Structural and Performance Optimization of Universal Brackets for Electric Vehicle

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***Abstract*—Electric vehicles (EVs) are subjected to high torque and rapidly changing load conditions, which place significant demands on drivetrain components. Conventional universal brackets made from structural steel increase overall vehicle weight and tend to develop high stress concentrations near geometric discontinuities such as slots and holes. Since reducing weight directly improves vehicle efficiency and driving range, there is a need for lightweight materials and optimized designs. This study evaluates the replacement of steel brackets with a Titanium alloy reinforced with silicon carbide (SiC) metal matrix composite. Finite Element Analysis (FEA) is used to analyze stress distribution and deformation behavior, followed by experimental validation through tensile testing. The findings show improved strength-to-weight ratio, enhanced fatigue life, and superior corrosion resistance. The proposed composite bracket demonstrates better structural performance and durability, making it suitable for advanced EV applications.**

***Index Terms*—Electric Vehicle, Universal Bracket, Metal Matrix Composite, Finite Element Analysis, Stress Concentration.**

I. INTRODUCTION

The shift toward sustainable mobility has accelerated the adoption of electric vehicles. Environmental concerns, strict emission regulations, and advancements in battery technology have significantly influenced modern vehicle design. Unlike conventional internal combustion engine vehicles, electric vehicles deliver torque almost instantly, which results in higher stress levels in mechanical components. In traditional systems, torque fluctuations are partially absorbed due to engine dynamics. However, in EVs, torque is directly transmitted, especially during rapid acceleration and regenerative braking. This leads to increased cyclic loading on components such as brackets and supports. Therefore, these components must possess high stiffness, fatigue strength, and dimensional stability. The universal bracket is an important component that maintains alignment between rotating shafts and supports torque transmission under angular motion. It is subjected to bending, shear, and localized stresses, particularly near features like holes and slots. Failure of this component can result in vibration, misalignment, or system malfunction.

Structural steel is commonly used due to its availability and ease of manufacturing. However, it adds significant weight to the system. In EVs, even small reductions in weight can improve efficiency and driving range. Hence, lightweight design is a key objective. Stress concentration is another critical issue. Features such as holes and sharp edges cause localized stress increases, which may initiate cracks under repeated loading. Therefore, both material selection and geometric optimization are essential. Composite materials provide a promising solution due to their high strength-to-weight ratio and improved mechanical properties. Metal Matrix Composites (MMCs), in particular, offer better stiffness, wear resistance, and thermal stability. Titanium alloys reinforced with silicon carbide particles combine corrosion resistance with high strength and stiffness.

Modern simulation tools such as Finite Element Analysis help predict stress behavior and identify critical regions before manufacturing. This study focuses on optimizing a universal bracket by replacing steel with a Titanium–SiC composite and validating the results through analysis and experimentation.

II. FUNDAMENTALS OF COMPOSITE MATERIALS

2.1 Advantages of Composite Materials

Composite materials are widely used in structural applications due to their superior strength and stiffness relative to weight. The combination of reinforcement and matrix improves load distribution and overall mechanical performance [1]. In automotive applications, composites reduce weight, leading to improved efficiency. They also exhibit better fatigue resistance by delaying crack initiation and propagation [2]. Additionally, composites offer improved corrosion resistance and reduced vibration transmission compared to conventional materials.

2.2 Classification of Composite Materials

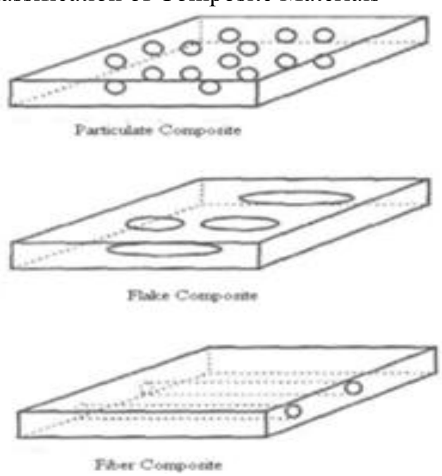

Fig 1. Side broom working and significance

Composites are classified based on reinforcement type:

- Particulate composites contain randomly distributed particles and exhibit nearly isotropic behavior.
- Flake composites use flat reinforcements to enhance bending stiffness.
- Fiber-reinforced composites consist of fibers embedded in a matrix, allowing tailored directional properties [4].

