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Design, Fabrication, And Finite Element Analysis Of Crash Energy Absorbing Bumper System For Electric Vehicles

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Abstract

The rapid growth of electric vehicles (EVs) has created the need for advanced crashworthy structures capable of protecting passengers and high-voltage battery systems during collision events. Conventional bumper systems developed for internal combustion engine vehicles are inadequate for EV architectures because of altered weight distribution, floor-mounted battery packs, and the increased risk of thermal runaway. This paper presents a comprehensive review and proposed methodology for the design, fabrication, and finite element analysis (FEA) of an advanced crash energy absorbing bumper system for electric vehicles. The study focuses on integrating lightweight materials, advanced geometries, battery protection mechanisms, computational crash simulations, and experimental validation techniques. Various energy absorbing materials such as carbon fiber reinforced polymers (CFRP), metallic foams, aluminum alloys, auxetic structures, and bio-inspired honeycomb geometries are reviewed. Finite element methods using LS-DYNA are proposed to evaluate stress distribution, deformation patterns, crash pulse behavior, and energy absorption efficiency under frontal and offset impact conditions. Multi-objective optimization techniques are discussed to balance crashworthiness, weight reduction, manufacturability, and cost-effectiveness. The paper also highlights research gaps in integrated battery protection, experimental validation, and manufacturable crashworthy structures. The proposed work aims to develop an optimized lightweight bumper system capable of improving crash safety and EV structural performance.

Keywords: *Index Terms— Electric Vehicles; Crash Worthiness; Energy Absorbing Bumper; Finite Element Analysis; Battery Protection; LS-DYNA; Auxetic Structures; Crash Simulation; Advanced Materials.*

1. Introduction

The global automotive industry is rapidly transitioning to-ward electric vehicles (EVs) due to increasing environmental concerns, stringent emission regulations, and advancements in battery technologies. Unlike conventional internal combustion engine (ICE) vehicles, EVs incorporate large battery packs positioned beneath the vehicle floor, which significantly alters vehicle mass distribution and crash dynamics. These battery packs account for nearly 20–30% of total vehicle weight and introduce new safety challenges including thermal runaway, electrolyte leakage, electrical hazards, and structural vulnerability during collisions.Traditional bumper systems primarily focus on passenger protection and frontal impact energy management. However, EV architectures demand integrated crash energy absorbing systems capable of protecting both occupants and battery enclosures. Therefore, advanced lightweight structures with enhanced crashworthiness characteristics are required. Recent developments in lightweight materials such as car-bon fiber reinforced polymers (CFRP), metallic foams, auxetic meta materials, aluminum honeycomb structures, and bio-inspired cellular geometries provide significant opportunities forim proving crash energy absorption while minimizing vehicle weight.Inaddition,advance dcomputationaltechniquesin-cluding finite element analysis (FEA), topology optimization, adaptive meshing, and multi-objective optimization enable the development of highly efficient crashworthy structures. This paper presents a detailed review of recent developments in EV crash energy absorbing bumper systems and proposes a methodology for the design, fabrication, analysis, and optimization of an advanced bumper structure integrated with battery protection mechanisms.

2. Literature Review

2.1.EV Crash worthiness and Battery Protection

Zhang et al. [1] investigated crashworthiness optimization of EV front structures and demonstrated that conventional ICE vehicle crash management systems are insufficient for EV applications due to the absence of engine block energy absorption and altered vehicle mass distribution. Their finite element analysis revealed that EV front structures require 15–20% higher energy absorption capacity to achieve equivalent occupant safety. Liu and Chen [2] conducted crash testing of electric vehicle battery enclosures and identified major failure modes including cell crushing, electrolyte leakage, and thermal runaway propagation. Their work emphasized the importance of integrating structural crash protection with thermal management systems.Wang et al.[3] proposed a multi objective optimization frame work for EV structural design considering crash worthiness, battery protection, and weight minimization.Their optimized design achieved nearly 12% weight reduction while improving crash performance by18%. Thompson and Rodriguez [4] studied crash pulse optimization for EVs and reported that EV bumper systems require modified energy absorption characteristics to minimize battery acceleration while maintaining occupant safety.

2.2.Advanced Energy Absorbing Materials

Anderson et al. [5] investigated braided carbon fiber rein-forced polymer tubes for automotive crash applications. Their experimental study demonstrated specific energy absorption values between 45–60 kJ/kg, significantly higher than traditional steel structures. Kumar and Singh [6] developed functionally graded aluminum foam structures for crash energy absorption. Their study showed improved force-displacement characteristics and better crash pulse management compared to uniform foam structures. Lee et al.[7]analyzed3D-printedauxeticstructuresun-der crash loading conditions and demonstrated stable energy absorption behavior over a wide range of impact velocities. Martinez and Brown [8] proposed bio-inspired honeycomb structures capable of providing high energy absorption with improved manufacturability and reduced production cost. Yang et al. [20] developed tailor able architected meta materials manufactured using additive manufacturing techniques. Their structures exhibited superior specific energy absorption and unidirectional self-locking capability.

