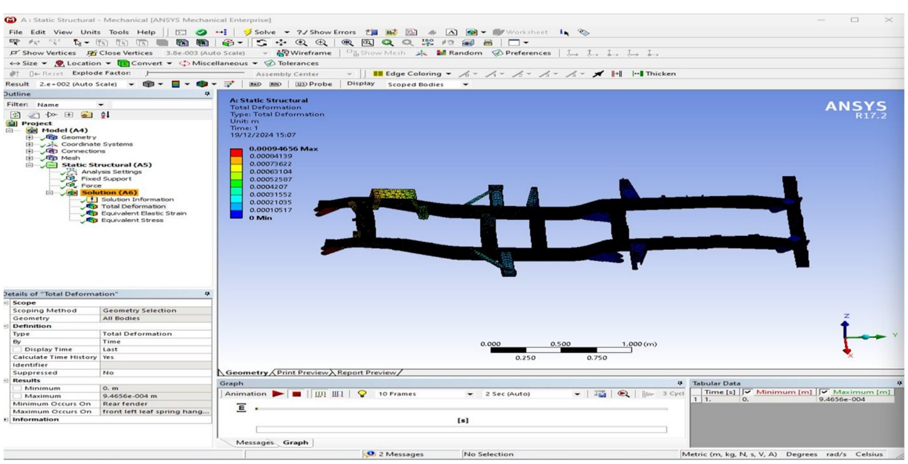

Figure 4.2: Total Deformation – Aluminum Alloy (6061-T6)

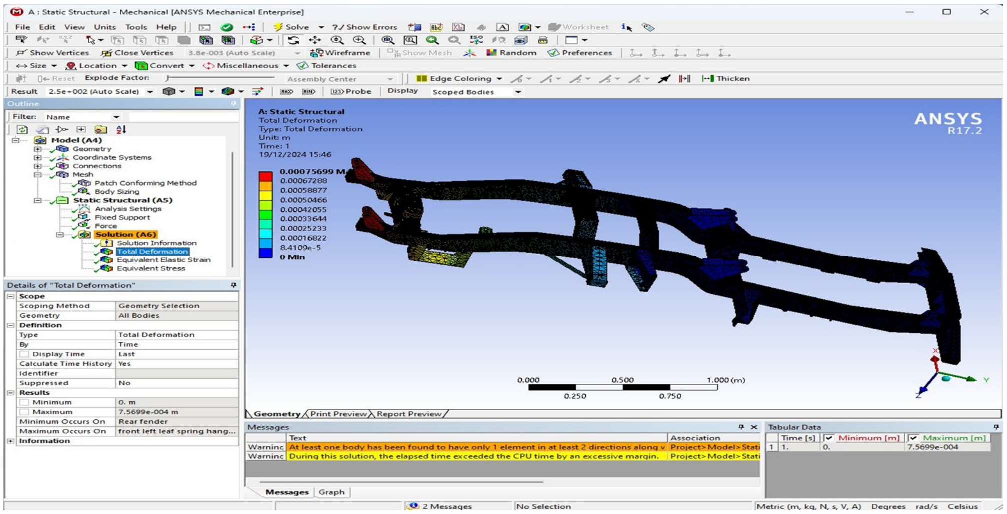

Figure 4.3: Total Deformation – Carbon Fiber Composite

B. Equivalent (von Mises) Stress

Von Mises stress is used to predict yielding of materials under complex loading. Lower stress values are preferable to avoid failure.

Table 4.2: Equivalent Stress of Materials under Load

Material	Equivalent Stress (MPa)
Structural Steel (AISI 1020)	71.838
Aluminum Alloy (6061-T6)	62.981
Carbon Fiber Composite	84.474

Analysis:

- Aluminum Alloy (6061-T6) had the lowest equivalent stress at 62.981 MPa, indicating efficient stress distribution and safe operating range.
- Structural Steel (AISI 1020) had 71.838 MPa, which is within acceptable limits for this material.
- Carbon Fiber Composite exhibited the highest stress of 84.474 MPa, but still below its yield limit, thus remaining safe under the applied load.

