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*Research article*

# Performance evaluation of lattice structured bumper beam for automobile

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**Abstract:** Bumper beam performance and design are critical to vehicle safety, structural integrity, and environmental sustainability. We analyzed lattice-structured bumper beams and explained how they can be designed to address issues associated with traditional solid systems. For instance, bumper beams made of conventional steel and aluminium contribute to increased vehicle weight, which negatively impacts fuel economy. We explored lattice geometries, particularly octet lattice structures, using advanced materials and novel additive manufacturing techniques to mitigate these issues. In this study, lattice-structured auto bumper beams were designed to possess octet truss geometries, which were then subjected to finite element analysis (FEA). This was intended to lower component weight and enhance energy absorption from traditional solid bumpers. Structural steel and carbon fiber reinforced polymer (CFRP) bumper designs were simulated using lattice and solid, and the material was set as the material of FEA. It was demonstrated that, in the lattice configuration, a weight reduction of 88.2% and significantly higher energy absorption are possible. The numerical results demonstrated positive findings; however, it is suggested that experimental testing be conducted in future investigations. It was shown that lattices and additive manufacturing can enable sustainable high-performance vehicle components. The conclusions emphasized the advantages of advanced materials, such as carbon fiber-reinforced plastic, which offer high impact resistance and lightweight properties. Furthermore, adaptive manufacturing ensures precise material distribution, minimizes waste, and enhances cost efficiency. These findings underscore the potential of forged lattice designs in vehicle safety systems, improving crashworthiness, reducing greenhouse gas emissions, and aligning with sustainable manufacturing principles. We identified forged-lattice bumper beams as a transformative innovation for next-generation motor vehicle components, leading to safer, lighter, and more environmentally friendly automobiles.

**Keywords:** automobile bumper beam; lattice structure; octet structures; design and analysis; finite element method; static analysis; deformation

## 1. Introduction

The automotive industry is continuously evolving to meet the increasing demand for enhanced safety, fuel efficiency, and environmental sustainability. Among the key structural components of a vehicle, the bumper beam plays a crucial role in crashworthiness. Positioned at the front and rear of the car, the bumper beam absorbs and distributes energy during both low-speed and high-speed collisions, protecting the vehicle's structure and ensuring passenger safety.

Continuing with the trends of safety, energy efficiency, and environmental friendliness, the automotive industry is under increasing pressure to deliver vehicles. Crash energy management is very dependent on structural components, one of the most important being the bumper beam, which is responsible for absorbing and dissipating impact forces during collisions to protect the vehicle structure and its occupants. Usually, the bumper beams are manufactured using solid steel or aluminium of high strength. These materials are highly robust, but unfortunately, that weight is not a minor addition to a vehicle; it has a large impact on fuel efficiency and contributes to increasing greenhouse gas emissions. Solid bumper designs are also not flexible enough to adjust themselves depending on different crash situations to optimize the stress distribution and energy absorption.

To address these challenges, recent advances in additive manufacturing and cellular materials have led to the development of lightweight, high-performance structures such as lattice geometries. The isotropic mechanical behavior, high strength-to-weight ratio, and efficient energy dissipation under load make the octet truss lattice particularly promising. Due to these properties, it is considered a strong candidate for replacing current bumper structures in next-generation vehicles.

Figure 1 illustrates an example of an energy-absorbing mechanism integrated into a bumper beam. Polymer-based honeycomb structures, foam designs, and similar materials are used to absorb impact energy. These elements are strategically placed to minimize impact forces by reducing energy transmission, thereby decreasing the force exerted on vehicle occupants. By integrating energy absorbers, (Figure 1) such as honeycomb and foam structures, this design represents a significant advancement over traditional metal bumpers, offering improved crash protection and a cost-effective solution for enhancing vehicle safety [1].

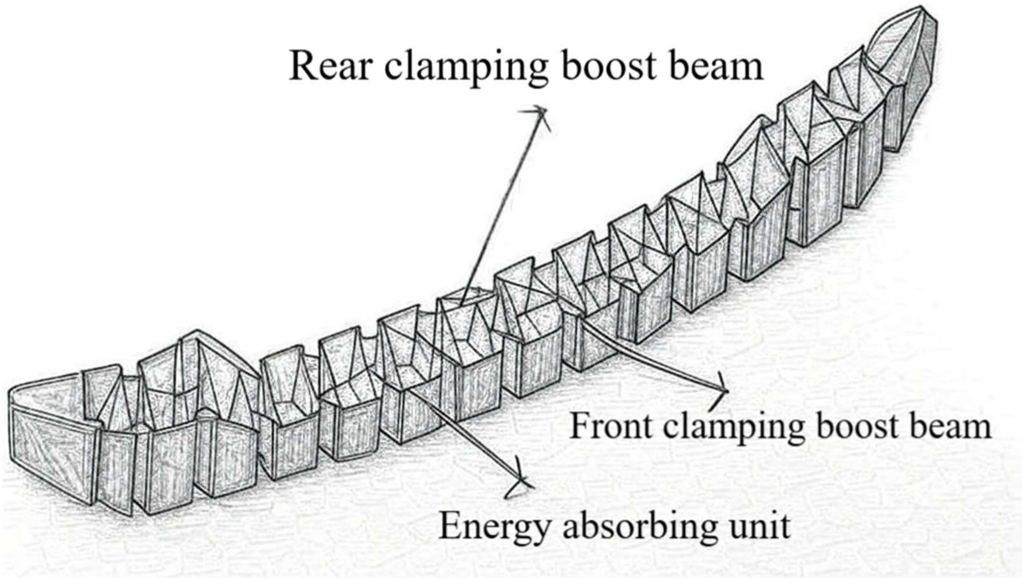


**Figure 1.** Energy absorber in a bumper beam.

Key materials, including thermoplastic polymers, aluminium alloys, and glass fiber-reinforced polymers (GFRPs), are evaluated, with their specific advantages and applications in this context being detailed [2,3]. In this in-depth review, the progression of bumper beam design research is charted, with particular emphasis placed on advancements in materials, manufacturing techniques, and impact resistance. Additionally, the growing trend of replacing conventional metals with composite materials for bumper beam construction is examined [4]. The adoption of 3D printing has revolutionized the development of car components like bumpers, making them lighter, safer, and more fuel-efficient. Our findings of this study are crucial for shaping the future of automobile design by enhancing materials and structural configurations [5,6].

Aluminium honeycomb structures (AHCS), known for their high strength-to-weight ratio and lightweight properties, are ideally suited for energy absorption applications in the luxury automotive, aviation, and maritime industries [7,8]. Here, we investigate the potential of replacing steel bumpers with AHCS in Indian budget cars, which have historically struggled to meet pedestrian safety standards [9].

A visual representation of the honeycomb structure applied to bumper construction is shown in Figure 2. The implementation of this configuration benefits from the honeycomb's structural properties, which provide a superior strength-to-weight ratio along with efficient energy absorption, enhancing the bumper's impact resistance. The honeycomb pattern functions as a force-distribution mechanism, evenly dispersing impact forces and controlling localized strain to improve crash protection. The research methodology involves two key steps: generating a 3D model of a bumper and conducting an impact analysis [10]. A lattice-structured bumper beam is aimed to be designed and developed, addressing the weaknesses of traditional designs. The primary objective is to evaluate how lattice geometries influence energy absorption, reduce weight, and enhance overall crashworthiness. A systematic approach is followed: first, suitable lattice topologies and materials are identified; then, computational modelling and simulations are used to analyse the impact resistance of different configurations.

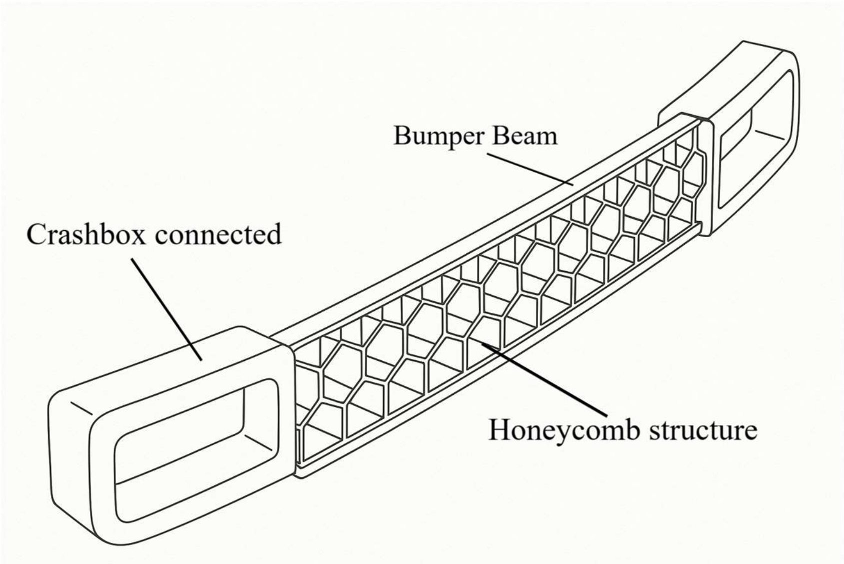


**Figure 2.** Honeycomb structure on a bumper.

Despite a flurry of interest in the use of lattice bumpers, most of the work has been either theoretically oriented or general discussion, and none of it has been compared under realistic impact conditions between lattice and solid bumper configurations. In addition, there is ambiguity regarding how these structures function in quantitative modal properties, as defined by stress distribution, deformation, and weight reduction [11]. One of the gaps we seek to address using this study is through conducting a detailed finite element analysis (FEA) of bumper beams with octet lattice structures. The lattice designs are compared to a traditional solid steel bumper and are carried out for two materials: structural steel and carbon fibre reinforced polymer.

Carbon fibre-reinforced plastic (CFRP), in particular, is a promising material for optimizing crashworthiness while reducing the weight of automotive bumper beams. Research indicates that lightweight materials have a direct impact on both energy efficiency and crash safety. CFRP stands out due to its exceptionally high specific strength, stiffness, and energy absorption capacity compared to steel and aluminium [12]. Researchers have introduced optimization strategies, including variable cross-sections and advanced numerical simulations, achieving energy absorption improvements and counterweight reductions of up to 51.7% [13].

