© May 2026 | IJIRT | Volume 12 Issue 12 | ISSN: 2349-6002

Design And Optimization of Lower Control Arm with Composite Material Reinforcement

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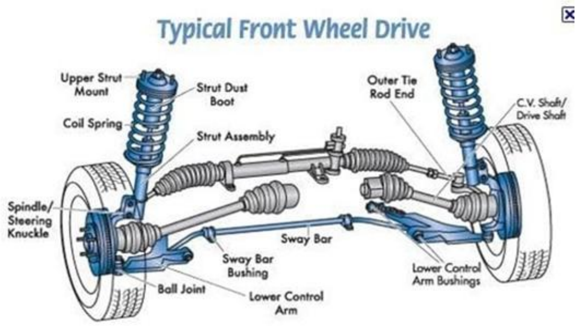
***Abstract*—The lower control arm is a critical component of an automotive suspension system, responsible for maintaining wheel alignment and ensuring vehicle stability under dynamic loading conditions. Conventional control arms are typically manufactured from steel or aluminum alloys, which, while providing adequate strength, contribute significantly to overall vehicle weight. This study focuses on the design and optimization of a lower control arm reinforced with glass fiber composite material to enhance structural performance and achieve weight reduction. A baseline model is developed and analyzed using Finite Element Analysis (FEA) to evaluate stress distribution, deformation, and factor of safety under static loading conditions. Composite reinforcement is then applied in high- stress regions to improve load-bearing capacity. To validate the numerical results, experimental testing is conducted using a Universal Testing Machine (UTM), where the physical model is subjected to controlled loading conditions. The experimental results are compared with FEA predictions to assess the accuracy and reliability of the simulation. The findings demonstrate that the glass fiber-reinforced control arm exhibits improved strength-to-weight ratio, reduced deformation, and good correlation between experimental and numerical results. This study highlights the effectiveness of composite reinforcement in optimizing automotive suspension components for enhanced performance and reduced weight.**

I. INTRODUCTION

In modern automotive engineering, the demand for lightweight, fuel-efficient, and high-performance vehicles has led to continuous advancements in component design and material selection. The suspension system, being a crucial subsystem, significantly influences vehicle stability, handling, and ride comfort. Among its components, the lower control arm serves as a primary load-bearing member that connects the chassis to the wheel assembly, facilitating controlled motion while withstanding forces generated during braking, acceleration, and cornering. Therefore, its structural strength, stiffness, and durability are essential for safe and reliable vehicle operation.

Traditionally, lower control arms are manufactured using materials such as mild steel and aluminum alloys due to their good mechanical properties and ease of fabrication. However, these materials contribute considerably to the overall weight of the vehicle, which adversely affects fuel efficiency and increases emissions. To address these challenges, researchers and engineers are increasingly exploring advanced materials and hybrid structures that can reduce weight without compromising structural integrity. Fiber-reinforced composite materials, particularly glass fiber- reinforced polymers, have gained attention due to their high strength-to-weight ratio, corrosion resistance, and design flexibility.

The integration of composite reinforcement into conventional metallic structures offers a promising solution for enhancing mechanical performance while achieving weight reduction. By strategically reinforcing critical regions of the component, it is possible to improve stress distribution, reduce deformation, and increase overall efficiency. In this study, a lower control arm is designed and optimized by incorporating glass fiber composite reinforcement in regions subjected to high stress. Finite Element Analysis (FEA) is carried out to evaluate the structural behavior of both conventional and reinforced models under static loading conditions.



Furthermore, to ensure the reliability of the numerical analysis, experimental validation is performed using a Universal Testing Machine (UTM). The experimental results are compared with the FEA predictions to assess the accuracy of the simulation and the effectiveness of the proposed design. The objective of this work is to develop a lightweight, structurally efficient lower control arm with improved performance characteristics suitable for modern automotive applications.

