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Design and Development of an Energy Absorber in Automobile

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ABSTRACT: Automobile frontal collisions at low and medium velocities are a major cause of structural damage and passenger injury. Conventional bumper systems equipped with metallic crush boxes exhibit limited energy absorption efficiency, permanent deformation, and high replacement costs after impact. In order to enhance crashworthiness performance and improve passenger safety, this research focuses on the design and development of a composite-based energy absorber integrated between the bumper fascia and bumper beam. The study presents a systematic approach involving literature review, mathematical modeling, material selection, geometric design, and finite element analysis (FEA). A mathematical impact model was developed based on kinetic energy and work-energy principles to estimate impact force for vehicle velocities ranging from 25 km/h to 80 km/h. A Mahindra Xylo vehicle model with a total mass of 2630 kg was considered for analysis. At 25 km/h impact velocity (6.94 m/s), the calculated kinetic energy was approximately 63 kJ, resulting in an estimated impact force of 320 kN under an allowable displacement of 200 mm. The impact force was observed to increase exponentially with velocity, highlighting the necessity of an efficient energy absorbing mechanism. Three absorber configurations—double cylinder, foam-filled double cylinder, and double half-cylinder models—were designed and evaluated. Composite materials such as S-Glass fiber reinforced polymer and Carbon fiber were considered due to their high strength-to-weight ratio and superior specific energy absorption capacity. Finite Element Analysis was performed using ANSYS Workbench to assess deformation characteristics, stress distribution, and energy dissipation behavior under dynamic loading conditions. The results indicate that the double half-cylinder composite configuration provides improved multi-stage compression and enhanced energy absorption compared to conventional crush box systems. The proposed composite energy absorber demonstrates reduced stress transmission to the vehicle frame, improved crash energy dissipation, lightweight characteristics, and cost-effectiveness. The findings suggest that polymer-based composite absorbers can significantly enhance low and medium velocity crash performance while maintaining structural integrity and passenger safety.

KEYWORDS: Energy Absorber, Impact Force, Finite Element Analysis, Composite Materials, Crashworthiness, Bumper System

I. INTRODUCTION

Road traffic accidents remain one of the leading causes of fatalities and severe injuries worldwide. A significant portion of these accidents occur at low and medium vehicle velocities, typically ranging between 20 km/h and 80 km/h, where structural deformation of the vehicle front-end directly influences passenger safety and repair cost. During a frontal collision, the kinetic energy of the moving vehicle must be effectively absorbed or dissipated to minimize force transmission to the passenger compartment. Therefore, the bumper system plays a critical role in crash energy management.

A conventional automobile bumper system primarily consists of a fascia, bumper beam, mounting brackets, and crush boxes. The crush box is a thin-walled metallic structure designed to collapse progressively under impact, thereby absorbing collision energy. However, traditional crush boxes suffer from several limitations such as permanent plastic deformation, low reusability, limited energy absorption efficiency, and high post-collision replacement costs. Additionally, metallic absorbers may transfer excessive peak impact forces to the vehicle frame, increasing the risk of structural damage and occupant injury. Recent advancements in lightweight composite materials have opened new possibilities for enhancing crashworthiness performance. Polymer matrix composites reinforced with fibers such as

S-Glass and Carbon Fiber exhibit high specific strength, improved energy absorption per unit mass, corrosion resistance, and reduced overall vehicle weight. These properties make them suitable candidates for next-generation energy absorbing components in automotive applications.

The impact force generated during a collision increases proportionally to the square of vehicle velocity, as governed by kinetic energy principles. Even a moderate increase in speed can result in a substantial rise in impact force. Hence, there is a growing need to design an energy absorber capable of efficiently dissipating energy during low and medium velocity impacts while maintaining structural integrity and passenger safety.

In this study, a composite-based energy absorber is proposed to be integrated between the bumper fascia and bumper beam. The research focuses on developing mathematical models for impact force estimation, selecting suitable composite materials, designing innovative absorber geometries such as double cylinder and double half-cylinder configurations, and evaluating performance through Finite Element Analysis (FEA) using ANSYS Workbench. The objective is to improve energy absorption efficiency, reduce stress transmission to critical vehicle components, and enhance overall crashworthiness performance.

