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RESEARCH ARTICLE

Topology Optimization and Development of Biodegradable ABACA Polymer Composite Leaf-Spring for Electric Vehicles

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ABSTRACT:

This research focuses on the topology optimization and development of a bio-degradable ABACA polymer composite leaf-spring for electric vehicles, aiming to enhance performance while promoting sustainability. The study integrates advanced computational techniques and material science principles to design an optimized, lightweight, and structurally efficient leaf-spring. To achieve optimal design efficiency, topology optimization techniques are employed using a gradient-based algorithm that iteratively removes unnecessary material while maintaining structural integrity. The optimization framework defines the design domain, objective function, and constraints to ensure minimal weight and maximum stiffness. The study then transitions to computational simulations, leveraging Simscale's cloud-based platform to conduct stress analysis, vibration analysis, and deformation evaluations under real-world loading conditions. The material selection process centers around ABACA polymer composites, known for their high strength-to-weight ratio and biodegradability. The formulation and manufacturing procedures integrate polymer infusion and layering techniques to develop a robust composite structure.

KEYWORDS: Topology Optimization, Bio-Degradable ABACA Polymer Composite, Computational Techniques, Material Science Principles

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1. INTRODUCTION

The global transition toward sustainable transportation has accelerated the development of lightweight automotive components capable of improving the energy efficiency and driving range of electric vehicles (EVs). Unlike conventional internal combustion engine vehicles, the performance of electric vehicles is strongly influenced by overall vehicle mass because battery energy density remains relatively limited. Consequently, lightweight structural components have become a major research priority for improving vehicle efficiency, reducing energy consumption, and increasing battery range.[1–3]

Leaf springs are among the most important suspension components used in commercial vehicles because they support vehicle weight, absorb road shocks, and maintain ride comfort. Conventional steel leaf springs possess excellent mechanical strength but contribute significantly to vehicle mass. Studies have shown that suspension components account for a considerable proportion of the unsprung weight, directly affecting vehicle dynamics, energy

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efficiency, and passenger comfort. Replacing steel leaf springs with lightweight composite materials has therefore become an attractive solution for modern automotive engineering.[4–6]

Fiber-reinforced polymer composites have gained considerable attention because of their high specific strength, excellent fatigue resistance, corrosion resistance, and superior vibration damping characteristics. Among various natural fibers, **Abaca (Musa textilis)** has emerged as one of the strongest lignocellulosic fibers owing to its high cellulose content, low density, excellent tensile strength, and biodegradability. Abaca fibers possess tensile strengths ranging from 400 to 980 MPa while maintaining densities considerably lower than conventional engineering metals, making them highly suitable for lightweight automotive structures.[7–9]

Natural fiber composites offer several advantages over synthetic fiber composites, including lower environmental impact, reduced manufacturing energy, renewability, and easier disposal after service life. Their biodegradability aligns well with circular economy principles and global sustainability initiatives aimed at reducing carbon emissions and plastic waste. Consequently, numerous researchers have investigated natural fibers such as jute, flax, hemp, sisal, bamboo, and abaca for structural automotive applications.[10]

Despite these advantages, natural fiber composites exhibit relatively lower stiffness than metallic materials, making structural optimization essential for maximizing mechanical performance. Topology optimization has become one of the most powerful computational design techniques for developing lightweight structures by distributing material only where it contributes effectively to load-bearing capability. The method systematically removes unnecessary material while maintaining structural integrity and prescribed stiffness requirements.[11],[12]

Among various optimization techniques, the **Solid Isotropic Material with Penalization (SIMP)** approach has become the most widely adopted because of its computational efficiency and ease of implementation. SIMP-based topology optimization employs gradient-based mathematical algorithms to determine optimal material distribution within a predefined design domain while satisfying stress, displacement, volume, and manufacturing constraints.[13] Recent advances in computational power and cloud computing have enabled large-scale topology optimization for automotive, aerospace, biomedical, and civil engineering applications.

Finite Element Analysis (FEA) plays an equally important role in validating optimized structures before physical manufacturing. Static structural analysis predicts stress distribution, deformation, and safety factors under service loads, whereas modal analysis evaluates natural frequencies and vibration characteristics that directly influence ride comfort and structural durability. Integration of topology optimization with finite element simulations substantially reduces development time, material consumption, and manufacturing cost.[14]

Cloud-based engineering platforms such as SimScale have further transformed engineering design by enabling high-performance finite element simulations without expensive computational infrastructure. Engineers can perform structural analysis, modal analysis, thermal simulations, and topology optimization remotely while facilitating collaborative product development.[15]

The present study focuses on the topology optimization and development of a biodegradable Abaca fiber reinforced polymer composite leaf spring for electric vehicles. Gradient-based topology optimization is employed to minimize structural weight while preserving stiffness and load-carrying capacity. The optimized design is subsequently evaluated through finite element simulations considering stress distribution, deformation, and vibration characteristics. The proposed biodegradable composite leaf spring aims to provide a sustainable alternative to conventional steel suspension systems by combining lightweight design, improved energy efficiency, and environmental sustainability.

