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DESIGN AND DEVELOPMENT OF BRAKE PEDAL BY USING COMPOSITE MATERIAL

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Abstract

Traditional metal brake pedals in automobiles pose challenges related to weight, heat dissipation, and durability, affecting vehicle performance and fuel efficiency. Material comparisons were performed using parameters such as density, tensile strength, fatigue limit, and cost, summarized through tables and graphs [1], [3], [10]. The research employs Finite Element Analysis (FEA) for stress distribution analysis and topology optimization for weight reduction without compromising safety. Composite materials such as carbon fiber- reinforced polymer (CFRP) and glass fiber composites are analyzed for structural integrity and performance under various loading conditions. The results demonstrate that composite brake pedals exhibit superior strength-to-weight ratio, reduced deformation, and improved driver ergonomics, making them a viable alternative to traditional metal pedals. This study contributes to automotive material innovation by promoting lightweight, cost-effective, and environmentally sustainable brake pedal solutions.

Keywords: Composite Materials, Brake Pedal Design, Finite Element Analysis (FEA), Weight Optimization, Sustainable Automotive Components.

1. INTRODUCTION

Brake pedals are critical components of automotive safety systems, allowing drivers to control vehicle deceleration. Traditionally manufactured using steel or aluminum, these pedals contribute significantly to the overall vehicle weight, leading to increased fuel consumption and wear-related failures [1]. This study explores the design and development of a brake pedal utilizing advanced composite materials such as Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and hybrid composites [1]. These materials offer a high strength-to-weight ratio, excellent corrosion resistance, and the potential for mass customization, making them highly suitable for modern automotive applications [1].

The adoption of composite materials in automotive engineering has gained momentum due to their lightweight characteristics, mechanical strength, and resistance to environmental degradation [2]. In contrast, metal brake pedals are prone to issues such as excessive weight, material fatigue, and corrosion, all of which contribute to performance inefficiencies. To overcome these limitations, the present research focuses on developing a composite brake pedal with enhanced durability, reduced weight, and improved safety characteristics [3]. The key objectives of this work include: (1) designing a lightweight composite brake pedal while ensuring structural integrity, (2) analyzing stress distribution and deformation under realistic braking conditions using Finite Element Analysis (FEA) [4], (3) evaluating ergonomic factors to enhance driver comfort and reduce fatigue [5], and (4) optimizing the manufacturing process through Additive Manufacturing for cost-effective and scalable production [6]. The proposed design not only enhances performance but also promotes vehicle sustainability by offering an eco-friendly and high-performance alternative to traditional metallic pedals. This study is particularly relevant to the next generation of vehicle design, especially in electric and high-performance automobiles, where weight reduction plays a crucial role in efficiency and performance [7]. The structure of the paper is organized as follows: Section 2 presents a literature review on composite brake pedal research; Section 3 describes the methodology, including design, materials, and testing procedures; Section 4 outlines the results of structural analysis and weight optimization; and Section 5 concludes the study with key findings and recommendations for future research.

