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Engineering an Ultra-Light Bumper for Passenger Vehicles

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Abstract

This study investigates the design and development of lightweight bumpers for four-wheeled vehicles, focusing on optimizing safety, efficiency, and aesthetics. It examines the evolution of bumper technology from steel structures to advanced composites, analyzing their impact on vehicle performance and crash safety. The research evaluates various materials for bumper components, including aluminium alloys, ABS plastics, carbon fiber-reinforced plastics for the body, and expanded polypropylene and polyethylene foam for energy absorbers. The study simulates bumper performance under low-velocity impact conditions using computer-aided design and finite element analysis. Three energy absorption geometries - triangular, diamond, and honeycomb structures - are assessed for crash scenarios. The paper highlights trade-offs between design complexity, manufacturing considerations, and energy absorption performance. This comprehensive study contributes to the understanding of bumper design optimization, material selection, and performance evaluation, offering valuable insights for automotive engineers developing next-generation vehicle safety systems. The main findings indicate that ABS polymer is the best material for bumper bodies because it offers the best impact resistance and the least amount of deformation while achieving significant weight reduction as compared to conventional materials. Although production difficulty must be taken into account, the best strength absorption and deformation characteristics in electricity absorber design are shown by the hexagonal cross-sectional shape in vertical orientation. While polyethylene foam performs well in prolonged impact situations, expanded polypropylene is more effective for initial impact absorption in power absorbers, indicating the possibility of hybrid solutions in future designs.

Keywords: Bumper, Crashworthiness-Test, Energy Absorber, Honeycomb Structure, Vehicle Safety.

Introduction

The purpose of the bumper is to absorb energy and force during a collision at a low speed from the front or rear end of the vehicle thereby preventing or reducing the damage caused during the collision. The vehicle's front and rear bumper systems are shields usually made up of steel or aluminium. Automotive engineers often work on the bumper ecosystem to improve the parameters of efficiency, safety, and aesthetic appeal, emphasising bumpers' vital function as the first line of defence against collisions. The exposed bumper body, the energy absorber bar behind it, and the impact rod, which makes up the third layer, comprise an automobile bumper. These parts need to be designed effectively and optimized so that they can minimise the impact during the crash and the risk of injury to the passengers by absorbing the maximum amount of energy and dissipating it properly across the body (1). The bumper beam is highlighted as the key structural Component; it must be flexible to absorb impacts and robust enough to shield pedestrian, cyclist and other car components.

Figure 1 depicts the three layers of the bumper ecosystem. The use of lightweight materials to replace traditional mild steel, such as carbon fibre, aluminium alloys, ABS plastics, and high-strength steel alloys, is highlighted in this article (2). It is emphasised how important it is to preserve impact energy absorption capacity as materials change. The impact reactions and damage mechanisms of various composite materials are also explored, highlighting their complexity and dependence on several variables. It is crucial to optimise the bumper design for increased performance and safety while overcoming obstacles with material choice, weight reduction, and the complexities of composite materials in impact situations.

This investigation will examine the front bumper's crashworthiness, which serves as a component protector. Bumper crashworthiness has been studied experimentally and by applying the finite element approach. Crashworthiness simulation is used in the automobile industry to forecast the

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magnitude of the impact on energy absorption and collision-induced deformation. ANSYS Explicit dynamics will be used in this study's finite element technique simulations, allowing this to demonstrate the collision's impact.

Since the invention of four four-wheeler vehicles, the styles have been evolving every decade, represented by modern smooth and old designs. Each era has specific design elements which tell something about the culture and history. Regional cultural backgrounds influence the consumer’s choices while brands use innovation to set themselves apart from others in the market (3).

Corrosion is a critical concern, especially for metal bumpers, as exposure to moisture, road salts, and temperature variations accelerates material degradation. Protective coatings, galvanization, and the use of corrosion-resistant materials like thermoplastics or stainless steel are employed to mitigate this. Effective design and material selection are essential to ensure long-term structural integrity and aesthetic preservation of bumpers (4).

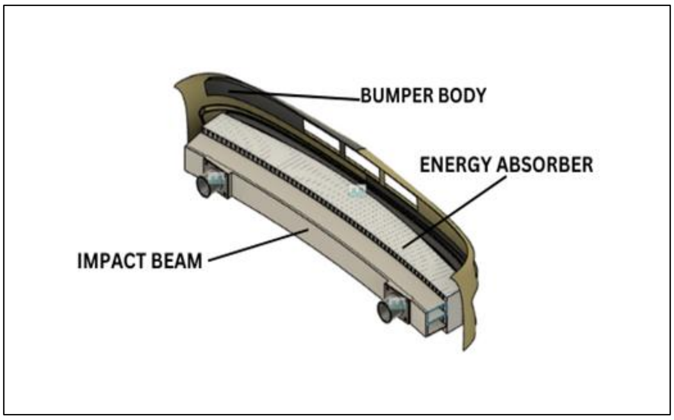

Figure 1: Three Layered Four Wheeler Bumper

The technology used in vehicle bumpers has seen a big transformation that has completely changed how car safety and design are done. Steel bumpers have been overtaken by innovative materials such as carbon fibre and other cutting-edge composites, thus improving the impact absorption and overall efficiency of vehicles greatly. Modern active bumper systems are equipped with sensors and actuators to enable them to take proactive measures to avoid accidents by using protocols like pre-tightening seat belts or releasing external airbags. The location of energy-absorbing structures within bumpers enables them to effectively disperse collision forces to minimize damage to vehicles while protecting occupants’ lives (5).

Additionally, pedestrian safety features like pop-up hoods ensure that protection extends beyond just the people inside the vehicle. Integrating advanced driver assistance systems through embedded sensors and cameras improves collision avoidance techniques. New technologies such as 3D printing allow for extensive customization options for vehicle owners who want their bumper designs tailored specifically to their preferences. Besides optimizing vehicle performance, aerodynamic enhancements also enhance fuel efficiency. The ongoing quest for self-healing materials promises long-lived bumpers at less cost and reduced maintenance. These are significant developments in the design of bumpers towards being safe, efficient and innovative in the world of four-wheeled automotive vehicles.