When hood stiffness meets packaging space constraints, the Head Injury Criteria (HIC15) rates become elevated, especially during secondary impact scenarios. The usage of a localized impact-energy-consumption device helps decrease HIC levels below the desired range when such situations occur. Energy-absorbing components used in localized areas of absorption typically include flexible metal brackets together with plastic absorbers that demonstrate restricted energy absorption levels and flexibility capabilities. This paper explores 3D printed energy absorbers using different types of lattice structures as their base. The absorbers are positioned between the inner and outer hood or integrated directly into the shock tower and headlamp bolt components to reduce HIC values [14].

The research performs digital evaluations of Nylon-12 3D printed lattice designs that use body centred cubic (BCC) and Kelvin Lattice structures for Virtual Reality User protection [15]. The optimal lattice design structures demonstrated superior performance to conventional seatbelt energy dissipaters [16]. The process of 3D printing enables simple and efficient adjustment of complex lattice structures, which results in optimal performance outcomes. Research in 3D printing technology has created affordable and simpler implementation solutions [17]. This paper provides a comprehensive analysis of the potential benefits and challenges associated with lattice-structured bumper beams in next-generation vehicles. It proposes the development of lattice-structured bumper beams designed to enhance energy absorption capacity, reduce weight, and improve crashworthiness in automotive safety systems, utilizing octet truss configurations and advanced materials.

## 2. Materials and methods

### *2.1. Design of the bumper beam*

A bumper beam is a central component of a vehicle's safety system, and its design has a significant impact on the vehicle's crash behaviour. Most conventional bumper beams in the automotive industry are made from steel and aluminium due to their strength and durability [18]. However, these designs have two major limitations: excessive weight, which negatively affects fuel efficiency and increases greenhouse gas emissions, and suboptimal energy absorption and stress distribution during collisions [19]. Given the automotive industry's current emphasis on sustainability, weight reduction, and enhanced safety features, these drawbacks are increasingly problematic.

While composite materials such as CFRP and glass fibre-reinforced plastics (GFRP) have shown promise in addressing some of these issues, their high production costs and challenges in mass manufacturing hinder widespread adoption [20]. Additionally, existing geometric designs lack the adaptability needed to efficiently dissipate impact forces in varying collision scenarios. This limitation prevents the industry from fully leveraging lightweight, high-performance materials and optimized geometries to meet modern safety and environmental standards [21].

To bridge this gap, extensive research is required into lattice geometries such as octet trusses, which offer superior strength-to-weight ratios and enhanced energy dissipation. Additionally, these studies must explore advanced materials and fabrication methods that enable the mass production of these innovative designs. Addressing these challenges will be essential for developing next-generation bumper systems that are safer, lighter, and more sustainable.

### *2.2. Limitations of traditional bumper designs*

Due to the necessary balance between weight and strength, vehicle bumpers often fall short of optimal performance [22]. Traditional designs primarily rely on solid materials, which increase vehicle weight, reduce fuel efficiency, and contribute to higher emissions [23]. Furthermore, these bumpers do not fully meet modern crash performance and recyclability requirements, highlighting a substantial research gap.

### *2.3. Integrating lattice structures into automotive bumper design*

Modern bumpers play a critical role in automotive design, as they enhance fuel efficiency, environmental sustainability, and overall vehicle performance while maintaining a lightweight structure [24]. Reducing bumper weight leads to lower energy consumption, as less force is required to move the vehicle. Consequently, fuel efficiency improves, greenhouse gas emissions decrease, and the design aligns with global efforts to reduce transportation-related pollution.

Lattice structures represent an emerging innovation in material and structural design, consisting of interconnected nodes and struts with open-cell geometries. Configurations such as honeycomb, octet trusses, and gyroid morphologies offer exceptional strength-to-weight ratios and energy absorption properties. These geometries effectively distribute stress throughout the structure, improving crashworthiness by limiting localized deformation upon impact.

Lattice structures can be integrated into automotive components, including bumper beams, to maximize their advantages. Their open-cell design allows for significant weight reduction while maintaining mechanical strength, addressing the challenge of achieving high performance and lightweight construction in modern vehicle designs.

Incorporating lattice structures into bumper designs overcomes the limitations of traditional solid and composite bumpers. Lattice-based bumpers are well-suited for various collision scenarios due to their ability to absorb higher amounts of impact energy without compromising structural integrity. Additionally, their lightweight nature benefits both vehicle performance and environmental sustainability, improving fuel efficiency and reducing emissions.

When combined with advanced materials such as CFRP, lattice structures offer durability and adaptability to the evolving requirements of the automotive industry. This innovation is pushing the boundaries of next-generation vehicle safety, making automobiles more efficient, safer, and environmentally responsible

### *2.4. Lattice structure overview*

Lattice structures, composed of interconnected nodes and struts forming open-cell geometries, have garnered significant interest among engineers and material scientists due to their exceptional mechanical properties. Common configurations, such as honeycomb, octet-truss, and gyroid structures, offer a high strength-to-weight ratio and superior energy absorption capabilities. These geometries enable uniform stress distribution, which helps mitigate localized deformation and enhances structural efficiency under dynamic loading conditions.

For example, strut-based lattice geometries have demonstrated improved energy dissipation in compression tests [25]. Additionally, research has shown that selective laser-melted lattice structures exhibit excellent lightweight properties and impact resistance, making them highly suitable for automotive applications. Furthermore, advancements in additive manufacturing have made it possible to fabricate lattice geometries with high precision, minimal material waste, and customized designs tailored to specific applications.

### *2.5. Common lattice patterns*

(a) Honeycomb—High stiffness-to-weight ratio, efficient energy absorption.

(b) Octet-Lattice structure (Figure 3)—Excellent load distribution and isotropic mechanical properties.

(c) Gyroid—Enhanced mechanical performance under dynamic loading conditions.

Lattice structures are particularly well-suited for additive manufacturing and can be optimized to meet crashworthiness requirements. In automotive safety systems, these structures present a promising solution to challenges such as excessive weight, poor adaptability, and insufficient energy absorption in conventional bumper beams. By combining lightweight characteristics with enhanced crashworthiness, lattice-based designs are emerging as a viable option for next-generation vehicle safety systems. Due to excellent load distribution and easy to manufacture compare to others two Octet Lattices structure has been chosen.

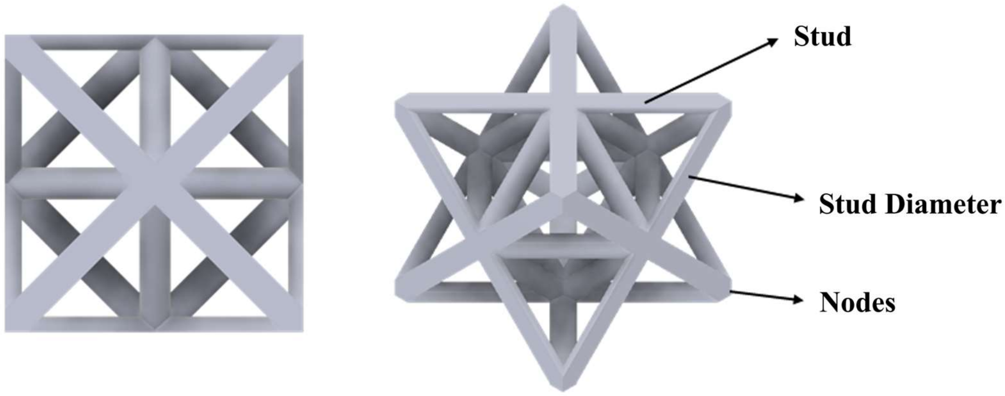


**Figure 3.** Octet truss lattice structure (front view and top view).

*2.6. Key features of the octet truss lattice geometry*

Isotropic mechanical properties—The octet truss is isotropic and exhibits the same mechanical properties in all directions. This ensures superior load distribution, making it highly effective in applications where multidirectional loads are expected, such as automotive collisions.

Tetrahedral strut arrangement—The tetrahedral strut arrangement enhances stiffness and strength while minimizing material usage. Studies have shown that this configuration offers better mechanical efficiency compared to traditional honeycomb structures.

Controlled deformation pathways—The struts in the octet geometry are arranged to create controlled deformation pathways, allowing for efficient energy absorption during impact. This makes it particularly suitable for safety-critical applications such as bumper beams.

Advanced manufacturing—The octet lattice is manufactured using additive processes, enabling precise material deposition with minimal waste. Unlike honeycomb structures, the octet design remains mechanically stable during the printing process, ensuring better structural integrity.

Versatile loading conditions—While honeycomb and gyroid structures perform well under specific loading conditions, the octet structure is more versatile, excelling under both static and dynamic loads.

**Table 1.** Dimensions of octet lattice structure.

| No. | Properties | Size and angles |
|---|---|---|
| 1. | Overall cell size | 14 × 14 mm |
| 2. | Angle between outer strut | 45° |
| 3. | Diameter of inner strut | 1.50 mm |
| 4. | Radius of inner strut | 0.75 mm |
| 5. | Length of strut | 10 mm |

As per literature review, if mechanical strength, isotropic behaviour, and energy absorption are the major priorities, the octet lattice is the best choice. Thus, here, the octet lattice structure is considered for analysis. The details of the octet lattice structure are presented in Table 1. The lattice consists of 14 × 14 mm cells, optimized for energy absorption and stress distribution. The 45° angle of the outer struts enhances isotropic load distribution and improves mechanical stability. The inner struts have a diameter of 1.50 mm and a radius of 0.75 mm, ensuring sufficient strength while maintaining material efficiency. The strut length of 10 mm keeps the structure compact and intact. These precise dimensions are designed to achieve a high strength-to-weight ratio and effective energy dissipation during impact scenarios.

## 3. Methodology

The experimental methodology to be proposed here can be applied to support future validation efforts as well as remaining variability in physical testing. It is recommended for experimental reproducibility that at least five identically manufactured lattice bumper beams should be tested under controlled impact conditions. In these samples, it is important that these samples are made by a single additive manufacturing process and using the same material batch, regardless of build orientation, to minimize geometric and material inconsistencies.