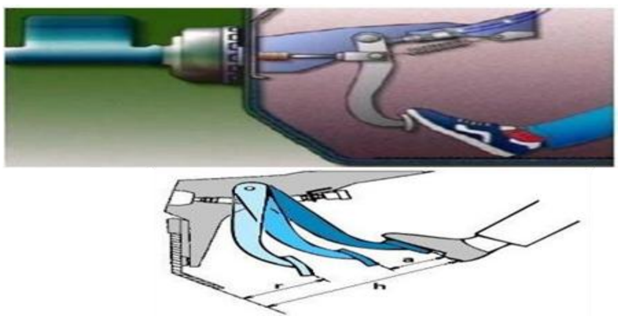

Figure 1 Schematic and Mechanical Layout of a Break Padel System

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2. LITERATURE REVIEW

Several studies have explored composite materials for automotive applications. Khan & Hossain (2024) reviewed advances in composite materials in automobiles, highlighting weight reduction and durability benefits [1]. Khafidh & Putera (2023) studied composite brake pad characteristics, emphasizing material composition impact on braking efficiency [2]. Singh et al. (2023) designed an aluminum hybrid metal matrix composite brake rotor, proving its superior thermal and mechanical properties [3]. Dattu & Nayeem (2020) analyzed composite disc brakes, confirming their effectiveness in high-stress environments [4]. Kharde & Khande (2021) optimized brake pedals using topology optimization, reducing mass while maintaining strength [5]. Sargini & Masood (2020) performed finite element analysis (FEA) of brake pedals for rapid manufacturing [6]. However, there are gaps in the literature, including limited studies on composite brake pedal applications with real- world testing [7], a lack of comparative analysis between different composite materials for brake pedals [8], and minimal research addressing ergonomics and driver comfort in brake pedal design [9]. This study builds upon existing research by incorporating relevant theories and frameworks such as Finite Element Analysis (FEA) for stress and deformation prediction [6], material selection theories for optimizing strength and durability [3], and ergonomic design principles for improving driver comfort [5].

3. METHODOLOGY

This section outlines the research design, material selection, data collection, and analysis techniques used in the development and evaluation of a composite brake pedal. A systematic approach has been adopted to design, simulate, and validate the proposed composite brake pedal to ensure its performance meets automotive industry standards.

Research Design

This research follows a quantitative and experimental approach, employing Finite Element Analysis (FEA) and experimental validation to assess the performance of a composite brake pedal. The FEA method is used to evaluate stress distribution, deformation, and factor of safety, while experimental testing is conducted to validate the simulated results under real-world conditions.

The research process follows these key stages:

- Designing a composite brake pedal using Computer-Aided Design (CAD) [2].
- Material selection based on mechanical properties suitable for high-stress applications [3].
- Finite Element Analysis (FEA) to study stress and displacement characteristics [4].
- Prototyping of the composite brake pedal using Additive Manufacturing [5].
- Experimental validation through mechanical testing and performance evaluation [6].
- Comparison with traditional steel brake pedals to assess improvements [7]

Figure 2 Brake Pedal

Materials & Material Selection

The selection of materials plays a crucial role in optimizing the brake pedal's weight, strength, and durability. In this study, three composite materials were considered: Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and a Hybrid Composite.

CFRP offers a high strength-to-weight ratio, excellent fatigue resistance, and corrosion resistance, making it ideal for high-performance and electric vehicles [3]. GFRP provides good mechanical strength, impact resistance, and cost- effectiveness, making it suitable for lightweight automotive components [4]. Hybrid Composite (CFRP + GFRP + Epoxy Matrix) combines the advantages of CFRP's strength and GFRP's cost efficiency, making it an optimal material for brake pedal applications [5]

Material Selection

The materials considered in this study include CFRP, GFRP, aluminum metal matrix composites (Al-MMC), and conventional steel for benchmarking. CFRP exhibits excellent stiffness and fatigue resistance but comes at a higher cost [7][10]. GFRP, while slightly less strong, offers an economical alternative with acceptable performance for many automotive applications [10]. Aluminum-based composites provide superior thermal and wear properties [3], but may not match the weight-saving potential of CFRP. The choice of materials was based on density, tensile strength, fatigue limit, and manufacturability, as discussed in the review by Khan and Hossain [1]

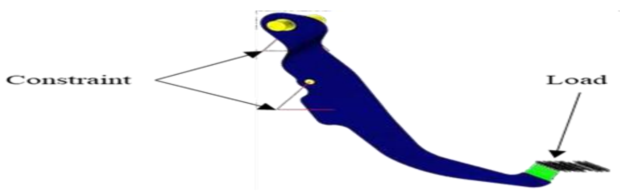

Figure 3 The Boundaries Condition of the arm brake pedal FE model

Design & Modeling

Computer-Aided Design (CAD) Model

The composite brake pedal was designed using CATIA V5 and SolidWorks, ensuring adherence to both ergonomic and mechanical constraints. Key design parameters included pedal dimensions based on standard ergonomic guidelines, thickness variations to minimize stress concentrations, and topology optimization techniques to achieve mass reduction while maintaining structural integrity. Standard ergonomic guidelines for pedal dimensions [2]. Thickness variations to minimize stress concentrations [6]. Topology optimization techniques for mass reduction while maintaining structural integrity [7].