III. MATERIAL SELECTION

3.1 Matrix Material

Titanium alloy Ti–6Al–4V is selected as the matrix material due to its superior strength-to-weight ratio and excellent fatigue resistance under cyclic loading conditions. Compared to conventional structural steel, titanium alloys possess significantly lower density while maintaining high tensile strength, which makes them highly suitable for lightweight structural components. In electric vehicle drivetrain applications, where repetitive torque transmission and dynamic loading occur, reduced mass combined with high mechanical strength is essential for improving structural efficiency and operational reliability [5].

In addition to its mechanical advantages, Ti–6Al–4V exhibits outstanding corrosion resistance in aggressive environmental conditions. This property enhances the durability of components exposed to moisture, road salts, and varying atmospheric conditions. The alloy also demonstrates good thermal stability and maintains mechanical integrity over a wide temperature range, which is beneficial in automotive systems subjected to frictional heating and fluctuating operating temperatures. Considering these properties, Ti–6Al–4V provides an optimal balance between strength, weight reduction, corrosion resistance, and durability, making it an appropriate choice for the matrix phase in the proposed composite universal bracket design.

Table 1. Titanium Alloy Thermal and Mechanical properties [5]

Property	Titanium Alloy
Density (kg/m^3)	4430
Young's Modulus (MPa)	1.1e+05
Poisson's Ratio	0.34
Tensile Ultimate Strength (MPa)	1100
Bulk Modulus (MPa)	1.12e+04
Shear Modulus (MPa)	4.43e+04

3.2 Reinforcement Material

Silicon carbide (SiC) particles with an average size of 90 µm are chosen as secondary reinforcement to enhance hardness, wear resistance, and stiffness while maintaining cost efficiency. SiC exhibits excellent thermal conductivity, high elastic modulus, and superior compressive strength, making it one of the most widely used reinforcements in titanium-based composites.[6]

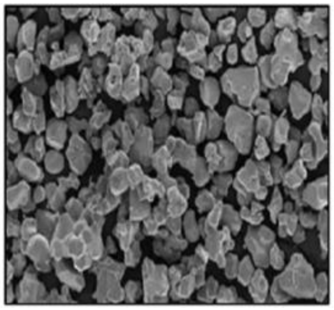

Fig 2. SEM images of SiC

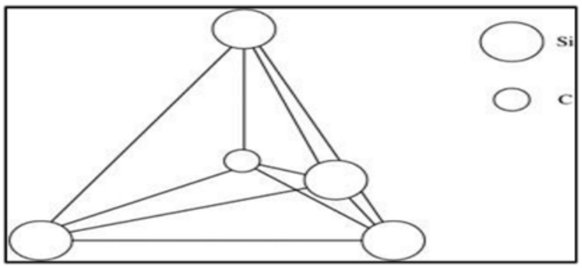

Fig 3. Molecular Structure of the SiC

3.3 Comparison of Structural Steel and Titanium Alloy–SiC Composite

The existing universal bracket is manufactured using structural steel, which provides adequate strength but contributes significantly to overall weight. To evaluate performance improvement, the proposed Titanium Alloy–SiC composite is compared with structural steel and unreinforced titanium alloy.The composite system offers nearly 40–45% reduction in density compared to steel while achieving higher tensile strength and improved stiffness. The addition of SiC particles enhances fatigue performance and wear resistance, making the material suitable for cyclic loading conditions. Unlike structural steel, the composite exhibits superior corrosion resistance, reducing the requirement for protective coatings or surface treatments [5].

From a structural perspective, the presence of reinforcement improves stress distribution near geometric discontinuities such as slotted holes. Effective load sharing between matrix and reinforcement lowers localized stress intensity, thereby reducing deformation and delaying crack initiation under dynamic loading. These characteristics make the Titanium Alloy–SiC composite a technically superior alternative for lightweight drivetrain components in electric vehicles.