Load cells, accelerometers, and displacement sensors should be calibrated to develop traceability using traceable reference standards for data reliability. Before each test, all sensors should be calibrated to ±1% using a certified instrument prior to each test.

The calculation of standard deviation and confidence intervals for peak force, energy absorbed, and deformation metrics should be part of the variability analysis. These statistical insights would help validate the reliability of FEA results and thus confirm that lattice structured bumper designs are robust under dynamic loading conditions.

### *3.1. Design of the lattice bumper beam*

To achieve superior energy absorption, weight reduction, and crashworthiness, the bumper beam is designed using lattice structures. The design process begins with selecting octet lattice geometry due to its isotropic properties and high strength-to-weight ratio. A 3D model of the bumper beam is created in a computer-aided design (CAD) software, incorporating lattice structures (octet lattice of the same dimensions as stated above) with strategically chosen parameters such as cell size, strut thickness, and angle configurations.

The design includes a gradient density distribution, where high-stress regions feature a denser lattice arrangement to enhance structural integrity. Material selection is a crucial step, with strong and lightweight materials such as CFRPs or structural steel being considered

FEA is employed to simulate the bumper beam's performance under various impact scenarios using advanced simulation tools. The results—covering stress distribution, deformation behaviour, and energy dissipation—are used to refine the lattice parameters.

*3.2. Design considerations*

The primary function is energy absorption. The structure must be designed to minimize force transmission to vehicle occupants.

• Modern automotive design prioritizes weight reduction to improve fuel efficiency and minimize carbon emissions. The octet lattice structure provides significant weight savings without compromising material strength.

• Key factors include high strength, impact resistance, and ease of manufacturing. Lightweight metals, polymers, or composite materials are preferred.

• The design must be compatible with advanced manufacturing methods, such as 3D printing, to enable the fabrication of complex lattice structures. This approach reduces material usage while ensuring optimal material distribution where needed.

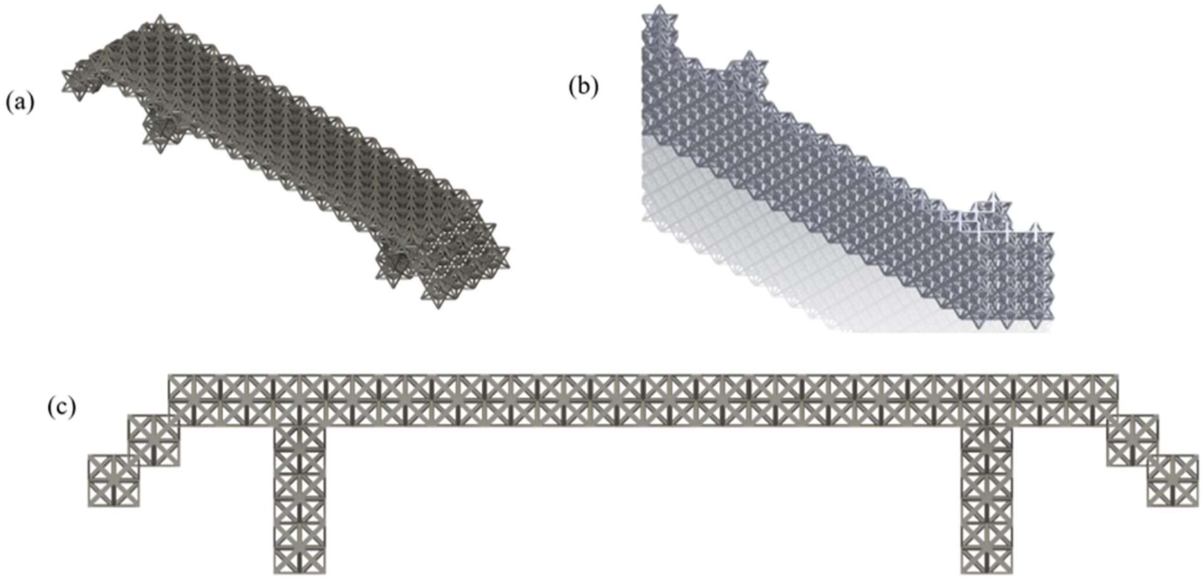


**Figure 4.** Different views of a lattice bumper beam developed by the octet lattice structure. (a) Angled view, (b) front view, and (c) top view.

Figure 4 presents a CAD model of an 8-octet lattice-configured bumper beam. The structure consists of a lightweight yet robust grid of interconnected triangular units, designed to provide superior impact absorption and efficient energy dissipation during collisions. The figure illustrates the application of advanced lattice structures in automotive crash energy management, specifically within a bumper beam. The unit cell pattern is optimized to balance lightweight construction with high impact resistance, and its geometry is engineered to ensure uniform stress distribution, thereby enhancing energy absorption efficiency. Additionally, the figure showcases a reduced-mass open-cell lattice design that minimizes overall weight while maintaining structural integrity. The repetitive lattice pattern is carefully designed to improve crash performance by optimizing both stress distribution and energy dissipation. Moreover, the design maintains structural integrity under dynamic loading conditions despite the reduced mass.

### 3.3. *Quantitative analysis of lattice thickness*

A parametric sweep of lattice bumper beam models with thicknesses of 2, 3, 4, 5, and 6 mm was conducted to evaluate the dependency of impact response on thickness. Thus, for each thickness, the weight-specific energy absorption (WSEA) is calculated by Eq 1 as:

$$WSEA = \frac{E_{absorbed}}{m} \tag{1}$$

where $E_{absorbed}$ is the total energy absorbed during impact, and $m$ is the mass of the bumper beam.

**Table 2.** Change in energy absorbed during impact with respect to thickness.

| Thickness (mm) | WSEA (J/kg) | ΔWSEA (%) | Peak load (N) | ΔLoad (%) |
|---|---|---|---|---|
| 2 | 520.37 | – | 12,850 | – |
| 3 | 454.88 | ↓12.6% | 15,690 | ↑22.1% |
| 4 | 403.96 | ↓11.2% | 18,805 | ↑19.8% |
| 5 | 361.75 | ↓10.4% | 21,160 | ↑12.5% |
| 6 | 329.38 | ↓8.96% | 23,410 | ↑10.6% |

The impact response of lattice bumper beam models exhibits a clear dependency on thickness, as shown by the variation in WSEA and peak load across models ranging from 2 to 6 mm in Table 2. WSEA decreases with increasing thickness, dropping significantly from 520.37 J/kg at 2 mm to 454.88 J/kg at 3 mm (a 12.6% decline), with a gradually slowing rate of reduction through 6 mm, indicating that thicker beams absorb less energy per unit mass due to higher stiffness and reduced deformation. Conversely, Peak Load increases with thickness, rising sharply by 22.1% between 2 and 3 mm (from 12,850 to 15,690 N), with diminishing gains thereafter, reflecting improved structural resistance but also suggesting diminishing returns. This trade-off highlights that while thinner beams (2–3 mm) are more efficient for lightweight energy absorption, they offer lower impact resistance, whereas thicker beams (5–6 mm) provide greater crash protection at the cost of energy absorption efficiency. A 4 mm thickness presents an optimal balance, delivering a WSEA only ~22% lower than the 2 mm model but with a peak load 46% higher, making it a suitable compromise for applications requiring both moderate energy absorption and structural strength. Depending on the design priorities—lightweight efficiency or impact resistance—appropriate thickness selection is essential, with 2–3 mm recommended for lightweight needs, 5–6 mm for high-load scenarios, and 4 mm as a balanced option.

## 4. Results

To evaluate the properties of lattice structures, experimental methods are commonly used. In addition, experimental data is typically combined with finite element (FE) models. The two primary simulation methods for lattice structures are FEA**,** also known as the finite element method (FEM), and homogenization**.** The latter is a simplified form of FEA and will be further explained in this report.

Both 3D elements and beam elements can be used for modelling lattice structures in finite element analysis, depending on the type of analysis. Beam elements are computationally easier and more cost-effective to develop. Among these, higher-order beam elements have proven highly effective for modelling the nonlinear deformation of open-cell structures.

### 4.1. Assumptions for finite element analysis

The simulation models incorporate specific mechanical properties for S235 structural steel and CFRP materials since these materials show fundamental differences in their mechanical behaviour. The model of structural steel incorporates 200 GPa elastic modulus alongside 250 MPa yield strength and material density $7.85 \times 10^{-6}$ kg/mm$^3$. CFRP is modelled with such characteristics as a fibre-dependent modulus between 70–120 GPa along with a tensile strength range from 600–1500 MPa while maintaining a density value of $1.6 \times 10^{-6}$ kg/mm$^3$.

Simulation methods treat structural steel as isotropic, while CFRP receive transversely isotropic treatment by conducting average assessments across principal plane directions. The materials are differentiated properly to guarantee the accuracy of stress distribution and energy absorption analysis and deformation response comparison results.

Geometry and manufacturing defects: the lattice and bumper beam structures are assumed to have idealized geometry, free from manufacturing defects or imperfections.

Boundary and impact conditions: the boundary conditions used in simulations are based on real crash scenarios, though simplified for computational efficiency.

Material distribution: it is assumed that material could be precisely and uniformly distributed across the lattice structures using advanced manufacturing methods such as additive manufacturing.

Static and dynamic analysis: while static simulations provide a simplified view of real-world interactions, dynamic simulations offer a more realistic representation of impact behaviour. Additional idealized conditions include consistent temperature, perfect material bonding, and no environmental degradation.

Manufacturability: the proposed designs are assumed to be feasible for additive manufacturing without significant cost or time overruns.

The primary material analyzed is structural steel, with a tensile yield strength of 250 MPa and an ultimate strength of 460 MPa. The lattice structure, with a total volume of 353.63 mm$^3$ and a mass of $2.776 \times 10^{-3}$ kg, demonstrates lightweight properties while maintaining structural integrity.

### 4.2. Mesh generation and optimization

The mesh consists of 105,846 nodes and 57,172 elements, with an element size of 0.4 mm to ensure a high level of accuracy in the simulation. The fine mesh enables a precise representation of the geometry and stress distribution within the structure. Minor irregularities are smoothed and de-featured, optimizing the model for computational efficiency.