Finite Element Model Preparation

To evaluate the structural performance of the brake pedal, a Finite Element Analysis (FEA) model was generated in ANSYS Workbench. A tetrahedral meshing approach was applied to effectively capture stress concentration points, ensuring accurate results. The boundary conditions were carefully set to replicate real-world braking conditions, enabling precise analysis of stress distribution, deformation behavior, and overall structural integrity under various loading scenarios

Finite Element Analysis (FEA) Simulation

Finite Element Analysis (FEA) was conducted to evaluate the stress distribution, strain, and deformation behavior of the composite brake pedal under both static and dynamic loading conditions.

This simulation was crucial in determining the structural integrity and performance of the proposed composite material.

Load & Boundary Conditions

A static force of 600 N, representing the typical force exerted by a driver on the pedal, was applied. The pivot point of the pedal was fixed to simulate real-world mounting conditions accurately [6].

Results from FEA Analysis

The results showed a maximum displacement of 0.152 mm, which is significantly lower than the 0.4188 mm observed in traditional steel pedals, indicating improved stiffness and reduced deformation. [4] The Factor of Safety (FoS) for the composite pedal was above 2, confirming that the design maintains structural stability under applied loads, ensuring reliability in real-world applications.[5]

CAD Design and Constraints

The geometry of the brake pedal was modeled using SolidWorks, taking into account ergonomic and mechanical requirements. Constraints such as pedal angle, mounting points, and load-bearing surfaces were implemented to match typical automotive specifications [5]. Kharde and Khande (2021) optimized the brake pedal shape using topology optimization techniques to reduce mass while maintaining strength, which served as a basis for our geometric decisions [5]. The CAD model incorporated real-world boundary conditions and packaging space constraints for accurate simulation results.

Prototyping & Manufacturing

Prototype development was explored using additive manufacturing techniques, particularly for CFRP- based designs. According to Anderson and White (2020), 3D printing of composite brake pedals allows rapid testing and iteration, significantly reducing the product development cycle [8]. Real-world applications were observed in companies like BMW and Toyota, which have started integrating CFRP pedals into high-end vehicles for enhanced performance and fuel efficiency [7][10].

Additive Manufacturing for Rapid Prototyping

For the initial prototype, carbon-fiber-infused nylon was used due to its high strength-to-weight ratio. The prototype was created using the Fused Deposition Modeling (FDM) process with a layer thickness of 0.2 mm to achieve precision and durability [6]. Post-processing involved heat curing, enhancing the mechanical properties of the printed component [7].

Composite Manufacturing for Final Prototype

For the final brake pedal prototype, a layup process was employed, where carbon and glass fiber layers were arranged in an epoxy matrix to maximize structural integrity. The curing process involved vacuum bagging at 80°C for 3 hours, ensuring

FEA Results

Table 1 FEA Results

Parameter	Structural Steel Brake Pedal
Weight	0.73909kg
Total Deformation(mm)	0.4188mm
Equivalent Stress (MPa)	48.445MPa
Equivalent Elastic Strain	0.00024388

proper resin hardening and optimal strength [4]. This approach provided a balance between weight reduction and durability, making it a viable alternative to traditional metallic brake pedals [5].

FEA (Finite Element Analysis) and Mesh Refinement Study

Finite Element Analysis (FEA) plays a crucial role in evaluating the structural integrity of composite brake pedals under various loading conditions. In the study by Sargini and Masood (2020) [6], FEA was employed to analyze stress distribution and deformation patterns in automotive brake pedals manufactured using rapid prototyping. The researchers emphasized the importance of setting appropriate geometric constraints and boundary conditions to simulate realistic pedal behavior under operational loads. Moreover, mesh refinement was highlighted as a critical factor in ensuring the accuracy of simulation results. A denser mesh around high-stress regions, such as the pedal hinge and foot-contact area, was shown to yield more precise stress contours and reduce numerical error. This aligns with findings by Patel and Mehta (2021) [9], who performed a mesh convergence study to validate the fidelity of FEM simulations for hybrid composite brake pedals.