Table 2. Comparison of Material Properties [6]

Property	Structural Steel (Existing Bracket)	Titanium Alloy (Matrix Material)	Ti-Alloy + SiC Composite (Proposed Material)
Density (kg/m³)	7850	4430	4300–4500
Young's Modulus (GPa)	200–210	110	120–150
Ultimate Tensile Strength (MPa)	400–550	1100	1200–1500
Shear Modulus (GPa)	79	44	50–65
Fatigue Strength	Moderate	High	Very High
Thermal Conductivity (W/m·K)	~50	7	20–30
Corrosion Resistance	Low	Excellent	Excellent
Wear Resistance	Moderate	High	Very High
Strength-to-Weight Ratio	Poor	Good	Excellent

3.4 Dimension of Universal Bracket

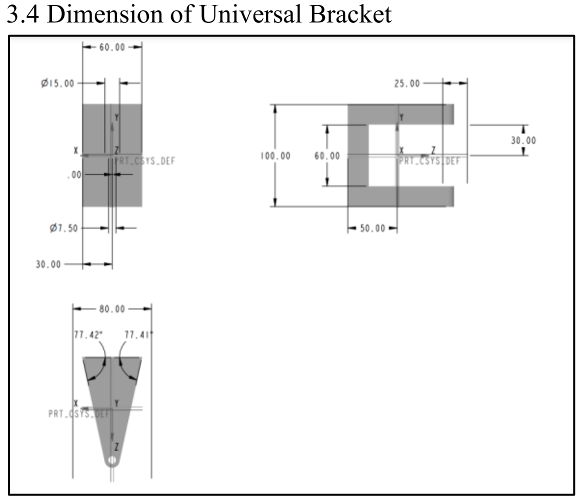

Figure: 4. Dimension of Motor bracket

IV. METHODOLOGY

The research follows a systematic approach combining Computer-Aided Design (CAD), Finite Element Analysis (FEA), and Experimental Validation using a Universal Testing Machine (UTM).

3.1 Design and Material Selection

The study focuses on a Universal Bracket used for e-vehicle battery support. Two materials—Structural Steel and Titanium Alloy (Ti-3Al-2.5V)—were selected to evaluate the potential for weight reduction and structural efficiency. The 3D geometry was modeled in CATIA and exported for numerical analysis.

3.2 Finite Element Modeling (FEA)

Numerical simulations were performed in ANSYS to predict structural behavior under load.

Discretization: The model was discretized using SHELL63 elements, chosen for their membrane and bending capabilities.

Boundary Conditions: Fixed constraints were applied to the internal surfaces of the mounting holes to simulate rigid attachment.

Loading: A tangential force of 5000 N was applied as a worst-case scenario.

Analysis: Static structural analysis was conducted to determine Total Deformation and Von-Mises Stress distribution.

3.3 Experimental Validation

To verify the accuracy of the FEA model, physical specimens were tested:

Specimen Preparation: Dog-bone samples were fabricated according to ASTM E8/E8M standards.

UTM Testing: Tests were conducted on a Unitech-Instron 4001 series machine.

Data Collection: Real-time values for load vs. deformation and load vs. stress were recorded for both materials.

3.4 Correlation and Error Analysis

The final step involved a quantitative comparison between the FEA results and the experimental data. The percentage error was calculated to establish the reliability of the computational model, ensuring the simulation accurately represents physical performance within an acceptable engineering margin (under 5%).

V. EXPERIMENTATION

The tensile strength. of the samples was determined using an automated Unitech-.Instronp 4001 series ISO .7500-1 standard UTM machine. To begin with, specimens were made in the shape of dog bones in accordance with the ASTM E8/E8M standard. To remove dirt and dust, emery sheets with a 900 grid were used to wipe the samples' surfaces. By using a progressive load of 1.5 N, the test's primary goal is to compare the yield, elongation, and ultimate strengths of pure and composite materials. Three samples were prepared for each configuration, and the outcomes were provided for the discussion. The dimensions of the samples used for the investigation are shown in Figures 6.1, along with a photograph of the tensile machine.