The first mass-produced passenger car was Ford Model T while steel bumpers came as the first safety enhancement during the era of vintage cars. Bumpers did not have a specific shape initially but rather they were constructed based on what looked good or felt like it worked well. However, this resulted in unexpected collision performance in cars. Even today, there are instances when taillights and bumper lights are one unit. Nowadays, the main lamps of modern cars rarely lie on the bumper too. In 1971 however, a Chrysler Dart with a tail light fixed on its bumper was found but it would be hard to drive safely if those lights broke or became useless. The "Exterior Protection" standard (FMVSS No. 215) was revised to make bumpers stronger by 1972 (6).

Durability and life estimation of automotive bumpers involve assessing their ability to withstand repeated mechanical stresses, impacts, and environmental conditions over the vehicle's lifespan. Finite Element Analysis (FEA) and accelerated fatigue testing are commonly used to predict failure modes and service life (7).

With time, laws governing bumpers have evolved; Relaxation by government administration to some of the regulations allows for lighter weight bumpers to be designed. This made it simpler for manufacturers because steel and alloys were being used more commonly in bumper construction till the 1980s. However, new polymers and thermoplastic materials such as polysilicon-11 enabled the production of light bumpers from the 1990s that conformed to specific car designs. An example of a widely used plastic synthesized compound is Acrylonitrile Butadiene Styrene (ABS), which is found in various products, including musical instruments and Lego parts. Also, carbon fibre or fibreglass can now be said to make up automobile bumpers due to their incorporation into composite materials. Its main advantage is that ABS is employed in many 3D printing applications; this makes it easier to implement in modern manufacturing techniques. Bumper technology has advanced over time due to new material innovations (8).

Methodology

Low-Velocity Impact Test

It is worth mentioning that over the last 40 years, low-speed impact tests have been considered to determine the safety of pedestrians. Crashes that occur at speeds slightly above stall speed of up to 15 kph are categorized as low-speed accidents. Most of the events involving the vehicles often occur when the vehicles barely exhibit any signs of a collision. Precisely, in car manufacturing, especially the engineering of cars and the safety aspect of it, issues to do with low-speed impacts as well as its impact on bumpers and their construction are crucial.

The performances that are acceptable according to the European and North American standards are different as are the verification tests. Therefore, depending on the market for which they are designed, honeymoon bumper systems on automobiles may differ. The North American law standard, or the FMVSS1 part 581, utilizes an impact pendulum with corner and longitudinal hits at two different heights, where the crashworthiness and airbag test dummies are utilized. The geometry only involves force as the impact pendulum strikes a flat and stationary anvil. In European car manufacturing Standards, the bumper beam should not give way when it is hit at a speed of 8 km/hr (9). Some of the tests used in the European Legislation Standard include the impact pendulum with front, rear, and corner impacts. The current investigation utilizes the IIHS4-defined North American insurance impact standard and performs four tests at eight km/hr. and estimates the cost of repairs. The tests consist of the following: Exit in a collision where the rear ends of the vehicle impact on a pole barrier, the front of the vehicle impacts an angled barrier, and both front and rear of the vehicle impact on a fixed and level barrier. The accident the European insurance organizations applied includes the total of the repair bills incurred from an accident of 16 km/hr with a fixed barrier at 40% offset. Since the permanent barrier draws to 40% of the front of the vehicle, this point indicates that 40% of the front face of the vehicle is covered by the permanent barrier (10).

Material for Bumper Body

Aluminium Alloy: Aluminium is an element that was first isolated in 1888 and has several interesting characteristics. Aluminium has a density of 2.69 g/cm3, which is about one-third that of regular steel (7.83 g/cm3). Therefore, exceptional special behaviours (such as specific strength or strength-to-weight ratio) enable the production of lighter cars made of aluminium that perform better in terms of handling, braking, acceleration, and fuel economy.

In particular, aluminium alloys are categorised into different families by four digits ranging from 1000 to 9000, according to nomenclatures proposed by the Aluminium Association. Each alloy denomination corresponds to particular compositions and characteristics, which in turn lead to a variety of automotive applications. Additionally, the aluminium alloys in the 6000 series, which include 6061, 6013, and 6063, have excellent corrosion resistance, high strength, and good formability, making them desirable options for automotive fenders, pillars, bumpers, frames, engine brackets, roofs, doors, and wheels. These alloys are primarily composed of silicon and magnesium.

The highest ultimate tensile strength of annealed 6061 (6061-O temper) is limited to 150 MPa, whereas the maximum yield strength is limited to 83 MPa or 110 MPa. The material has an elongation of 10–18%, or stretch before ultimate failure. For two to three hours, the alloy is usually heat-soaked at 415 °C to achieve the annealed condition. The temper, or heat treatment, of the material has a significant impact on the mechanical properties of 6061.68 GPa is Young's modulus, independent of temper (11). Aluminium alloy and other light metals have some disadvantages, such as high cost, low press formability, adhesion (welding) problems, and difficulty with surface treatment.

ABS: ABS is a copolymer made by polymerizing styrene and acrylonitrile in polybutadiene. The styrene gives the plastic a shiny, impervious surface. Butadiene, a rubbery substance, provides resilience even at low temperatures. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance. ABS provides favourable mechanical properties such as impact resistance, toughness, and rigidity when compared with other common polymers. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance. Bumpers are one of the most important safety features in a car, as they protect the vehicle and passengers in the event of a collision. ABS plastic material is ideal for bumper production because it is lightweight, durable, and has good impact resistance. It also has good dimensional stability, which is important for parts that need to fit precisely.

CFRP: Carbon fibre-reinforced plastic (CFRP) has lots of advantages such as low density, high specific strength and specific stiffness, strong corrosion resistance, ability to relieve and absorb a quantity of impact energy, high design flexibility, and the possibility to achieve the optimal mechanical properties and processing performances through rational allocation of material component. Carbon fibre–reinforced plastic bumper beam has better energy absorption capabilities and dynamic response characteristics than those of the steel one; the weight has decreased remarkably close to 50% (12). The material properties of the bumper used in this investigation are listed in Table 1 below.

Table 1: Material Properties of Bumper

Material	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio
Aluminium - 6061 series	2713	69040	0.33
ABS Polymer -polypropylene	940	3500	0.42
Carbon Fiber Reinforced Plastic	1400	30000	0.3

Material for Absorber

Expanded Polypropylene: To create a bumper foam energy absorber that is lightweight, cost-effective, and energy-efficient, it is crucial to optimise the coring shape used in the system's design. This research examines many foam coring patterns using both analytical and empirical techniques. A thorough analysis is conducted on the dimensions and forms of the suggested core designs, taking into account various expanded polypropylene (EPP) foam densities. The finite element structural analysis approach allows one to examine the stress distribution inside foam structures as they flex. As an efficiency metric, the energy absorption ratio is used in finite element optimization research. For bumper foam core design, several coring designs are researched and suggested based on high energy absorption efficiency and low rip stress (13).