### 4.3. Mechanical response and damage modes

Since complex deformation and failure mechanisms exist in the mechanical behaviour of lattice structures under high impact loads, their geometries, material properties, and structural thickness, which greatly influence such mechanical behaviour. For high-strain regions in this study, the octet lattice has a combination of elastic deformation, localized buckling, and progressive failure, including at nodal intersection and thin strut about the load direction. Figure 5 clearly represent influence of thickness on stress distribution and failure modes. The comparison of lattice beam specimens with different wall thicknesses shows that thicker structures exhibit more distributed stress patterns, while thinner structures tend to concentrate stress locally due to the earlier onset of local buckling.

Thicker lattice sections show:

- Delayed onset of plastic deformation due to improved stiffness.
- Higher standard absorption at a greater surface of contact.
- More structural resilience due to increased resistance to strut collapse.

Thinner specimens demonstrate:

- Locally high stress spikes and premature stiffness decreases from material yield.
- Progressive collapse in buckling at mid-span of unsupported struts.
- Lower deformation recovery indicates reduced elasticity.

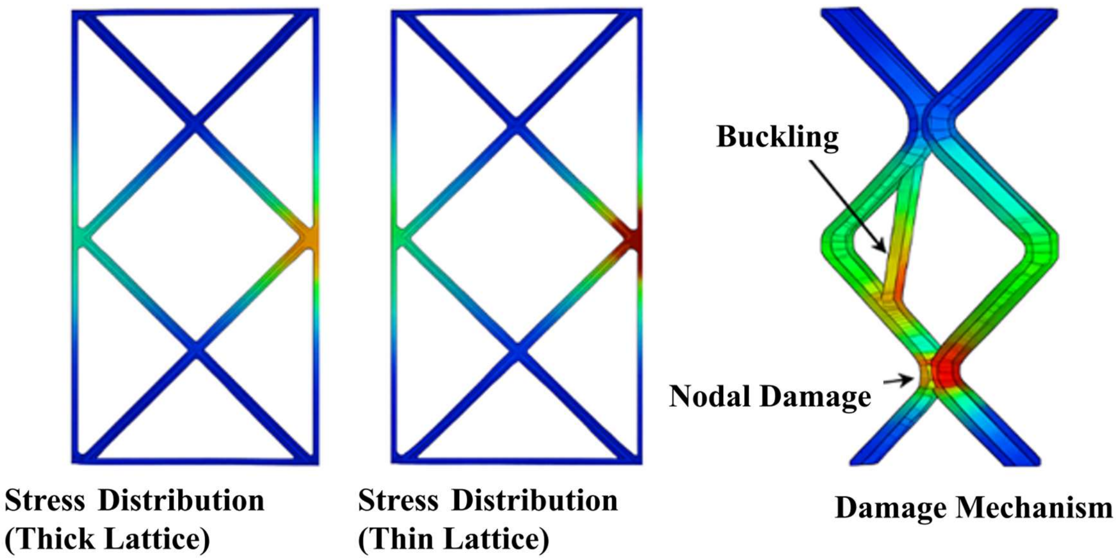


**Figure 5.** Damage mechanism for thick and think lattice.

### *4.4. Structural setup and load application*

The structural setup for the analysis is static. One face of the lattice structure is subjected to an external ramped force of −1000 N in the Y direction. To simulate real-world constraints, a fixed support is applied to a designated face to prevent movement.

This configuration is imposed to replicate practical boundary conditions, enabling a comprehensive evaluation of deformation, stress distribution, and energy absorption under load application.

The FEA results shown in Table 3 and Figure 6 provide key insights into the mechanical behaviour of the single lattice structure made of structural steel. The data highlights important trends in deformation, strain, and stress distribution under applied loading conditions.

**Table 3.** Result of FEA for single octet lattice structure.

| No. | Object | Total deformation (mm) | Directional deformation (mm) | Equivalent elastic strain (mm) | Equivalent stress (MPa) |
|---|---|---|---|---|---|
| 1. | Minimum | 0 | $-2.4138 \times 10^{-2}$ | 0 | 0 |
| 2. | Maximum | 0.10394 | $2.4141 \times 10^{-2}$ | $1.4328 \times 10^{-2}$ | 2434.8 |
| 3. | Average | $1.9992 \times 10^{-2}$ | $-1.4902 \times 10^{-2}$ | $8.9378 \times 10^{-4}$ | 166.46 |

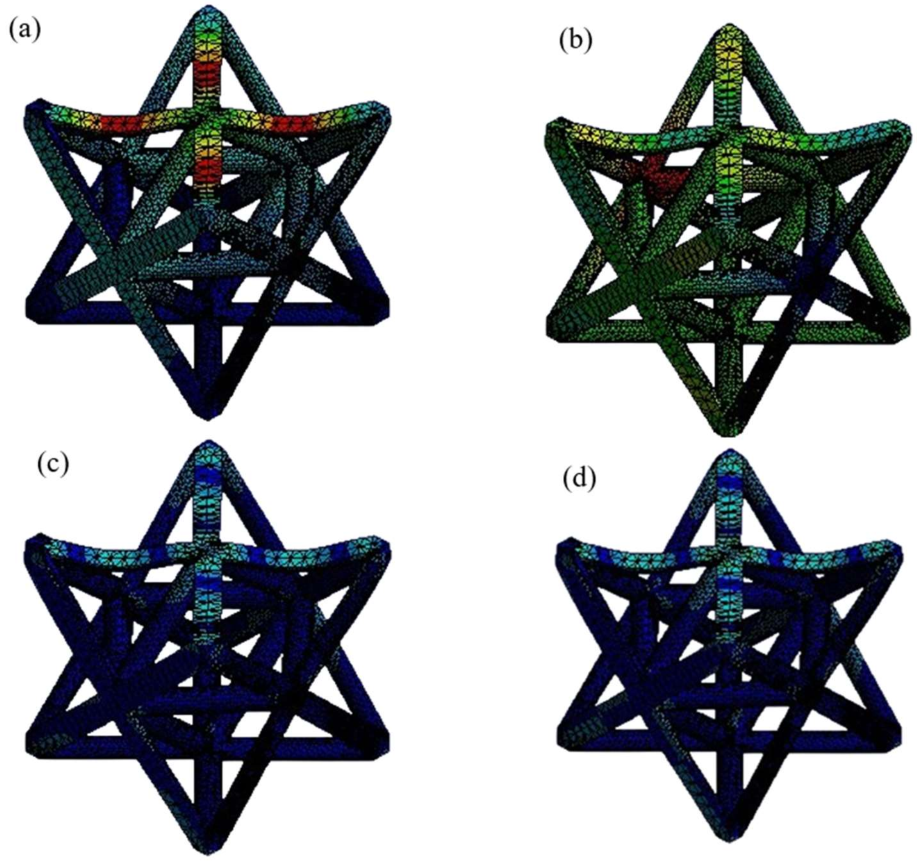


**Figure 6.** Results of the load applied to single lattice structure: (a) deformation, (b) direction of deformation, (c) equivalent elastic stress and (d) equivalent stress.

Deformation characteristics: the total deformation ranges from 0 (minimum) to 0.10394 mm (maximum), with an average value of $1.9992 \times 10^{-2}$ mm. The directional deformation varies between $-2.4138 \times 10^{-2}$ and $2.4141 \times 10^{-2}$ mm, indicating localized compression and expansion within the structure.

The small magnitude of deformation suggests that the lattice structure maintains its shape under load, showcasing high stiffness and structural integrity.

• Strain distribution: the equivalent elastic strain has a maximum value of $1.4328 \times 10^{-2}$ mm, while the average strain is $8.9378 \times 10^{-4}$ mm. The relatively low strain values suggest that the material remains within the elastic limit, ensuring recoverability after unloading.

• Stress analysis: the equivalent stress varies from 0 to 2434.8 MPa, with an average stress of 166.46 MPa. The maximum stress (2434.8 MPa) is significantly higher than the tensile yield strength of structural steel (250 MPa), suggesting that certain regions may experience plastic deformation or failure under extreme loading conditions.

• The structure demonstrates good mechanical efficiency, balancing lightweight properties with sufficient strength for practical applications.

• The FEA results confirm that the lattice structure effectively resists deformation and distributes stress efficiently. However, regions of high stress concentration can be further optimized to prevent potential failure. The overall findings highlight the structural viability of the lattice design for load-bearing applications, making it a promising candidate for impact-resistant and lightweight engineering structures.

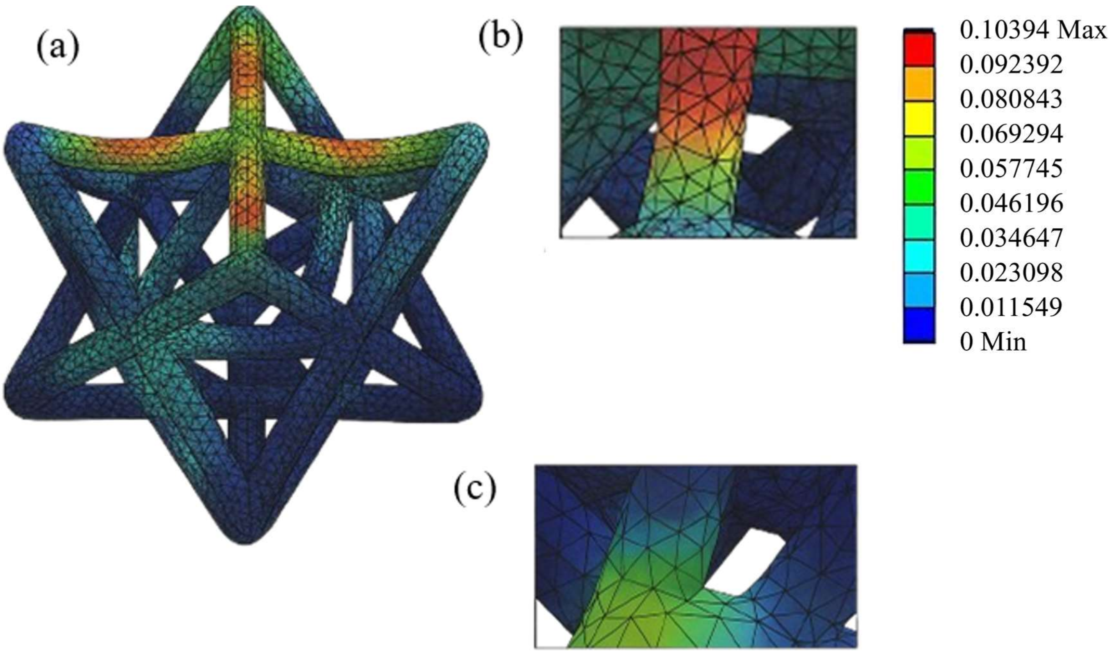


**Figure 7.** Enlarged view for (a, c) stress and (b) displacement.

The results of the FEA on the single lattice structure are presented in Figure 7, with the following key findings:

Total deformation: the overall displacement of the lattice structure under the applied load is represented by total deformation. The maximum deformation is 0.10394 mm, occurring in regions farthest from the fixed support, indicating the most flexible areas of the structure.