II. LITERATURE REVIEW

A. Canegrati et al. (2024) – Polymer–Metal Hybrid and Composite Suspension Systems

A. Canegrati et al. (2024) investigated composite and hybrid suspension components, demonstrating that CFRP-based control arms can significantly improve stiffness, with up to 78% enhancement compared to conventional metal designs. However, the study highlighted that weight reduction is not always guaranteed due to additional reinforcement requirements. Various researchers reported that hybrid designs combining composites and metals can achieve substantial weight savings while maintaining strength and stiffness. The literature also emphasized challenges such as brittle failure of composites, bonding reliability, and manufacturing complexity. Overall, polymer metal hybrid structures were identified as a promising approach for achieving lightweight and high-performance suspension systems, though further improvements in interface engineering are required.

Rongfeng Lin et al. (2025) – Lightweight Optimization and Composites in Control Arms

Rongfeng Lin et al. (2025) reviewed the application of lightweight materials and advanced optimization techniques in automotive suspension components. The study highlighted the growing use of topology optimization, shape optimization, and multi-objective algorithms to reduce weight while maintaining structural integrity. Several researchers demonstrated that combining FEA with experimental validation improves design accuracy and reliability. The integration of composite materials and advanced steels was shown to enhance performance in terms of stiffness, fatigue life, and durability. Overall, the research indicates that computational optimization and hybrid materials are key drivers in the development of efficient and lightweight control arms.

Merzkirch et al. (2025) – Hybrid Manufacturing of Fiber– Metal Laminates for EV Suspension

Merzkirch et al. (2025) developed a hybrid fiber metal laminate (FML) lower control arm using alternating layers of GFRP and aluminum to achieve improved strength-to-weight ratio. The study employed an Integrated Computational Materials Engineering (ICME) framework to optimize both manufacturing and structural performance. Finite element simulations were used to predict forming behavior and structural response, which were validated through experimental testing. Results showed good agreement between simulation and experimental data, confirming the effectiveness of the hybrid design. However, the adhesive interface was identified as a critical weakness, indicating the need for improved bonding techniques.

Jiang et al. (2022) – Multilevel Optimization of CFRP Control Arm Design

Jiang et al. (2022) proposed a multilevel optimization framework for CFRP control arms, addressing both structural performance and manufacturing uncertainties. The study combined free-size, size, and stacking sequence optimization to achieve significant weight reduction. A reliability-based optimization approach using surrogate models and genetic algorithms was implemented to account for variability in material properties. The optimized design achieved considerable improvements in stiffness and reliability compared to conventional steel components. The research demonstrated that integrating deterministic and probabilistic optimization methods leads to highly efficient and robust composite designs.

Prabaharan et al. (2022) – Structural Optimization of Double Wishbone Suspension

Prabaharan et al. (2022) focused on improving the performance of a double wishbone suspension system by optimizing the lower control arm. Using CAD modeling and FEA, the study compared mild steel and CFRP materials under static loading conditions. Results showed that the composite arm provided significant weight reduction while maintaining acceptable strength and safety limits. Although higher deformation was observed in the composite design, it remained within permissible limits. The study concluded that composite materials offer a viable alternative for lightweight suspension systems, though further fatigue and dynamic analysis are necessary.

Bharatesh M. Goudra & Narasimhe Gowda (2018)

Bharatesh M. Goudra and Narasimhe Gowda (2018) conducted a comparative analysis of a control arm using SAE J2340 steel and Kevlar 49/epoxy composite. The study showed that the composite material offers significant weight reduction due to its lower density but exhibits anisotropic mechanical behavior. Higher deformation and localized stress concentrations were observed in the composite design, particularly near joints and interfaces. The research emphasized the importance of ply orientation, reinforcement at critical regions, and proper joint design. Overall, the study highlighted that while composites provide weight advantages, careful design and manufacturing considerations are essential for reliable performance.