Polyethylene Foam: Because of its special qualities, polyethylene foam may be employed in automobile bumpers as an energy absorber. Because polyethylene foam is lightweight, it can assist in preserving overall vehicle performance and fuel economy in automotive applications. Foam made of polyethylene is renowned for its capacity to both absorb and release energy when struck. This characteristic of a bumper material is essential because it lessens the force that a collision transfers to the car and its occupants. Polyethylene foam can bear repeated knocks because of its strength and resilience without losing its usefulness. This is crucial for a material used in bumpers since during a vehicle's lifetime, it may be involved in a variety of crashes. When compared to certain other materials, polyethylene foam is comparatively more affordable. This may enhance the overall cost-effectiveness of the car production process. Polyethylene foam is adaptable and can be readily moulded into a variety of sizes and forms for use in different automobile bumper designs. One advantage of polyethylene's resistance to several chemicals is that it can withstand exposure to a wide range of substances and environmental conditions (14). Expanded polypropylene and polyethylene foam were the materials chosen for the bumper's energy absorber. The density, Young's Modulus and yield strength of these materials are listed in Table 2 below.

Table 2: Material Properties of Absorber

Material	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's ratio
Expanded Polypropylene	40	77	0.3
Polyethene Foam	32	151	0.45

Material for Beam

AA6061: AA6061 aluminium alloy demonstrates the potential for certain bumper beam applications due to its relatively high strength (310 MPa tensile strength) and excellent workability. Its good weldability facilitates seamless component joining. However, AA6061's limitations include lower overall strength compared to some steel and high-strength aluminium alloys, potentially restricting its use in heavy-duty vehicles or applications with stringent collision standards. Additionally, it may not be optimal for maximum energy absorption upon impact. The suitability of AA6061 for bumper beams depends on specific design considerations, vehicle type, anticipated impact severity, and manufacturing costs. For safety-critical applications, consultation with automotive engineers and reference to material selection charts is advisable to ensure AA6061 meets the design requirements (15).

Modelling

Over time, automobile bumpers have changed. Despite its ergonomic evolution, front bumper design and analysis in the face of solid mechanics and sophisticated FEA tools have not been thoroughly studied. CAD software is used to model the front bumper and its parts. A review of the current bumper systems from different passenger cars has been conducted to achieve the project's goals. The evolution and development of bumper systems have also been looked at. The relationship between performance and weight is balanced. Early cars were mostly equipped with metallic bumper systems, which occasionally contained foam or rubber to absorb impact.

Bumper Body: Designing a Beam Bar as shown in Figure 2 with Fusion 360 enables accurate modelling and performance simulation. The software's features allow for straightforward modifications to dimensions, materials, and load conditions, ensuring the beam achieves optimal strength and weight. Fusion 360's simulation tools validate designs, improving efficiency and minimizing material use. When crafted from AA6061 aluminium alloy, the Beam Bar design as shown in figure 3 benefits from outstanding mechanical properties, making it ideal for various structural uses. AA6061's strength ensures reliable performance in load-bearing scenarios, while its lightweight nature enhances overall efficiency and reduces structural weight (16). Its inherent corrosion resistance is advantageous for outdoor or harsh environments, eliminating the need for additional coatings and lowering long-term maintenance costs.

The study examines three cross-sectional geometries for energy absorption in low-velocity crash tests: triangular, diamond, and honeycomb structures. These designs represent a progression in complexity and performance for bumper energy absorbers.

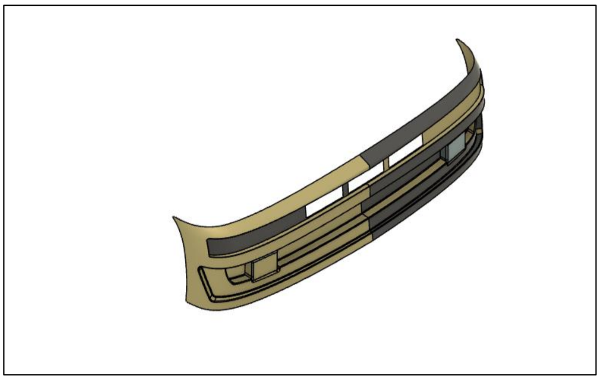

Figure 2: Bumper Body Model

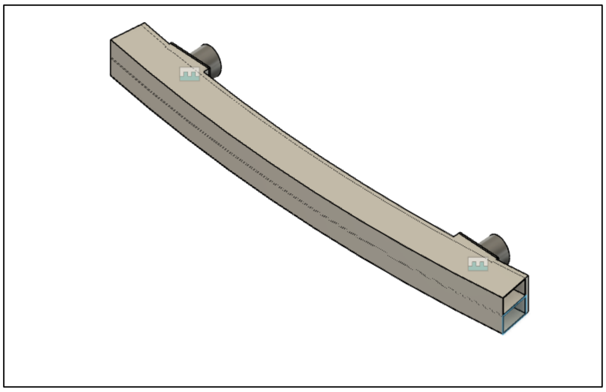

Figure 3: Bumper Beam Model

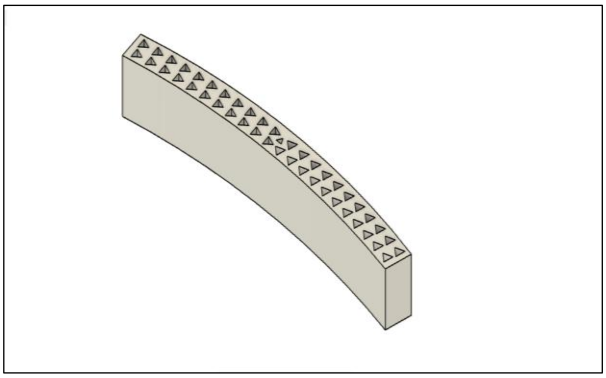

Figure 4: Energy Absorber Model with Triangular Geometry

Energy Absorber with Vertical Triangular Geometry: Triangular cross-sections shown in Figure 4 offer a baseline solution that balances simplicity and functionality. They provide cost-effective manufacturing and adequate stiffness-to-weight ratios. However, they exhibit directional performance variations and non-uniform crush behavior. The sharp corners concentrate stress, potentially leading to premature failure and reduced energy absorption capabilities.