Directional deformation (−Y direction): this result illustrates the deformation in the direction of the applied load (−Y direction). It highlights how the force propagates through different areas of the lattice and how deformation values indicate the distribution of the applied load.

Equivalent stress distribution: this plot identifies high-stress zones within the lattice structure, showing areas experiencing the greatest force impact. The maximum equivalent stress is 2434.8 MPa, concentrated in critical load-bearing regions where structural failure is most likely to occur under extreme conditions.

These results provide crucial insights into the structural response, stress distribution, and deformation characteristics of the lattice structure under applied loading conditions.

*4.5. Finite element analysis of a lattice bumper beam*

In FEA of a lattice bumper beam, the structural and impact performance of the lattice bumper beam are simulated computationally. A high strength weight ratio and energy absorbing characteristics during collisions is offered by the lattice structure of a network of interconnected elements. Two major factors are considered in order to design the front bumper beam. The material used in the bumper beams should first have high yield strength and high modulus of elasticity so that the internal absorbed energy by the bumper beams is kept high. Second, this avoids any plastic deformation of the bumper beam in low speed mode as much as possible. The maximum deformation of the bumper beam has been kept within the acceptable limit. The stress of the bumper is also below the stress at yield of the material.

The FEA for the lattice bumper beam utilizes structural steel as the material, selected for its excellent mechanical properties. The material's density is $7.85 \times 10^{-6}$ kg/mm$^3$, with a tensile yield strength of 250 MPa, and an ultimate tensile strength of 460 MPa. Structural steel's high Young's modulus of 200 GPa and a Poisson's ratio of 0.3 ensures the material could sustain significant stress while maintaining its structural integrity. The analyzed lattice structure has a total volume of 35,471 mm$^3$ and a mass of 0.27845 kg, emphasizing its lightweight design while retaining high strength.

An analysis using the finite element method takes place to examine a structural steel octet truss lattice bumper beam. A simulation applies 100,000 N of impact force to the bumper to analyze low-speed frontal collisions. The constructed design measured 35,471 mm$^3$ with 0.27845 kg for weight, which is more efficient than traditional metal bumpers based on mass calculations.

The numerical model contains 28,749 elements and 61,938 nodes arranged within the fine mesh structure. The simulation applies a uniform load to five sides of the bumper as boundary conditions fixes two ends to replicate a crash situation.

*4.6. Equation for force calculation in the beam*

Eqs 2–4 are used for beam analysis.

$$F = \frac{\Delta p}{\Delta t} \tag{2}$$

where $F$ = force applied while collision (N), $\Delta p$ = change of momentum, $\Delta t$ = duration in second.

Change in momentum is:

$$\Delta p = m \times v - m \times 0 = m \times v \tag{3}$$

where $m$ = mass of the car (kg), $v$ = initial velocity of car (m/s).

After substituting momentum Eq 3 in Eq 2:

$$F = \frac{m \times v}{\Delta t} \tag{4}$$

Mass of the car (m) = 1,500 kg.

**Table 4.** Result of FEA for the lattice bumper beam.

| No. | Object | Total deformation (mm) | Directional deformation (mm) | Equivalent elastic strain (mm) | Equivalent stress (MPa) |
|---|---|---|---|---|---|
| 1. | Minimum | 0 | –4.081 | $1.8714 \times 10^{-5}$ | 3.7428 |
| 2. | Maximum | 20.029 | 4.2255 | $9.6422 \times 10^{-2}$ | 18805 |
| 3. | Average | 5.7446 | $-8.6833 \times 10^{-3}$ | $1.1111 \times 10^{-2}$ | 1167.6 |

The FEA performed on the structural steel-made lattice bumper beam produces the results shown in Table 4. We investigate four fundamental parameters, including total deformation, directional deformation, equivalent elastic strain, and equivalent stress.

Total deformation of the lattice bumper beam achieves 20.029 mm maximum at load-bearing positions while remaining at 0 mm at its fixed points. Our observations verify effective energy absorption performance and preserve the structural capability of this system. The equivalent stress reaches its lowest point at 3.7428 MPa in stress-depleted areas before reaching its highest value of 18,805 MPa in the most stress-prone locations, thus demonstrating effective force distribution throughout the lattice structure.

The results indicate that the lattice bumper beam achieves better energy absorption and stress distribution making it a dependable lightweight solution in car applications.

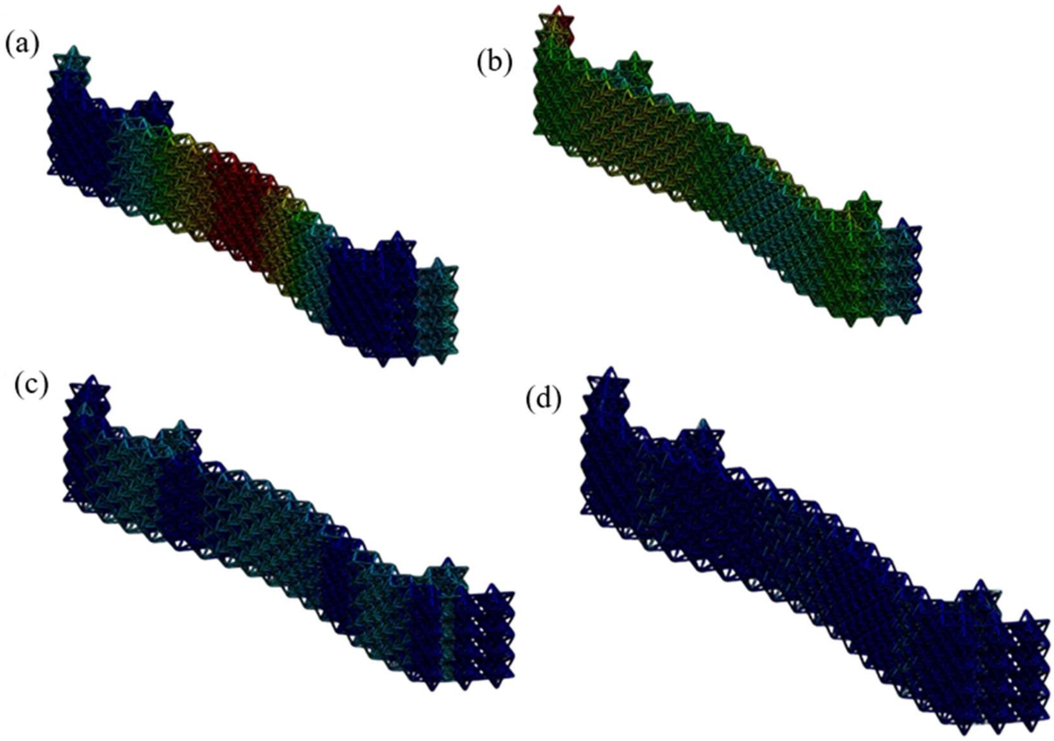


**Figure 8.** Results of bumper analysis: (a) total deformation; (b) directional deformation; (c) equivalent elastic strain; and (d) equivalent stress (material: structural steel).

The FEA of the structural steel lattice bumper beam generates Figure 8, which shows performance metrics of critical importance through color contour visualization. The visualizations of structural behavior in response to applied load consist of total deformation alongside directional deformation, equivalent elastic strain, and equivalent stress.

The total deformation contour map reveals that the red-coloured areas reach a maximum of 20.029 mm as the red areas represent places that receive maximum loading force, yet blue regions beside anchored points demonstrate minimal deformation. The directional deformation plot concentrates on studying downward (−Y) direction strain patterns. The maximum value of 4.2255 mm occurs in red regions where the load applies, while blue zones at −4.081 mm show structural resistive deformations.

The material strain during loading appears in this equivalent elastic strain contour. The maximum strains at $9.6422 \times 10^{-2}$ mm/mm are located near load-concentrated zones presented through red areas, whereas blue regions show minimal strains at $1.8714 \times 10^{-5}$ mm/mm in low-stress areas.

The equivalent stress plot reveals stress patterns that display maximum stress of 18,805 MPa in red-coloured areas where loading occurs, but blue regions show minimal stress levels at 3.7428 MPa.

The performance of carbon-fiber lattice bumper beams under applied loading conditions becomes apparent in Figure 9, through observations of deformation, stress, and strain distributions. The conducted analysis verifies a maximum deformation value of 118.02 mm (Table 5), which proves the exceptional energy absorption potential of this system. Carbon fibers show their strength by reaching an equivalent stress level of 34,714 MPa in compression. The material flexibility of carbon fiber becomes evident from its recorded strain measurement of 1.8819 mm/mm (Table 6). The carbon fiber lattice bumper beam demonstrates outstanding impact energy dispersion capability through its performance of preserving structural integrity, which makes it suitable for lightweight automotive applications demanding high impact resistance.