5.1 Experimental Validation

A specimen of Titanium Alloy (Ti-3Al-2.5V) material is made for UTM test. Density & Modulus of elasticity of that material is determined by these tests to use these values in FEM analysis. FEM results are validated experimentally using UTM. Following steps are followed for experimental validation.

- ✓ Arrangement of setup is done on UTM.
- ✓ Selections of location of deflection measurement.
- ✓ Deflection measurement at predefined loading conditions.
- ✓ Comparison of loading/deflection values obtained from FEM analysis and those from experimentation with UTM for sample glass fiber rod.
- ✓ Comparison of stresses Values obtained from FEM analysis for Titanium Alloy (Ti-3Al-2.5V) sample and experimentation.

5.2 Observation

5.2.1 Experimental Deformation and Stress analysis of Universal Bracket (Structural Steel):

Table: 3 : Loading / deformation experimentation of Structural Steel Universal Bracket at UTM.

SN	LOAD (N)	Deformation (mm)
1	50	0.0015
2	100	0.0110
3	150	0.0153
4	200	0.0185

5	250	0.0210
6	300	0.0255
7	350	0.0287
8	400	0.0325
9	450	0.0395
10	500	0.0412

5.2.2 Experimental Deformation and Stress analysis of Universal Bracket (Titanium alloy Ti-3Al-2.5V):

Table: 4: Loading / deformation experimentation of Titanium alloy Ti-3Al-2.5V Universal Bracket at UTM.

SN	LOAD (N)	Deformation (mm)
1	50	0.0015
2	100	0.0061
3	150	0.0128
4	200	0.0170
5	250	0.0195
6	300	0.0225
7	350	0.0281
8	400	0.0298
9	450	0.0320
10	500	0.0385

VI. CONCLUSION

The comparative study is performed with the e vehicle Universal bracket model for battery pack load support and has reached at the following conclusion:

- ✓ The Deformation in modified Universal bracket (Ti-3Al-2.5V) is minimum i.e 0.0385mm found lesser than structural steel bracket which is 0.0412 mm.
- ✓ The Von-Mises stress in modified Universal bracket (Ti-3Al-2.5V) is minimum i.e. 247Mpa, found almost near to structural steel bracket which is 254 Mpa.
- ✓ The comparison between titanium alloy (Ti-3Al-2.5V) and structural steel highlights a significant advantage in weight reduction with the use of titanium alloy. The titanium alloy bracket is approximately 19% lighter than its counterpart made from structural steel. This difference in weight directly translates to a superior weight-to-strength ratio for titanium alloy components.
- ✓ Thus, modified design of Universal bracket most suitable and feasible for the current application from strength to weight ratio, design and manufacturing perspective.

Table 3. FEA & Experimental Results Summary

Test	FEA Results	Experimental Results	% Error
Deformation (mm) Ti-3Al-2.5V	0.0405	0.0385	4.93%
Deformation (mm) Structural Steel	0.0431	0.0412	4.40%
Von Mises Stress (Mpa) Ti-3Al-2.5V	255	247	3.13%
Von Mises Stress (Mpa) Structural Steel	261	254	2.29%

VII. FUTURE SCOPE

With continuous advancements in manufacturing technologies, especially in precision machining and additive manufacturing, there is significant potential to explore alternative geometric configurations for structural components. Most existing research on brackets and plates with cutouts primarily focuses on conventional geometries such as circular, rectangular, or triangular openings. However, these standard shapes may not always provide optimal stress distribution or weight reduction. The development of advanced fabrication methods, including 3D printing and hybrid manufacturing techniques, now allows the production of complex and non-conventional cutout geometries that were previously difficult to manufacture. This opens opportunities to investigate customized cutout designs aimed at minimizing stress concentration while maintaining structural integrity. Irregular or topology-optimized shapes can be studied to further enhance mechanical performance and material efficiency.

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