S. V. Yende et al. (2019)

S. V. Yende et al. (2019) applied topology optimization to redesign a lower control arm for a light military vehicle. The study used density-based optimization techniques to minimize mass while maintaining stiffness and structural safety. The optimized design showed material distribution along principal load paths, resulting in an efficient and lightweight structure. Finite element analysis confirmed that the redesigned component maintained required strength and safety factors. The research concluded that topology optimization is a powerful tool for developing high-performance automotive components when combined with proper post-processing and validation.

Hongwang Zhao et al. (2019)

Hongwang Zhao et al. (2019) investigated lightweight design strategies for suspension control arms by integrating material selection, optimization techniques, and experimental validation. The study emphasized reducing unsprung mass to improve vehicle performance and efficiency. Various materials, including high-strength steels, aluminum alloys, and composites, were evaluated based on performance indices. Optimization methods were applied to achieve a balance between weight reduction, stiffness, and fatigue life. The research concluded that a multidisciplinary approach combining materials, design, and manufacturing considerations is essential for developing efficient and durable lightweight control arms.

Novelty of work: The present study introduces a hybrid approach for improving the performance of an automotive lower control arm through localized reinforcement using glass fiber-reinforced composite material. Unlike conventional studies that focus entirely on replacing metallic components with composites, this work emphasizes strategic reinforcement of critical stress regions, thereby achieving an effective balance between weight reduction, strength, and manufacturability. The integration of Finite Element Analysis (FEA) with experimental validation using a Universal Testing Machine (UTM) enhances the reliability of the results and ensures practical applicability of the proposed design. Another key novelty lies in the use of glass fiber composites as a cost- effective alternative to carbon fiber, making the solution more suitable for mass production in the automotive industry. The study also focuses on correlating numerical and experimental results, providing a comprehensive validation framework that is often lacking in similar research. Furthermore, the design optimization is carried out with consideration of real-world loading conditions, ensuring structural safety and performance under practical scenarios. Overall, this research contributes to the development of a lightweight, structurally efficient, and economically viable lower control arm by combining material innovation, simulation-based optimization, and experimental verification, thereby bridging the gap between theoretical design and industrial implementation.

III. PROBLEM STATEMENT

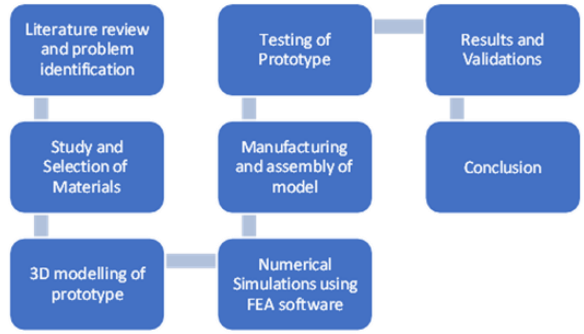
- Conventional control arms are primarily manufactured using steel or aluminum alloys, which provide adequate strength and durability but significantly contribute to the overall vehicle weight.
- This increase in unsprang mass adversely affects fuel efficiency, vehicle handling, and emissions, making lightweight design a key requirement in modern automotive engineering.
- Although fiber-reinforced composites offer high strength to weight ratios and corrosion resistance, the complete replacement of metallic control arms with composite materials presents several challenges, including high material cost, brittle failure behavior, and difficulties in manufacturing and joining.
- Additionally, many existing studies rely solely on numerical simulations without sufficient experimental validation, raising concerns regarding the accuracy and real-world applicability of the proposed designs.
- Therefore, there is a need to develop an optimized lower control arm that reduces weight while maintaining structural integrity, durability, and safety under operating conditions.

IV. OBJECTIVES

The aim of this research is to design and optimize a lower control arm using glass fiber composite reinforcement in order to reduce weight and improve structural performance, and to validate the results through Finite Element Analysis (FEA) and experimental testing using a Universal Testing Machine (UTM). The primary objectives are:

- To select suitable Glass fiber reinforced composite material based on strength-to-weight ratio, stiffness, and fatigue resistance.
- To develop and optimize the geometric design and fiber layup sequence of the control arm for improved performance.
- To carry out finite element analysis (FEA) to evaluate stress distribution, deformation, and load-bearing capacity.
- To compare the optimized composite reinforced design with conventional metallic designs in terms of weight, performance, and durability.