II. LITERATURE REVIEW

Several researchers have investigated vehicle crashworthiness and energy absorption mechanisms to enhance passenger safety. Otte et al. [1] analyzed the influence of bumper height and geometry on pedestrian lower limb injuries and concluded that bumper design significantly affects fracture patterns. Yong Han et al. [2] studied the effect of vehicle impact velocity and front-end shape on pedestrian injury risk and reported that injury severity increases considerably with impact speed. Similarly, Li et al. [3] demonstrated that lower bumper height and flat front-end structures reduce leg injury probability.

Research on structural energy absorption has focused largely on metallic crush boxes. Siva Kumar [6] performed LS-DYNA simulations on crush boxes and found that although they effectively absorb energy, they undergo permanent deformation and require replacement after impact. Jiga et al. [10] examined the influence of crash-box material and geometry, showing that foam-filled structures improve axial crushing performance. Abdulqadir [11] further enhanced specific energy absorption using aluminum foam integrated longitudinal members.

Recent studies emphasize composite materials for improved crash performance. Schmidova et al. [13] developed adaptable CFRP energy absorbers and observed improved impact response compared to conventional metallic systems. Kusaseh et al. [14] investigated glass fiber reinforced polymer composites and reported enhanced impact strength and flexural properties. Mo et al. [15] proposed a modular X-shaped bumper absorber capable of balancing pedestrian safety and low-speed impact requirements.

Despite these advancements, limited research has been conducted on polymer-based half-cylinder energy absorber configurations specifically designed for low and medium velocity automotive impacts. Therefore, the present study focuses on developing and analyzing a composite energy absorber to improve crash energy dissipation while reducing structural damage and cost.

TABLE I Literature Review

Ref. No.	Author(s) & Year	Title / Study Focus	Methodology	Key Findings	Research Gap Identified
[1]	Otte et al., 2007	Influence of bumper height on pedestrian leg fractures	Accident data analysis	Bumper geometry significantly affects lower limb injury	Limited focus on material-based energy absorption

[2]	Yong Han et al., 2012	Effect of vehicle impact velocity and front-end shape	Statistical & simulation study	Impact velocity strongly influences injury severity	No absorber optimization proposed
[3]	Guibing Li et al., 2017	Passenger car front shape influence on pedestrian injury	In-depth accident data study	Lower bumper height reduces leg injury risk	Structural energy absorption not addressed
[4]	Bingyu Wang et al., 2016	Vehicle front design variables & lower extremity injury	Real-world accident data analysis	Impact speed and bumper height are critical parameters	No composite absorber modeling
[5]	Rasoul Moradi et al., 2011	Pedestrian kinematics in SUV impacts	Finite element modeling	Vehicle front stiffness impacts injury potential	Lack of innovative absorber geometry
[6]	A. Siva Kumar, 2014	Crush box simulations using LS-DYNA	Numerical crash simulations	Crush boxes absorb energy but deform permanently	No reusable composite design
[7]	H. Naderpour et al., 2014	Model for calculating impact force and energy dissipation	Mathematical modeling	Proposed improved impact force equations	No integration with vehicle absorber design
[8]	Xiwu Zhou et al., 2019	Cumulative impact force study	Experimental + numerical modeling	Impact force varies with structural stiffness	No polymer composite application
[9]	A.V. Kireev et al., 2017	Energy-regenerative shock absorber model	Mathematical modeling	Energy recovery possible from suspension	Not applicable to bumper impact system
[10]	Gabriel Jiga et al., 2016	Crash-box material and shape influence	Numerical axial crushing analysis	Foam-filled tubes improve energy absorption	Limited study on polymer matrix composites
[11]	Samer Abdulqadir, 2018	Longitudinal energy absorber design	FEA with aluminum foam	Enhanced specific energy absorption (SEA)	High cost materials
[12]	Rahul Nair et al., 2018	Functionally graded material absorber	Explicit dynamic FEA	Polyurethane improves impact resistance	Geometry optimization limited
[13]	Nikola Schmidova et al., 2018	Adaptable CFRP absorbers	Experimental + FEA	Composite beams improve crash response	No low-velocity optimization

[14]	N.M. Kusasch et al., 2018	Glass fiber reinforced composites impact properties	Experimental testing	GF reinforced polymers show improved impact strength	Not integrated into bumper system
[15]	Fuhao Mo et al., 2018	Modular X-shaped bumper absorber	Finite element simulation	Improved balance between pedestrian safety and low-speed impact	Complex manufacturing
[16]	Chuanqing Chen et al., 2024	Foam-filled composite auxetic energy absorbers	Numerical impact analysis	Hybrid composite absorbers enhance energy dissipation	Limited automotive application validation