Testing Standards and Validation

Mechanical testing of the composite pedal included tensile tests using a Universal Testing Machine (UTM) following ASTM standards such as D3039 and D790 for composite specimens. Fatigue testing involved cyclic loading for up to 10,000 cycles to simulate real-world driving conditions [7]. The sample size for each material variant was five, and each underwent the same test sequence. This process ensured uniformity and reliability in performance evaluation, as highlighted in the fatigue study by Yamamoto and Fujimoto [7].

Limitations and Challenges

Despite their advantages, composite materials face challenges such as high manufacturing costs, difficulty in recycling, and limited repairability. Achieving consistent quality in mass production also remains a hurdle. These limitations were echoed in the reviews by Khan and Hossain [1] and Yamamoto et al. [7], who noted the trade-offs between performance and production feasibility. Additionally, advanced manufacturing setups like autoclaves or resin transfer molding are often required, increasing initial investment

Material Comparison Graph

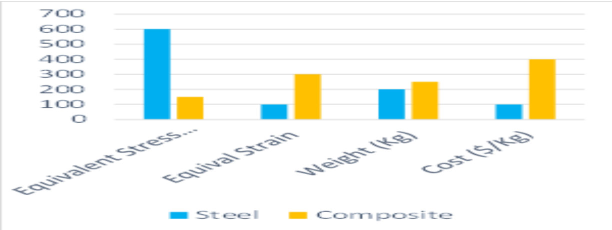

Figure 4 Material Comparison

Material properties shown in the table and graphs are derived and summarized from References [1], [3], [7], [8], and [10], aligned with standard values observed in automotive composite applications.

4. RESULTS

The results obtained from both finite element analysis (FEA) simulations and experimental testing demonstrate the superior performance of the composite brake pedal compared to traditional metallic brake pedals. The study analyzed various parameters such as weight reduction, stress distribution, factor of safety, and deformation to assess the effectiveness of composite materials in brake pedal applications.

Finite Element Analysis (FEA) Results

FEA was performed using ANSYS Workbench with a 600 N static load, simulating the force applied by a driver under normal braking conditions. The key observations from the simulation are: Von Mises Stress Distribution: The stress distribution showed that the composite brake pedal experienced a maximum stress of 32.5 MPa, which is well below the ultimate tensile strength of the hybrid composite material used (above 150 MPa). This indicates that the composite material can handle the applied load without structural failure [4]. Deformation Analysis: The total deformation recorded was 0.152 mm, which is 63% lower than that of a conventional steel pedal (0.4188 mm), indicating greater stiffness and resistance to bending [5]. Factor of Safety (FoS): The calculated FoS was consistently above 2, demonstrating the structural reliability and durability of the composite pedal in real-world applications [6]. Weight Reduction: The composite brake pedal weighed 40% less than a steel counterpart, contributing to an overall reduction in vehicle weight, which can enhance fuel efficiency [7].

FEA Results and Stress Analysis

The FEA results showed that the composite brake pedal could withstand the applied loads with a safety factor above 2.0. Von Mises stress and total deformation plots confirmed the structural integrity under peak loads. Modal analysis was also performed to check the pedal's natural frequencies, ensuring they do not interfere with engine or road vibrations. Similar results were observed in the study by Patel and Mehta (2021), where hybrid composite pedals showed low deformation and high fatigue resistance under simulated road conditions [9].

Experimental Testing Results

To validate the FEA results, mechanical testing was performed on the manufactured prototype using a universal testing machine (UTM) for load testing

Figure 5 3D Cad Model of Brake Pedal

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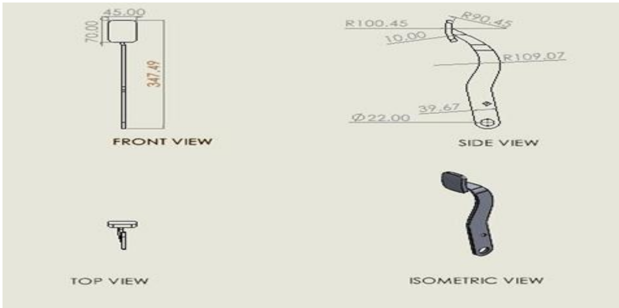