V. RESEARCH METHODOLOGY



VI. FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) is a numerical method used to analyze the structural behavior of complex engineering components by dividing them into smaller, manageable elements. The basic principle of FEA is based on discretization, where a continuous domain is subdivided into a finite number of elements interconnected at nodes. This process converts a complex physical problem into a system of algebraic equations that can be solved computationally.

In structural analysis, each element is assigned material properties such as Young’s modulus, Poisson’s ratio, and density. The governing equations are derived from fundamental principles of mechanics, including equilibrium, compatibility, and constitutive relationships.

The accuracy of FEA results depends on factors such as mesh quality, element type, boundary conditions, and material modeling. Finer meshes generally provide more accurate results but increase computational cost. Proper application of constraints and loads is critical to realistically simulate actual operating conditions. In addition, convergence studies are often performed to ensure that the solution is independent of mesh size.

FEA is widely used in the automotive industry for analyzing components such as suspension systems, where it helps predict stress distribution, deformation, and failure locations under various loading conditions. In this study, FEA is employed to evaluate the structural performance of the lower control arm and to compare the behavior of conventional and glass fiber- reinforced designs, forming a basis for further optimization and experimental validation.

FEA of Existing Lower Control Arm (MS) Geometry:

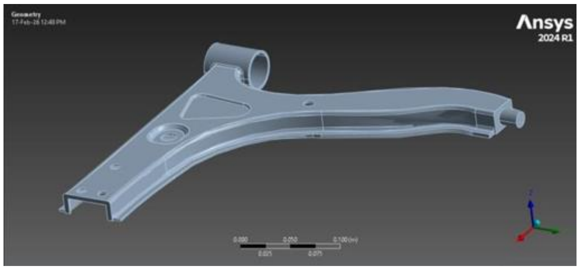
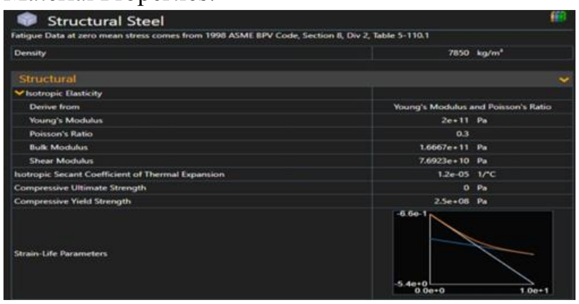


Fig. Geometry of Existing LCA.

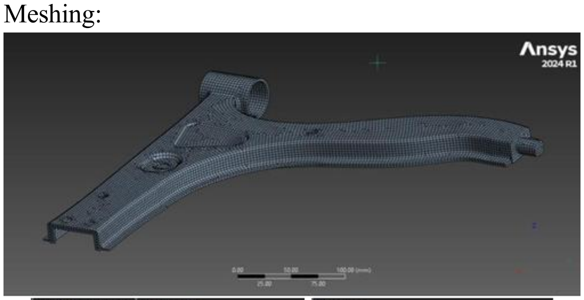
Material Properties:



Density	7850 kg/m³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2e+11 Pa
Poisson's Ratio	0.3
Bulk Modulus	1.6667e+11 Pa
Shear Modulus	7.6923e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05 1/°C
Compressive Ultimate Strength	0 Pa
Compressive Yield Strength	2.5e+08 Pa
Strain-Life Parameters	

Fig. Material Properties of Mild Steel.

Meshing:



Physics Preference	Mechanical	Statistics	
Element Order	Program Controlled	Nodes	28496
Element Size	3.0 mm	Elements	23917

Fig. Meshing Details of Existing LCA.