III. METHODOLOGY

The methodology adopted in this research involves a systematic approach comprising impact analysis, mathematical modeling, material selection, geometric design, and finite element simulation to evaluate the performance of the proposed energy absorber under low and medium velocity impact conditions. The study begins with an understanding of frontal collision mechanics in automobiles, where parameters such as vehicle mass, impact velocity, kinetic energy, allowable displacement, and resulting impact force play a crucial role in crash behavior.

A Mahindra Xylo SUV model was selected as the impactor due to its higher kerb weight and practical passenger load capacity. The total mass of the vehicle was calculated by considering kerb weight, passenger weight, and luggage load. Using the work-energy principle, the velocity of the vehicle was converted from km/h to m/s, and the kinetic energy generated during impact was determined using the classical kinetic energy equation. The allowable displacement in the bumper region was assumed to be 200 mm, corresponding to the available deformation space between the fascia and bumper beam. Based on this assumption, the impact force was estimated by dividing the work done during collision by the allowable displacement. The impact forces were calculated for various velocities ranging from 25 km/h to 80 km/h to analyze the variation of force with speed.

Following the mathematical modeling, suitable materials were selected based on mechanical properties and energy absorption capability. Polymer matrix composites reinforced with S-Glass and Carbon fibers were evaluated due to their high strength-to-weight ratio, superior specific energy absorption, corrosion resistance, and manufacturability. Among these, S-Glass fiber reinforced polymer was chosen for detailed analysis because of its higher tensile strength and structural reliability under impact loading.

Subsequently, three different energy absorber configurations were designed using Creo software, namely the double cylinder model, foam-filled double cylinder model, and double half-cylinder model. The double half-cylinder configuration was developed to provide progressive multi-stage compression, thereby improving energy dissipation efficiency during impact. The car body, bumper beam, and absorber components were modeled with appropriate dimensions and material properties for simulation.

Finite Element Analysis (FEA) was conducted using ANSYS Workbench to simulate dynamic impact conditions and evaluate structural response. The simulation process involved geometry import, material assignment, meshing, application of boundary conditions, and impact loading. Multiple simulation cases were considered, including the car body without a bumper, with a bumper, with a half-cylinder absorber, and with a double-cylinder absorber. The structural performance of each configuration was assessed based on deformation characteristics, equivalent stress distribution, and energy absorption capacity. The comparative analysis enabled identification of the most effective

energy absorber configuration capable of minimizing stress transmission to the vehicle frame while enhancing crashworthiness performance.

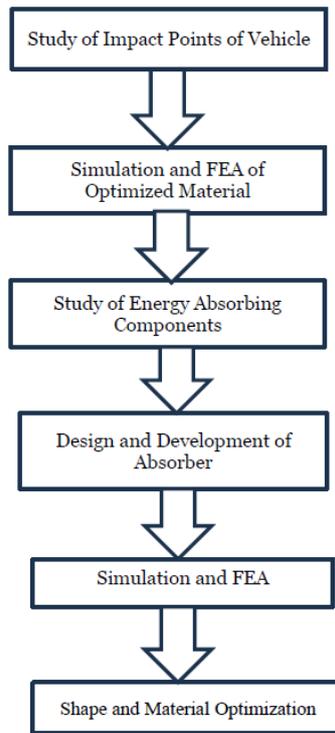


Figure 1. Proposed Methodology

A. Study of Impact Parameters

Initially, the impact mechanism of an automobile frontal collision was studied. The primary parameters influencing crash behavior include:

- Vehicle mass
- Impact velocity
- Kinetic energy
- Allowable displacement
- Impact force

A Mahindra Xylo vehicle model was considered as the impactor due to its higher kerb weight and SUV classification. The total vehicle mass was calculated considering passenger and luggage load conditions.

IV. RESULTS AND DISCUSSION

The performance of the proposed energy absorber configurations was evaluated through mathematical modeling and finite element analysis under low and medium velocity impact conditions. The results were analyzed in terms of impact force variation, deformation characteristics, stress distribution, and overall energy absorption efficiency.