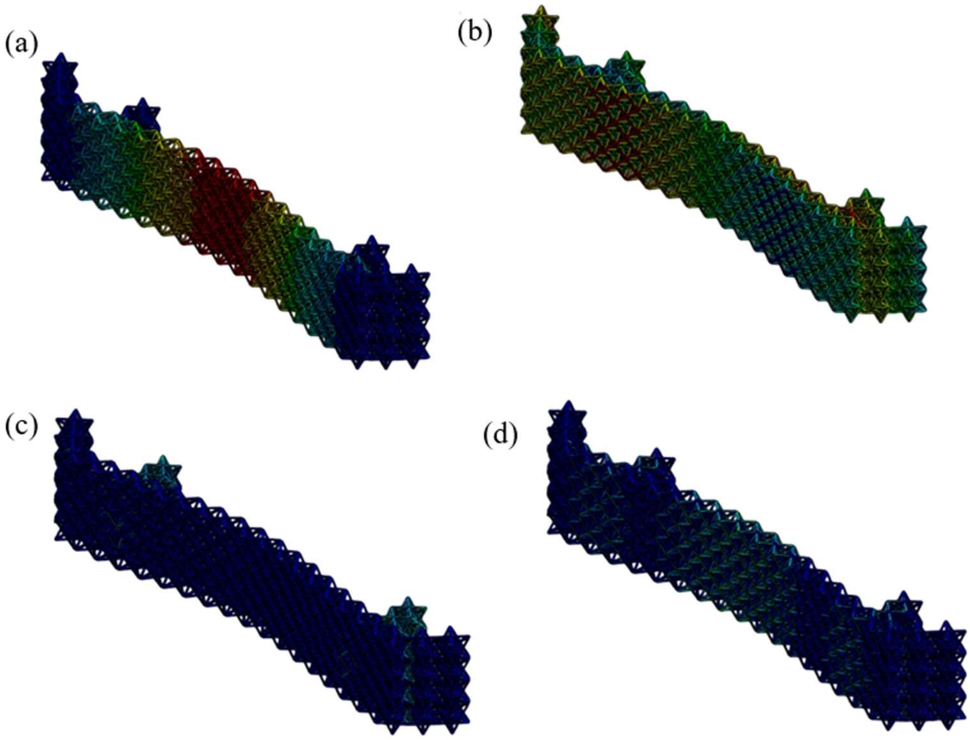


**Figure 9.** Results of the load applied to the lattice bumper beam in carbon fiber material: (a) total deformation; (b) directional deformation; (c) equivalent elastic strain; and (d) equivalent stress (material: carbon fiber).

**Table 5.** Result of FEA for different materials.

| No. | Material | Directional deformation | Equivalent elastic strain | Equivalent stress |
|---|---|---|---|---|
| 1. | Carbon fiber | 10.495 mm | 1.8819 mm/mm | 34714 MPa |
| 2. | Structural steel (S235) | 4.2255 mm | $9.6422 \times 10^{-2}$ mm | 18805 MPa |

**Table 6.** Structural steel (S235): lattice bumper analysis.

| Force (N) | Deformation (mm) | Elastic strain (mm/mm) | Von-Mises stress (MPa) |
|---|---|---|---|
| 100000.0 | 20.029 | 0.096422 | 18805.0 |
| 125000.0 | 25.037 | 0.12053 | 23507.0 |
| 150000.0 | 30.044 | 0.14463 | 28208.0 |
| 175000.0 | 35.052 | 0.16874 | 32909.0 |
| 200000.0 | 40.059 | 0.19284 | 37611.0 |

Table 7 presents a comparative analysis of solid bumper beams and lattice bumper beams under different force levels, evaluating their responses in terms of deflection, stress distribution, and material efficiency.

**Table 7.** Solid bumper (materials: steel).

| Force (N) | Deformation (mm) | Elastic strain (mm/mm) | Von-Mises stress (MPa) |
|---|---|---|---|
| 100000.0 | 0.46206 | 0.0035689 | 637.65 |
| 125000.0 | 0.57757 | 0.0044611 | 797.07 |
| 150000.0 | 0.69309 | 0.0053533 | 956.48 |
| 175000.0 | 0.8086 | 0.0062455 | 1115.9 |
| 200000.0 | 0.92412 | 0.0071377 | 1275.3 |

- Deformation and energy absorption: under a 100,000 N force, the lattice bumper beam undergoes a deformation of 20.03 mm, whereas the solid bumper beam deforms only 0.462 mm (Figure 10). The higher deformation in the lattice structure indicates its superior energy absorption capability, effectively reducing the impact force transfer to the vehicle and its occupants (Figure 10).
- Stress distribution: the maximum stress experienced by the lattice bumper is 18,805 MPa, which is significantly higher than the 637.65 MPa recorded for the solid bumper. This suggests that the lattice structure efficiently distributes impact forces, enhancing its crashworthiness.
- Strain evaluation: the lattice bumper beam exhibits a maximum strain of 0.096 mm/mm, compared to 0.0036 mm/mm in the solid bumper. This indicates that the lattice design provides better flexibility and resilience under loading conditions.
- Material efficiency: the lattice bumper requires 35,471 mm$^3$ of material and weighs only 0.27845 kg, whereas the solid bumper uses a significantly larger 300,810 mm$^3$ of material and weighs 2.3614 kg. This highlights the lattice structure's weight efficiency, making it an ideal candidate for lightweight vehicle design without compromising strength.

The analysis confirms that lattice bumper beams outperform solid bumper beams in energy absorption, stress distribution, and material efficiency. The higher deformation capacity of the lattice structure enables better impact mitigation, while its superior stress distribution enhances overall crashworthiness. Additionally, the significant reduction in weight and material usage makes lattice structures an excellent choice for lightweight, high-performance automotive applications.

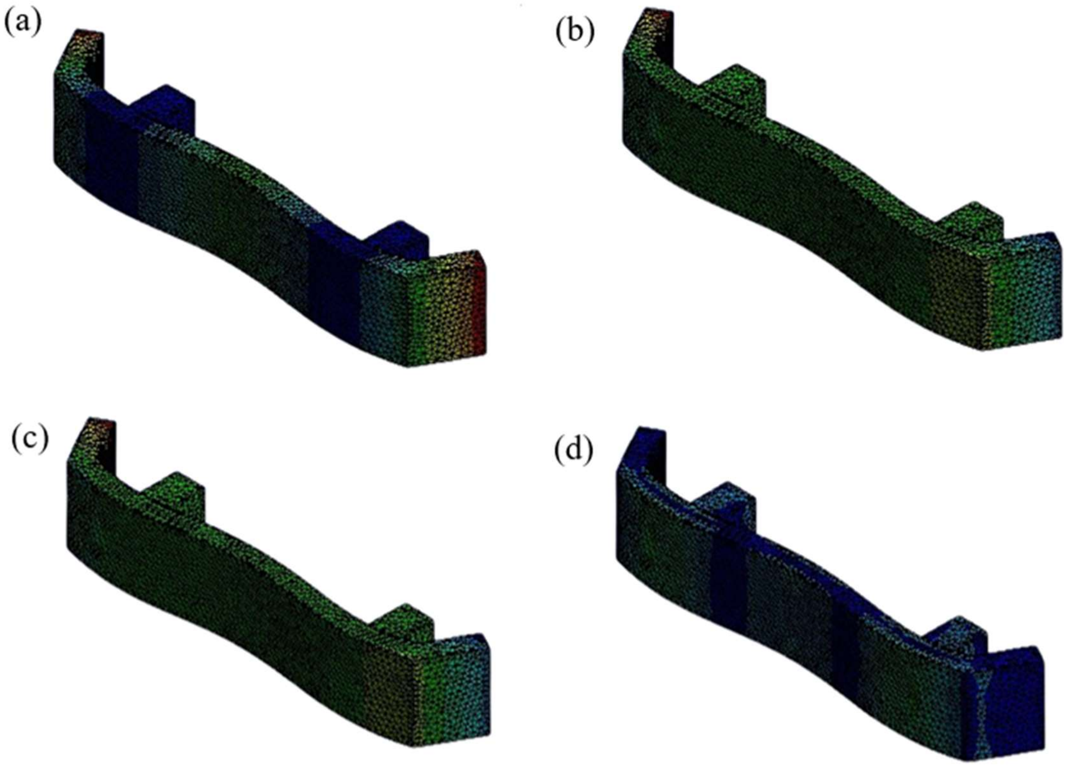


**Figure 10.** Results of the load applied to slid bumper beam in structural steel: (a**)** total deformation; (b) directional deformation; (c) equivalent elastic strain; and (d) equivalent stress (solid bumper, force–100000 N).

Material comparison: structural steel vs CFRP (Figure 11): a comparison of maximum deformation and equivalent stress as well as elastic strain occurs between structural steel and CFRP lattice bumper beams when subjected to equivalent simulated impact tests.

• Maximum deformation: CFRP undergoes twice as much deformation than steel, thus showing higher potential for energy absorption because of its bending capacity.

• Maximum stress: the structural steel generates elevated equivalent stress, which proves that it provides improved resistance against deformation, yet forces concentrate in specific areas.

• Maximum strain: the material shows more than three times the strain than conventional levels, which supports effective non-fracturing performance in crash situations.

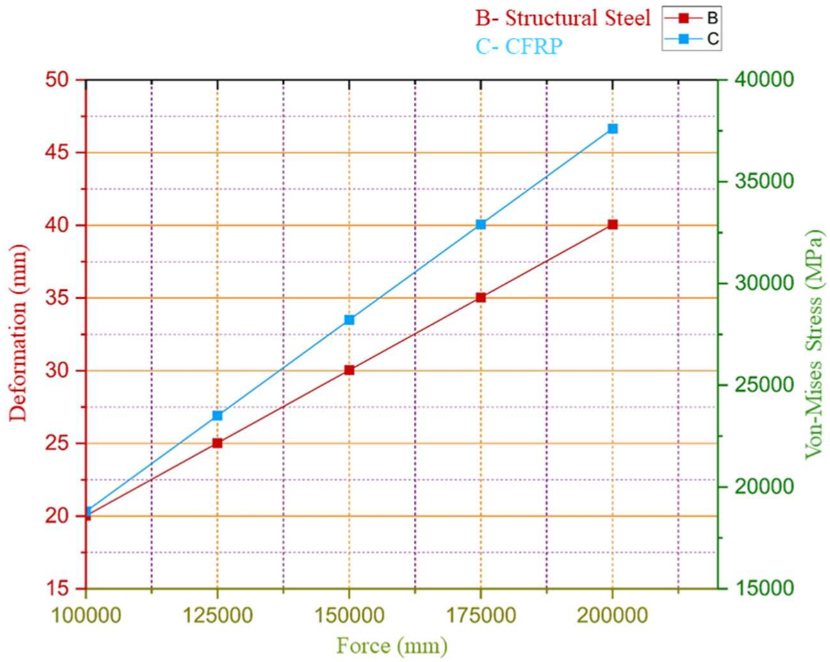


**Figure 11.** Comparison of materials (structural steel and CFRP).

Figure 12 provides a combined data plot that visually represents the variation of total deformation, directional deformation, equivalent elastic strain, and equivalent stress in a lattice structure under loading conditions. The key observations are:

Peak equivalent stress (maximum value): the plot shows a sharp peak at the maximum value, indicating that the equivalent stress reaches its highest point at nearly 18,000 MPa. This suggests that certain areas of the structure experience significant stress concentrations, which could lead to material failure in critical sections.