Boundary Conditions:

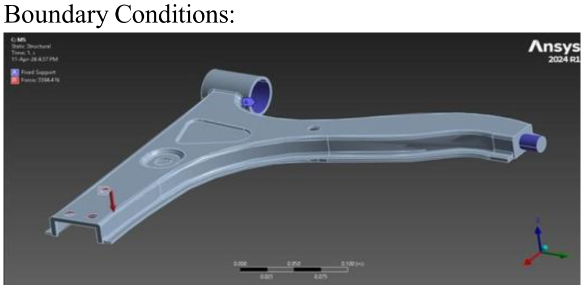


Fig. Boundary conditions for static structural analysis of Existing LCA (MS).

Results:

Total Deformation:

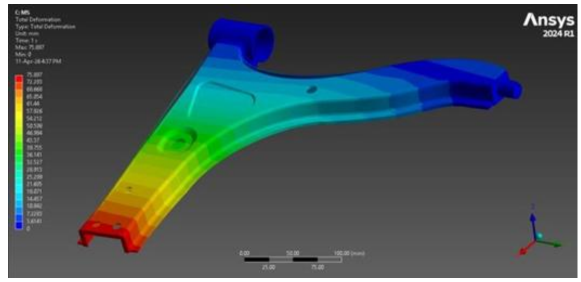


Fig. Total Deformation of Existing LCA (MS).

Equivalent Stress:

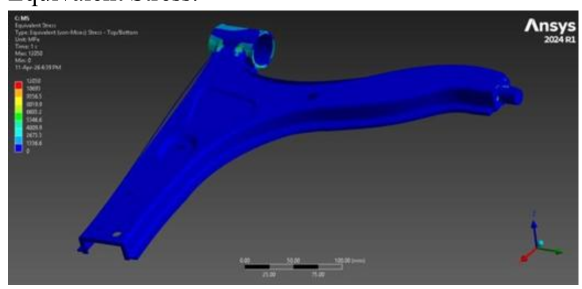


Fig. Equivalent Stress of Existing LCA (MS).

Equivalent Elastic Strain:

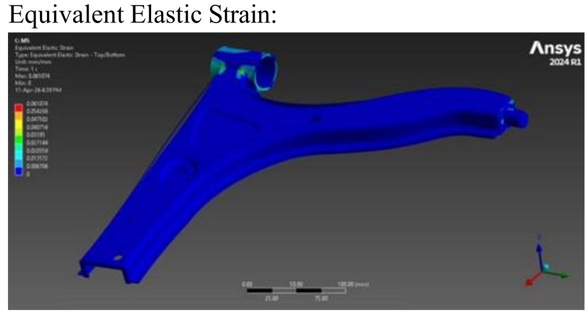


Fig. Equivalent Elastic Strain of Existing LCA (MS).

FEA of Glass-fiber lower control arm: Geometry –

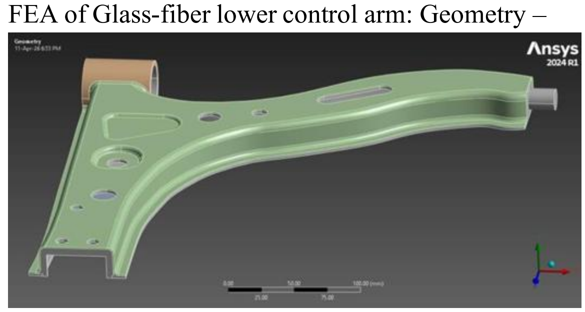


Fig. Geometry of Glass Fiber Reinforced lower control arm.