2.3.Crash Simulation and Material Modeling

Davis et al. [9] developed high strain-rate material models for advanced composite structures under crash loading conditions considering strain-rate dependency and failure transitions. Johnson and Kim [10] proposed a multi-scale modeling framework linking molecular-level material behavior with macro-scale crash response. Patel et al. [11] introduced adaptive mesh refinement methods for automotive crash simulation, reducing computational cost while improving solution accuracy. Wilson and Taylor[12] developed validation methodologies for EV crash simulation models using component-level and full-vehicle validation techniques.

2.4.Battery Safety and Thermal Protection

Chen et al.[13] Experimentally investigated failure mechanisms of lithium-ion battery cells under mechanical loading conditions and established deformation-based failure criteria. Garcia and Patel[14] analyzed thermal runaway propagation in damaged battery packs and emphasized the need for integrated thermal and mechanical protection systems.Roberts et al.[15] proposed multifunctional battery enclosures capable of providing both thermal management and crash protection.

2.5.Recent Developments

Guo et al. [16] proposed a hybrid deformation framework for reducing EV tire rolling resistance using zonal tread design methods. Pavan Kumar Archakam and Sreekumar Muthuswamy [17] proposed a crash energy absorption system integrated with a Magneto-Rheological Absorber (MRA) for improved frontal crash protection. Mehmet Umut Erdas¸etal. [18] develop dadditivelymanufacturedthin walledcrash boxes using PLA and ABS materials and validated their performance experimentally and numerically. Ajit Sanjaykumar Naik [19] performed simulation and photo elastic stress analysis of slip yoke components under tensional loading conditions using finite element analysis.

3. Research Gaps

3.1.The literature review identifies several major research gaps:

- Limited experimental validation of advanced crashworthy structures.
- Lack of integrated bumper and battery protection systems.
- Manufacturing feasibility challenges for complex geometries.
- Limited studies on hybrid material systems under multi-axial crash conditions.
- Insufficient balance between crashworthiness, weighs t reduction, and cost optimization.
- Limited thermal electrical safety integration in bumper systems.

4. Problem Statement

Conventional bumper systems designed for ICE vehicles are unsuitable for electric vehicles because they primarily focus on passenger protection while ignoring battery safety. Existing structures increase vehicle weight and reduce driving range. Therefore, there is a need to develop lightweight, high-strength, crashworthy bumper systems capable of absorbing impact energy, protecting battery packs, minimizing structural intrusion, and ensuring manufacturability.

5. Working Principle of Proposed Bumper System

The proposed EV bumper system operates using controlled deformation and progressive energy absorption mechanisms. During impact events, composite crash boxes, metallic foams, auxetic structures, and honeycomb geometries deform progressively and dissipate crash energy before it reaches the passenger cabin and battery enclosure. The system also incorporates thermal barriers, insulating materials, and fire-resistant coatings to minimize thermal run-away risks during severe impacts.

6. Proposed Methodology

6.1.Design Phase

Advanced materials including CFRP, aluminum alloys, metallic foams, and auxetic structures will be used to develop lightweight crashworthy bumper geometries. CAD modeling software will be used to create integrated bumper-battery protection systems.

6.2.Finite Element Analysis

Finite element simulations will be conducted using LS-DYNA software under frontal, offset, and side impact conditions. Parameters such as stress distribution, deformation, energy absorption, peak force, crash pulse, and intrusion will be analyzed.

6.3.Experimental Testing

Scaled and full-scale prototypes will be fabricated using Resin Transfer Molding (RTM) and additive manufacturing techniques. Impact testing will be performed using pendulum and drop-weight testing setups.

6.4.Optimization

Multi-objective optimization techniques including Genetic Algorithms (GA) and Response Surface Methodology (RSM) will be used to optimize bumper geometry, material thickness, and crash performance.

7. Experimental Work

7.1.Prototype Fabrication

Composite structures will be fabricated using CFRP and aluminum honeycomb panels. Auxetic structures and meta-materials will be manufactured using additive manufacturing techniques.

7.2.Testing Procedures

- Crash impact testing
- Thermal and electrical safety testing
- High-speed camera analysis
- Digital Image Correlation(DIC)
- Force and displacement measurements

7.3.Safety Materials

Thermally resistant coatings, phase change materials (PCM), and electrically insulating barriers will be used to improve thermal safety and prevent battery damage.

8. Expected Outcomes

The proposed research is expected to achieve:

- Improved crash energy absorption
- Enhanced battery protection
- Reduced vehicle weight
- Improved crash pulse management
- Better manufacturability
- Increased EV safety and structural efficiency.

Conclusion

This paper presents a comprehensive review and proposed methodology for the development of advanced crash energy absorbing bumper systems for electric vehicles. The literature demonstrates that lightweight composite materials, metallic foams, auxetic structures, and bio-inspired geometries significantly improve crashworthiness and energy absorption performance. Finite element analysis and multi-objective optimization techniques provide efficient tools for developing lightweight and crashworthy EV structures. However, current research lacks sufficient experimental validation and integrated battery protection systems. The proposed work aims to address these gaps through computational modeling, prototype fabrication, experimental testing, and optimization. The development of optimized crashworthy bumper systems will contribute significantly to improving electric vehicle safety, light weighting, and battery protection.

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