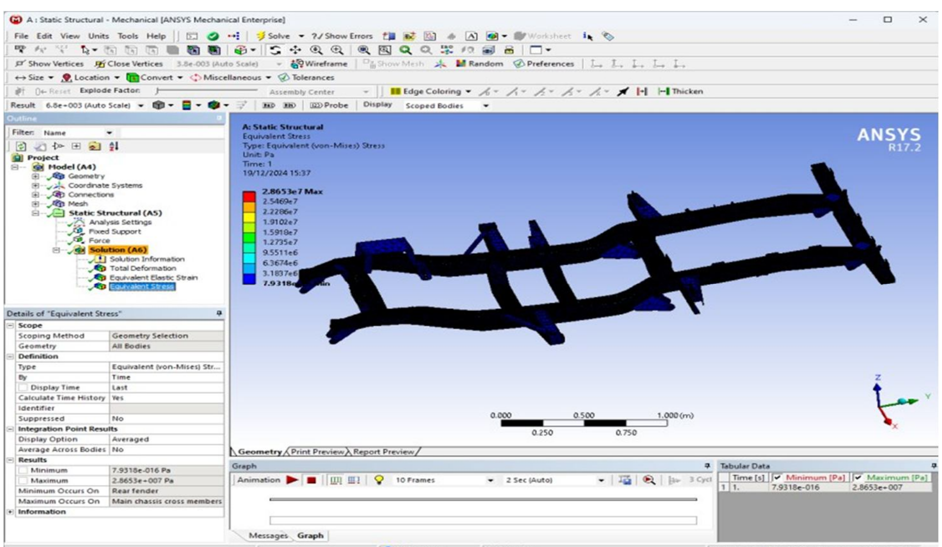

Figure 4.4: Von Mises Stress – Structural Steel (AISI 1020)

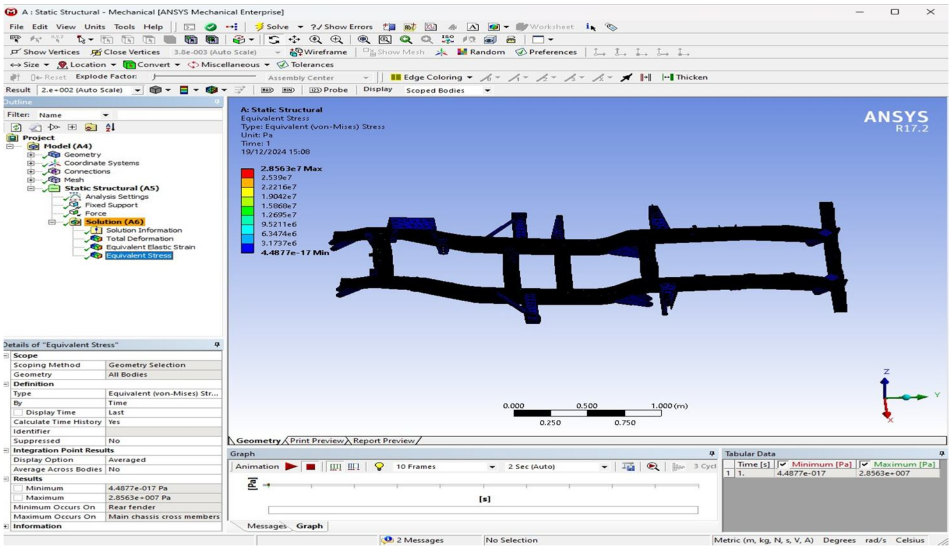

Figure 4.5: Von Mises Stress – Aluminum Alloy (6061-T6)

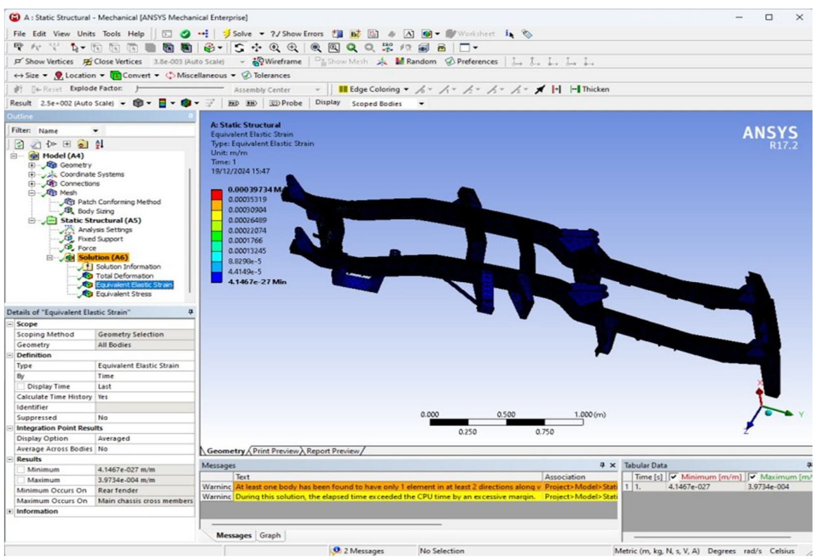

Figure 4.6: Von Mises Stress – Carbon Fiber Composite

C. Strain Distribution

Strain reflects the material's deformation per unit length under load, revealing ductility and elasticity.