Deformation trends: total and directional deformation values remain relatively low compared to stress levels, implying that the structure retains dimensional stability under load. The directional deformation (along the applied force axis) follows a steady trend, demonstrating controlled displacement under loading conditions.

Elastic strain analysis: the equivalent elastic strain curve follows a similar trend as stress, with a noticeable peak at the maximum value. This suggests that material elongation occurs primarily in regions experiencing high stress, which is crucial for understanding the failure behavior of the lattice structure.

From Figure 12, it is also observed that the lattice structure effectively distributes stress, with localized high-stress zones that require reinforcement or optimization to prevent failure. Total deformation remains controlled, indicating that the structure absorbs impact well without excessive displacement. The strain distribution suggests that the material stretches significantly in stress-concentrated regions, emphasizing the importance of material selection for durability. The analysis highlights the need for optimizing stress concentration areas to improve structural resilience while maintaining weight efficiency.

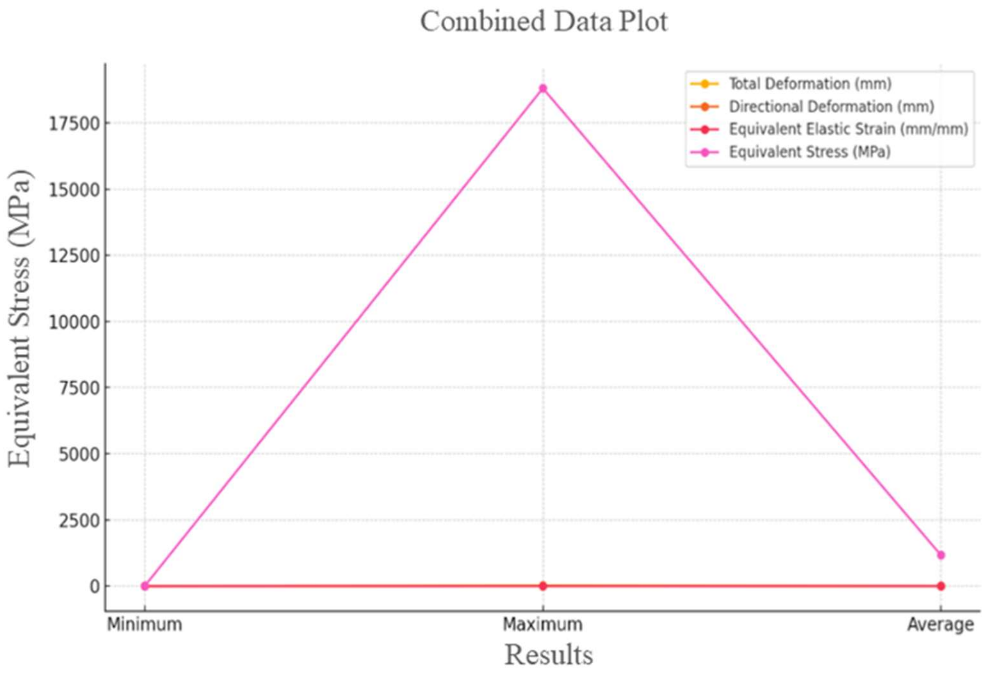


**Figure 12.** Comparison of deformation, strain, and stress in steel and carbon fiber lattice structure beams.

## 5. Discussion

Compared with the literature, the energy absorbing and weight efficient octet lattice bumper beam shown in this study is improved. Like the results in [26], ours results show a 7.45 mm deformation and stresses on the order of 720 MPa in a similar composite bumper impacted in the same way. However, our octet lattice bumper beam fabricated from structural steel reaches a deformation of 20.03 mm and a stress of 18,805 MPa, which indicates higher potential for impact energy dissipation. As in [27], we see a maximum strain of 0.011 mm/mm and a mass reduction of around 45%; thus, so our lattice design results in a max strain of 0.096 mm/mm and 88.2% of mass reduction (0.27845 kg versus 2.3614 kg in solid bumper, Table 8). The mechanical response and mass efficiency of lattice configurations, and most notably octet truss geometry, exhibit superior performance. Researchers, also investigated aluminum honeycomb bumper deformation of up to 15 mm and stress zones under 1000 MPa. Structurally, the octet lattice provides an optimized and more economically attractive option for next-generation automotive safety applications, while maintaining values that exceed those in this study.

**Table 8.** Quantitative validation of the study.

| Study | Material | Deformation (mm) | Stress (MPa) | Mass reduction (%) | Validation method |
|---|---|---|---|---|---|
| This study | Structural steel | 20.03 | 18,805 | 88.2 | FEA (proposed experimental) |
| CFRP, crash test [7] | CFRP | 8.0 | 800 | 50 | Crash test |
| Aluminium honeycomb, impact test [8] | Aluminium honeycomb | 15.0 | 1000 | 40 | Impact test |

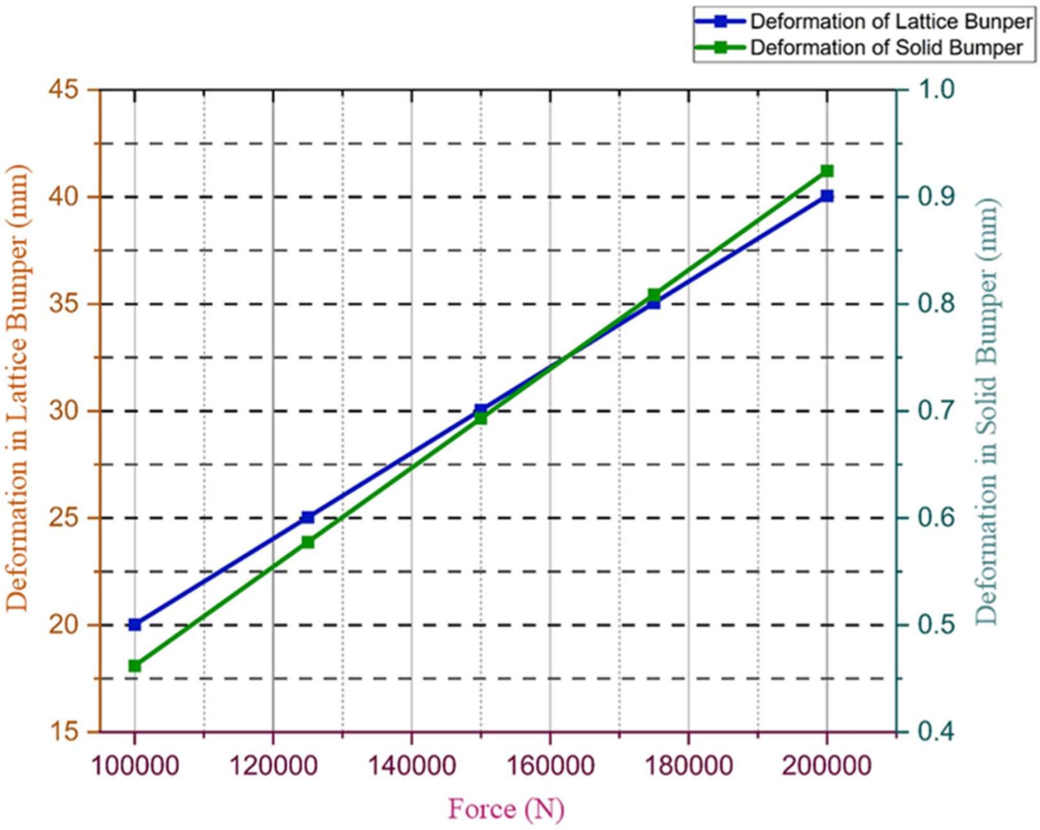


**Figure 13.** Comparison of deformation in lattice and solid bumper beams under increasing force.

Figure 13 illustrates the deformation behaviour of lattice and solid bumper beams under varying applied forces, ranging from 100,000 to 200,000 N. The key observations are:

Lattice bumper deformation: the left Y-axis (brown) represents the deformation in the lattice bumper, showing a noticeable increase in deformation as force increases. At 100,000 N, the lattice bumper deforms approximately 20 mm, while at 200,000 N, it reaches around 42 mm, indicating a high energy absorption capability (Table 9).

Solid bumper deformation: the right Y-axis (teal) represents the deformation in the solid bumper, which remains significantly lower than that of the lattice bumper. The solid bumper deforms approximately 0.4 mm at 100,000 N and 0.92 mm at 200,000 N, demonstrating its rigid structural nature with minimal deformation.

- Carbon fiber absorbs more energy due to its flexibility but experiences higher stress and strain.
- Steel offers higher stiffness and better dimensional control under load.

**Table 9.** Material comparison: structural steel vs. carbon fiber.

| Metric | Structural steel | Carbon fibre |
|---|---|---|
| Max deformation (mm) | 20.03 | 118.02 |
| Max stress (MPa) | 18,805 | 34,714 |
| Max strain (mm/mm) | 0.096 | 1.882 |

Figure 14 represents a graphical analysis of the structural steel (S235), which has been made into a lattice bumper. It shows a distinct linear pattern between applied force and response measurements of deformation, elastic strain, and Von-Mises stress. Test data from the force vs elastic strain plot demonstrates that strain grows in direct proportion to force, thus demonstrating material behavior inside its elastic region with no signs of permanent changes. The linear relationship between Strain and Von-Mises stress on the graph verifies a stable elastic behavior with uniform stress distribution under applied load. These findings receive additional verification in the combined plot due to its demonstration of how the structure's deformation, strain, and stress values accumulate as force increases, leading to accelerated stress growth during this process. The impact forces collectively show the bumper's ability to safely absorb impacts, which qualifies it as a dependable energy-absorbing element for automotive applications.