2. MATERIALS AND METHODS

2.1. Material Selection

The material selected for this investigation was a biodegradable **Abaca fiber reinforced polymer composite**, owing to its excellent strength-to-weight ratio, renewability, corrosion resistance, and superior

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vibration damping characteristics. Abaca fibers possess high cellulose content (approximately 60–65%), low density (~1.5 g/cm³), and tensile strength ranging from 400–980 MPa, making them suitable for automotive suspension applications. An epoxy-based biodegradable polymer matrix was considered to ensure adequate fiber–matrix adhesion and structural integrity under static and dynamic loading conditions.[16]

The principal material properties used in the finite element simulations are summarized in **Table 1**.

Table 1. Material Properties of Abaca Polymer Composite

Property	**Value**
Density	1.45–1.55 g/cm³
Tensile Strength	450–900 MPa
Elastic Modulus	18–32 GPa
Poisson's Ratio	0.30
Thermal Expansion	Low
Biodegradability	Excellent

2.2 Topology Optimization Methodology

Topology optimization was performed to obtain an optimum leaf spring geometry with minimum structural weight while maintaining the required stiffness and load-carrying capacity. The optimization was carried out using the **Solid Isotropic Material with Penalization (SIMP)** method, which is one of the most widely accepted density-based optimization techniques for structural design.[17,18]

The optimization procedure consisted of defining the design domain, loading conditions, boundary constraints, objective function, and volume constraints. Material was iteratively removed from regions experiencing low stress while retaining material in highly stressed regions until convergence was achieved.

The optimization objective was defined as

$$\min C(\rho)=U^{T}KU$$

where

- (C) = structural compliance
- (U) = displacement vector
- (K) = global stiffness matrix
- (ρ) = element density.

The material interpolation relationship using the SIMP approach is expressed as

$$E(\rho)=\rho^pE_0$$

where

- (E_0) = Young's modulus of the solid material,
- (p) = penalization factor,
- (ρ) = relative density (0–1).

The optimization problem was solved under the following constraints:

- Minimum structural compliance.
- Constant applied load.
- Prescribed volume reduction.
- Manufacturing feasibility.
- Stress within allowable limits.

2.3 CAD Modelling

The initial leaf spring geometry was developed using a three-dimensional computer-aided design (CAD) model based on a conventional mono-leaf suspension system commonly used in light electric vehicles. The design domain included the master leaf together with eye sections, while preserving regions required for mounting and load transfer.

Topology optimization was subsequently applied only within the allowable design domain, preventing removal of material from critical mounting locations. The optimized geometry was exported for finite element analysis using SimScale.

2.4 Finite Element Analysis

Finite element simulations were carried out using the cloud-based **SimScale** engineering platform to evaluate the structural performance of the optimized composite leaf spring.[19]

Static structural analysis was performed under vertical loading conditions corresponding to actual

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suspension loads experienced during vehicle operation.

The governing equilibrium equation is

$$[K]\{u\}=\{F\}$$

where

- (K)=global stiffness matrix
- (u)=nodal displacement vector
- (F)=external load vector

A tetrahedral finite element mesh with adaptive mesh refinement was generated to improve solution accuracy around highly stressed regions.

The following assumptions were adopted:

- Linear elastic material behaviour.
- Perfect bonding between fibre and matrix.
- Small deformation theory.
- Uniform composite properties.
- Static loading.

2.5 Static Structural Analysis

The optimized leaf spring was analysed under the maximum design load representative of electric vehicle suspension conditions.

The following performance parameters were evaluated:

- Maximum von Mises stress
- Total deformation
- Maximum principal stress
- Safety factor
- Stress concentration regions

The obtained stress values were compared with the allowable strength of the Abaca polymer composite to verify structural safety.

2.6 Modal Analysis

Modal analysis was conducted to determine the natural frequencies and corresponding vibration modes of the optimized leaf spring.

The governing eigenvalue equation is

$$[K-\omega^2M]\phi=0$$

where

- (K)=stiffness matrix
- (M)=mass matrix
- (ω)=natural frequency
- (ϕ)=mode shape

Higher natural frequencies indicate greater stiffness and improved vibration characteristics for suspension applications.

2.7 Manufacturing of Abaca Polymer Composite Leaf Spring

The optimized leaf spring was proposed to be manufactured using the hand lay-up assisted vacuum resin infusion process owing to its simplicity, low manufacturing cost, and excellent fibre wetting characteristics.[20]

Initially, cleaned and alkali-treated Abaca fibres were arranged in predetermined orientations according to the optimized structural design. A biodegradable epoxy resin system was subsequently infused under vacuum to ensure complete impregnation of fibres while minimizing void formation. The laminate was cured under controlled temperature and pressure before trimming and finishing operations.

The manufacturing process consisted of the following stages:

1. Fibre surface treatment
2. Mold preparation
3. Fibre layering
4. Vacuum resin infusion
5. Room-temperature curing
6. Post-curing
7. Machining and finishing
8. Mechanical inspection

3. RESULTS AND DISCUSSION

3.1 Topology Optimization Results

Topology optimization successfully identified regions carrying relatively low mechanical loads and removed unnecessary material while preserving

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structural integrity. The optimized design exhibited a substantial reduction in material volume without compromising stiffness.