Energy Absorber with Vertical Diamond Geometry: Diamond cross-sections shown in figure 5 demonstrate enhanced energy absorption through improved force distribution and additional folding zones. They offer superior load uniformity and multi-directional impact resistance compared to triangular structures. The elongated design promotes controlled deformation along the impact axis, enabling better energy absorption over a larger surface area. Diamond-shaped holes also create predictable deformation patterns, improving crash performance.

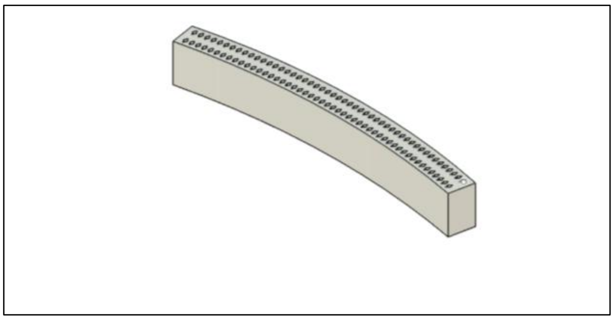

Figure 5: Energy Absorber with Vertical Diamond Geometry

Energy Absorber with Vertical Hexagon Geometry: Honeycomb structures or hexagon shape shown in figure 6. emerge as the most sophisticated and efficient design. Their cellular architecture yields the highest surface area-to-volume ratio, resulting in exceptional strength-to-weight characteristics and superior energy absorption. The uniform composition ensures consistent and predictable deformation under impact. Energy dissipation occurs through multiple mechanisms, including cell wall buckling, crush zone formation, and air compression within the cells. The honeycomb design excels in load distribution, offering the most consistent crush force—a critical factor in occupant protection. Its performance remains robust across various impact angles, making it suitable for scenarios with unpredictable crash orientations (17). Although it presents the greatest manufacturing challenges and potential cost implications, its superior performance often justifies its application in high-performance energy absorption scenarios.

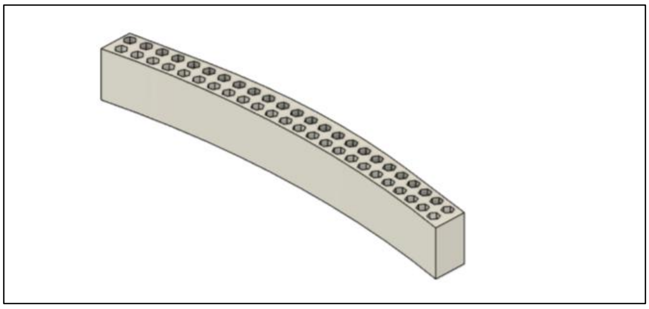

Figure 6: Energy Absorber with Vertical Hexagon Geometry

This comparative analysis underscores the trade-offs between design complexity, manufacturing considerations, and energy absorption performance in low-velocity crash protection systems. The findings provide valuable insights for engineers and designers in selecting appropriate geometries based on specific application requirements and constraints.

Finite Element Analysis

The software used for the analysis is ANSYS Explicit Dynamics. It can solve bumper dynamics by analyzing how the structure holds up. In this investigation, ANSYS 18.1 Workbench was used to do the FEA of the model. It is a practical tool that allows us to simulate all these complex situations without building and testing everything in real life. The Finite Element Analysis (FEA) analysis revealed how the bumper deforms under various conditions, giving valuable insights into its performance during dynamics and impacts. By carefully setting up the boundary conditions for each material tested, it is possible to measure how the bumper deformed under dynamic forces. To keep things consistent across various tests, a vehicle moving at a steady pace of 4 meters per second, with the bumper encountering an obstacle measuring 20 cm wide, 10 cm deep, and 20 cm tall was simulated.

Bumper Body Analysis: The finite element analysis (FEA) simulation depicted in the Figure 7 shows the stress distribution and deformation pattern of the bumper under frontal influence. The bumper is constructed of three different materials: aluminium 6061 series, carbon fiber, 2005; and ABS polymer. Coloured contours represent von Mises stresses, with red indicating the highest stress areas. The results show that the carbon fiber material exhibits good performance in terms of impact strength tensile and fracture, as evidenced by its lower strain rate and less deformation compared to other materials Aluminum alloy also exhibits an acceptable stress distribution even though it exhibits moderate deformation. In contrast, ABS polymer despite its flexibility is prone to deformation and may not provide adequate protection under high-impact conditions. These findings highlight the importance of selectivity in optimizing the bumper system for crashworthiness and weight reduction is emphasized.

Beam Body Analysis: Figure 8 shows the explicit dynamic analysis of the bumper beam body in ANSYS. First, the CAD model was imported into the software, the buffer components and created the mesh. Then add all the boundary conditions required for the shock analysis. The main factors that are focused on are how fast the bumper is moving and the exact location of the impact.

