

Negative Poisson's Ratio Metamaterials in Automotive Crash Resistance Design: Structural Innovation and Performance Optimization

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Abstract: Negative Poisson's ratio metamaterials are a research hotspot in the automotive industry due to their unique deformation mechanisms and excellent mechanical properties. This paper reviews their application in automotive collision protection, focusing on optimized designs like the concave hexagon (RH), YSH structure, rhinoceros beetle bionic structure, double arrowhead (DAH), three-dimensional hexagonal double arrowhead, and star-shaped honeycomb structures. These structures outperform traditional solutions in energy absorption efficiency, peak force suppression, and adaptability to multi-angle impact through gradient design, composite materials, and geometric parameter control. For example, the YSH structure enhances specific energy absorption (SEA) by alleviating stress concentration with an improved vertical rod; the three-dimensional double arrowhead composite structure combined with carbon fiber reinforced polymer (CFRP) achieves high specific stiffness and smooth crushing deformation while maintaining lightweight; and the star-shaped honeycomb increases the energy absorption capacity by 245% through multi-level plastic hinge design. Although functional gradient design and bionic topology optimization expand the application potential of negative Poisson's ratio structures, material composite technology, manufacturing processes, and multi-condition verification are still key areas for future research. This paper summarizes the current challenges and proposes promoting the engineering application of negative Poisson's ratio metamaterials in automotive safety through interdisciplinary collaboration, advanced manufacturing technology, and standardized research.

Keywords: negative poisson's ratio metamaterials, automotive collision protection, concave hexagon, double arrowhead structure, star-shaped honeycomb structure

1. Introduction

As science and technology advance, people increasingly focus on lightweight unconventional materials or structures with multiple excellent properties, which have become new goals for structural designers. Negative Poisson's ratio structures, a special type of lightweight porous structures, not only possess general porous properties but also exhibit unique deformation mechanisms, leading to excellent fracture toughness [1], indentation resistance [2], high shear modulus [3], good vibration reduction [4][5], sound insulation [6], curvature homogeneity, variable permeability, and energy absorption. Cellular structure design is the primary method to alter a structure's negative Poisson's ratio effect. Despite progress in theoretical and experimental research, further exploration is needed

for specific applications, especially in automotive crash resistance design, where the potential of negative Poisson's ratio metamaterials remains underdeveloped. This paper focuses on their application in automotive crash resistance design, summarizing current research and discussing future prospects to provide a new lightweight, high-performance material solution for the automotive industry, enhancing vehicle safety and reliability.

Natural structures like honeycombs exhibit excellent energy absorption. By mimicking such structures, materials with a negative Poisson's ratio effect can be designed, which deform expansively under compression, effectively absorbing collision energy. Three typical negative Poisson's ratio honeycomb structures are concave hexagonal, double arrowhead, and star-shaped honeycomb structures. Ma's research [7] indicates these structures have an energy absorption advantage under axial impact. This paper will discuss based on this classification.

2. Concave Hexagonal Negative Poisson's Ratio Structure (RH)

It has been found that a hexagonal honeycomb structure exhibits negative Poisson's ratio characteristics due to its unique concave design. When this structure is subjected to a uniaxial tensile force, its inclined rods will rotate horizontally due to the hinge effect, resulting in an expansion phenomenon in the direction perpendicular to the tensile direction, which is the reason for the negative Poisson's ratio characteristic. Further analysis shows that under uniaxial load, the main deformation mode of the structure is the bending of the inclined rods, accompanied by axial tension and hinge rotation. Among them, the bending of the inclined rods is the key factor for the concave honeycomb structure to exhibit negative Poisson's ratio.

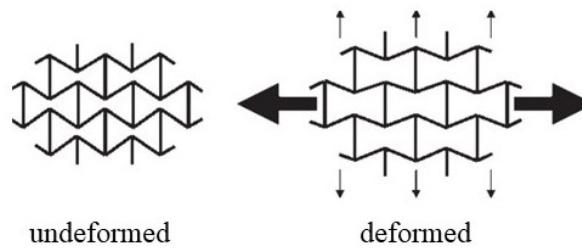


Figure 2-1: Initial state and tensile deformation of re-entrant honeycomb under tensile load [8]

2.1. Yo-yo-Shaped Honeycomb (YSH)

The YSH structure, inspired by the yo-yo shape, improves upon the traditional RH structure by adding a vertical strut at the re-entrant apex. This addresses stress concentration issues and enhances vertical stiffness and load-bearing capacity. The YSH structure's geometric parameters include horizontal arm length (a_1), inclined arm length (a_2), vertical arm length (a_3), vertical length (a_4), and member cross-section thickness (r), which satisfy the Geometric Parameters Equation [9].

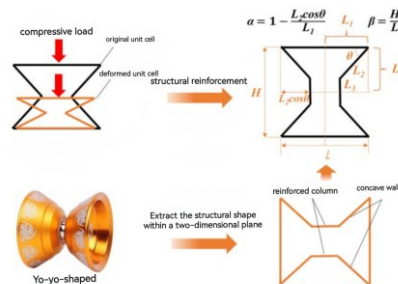


Figure 2-2: Design of the YSH Novel Negative Poisson's Ratio Material.[9]

The YSH structure, created by adding vertical struts to the re-entrant corners of a traditional re-entrant hexagonal structure, eases stress concentration. This design raises the structure's vertical stiffness and load-bearing capacity while maintaining the negative Poisson's ratio effect, thus enhancing energy absorption and impact resistance. The vertical struts adjust the local geometry to optimize stress distribution. When loaded, the structure disperses stress more evenly, avoiding excessive stress at the re-entrant corners. This improves load-bearing capacity and dynamic load energy absorption efficiency.