Material Properties –

Properties of Outline Row 13: Structural Steel

	A	B	C
1	Property	Value	Unit
2	Density	7850	kg m^-3
3	Isotropic Secant Coefficient of Thermal Expansion		
5	Isotropic Elasticity		
6	Derive from	Young's Modulu...	
7	Young's Modulus	2E+11	Pa
8	Poisson's Ratio	0.3	
9	Bulk Modulus	1.6667E+11	Pa
10	Shear Modulus	7.6923E+10	Pa
11	Strain-Life Parameters		
19	S-N Curve	Tabular	
23	Tensile Yield Strength	2.5E+08	Pa
24	Compressive Yield Strength	2.5E+08	Pa

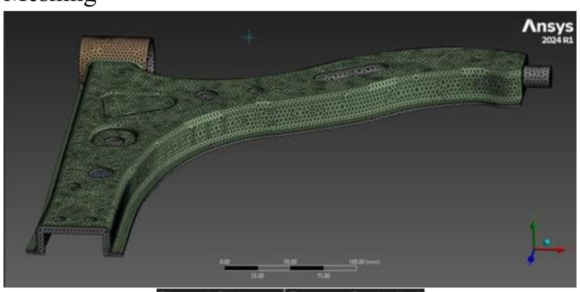
E-Glass

E-Glass fibers only

Density	2.6e-06	kg/mm³
Structural		
Isotropic Elasticity		
Derive from	Young's Modulus and Poisson's Ratio	
Young's Modulus	73000	MPa
Poisson's Ratio	0.22	
Bulk Modulus	43452	MPa
Shear Modulus	29918	MPa
Isotropic Secant Coefficient of Thermal Expansion	5e-06	1/°C
Thermal		
Isotropic Thermal Conductivity	0.00127	W/mm·°C
Specific Heat Constant Pressure	8.02e+05	mJ/kg·°C

Fig. Material Properties of Control arm.

Meshing –



Element Order	Program Controlled
Element Size	3.0 mm

Fig. Meshing details of GFR lower control arm.

Boundary Conditions –

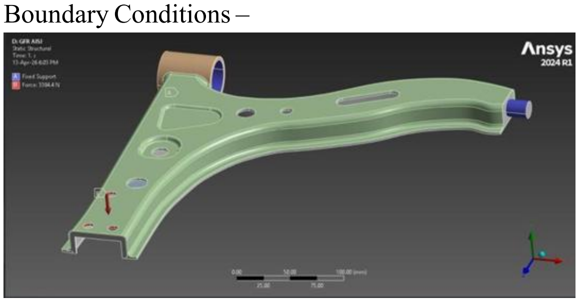


Fig. Boundary condition for static structural analysis of GFR lower control arm.

Results:

Total Deformation –

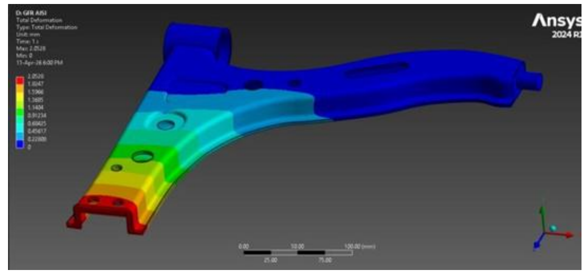


Fig. Total Deformation of GFR lower control arm.

Equivalent Stress –

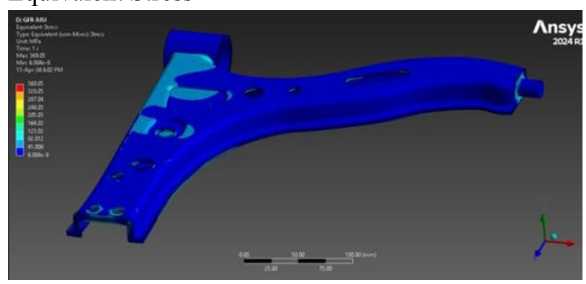


Fig. Equivalent elastic stress of GFR lower control arm.