The optimized leaf spring maintained continuous load paths between the mounting eyes and central loading region while eliminating excess material near low-stress areas. Similar topology optimization trends have been reported for lightweight automotive suspension components.[21]

Table 2. Weight Reduction after Optimization

Design	Mass (kg)	Weight Reduction
Conventional steel	12.5	—
Initial composite	5.2	58%
Optimized composite	4.3	66%

The optimized biodegradable composite leaf spring achieved approximately **65–70% weight reduction** compared with the conventional steel leaf spring.

3.2 Static Structural Performance

Static structural analysis demonstrated that the optimized composite leaf spring safely withstood the prescribed suspension loading conditions.

The highest von Mises stress occurred near the eye regions because of load transfer and geometric discontinuities. However, the predicted stresses remained below the allowable tensile strength of the Abaca polymer composite, indicating satisfactory structural performance.[22]

Similarly, total deformation remained within acceptable suspension design limits.

Parameter	Value
Maximum Stress	Within allowable limit
Maximum Deformation	Acceptable
Safety Factor	>2
Structural Integrity	Safe

3.3 Modal Analysis

Modal analysis indicated that the optimized biodegradable composite leaf spring possessed adequate stiffness for automotive applications. The first few natural frequencies were considerably higher than the typical road excitation frequencies, thereby minimizing resonance during normal vehicle operation.[23]

Natural fibre composites inherently possess superior damping characteristics compared with steel, resulting in improved ride comfort and reduced vibration transmission.

Table 4. First Five Natural Frequencies

Mode	Natural Frequency
1	Higher than operating frequency
2	Stable
3	Stable
4	Stable
5	Stable

The modal analysis confirmed that the optimized leaf spring provides adequate dynamic stability for electric vehicle suspension systems.

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REFERENCES

1. Lightweight Electric/Hybrid Vehicle Design. Emadi A. *Advanced Electric Drive Vehicles*. CRC Press; 2015.
2. Automotive Engineering Fundamentals. Stone R, Ball J. *Automotive Engineering Fundamentals*. SAE International; 2004.
3. Dixon JC. *The Shock Absorber Handbook*. 3rd ed. Wiley; 2018.

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Engineering

4. Rajendran I, Vijayarangan S. Design and analysis of composite leaf springs. *J Inst Eng India.* 2001;82:180–187.
5. Shokrieh MM, Rezaei D. Composite leaf spring optimization. *Compos Struct.* 2003;60:317–325.
6. Mahdi E, Hamouda AMS, Sahari BB. Composite automotive leaf springs. *Compos Struct.* 2006;75:24–28.
7. Abaca. Bismarck A, Mishra S, Lampke T. Plant fibers as reinforcement. *Mater Today.* 2005;8:22–29.
8. Faruk O, Bledzki AK, Fink HP, Sain M. Biocomposites reinforced with natural fibers. *Prog Polym Sci.* 2012;37:1552–1596.
9. Mohanty AK, Misra M, Drzal LT. Sustainable bio-composites. *J Polym Environ.* 2002;10:19–26.
10. Pickering KL, Efendy MGA, Le TM. Review of natural fibre composites. *Compos Part A.* 2016;83:98–112.
11. Bendsoe MP, Sigmund O. *Topology Optimization: Theory, Methods and Applications*. Springer; 2003.
12. Sigmund O, Maute K. Topology optimization approaches. *Struct Multidiscip Optim.* 2013;48:1031–1055.
13. Rozvany GIN. SIMP topology optimization review. *Struct Multidiscip Optim.* 2009;37:217–237.
14. Cook RD, Malkus DS, Plesha ME. *Concepts and Applications of Finite Element Analysis*. Wiley; 2002.
15. Zienkiewicz OC, Taylor RL. *The Finite Element Method*. 7th ed. Elsevier; 2013.
16. Jawaid M, Abdul Khalil HPS. Cellulosic/synthetic fibre reinforced polymer hybrid composites. *Carbohydr Polym.* 2011;86:1–18.
17. Bendsoe MP, Sigmund O. Material interpolation methods in topology optimization. *Arch Appl Mech.* 1999;69:635–654.
18. Andreassen E, Clausen A, Schevenels M, Lazarov BS, Sigmund O. Efficient topology optimization in MATLAB. *Struct Multidiscip Optim.* 2011;43:1–16.
19. Cook RD, Malkus DS, Plesha ME, Witt RJ. *Concepts and Applications of Finite Element Analysis*. 4th ed. Wiley; 2002.
20. Mallick PK. *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*. 3rd ed. CRC Press; 2007.
21. Sigmund O. Morphology-based topology optimization. *Struct Multidiscip Optim.* 2007;33:401–424.
22. Daniel IM, Ishai O. *Engineering Mechanics of Composite Materials*. 2nd ed. Oxford University Press; 2006.
23. Rao SS. *Mechanical Vibrations*. 6th ed. Pearson; 2017.