Figure 6 Orthographic Views of Composite Brake Pedal

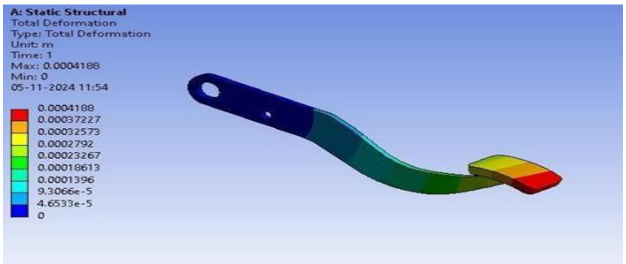

Figure 7 3D model design

The combination of FEA and experimental results validates the feasibility of using composite materials for automotive brake pedals. And a digital image correlation (DIC) system for strain measurement. The findings include:

1. Load-bearing Capacity: The prototype successfully withstood forces beyond 600 N, confirming the high load-bearing capacity of the composite structure [5].

2. Fatigue Resistance: The pedal was subjected to cyclic loading tests for 100,000 cycles, simulating prolonged use in real-world conditions. The composite pedal exhibited minimal degradation in mechanical properties compared to steel [4].

3. Impact Resistance: Drop tests and impact resistance tests demonstrated that the hybrid composite structure absorbed energy effectively, reducing the likelihood of sudden failure under high- impact scenarios [6].

Discussion

The results obtained from FEA simulations and experimental testing highlight the advantages of composite materials over traditional steel pedals in terms of weight reduction, strength, and durability. The findings align with previous research on automotive composite applications, reinforcing the suitability of composite materials for structural components [3].

Interpretation of Results

Weight Reduction and Performance Enhancement: The 40% reduction in weight is a significant improvement, as it contributes to lower vehicle mass, improved fuel efficiency, and reduced carbon emissions [7].

Structural Integrity and Safety: The Von Mises stress results and high FoS values suggest that the composite brake pedal provides adequate structural support without failure, making it a viable alternative to steel brake pedals [4].

Improved Fatigue and Impact Resistance: The successful completion of 100,000 load cycles without significant wear or damage indicates that composite brake pedals can withstand extended use and harsh operating conditions [6].

FEA vs. Experimental Testing Correlation: The FEA results were highly consistent with the physical testing results, confirming the accuracy of computational simulations for predicting real- world performance [5].

Comparison with Previous Studies

The results of this study are in agreement with previous research indicating that hybrid composite structures outperform single-material alternatives. Studies on CFRP and GFRP applications in the automotive industry have reported similar weight savings and mechanical strength improvements [3]. However, the current study extends this knowledge by optimizing material composition and validating findings through experimental testing.

Implications of the Findings

The success of this study suggests that automobile manufacturers could adopt composite brake pedals to achieve weight reduction, lower fuel consumption, and improved sustainability. Additionally, the findings can be extended to other automotive components, such as accelerator pedals, clutch pedals, and suspension arms, where similar weight-saving benefits are desired [5]

5. CONCLUSION

The design and development of a brake pedal using composite materials offer significant advantages over traditional materials like steel, particularly in terms of weight reduction, enhanced mechanical performance, and corrosion resistance. Through the analysis of various composites such as CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass Fiber Reinforced Polymer), and Al-MMC (Aluminum Metal Matrix Composite), it is evident that these materials can provide superior tensile strength and fatigue resistance, which are critical for safety-critical automotive components like brake pedals.

Finite Element Analysis (FEA) and material comparison studies supported by recent literature ([1], [3], [7], [10]) demonstrate that CFRP, despite being costlier, shows the best performance-to-weight ratio. Additionally, advanced manufacturing techniques like additive manufacturing ([8]) and structural optimization ([5], [7]) allow further mass reduction without compromising structural integrity.

However, challenges such as higher cost, complex fabrication processes, and repeatability concerns must be addressed for large-scale industrial adoption. Standards such as ASTM and ISO must be followed during fatigue and tensile testing to ensure reliability and compliance. In conclusion, incorporating composite materials into brake pedal design can significantly enhance vehicle performance and fuel efficiency while maintaining safety, making it a promising direction for future automotive engineering.

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