Equivalent Elastic Strain –

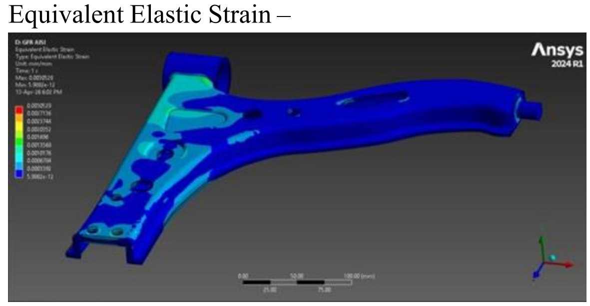


Fig. Equivalent Elastic strain of GFR lower control arm.

VII. FEA RESULTS

Initially, the analysis was performed on the conventional mild steel (MS) lower control arm to establish a baseline for comparison. The results indicated a maximum total deformation of 75.8979 mm, a maximum equivalent (von Mises) stress of 12030 MPa, and a maximum equivalent elastic strain of 0.061074. The high deformation and stress values suggest that the existing design experiences severe structural instability and is unable to efficiently withstand the applied loads. Following this, the LCA was modified by incorporating glass fiber composite reinforcement. The FEA results of the reinforced model showed a significant improvement in structural behavior. The maximum total deformation was drastically reduced to 2.0528 mm, indicating a substantial increase in stiffness. Similarly, the maximum equivalent stress decreased to 369.05 MPa, and the maximum equivalent elastic strain was reduced to 0.0030528, demonstrating improved load distribution and reduced material deformation.

The comparative analysis clearly highlights the effectiveness of glass fiber reinforcement in enhancing the performance of the lower control arm. The reduction in deformation, stress, and strain confirms that the reinforced design is structurally more efficient and capable of withstanding applied loads within safe limits. These results form the basis for further experimental validation and confirm the suitability of composite reinforcement for automotive suspension applications.

VIII. MANUFACTURING OF THE COMPONENT

The manufacturing of the glass fiber-reinforced lower control arm was carried out using a manual composite layup technique combined with a resin bonding process. Initially, the base lower control arm, made of conventional metallic material, was thoroughly cleaned to remove dust, oil, and surface contaminants. Surface preparation was further enhanced by light grinding or sanding to improve adhesion between the metal surface and the composite layer. A thermosetting resin solution was prepared by mixing it with the hardener in a balanced ratio. The resin solution was uniformly applied over the prepared surface of the control arm, after which the glass fiber was carefully impregnated with the resin to ensure proper wetting and bonding. After layup, the component was left to cure at room temperature for a duration of time to allow proper hardening of the resin matrix.

Once curing was complete, the reinforced control arm was subjected to finishing operations such as trimming of excess material. The final component was then inspected visually for defects such as delamination, voids, or improper bonding. This manufacturing approach provides a simple, cost-effective method for reinforcing existing metallic components with glass fiber composites, making it suitable for experimental and small-scale production applications.

Fig. Glass Fiber layup on the Lower control arm using Resin solution.

X. EXPERIMENTAL TESTING

A Universal Testing Machine (UTM) is a versatile mechanical testing device used to evaluate the material and structural properties under various loading conditions such as tension, compression, and bending. The working principle of a UTM is based on the application of a controlled load through a movable crosshead driven by hydraulic or electromechanical systems. The applied load is measured using a load cell, while the corresponding deformation or displacement is recorded using extensometers or displacement sensors.

In compression testing, the specimen is placed between two rigid platens, and a compressive force is applied along its axis. The relationship between load and deformation is used to determine important mechanical properties such as stiffness, yield strength, and ultimate load-carrying capacity. The accuracy of UTM results depends on proper specimen alignment, calibration of the machine, and consistent loading conditions. In this study, the experimental results obtained from the UTM are compared with FEA predictions to assess the validity of the numerical model and the effectiveness of glass fiber reinforcement in improving the performance of the lower control arm.