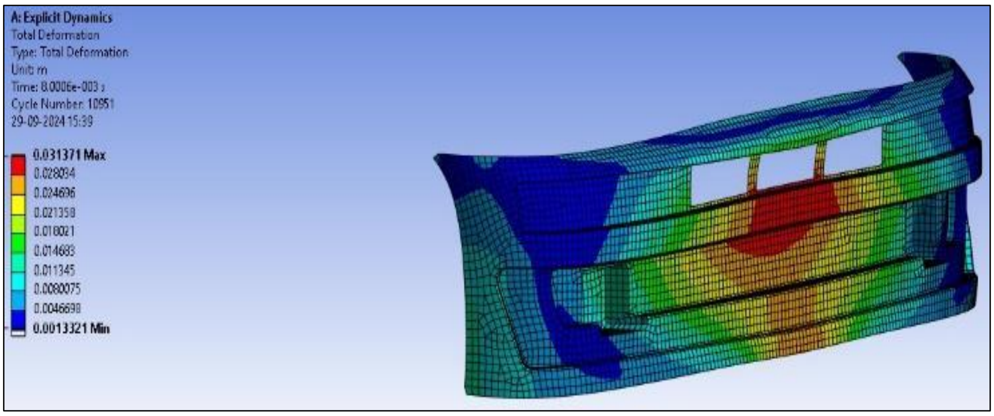

Figure 7: Stress Distribution of Bumper Body

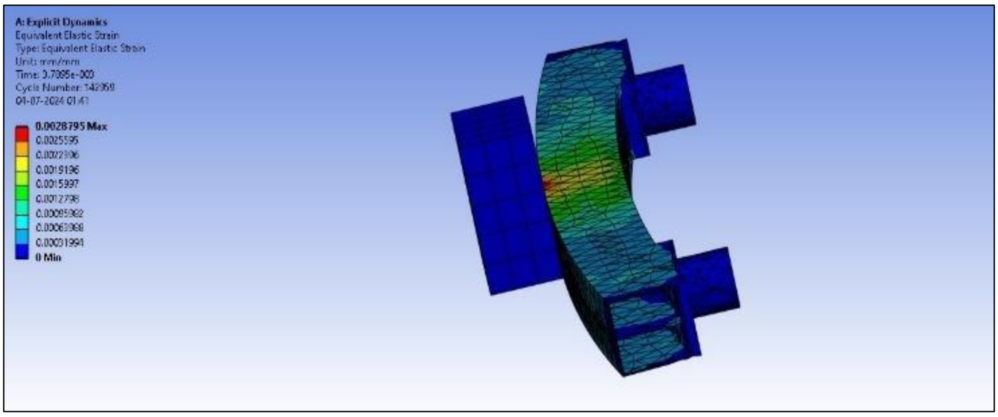

Figure 8: Stress Distribution of the Bumper Beam Body

Energy Absorber Analysis: Energy Absorber with Diamond Geometry – Figure 9 shows the deformation and stress distribution of a strength absorber with a diamond-formed reduce-via cross-section from a finite element evaluation (FEA) simulation Expanded polypropylene, a fabric regarded for its wonderful tensile power, is used so is used to create an absorber. Von Mises pressure is represented using a colouration code, with pink indicating the best strain areas. Studies display that diamond-formed geometry better determines the deformation route at impact, and promotes homogeneous energy dissipation and gradual collapse This will increase the absorber's multiplied crashworthiness overall performance, simulation effects of electricity absorption through plastic deformation of herbal forces of improved polypropylene show with the proposed layout there can improve 4-wheel pressure safety and safety.

Energy Absorber with Hexagon Geometry – Figure 10 indicates a finite element evaluation (FEA) simulation that suggests the stress distribution and deformation of a strength absorber with a cut-through cross-section this is hexagon-fashioned. Expanded polypropylene, a substance famed for its superior energy-absorbing characteristics, is used to manufacture the absorber. The von Mises strain is proven through the colour-coded contours, where red denotes regions of highest strain attention. The findings show that the effect deformation route is efficaciously guided by way of the hexagon-formed geometry, resulting in a gradual fall apart and homogeneous energy dissipation. This adds to the absorber's greater crashworthiness overall performance, collectively with the accelerated polypropylene's herbal ability to soak up energy through plastic deformation. The outcomes of the simulation imply that there is capacity for enhancing the safety and safety of 4-wheeled motors with the cautioned design.

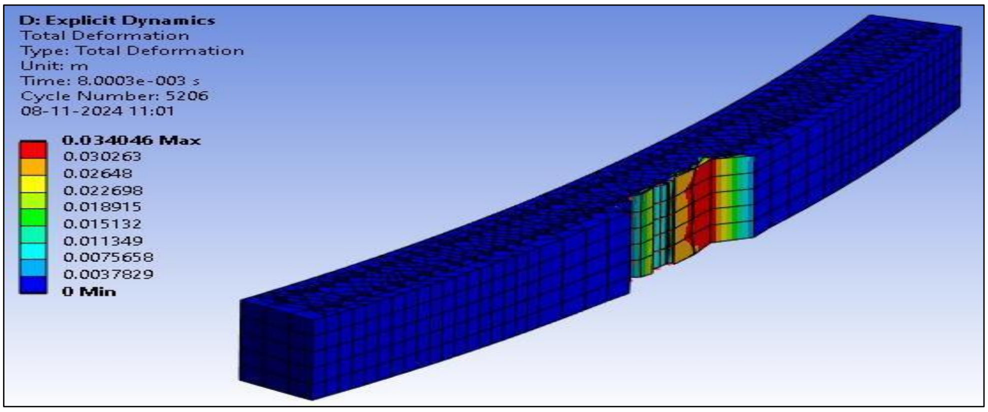

Figure 9: Stress Distribution of Energy Absorber with Diamond Geometry

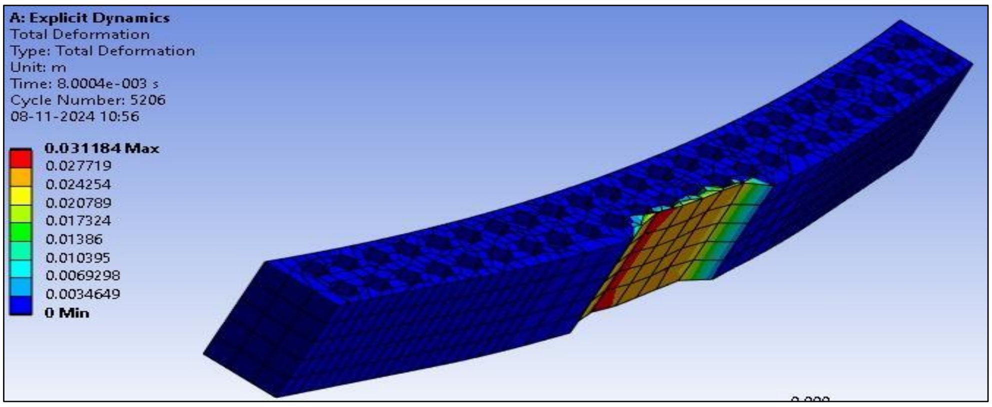

Figure 10: Stress Distribution of Energy Absorber with Hexagon Geometry

Energy Absorber with Triangular Geometry – The deformation and stress distribution of an absorber with a triangular-shaped geometry is shown in Figure 11. The deformation and stress reduce-through cross-phase from a finite element analysis (FEA) simulation. Expanded polypropylene, a substance famed for its advanced energy-absorbing qualities, is used to fabricate the absorber. The von Mises stress is shown with the aid of the coloration-coded contours, where red denotes regions of maximum stress concentration. The findings show that the triangular-shaped layout effectively directs the deformation direction at some stage in impact, encouraging homogeneous energy dissipation and gradual disintegration. This provides the absorber's greater crashworthiness performance, collectively with the expanded polypropylene's natural potential to absorb energy through plastic deformation. The effects of the simulation suggest that there is capability for improving the protection and protection of four-wheeled automobiles with the cautioned design.