Table 4.3: Strain Distribution of Materials

Material	Maximum Strain (unitless)
Structural Steel (AISI 1020)	0.0005
Aluminum Alloy (6061-T6)	0.0011
Carbon Fiber Composite	0.0013

Analysis:

- Structural Steel (AISI 1020) displayed the least strain (0.0005), reflecting its high stiffness and minimal elastic deformation.
- Carbon Fiber Composite had the highest strain (0.0013), which is expected due to its fiber structure and anisotropic properties.
- Aluminum Alloy (6061-T6) showed moderate strain (0.0011), balancing flexibility and strength.

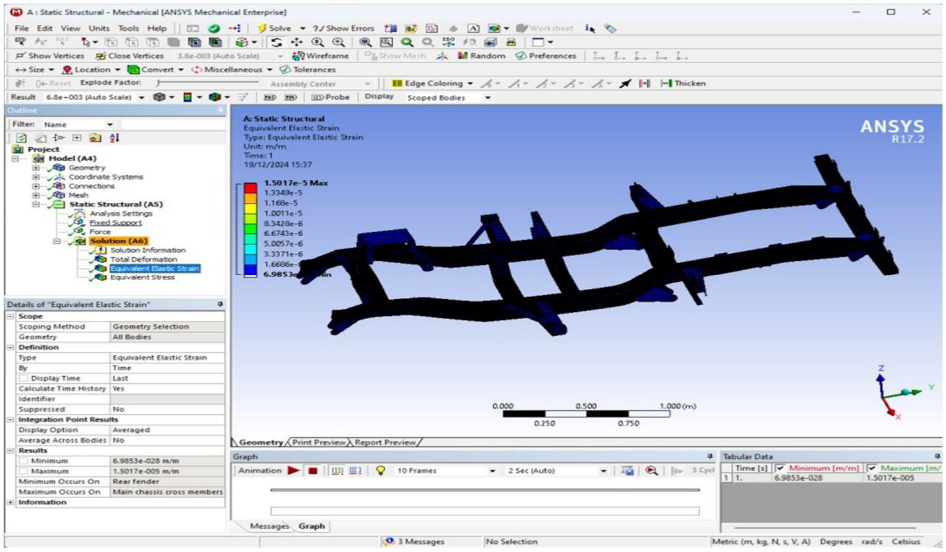

Figure 4.7: Strain Distribution – Structural Steel (AISI 1020)

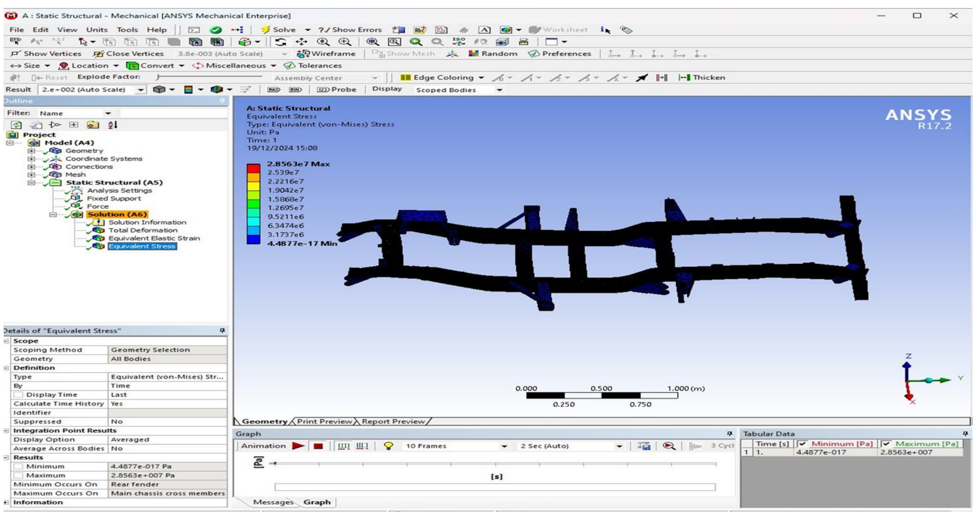

Figure 4.8: Strain Distribution – Aluminum Alloy (6061-T6)