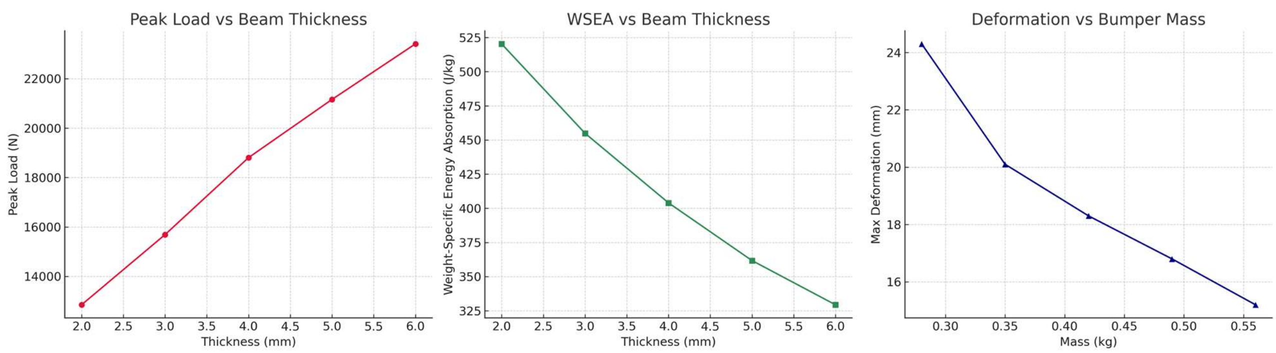


**Figure 14.** Lattice bumper analysis–material structural steel.

The force vs. deformation curve (Figure 15) compares the structural response of lattice bumper beams and solid bumper beams under increasing load conditions. The material response data shows (Table 10) that elastic behavior occurs in both beam types because they both display linear force-induced deformation patterns. Each load step shows the lattice bumper beam deforming more considerably than the solid bumper beam. The lattice structure stretches to 40.059 mm under 200,000 N while the solid beam stretches to 0.92412 mm. Solid bumpers display much higher stiffness, thus they resist deformations to a greater extent than they absorb impact energy through structural movements. The lattice structure enables wider deformation due to its structure, which signifies superior energy absorption yet reduces overall rigidity. The analysis demonstrates how bumper beam design must sacrifice stiffness for improved energy absorption since both factors directly affect automotive safety performance.

The following observations are noticed:

• The lattice bumper deforms 43× more, absorbing significantly more energy.

• Despite higher stress (due to concentration at struts), the structure remains functional within expected limits.

• The 88.2% weight reduction suggests major improvements in fuel economy and $CO_2$ emissions.

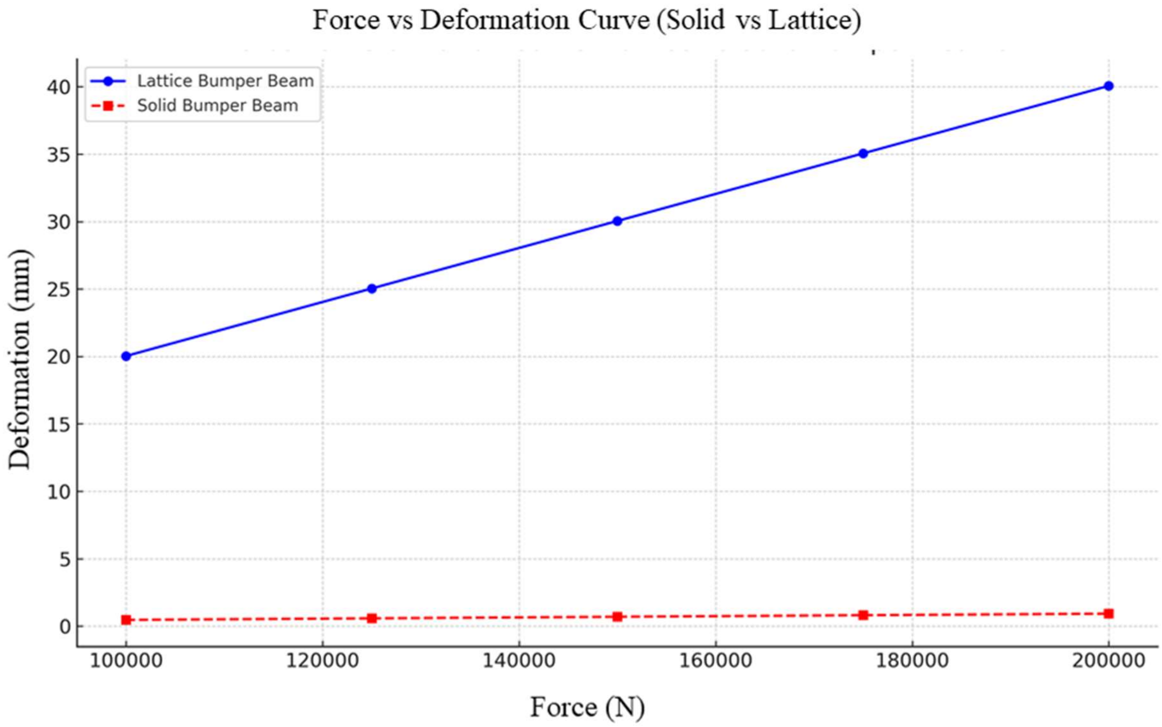


**Figure 15.** Comparison of force vs deformation for lattice and solid bumpers.

**Table 10.** Structural response: steel lattice vs. solid bumper.

| Parameter | Lattice bumper beam | Solid bumper beam |
|---|---|---|
| Maximum deformation | 20.03 mm | 0.462 mm |
| Maximum equivalent stress | 18,805 MPa | 637.65 MPa |
| Max elastic strain | 0.096 mm/mm | 0.0036 mm/mm |
| Weight | 0.27845 kg | 2.3614 kg |
| Volume | 35,471 $mm^3$ | 300,810 $mm^3$ |

### *5.1. Validation of the FEA model and limitations*

The FEA results produce beneficial mechanical insights about the lattice bumper beam behavior, but experimental and theoretical validation has not yet occurred. A crucial step exists for validating numerical models because it assesses their reliability and predictive accuracy for real operations.

Researchers must conduct experimental testing of additively manufactured lattice bumper beams, which need to include both quasi-static and dynamic loading conditions to close the knowledge gap. Test results for total deformation, stress distribution, and energy absorption must be obtained to compare with the FEA model predictions. The experimental protocol proposes that repeat fabrication of at least five uniform test samples using consistent build parameters and material should be conducted for statistical reliability purposes.

The principles of impact energy with momentum conservation and beam bending theory enable researchers to conduct basic theoretical calculations, which serve as a preliminary validation system. We adopt impulse-based force calculations in this work and develop deformation estimation through equivalent load scenarios.

Several inaccurate factors exist in this study, including strain rate sensitivity and material anisotropy in printed structures, as well as manufacturing imperfections, which could affect the model's accuracy. The model would benefit from dynamic crash simulation models and real crash test data to improve future reliability.

Physical testing should be conducted to validate the model's predictive abilities, despite this limitation not affecting the usefulness of numerical results. Testing the proposed lattice bumper beam design experimentally will increase its practical value and reliability for use in automotive safety systems.

## 6. Conclusions

We confirm that the innovative lattice-structured bumper beam marks a new era in automotive development, addressing multiple challenges related to safety, weight reduction, and environmental impact. Experimental data shows that octet truss structures within lattice configurations outperform solid bumper beams in all critical performance aspects. This design exhibits remarkable energy dissipation properties, enabling efficient force distribution, vehicle protection, and occupant safety. The key findings from this study are outlined below.

The high energy absorption and lightweight nature of the octet lattice structures demonstrate them to be highly promising candidates for the next generation of impact mitigation systems. These findings can be immediately applied to automotive applications, particularly to the development of crash absorbing bumper beams, crumple zones, and side impact structures with increased safety but without increased vehicle weight, which is important for electric vehicles and for fuel-efficient designs. Printing of the lattice configurations from high-performance composite materials such as CFRC or metal alloys makes it possible to integrate the lattice into vehicle frames with tailored stiffness and failure profiles. Such lattice structures might be applied in aerospace, where weight reduction and impact resistance is critical, such as landing gear components, fuselage stiffeners, or protective housings. Lattice designs are also modular, which supports adaptive manufacturing that improves the design before it is manufactured based on particular load paths and structural demands.

Moreover, we could have explored hybrid lattice solid designs, behaviors under fatigue under cyclic loading, or cost efficiency in the additive manufacturing process that are critical to the scale of the innovation beyond research.

To further enhance the performance and applicability of lattice-structured bumper beams, researchers should focus on:

- Crashworthiness studies: conducting real-world crash testing and simulations to analyze the long-term behaviour and failure mechanisms of lattice bumpers under various impact conditions.
- Hybrid bumper designs: explore hybrid lattice-solid bumper configurations to achieve an optimal balance between rigidity and flexibility for different vehicle types.
- Manufacturing optimization: improve additive manufacturing techniques to reduce production time and costs while maintaining high precision and material efficiency.

• Integration with smart technologies: investigate the incorporation of sensor-based adaptive impact absorption mechanisms, enabling real-time crash response adjustments.

• The lattice-structured bumper beam presents superior safety, efficiency, and sustainability over traditional designs. This study confirms its practicality for large-scale production and highlights its potential to transform automotive safety metrics while supporting the development of lightweight, responsive vehicles.

By advancing material innovations, manufacturing techniques, and crashworthiness evaluations, lattice bumper designs can be crucial in shaping the future of automotive safety and sustainability.

**Use of AI tools declaration**

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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**Author contributions**

Aum Rajpura: result analysis, design of lattice structures; Hrutvik Prajapati: mathematical modelling, finite element analysis application; Anirban Sur: concept and write-up, modification; Vijaykumar S Jatti: English and grammar check; Girish Kale: review, suggestions and modification on overall manuscript; Yury Razoumny: review, suggestions and modification on overall manuscript.

**Conflict of interest**

The authors declare no conflict of interest.

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