Energy Absorber with Hexagon Geometry Hole in the Longitudinal Axis – Figure 12 depicts a hexagonal energy absorber's Finite Element Analysis (FEA) model simulation indicating stress/strain distribution measured in (from 0 to 0.031184) using a contour colour coat. The model has a thin wall capable of having uniform mesh elements and shows that the middle part of the assembly has a localised deformation, which implies a progressive crushing mode. Such analysis is often applied in the study of automobile crashworthiness due to the hexagonal profile representing an optimum axial loading design balancing structural efficiency with energy absorption characteristics.

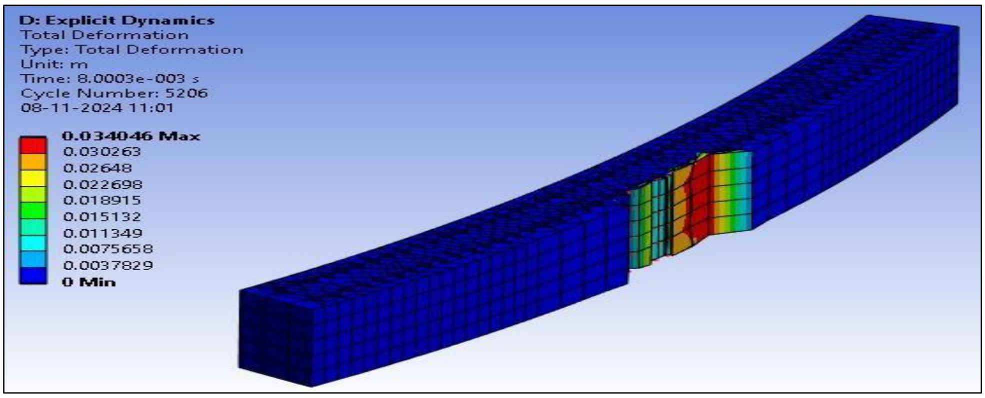

Figure 11: Stress Distribution of Energy Absorber with Triangular Geometry

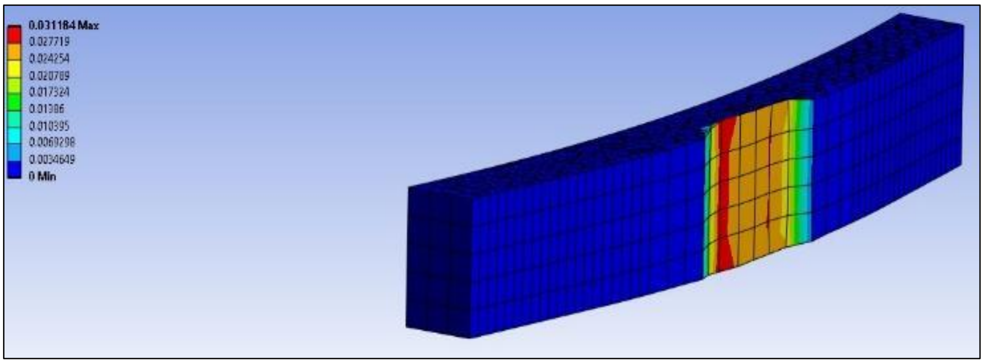

Figure 12: Stress Distribution of Energy Absorber with Hexagon Geometry in Longitudinal Axis

Results and Discussion

There are two important parameters of the bumper components needs to be analyzed for the performance under crash condition. One is deformation of the components of the bumper and the internal energy absorption. The following section provides detailed analysis of the bumper body, energy absorber, bumper material and cross sectional variation of bumper.

Bumper Body

There are three kinds of bumper bodies are analysed in this investigation, ABS, Aluminium and CFRP.

Figure 13 provides the detailed deformation of the bumper body for the duration of 20 20-second crash. It shows that the CFRP is considerably lower deformation compared to the other materials.

Similarly, time vs. internal energy in Figure 14, CFRP appears to be the best material for a bumper body. Its limited deformation and low energy absorption illustrate its capacity to absorb hits without substantial bending or deforming, lowering the danger of damage to the vehicle. While ABS and aluminium may have cost and manufacturing advantages, CFRP's combination of high stiffness and low energy absorption provides excellent safety and performance, making it the preferable material for a bumper body.

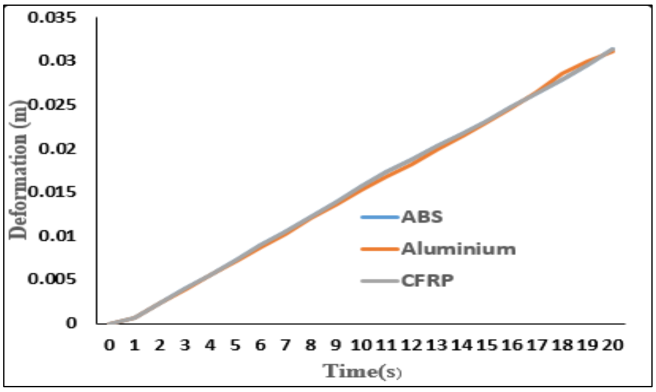

Figure 13: Time Vs Deformation of the Bumper Body

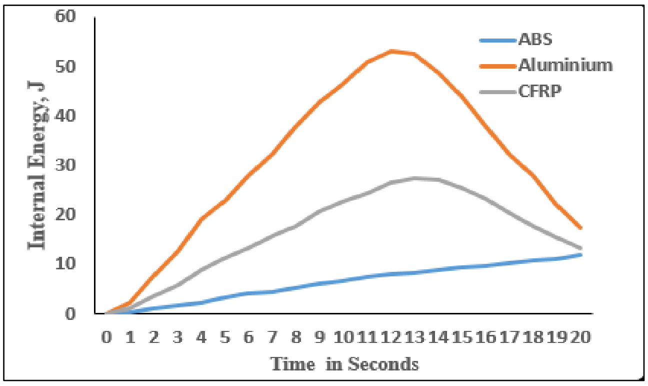

Figure 14: Time Vs Internal Energy of Bumper Body

Energy Absorber

Cross-Sectional Geometry Variation: There are three types of energy absorber geometry are investigated for their performance. A hexagonal, diagonal and triangular cross section are considered for the study.