The mathematical analysis revealed that the impact force increases significantly with vehicle velocity due to the quadratic relationship between velocity and kinetic energy. At an impact speed of 25 km/h, the kinetic energy was approximately 63 kJ, resulting in an estimated impact force of about 320 kN for an allowable displacement of 200 mm. As the velocity increased to 40 km/h and 60 km/h, the calculated impact forces increased sharply, demonstrating the

exponential growth in collision severity. This confirms that even moderate increases in speed result in substantial increases in impact load, emphasizing the need for an efficient energy absorption mechanism.

Finite Element Analysis was conducted to compare different structural configurations, including the car body without a bumper, with a conventional bumper, with a double-cylinder absorber, and with a double half-cylinder absorber. The simulation results showed that the car body without an energy absorber experienced higher stress concentration near the front-end structural members, leading to larger deformation and potential structural damage. The addition of a conventional bumper reduced the stress marginally; however, peak stress values remained significantly high.

The double-cylinder absorber configuration demonstrated improved energy dissipation through progressive deformation. The stress distribution was more uniform, and peak stress values were lower compared to the conventional bumper system. However, the deformation pattern indicated limited multi-stage compression behavior.

Among all configurations, the double half-cylinder energy absorber exhibited superior performance. The structure provided multi-stage compression during impact, allowing gradual energy dissipation and reduced peak stress transmission to the vehicle frame. The Von-Mises stress distribution showed lower maximum stress values in critical regions, indicating improved structural safety. Additionally, the deformation was controlled within the allowable displacement range, ensuring protection of internal vehicle components and passenger space.

Material selection also influenced performance significantly. The S-Glass fiber reinforced polymer absorber demonstrated high strength and improved specific energy absorption compared to metallic crush boxes. Due to its lightweight nature and favorable mechanical properties, the composite absorber reduced overall structural load while maintaining durability. Compared to traditional steel-based crush boxes, the proposed composite absorber offered better energy absorption per unit mass and reduced permanent damage.

Overall, the results indicate that the proposed composite-based double half-cylinder energy absorber effectively enhances crashworthiness performance during low and medium velocity impacts. The improved stress distribution, controlled deformation, and higher energy dissipation capacity confirm that the developed design can reduce structural damage and improve passenger safety while remaining cost-effective and lightweight.

Table.2. Comparison Of Different Energy Absorber Configurations

Configuration	Maximum Deformation	Peak Von-Mises Stress	Energy Absorption Capacity	Stress Distribution	Overall Performance
Car Body without Bumper	Very High	Very High	Very Low	Highly Concentrated at Front	Poor
Car Body with Conventional Bumper	High	High	Moderate	Partially Distributed	Fair
Double Cylinder Absorber	Moderate	Moderate	High	More Uniform	Good
Double Half-Cylinder Absorber	Controlled (Within 200 mm)	Low	Very High	Uniform & Progressive	Excellent

V. CONCLUSION

This study presented the design and analysis of a composite-based energy absorber for automobile applications subjected to low and medium velocity frontal impacts. A systematic approach involving mathematical modeling, material selection, geometric design, and finite element analysis was adopted to evaluate the crashworthiness performance of different absorber configurations. The impact force was analytically determined using the work-energy principle, and the results showed that impact force increases exponentially with vehicle velocity due to the quadratic relationship between velocity and kinetic energy. At 25 km/h, the impact force was approximately 320 kN, and it increased significantly with higher speeds, emphasizing the need for efficient energy dissipation mechanisms. Finite

Element Analysis results demonstrated that conventional bumper systems provide limited stress reduction and undergo significant deformation under impact loading. The introduction of composite-based absorbers significantly improved structural response. Among the configurations analyzed, the double half-cylinder energy absorber exhibited superior performance in terms of controlled deformation, reduced peak Von-Mises stress, and improved energy absorption capacity. The multi-stage compression behavior enabled gradual energy dissipation, thereby minimizing stress transmission to the vehicle frame and protecting critical components. The use of S-Glass fiber reinforced polymer material contributed to enhanced strength-to-weight ratio and higher specific energy absorption compared to traditional metallic crush boxes. The proposed design not only improves crashworthiness performance but also offers advantages such as reduced weight, corrosion resistance, and cost-effectiveness. Therefore, the developed composite energy absorber can be considered a viable alternative to conventional metallic crush box systems for improving passenger safety in low and medium velocity impacts.

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