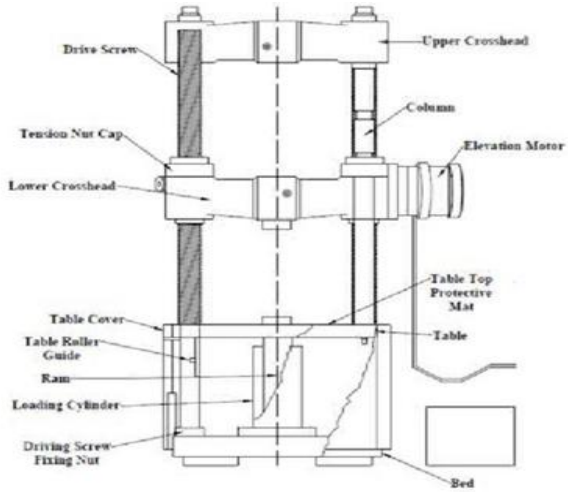


Fig. Components of UTM.

To validate the numerical results obtained from Finite Element Analysis (FEA), experimental testing of the lower control arm was carried out using a Universal Testing Machine (UTM). Compression testing was performed to simulate the loading conditions experienced by the control arm during vehicle operation, particularly under vertical and impact loads.

The specimen was carefully mounted on the UTM with appropriate fixtures to ensure proper alignment and load transfer. Boundary conditions similar to those used in the FEA model were maintained as closely as possible. A gradually increasing compressive load was applied until the desired load limit or failure condition was reached. During the test, parameters such as applied load and corresponding deformation were recorded continuously. These results were used to generate load–displacement curves, which were further analyzed to evaluate the stiffness and structural performance of the reinforced component.

Fig. Specimen under compression testing on the UTM.

Testing Graph:

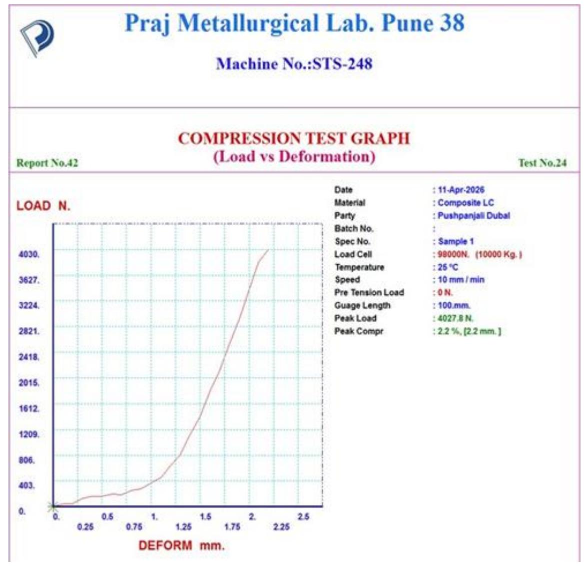


Fig. Compression Test Graph of the GFR LCA.

The above graph shows the load vs deformation of the GFR LCA. The X-axis shows deformation and the Y-axis shows the Load.

XI. CONCLUSION

This study successfully demonstrated the design and optimization of a lower control arm using glass fiber composite reinforcement to enhance structural performance and reduce deformation.

The Finite Element Analysis (FEA) results revealed that the conventional mild steel control arm exhibited excessive deformation, stress, and strain under applied loading conditions, indicating the need for structural improvement. The introduction of glass fiber reinforcement in critical regions led to a significant reduction in deformation, stress, and strain, thereby improving stiffness and load-bearing capacity.

The optimized design was fabricated using a resin-based composite layup process, and experimental validation was carried out using a Universal Testing Machine (UTM) under compression loading.

The experimental results showed good agreement with the FEA predictions, confirming the accuracy and reliability of the numerical analysis. This correlation validates the effectiveness of the proposed reinforcement approach and the overall design methodology. In conclusion, the incorporation of glass fiber composite reinforcement provides a practical, cost-effective, and efficient solution for improving the performance of automotive suspension components. The study highlights the potential of hybrid material design in achieving lightweight and structurally robust components without complete material replacement.

The findings contribute to the advancement of composite applications in automotive engineering and provide a foundation for further research in durability, fatigue performance, and large-scale implementation.

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