Through analysis of time vs. deformation in Figure 15 and time vs. internal energy in Figure 16, shows that the hexagonal shape appears to be the best fit for the hole in the energy absorber. Its repeated display of maximum deformation and internal energy absorption demonstrates a superior ability to absorb impact energy effectively. While the diamond shape strikes a compromise between deformation and energy absorption, the hexagonal shape's overall performance advantage makes it the favored choice for maximum energy absorption and durability as an energy absorber for the bumper.

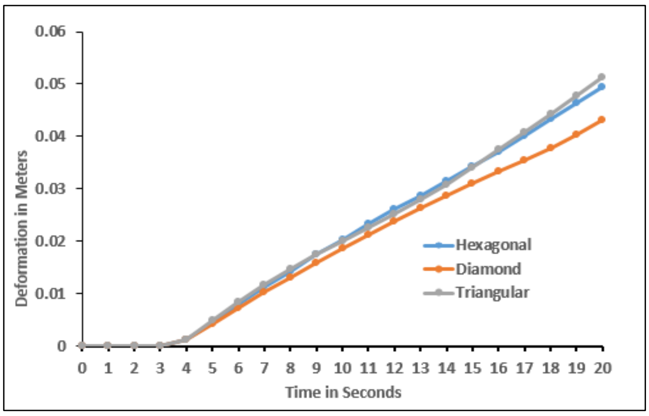

Figure 15: Time Vs Deformation of Different Absorber Geometries

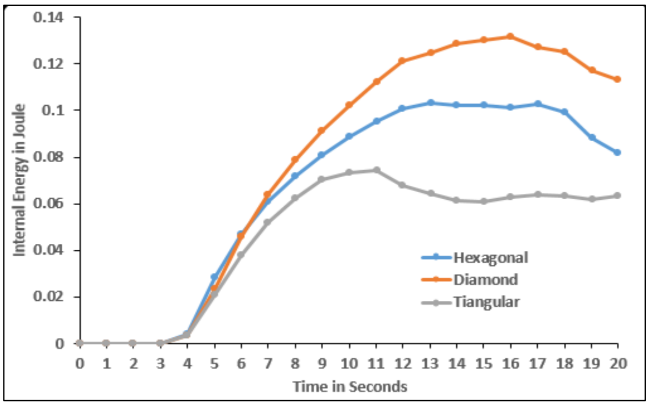

Figure 16: Time Vs Internal Energy of Different Absorber Geometries

Energy Absorber Material

Once hexagonal geometry has been selected for the energy absorber cross section, different materials are researched for the selection. Here, it was decided to investigate expanded polypropylene and polythene foam are selected based on the literature (6, 9, 12).

The comparative analysis of expanded polypropylene and polyethylene foam reveals distinct performance characteristics in automotive impact absorption applications. Expanded polypropylene demonstrates superior initial energy absorption rates, making it particularly effective for low-speed impact protection. In contrast, polyethene foam exhibits a more gradual energy absorption curve, providing sustained energy dissipation over extended impact durations, which proves advantageous in higher-speed collision scenarios (10).

When examining deformation behavior in Figure 17, expanded polypropylene shows more rapid deformation, particularly during initial impact stages, while polyethylene foam maintains a more controlled, gradual deformation pattern that better preserves structural integrity. The selection between these materials necessitates careful consideration of various factors, including the intended impact severity range, acceptable deformation limits, and cost constraints. Through examination of Figure 18. Indicates that the expanded polypropylene offers a cost-effective solution with excellent low-speed impact performance, whereas polyethylene foam's gradual energy dissipation and controlled deformation characteristics make it suitable for applications requiring sustained impact protection and minimal structural deformation. This analysis emphasizes the importance of matching material properties with specific application requirements to achieve optimal impact protection performance.

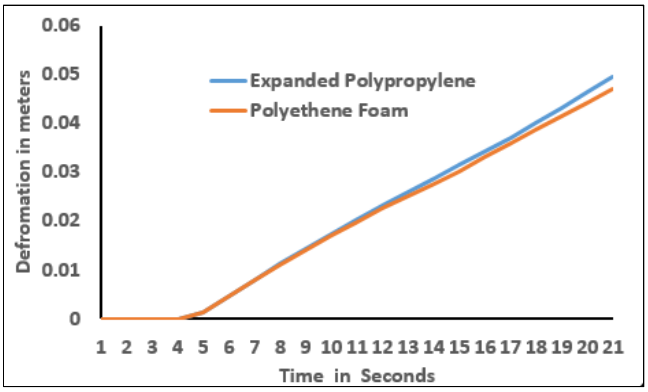

Figure 17: Time Vs Deformation of Energy Absorber

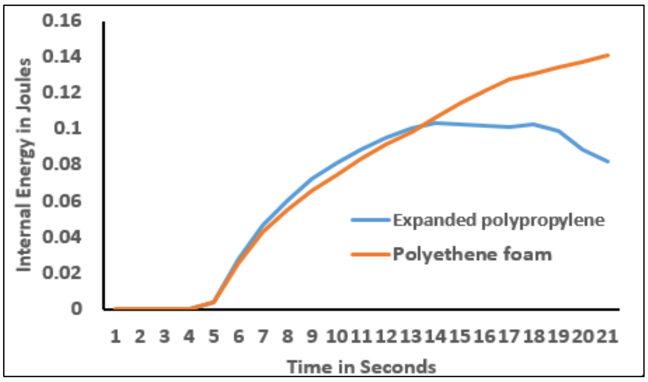

Figure 18: Time Vs Internal Energy of Energy Absorber

Polypropylene Cross-Sectional Geometry Variation

Further investigation was carried out between the vertical and horizontal cross sections of the hexagonal geometry of the polypropylene energy absorber. An analysis of low-speed impact test data comparing horizontal and vertical absorbers for automobile bumpers reveals compelling evidence favoring the vertical design. The test results demonstrate that vertical absorbers exhibit

superior performance characteristics, particularly regarding energy absorption capabilities (12).
Specifically, the vertical absorber consistently demonstrates higher internal energy values across most deformation points, indicating enhanced capacity to absorb impact forces and reduce force transmission to both the vehicle structure and its occupants, as seen in Figure 20.
Additionally, Figure 19 shows that, the vertical configuration achieves greater deformation at given internal energy levels, allowing for more effective energy dissipation before reaching maximum deformation limits. This characteristic is particularly advantageous as it helps mitigate impact forces while maintaining the structural integrity of the bumper system. While these performance metrics strongly support the selection of vertical absorbers for low-speed impact applications in automobile bumpers, it's essential to acknowledge that a comprehensive design decision should incorporate additional considerations such as manufacturing costs, weight implications, and long-term durability requirements. This holistic approach ensures that the final absorber selection optimally balances performance benefits with practical implementation constraints.