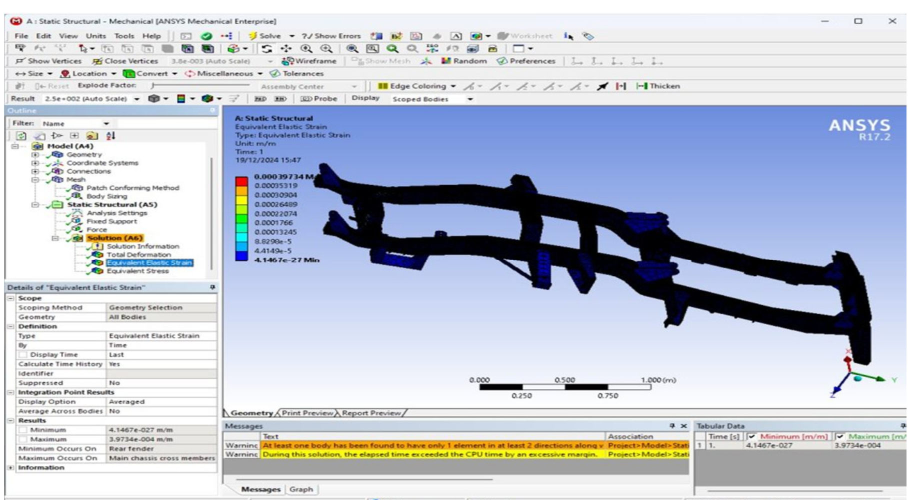

Figure 4.9: Strain Distribution – Carbon Fiber Composite

D. Comparative Discussion

Parameter	Best Performer	Remarks
Total Deformation	Structural Steel	Least flexible; most rigid frame
Equivalent Stress	Aluminum Alloy	Most effective stress distribution; low material weight
Strain Distribution	Structural Steel	Highest stiffness; lowest elastic deformation
Overall Balance	Carbon Fiber Composite	High stiffness, low weight; best for high-performance use

- Structural Steel proves ideal for heavy-duty, cost-effective applications due to its low deformation and strain.
- Aluminum Alloy is favorable in commercial and passenger trucks where lightweighting is key.
- Carbon Fiber Composite, although expensive, is best suited for motorsport or premium automotive segments demanding high performance.

V. CONCLUSION

This study investigated the structural performance of a truck chassis frame using three different materials Structural Steel (AISI 1020), Aluminum Alloy (6061-T6), and Carbon Fiber Composite by employing Finite Element Analysis (FEA) through ANSYS Workbench. The primary objective was to analyze and compare the chassis behavior under identical loading and boundary conditions, evaluating each material based on total deformation, equivalent stress, and strain distribution. The simulation results clearly demonstrated that Structural Steel exhibited the least amount of deformation and strain, affirming its superior stiffness and ability to maintain structural integrity under load. Its high strength and rigidity make it a reliable choice for robust and durable applications.

However, its significant weight contribution remains a disadvantage, particularly when fuel efficiency and truck dynamics are critical. Aluminum Alloy (6061-T6), in contrast, showed the highest deformation, reflecting its lower stiffness but significantly lighter mass. It recorded the lowest equivalent stress among the three materials, indicating a good capacity to distribute mechanical loads within its elastic limit. This makes it a highly favorable option where weight reduction and efficiency are prioritized, especially in the manufacturing of passenger trucks aimed at reducing fuel consumption and emissions. Carbon Fiber Composite offered a balanced profile, with moderate deformation and the highest stress values, yet well within its safe operating range due to its superior strength-to-weight ratio.

While it outperforms both steel and aluminum in specific high-performance criteria, the cost and complexity involved in its production make it more suitable for specialized applications such as motorsports or premium truck segments. Overall, the study concludes that material selection for chassis design should be based on a careful evaluation of performance requirements, weight considerations, cost implications, and intended application. Each material demonstrated distinct advantages under controlled simulation conditions, highlighting the trade-offs between strength, stiffness, deformation, and manufacturability. Future research can build upon this work by exploring hybrid or composite material combinations, real-world crash testing, and dynamic simulations to further enhance the structural optimization of automotive chassis systems. The findings of this study can guide manufacturers in optimizing commercial truck chassis by selecting materials that balance strength, weight, and cost under realistic load-bearing conditions.

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