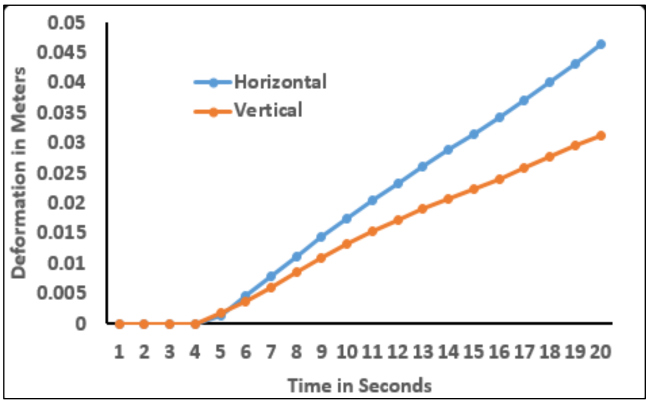

Figure 19: Time Vs Deformation of Polypropylene

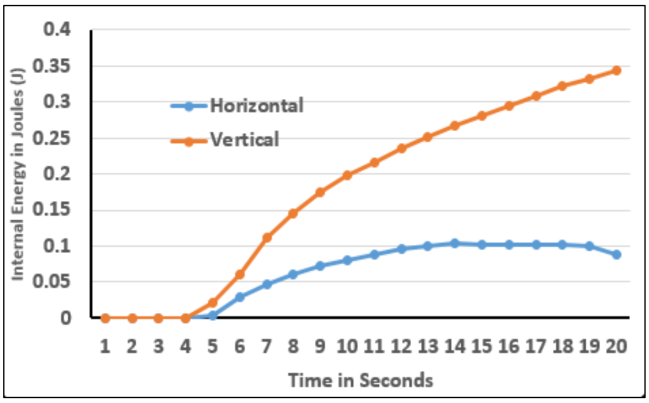

Figure 20: Time Vs Internal Energy of Polypropylene

Table 3: Comparison of Evaluated Materials

Component	Material	Key Properties	Drawbacks	Final Selection & Rationale
Bumper Body	Aluminium 6061	Lightweight, corrosion-resistant, moderate strength	High cost, moderate deformation under impact	Rejected: Deformation too high under load
	ABS Polymer	Lightweight, good impact resistance, cost-effective	High deformation under high impact	Rejected: Excessive deformation under dynamic loading

Component	Material	Key Properties	Drawbacks	Final Selection & Rationale
Absorber	Carbon Fiber Reinforced Plastic	High stiffness, low deformation, excellent crash resistance	Expensive, complex processing	Selected: Best performance in impact tests
	Expanded Polypropylene	High initial energy absorption, low cost	Less effective in prolonged impacts	Selected: Effective for low-speed crash protection
	Polyethene Foam	Sustained energy absorption, chemical resistant	Gradual response, higher weight	Rejected: Less efficient in initial impact response
Absorber Shape	Triangular, Diamond, Hexagonal	Hexagonal shows highest energy absorption and uniform crush	Complex to manufacture	Selected: Superior performance in all impact scenarios

Results of the investigation are tabulated in Table 3 to determine the suitable bumper for the four-wheeler. A bumper body with carbon fibre and an absorber with polyethylene foam and a hexagonal shape are found to be a suitable bumper.

Conclusion

The bumper beam in an automobile absorbs impact energy during collisions. This research uses FEM modelling to characterize it under low-velocity impact situations based on European regulations. Analytical methods were used to evaluate a few commercial materials based on design characteristics like thickness, supports, cross-section, and impact situations. Conventional materials exhibited unacceptable properties, including structural failure and heavy bumper beams. Passenger car bumper beams must survive frontal and rear low-velocity impacts without significant damage, as per automobile specifications.

Through finite element analysis and performance benchmarking, carbon fibre-reinforced plastic emerged as the most suitable material for bumper body applications, offering superior impact resistance and minimal deformation compared to ABS and aluminium.

This research demonstrates large advances in lightweight bumper layout for 4-wheeled cars through complete material evaluation and geometric optimization. The key conclusions are ABS polymer emerges as the most effective material for bumper bodies, supplying superior impact resistance and minimum deformation whilst achieving enormous weight loss in comparison to standard substances. In the case of geometry of absorber design, hexagonal cross-sectional geometry in vertical orientation presents the best strength absorption and deformation traits, though production complexity has to be considered. For power absorbers, expanded polypropylene proves extra effective for initial impact absorption, even as polyethene foam excels in sustained effect scenarios, suggesting the ability for hybrid solutions in future designs.

Integrating CFRP bumpers with polypropylene absorbers necessitates attention to joining methodologies and quality assurance protocols. Despite higher manufacturing complexity, the proposed hybrid design delivers substantial benefits in safety, durability, and weight reduction, supporting the advancement of lightweight automotive safety systems tailored for next-generation passenger vehicles.

The integration of advanced CAD/CAE gear with finite detail evaluation permits specific optimization of bumper systems, balancing performance necessities with production constraints. The examination validates that lightweight materials and optimized geometries can meet or exceed safety standards even as decreasing vehicle weight, contributes to improved gas performance and decreased emissions.

Finally, tooling for complex shapes like hexagonal absorbers requires precision molding and CNC fabrication, increasing initial setup costs. Joining multi-material assemblies, particularly CFRP to polypropylene, demands hybrid joining techniques such as adhesive bonding and mechanical fastening to maintain structural integrity. Welding is unsuitable due to material incompatibility. Quality assurance must integrate non-destructive testing (e.g., ultrasonic inspection for CFRP) and dimensional tolerance checks using 3D scanning to ensure crash performance and repeatability across batches. Consistent material characterization and simulated crash testing are crucial to validate energy absorption behavior and maintain compliance with automotive safety regulations.

Abbreviations
None.

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Author Contributions
All authors contributed equally in all aspect of the project.

Conflict of Interest
The authors declare that they have no conflicts of interest to report regarding the present study.

Ethics Approval
Not Applicable.

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