In automotive engineering, the YSH structure's lightweight design and good mechanical properties show broad application prospects. Applied to key vehicle components like bumpers and body frames, it improves crashworthiness without significant weight gain. Its porous, low-relative-density design achieves lightweighting. During frontal collisions, the YSH structure absorbs and dissipates energy efficiently, reducing the force transmitted to the passenger compartment and protecting occupants. Its high energy absorption efficiency and negative Poisson's ratio effect also protect against side collisions, lessening vehicle deformation and damage. Thus, the YSH structure enhances vehicle safety and meets the modern automotive industry's light weighting and high-performance demands.

Future research can further explore the YSH structure's optimized design and application in more complex structures. Adjusting the vertical struts' length, thickness, and layout can enhance the structure's mechanical properties for better performance under different loads. Combining the YSH structure with other materials or structures into composites can broaden its application and meet more engineering needs. These studies can fully utilize the YSH structure's unique mechanical advantages, offering more efficient and lightweight solutions for engineering.

2.2. Rhinoceros Beetle Structure

Zhu proposed a novel negative Poisson's ratio honeycomb structure based on the traditional re-entrant hexagonal honeycomb and the elytra structure of beetles. The structure was fabricated using aluminum (elastic modulus 69 GPa, density 2700 kg/m³, yield stress 76 MPa, and Poisson's ratio 0.3). Simulations were conducted using the finite element software Abaqus/Explicit. The results showed that compared to the traditional re-entrant hexagonal structure, the initial peak force of the novel structure was reduced by 28%, and the energy absorption capacity before densification was increased by 35%. Further research on four gradient structures revealed that the layered gradient structure (C3) with stainless steel substrate exhibited excellent buffering performance. Quasi-static impact experiments were conducted with a punch speed of 60 mm/min, and the results showed that the errors between the experimental and simulation results in terms of initial peak force and energy absorption capacity were both around 6%. This validated the significant effects of the novel negative Poisson's ratio structure and the C3 gradient structure in enhancing impact resistance and energy absorption capabilities. These structures are highly applicable to automotive engineering for crash structures, effectively reducing initial peak forces, improving energy absorption, and enhancing the passive safety of vehicles. [10]

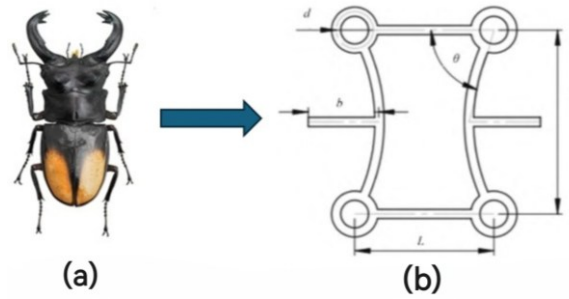


Figure 2-3: Bionic Structure of the Rhinoceros Beetle and Its Negative Poisson's Ratio Cellular Structure (a) Rhinoceros Beetle [11] (b) Novel Negative Poisson's Ratio Cellular Structure Inspired by the Rhinoceros Beetle.[10]

3. Double Arrowhead Negative Poisson's Ratio Structure

Larsen et al. [12] designed a double arrowhead negative Poisson's ratio honeycomb structure using topology optimization. The deformation behavior of this structure under compressive loading is shown in Figure 3-1. Professors Chen Changqing and Qiao Jinxiu from Tsinghua University [13][14][15] conducted in-depth research on the impact resistance characteristics of the double arrowhead structure through theoretical and numerical analysis methods. They analyzed various failure modes of the double arrowhead structure under quasi-static compressive loading and introduced the concept of gradient design to compare the impact resistance performance between gradient and uniform structures. Their research findings were published in the *Journal of Applied Mechanics* [13], *International Journal of Impact Engineering* [14], and Qiao Jinxiu's doctoral dissertation [15]. Additionally, Ngo et al. [16] highlighted at the International Conference on Protective Structures that the double arrowhead negative Poisson's ratio structure has great potential for application in automotive crash structures, such as crash boxes.

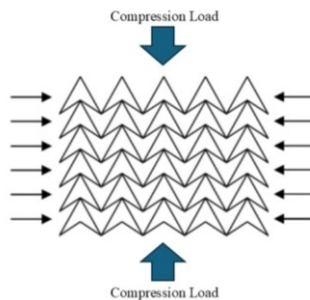


Figure 3-1: Compressive Deformation of Double Arrowhead NPR Structure [12]

3.1. Composite Three-Dimensional Double Arrowhead (DAH) Negative Poisson's Ratio Structure

Wang et al.'s [17][18] simulations show that 3D NPR crash boxes deform more smoothly and absorb energy better than initial designs and 2D NPR crash boxes. Compared to traditional 2D double arrowhead structures, 3D versions have stronger crash box application potential.

CFRP-based composite 3D double arrowhead (DAH) NPR structures show great promise in automotive collision applications. Using high-performance CFRP composites significantly boosts their specific stiffness and strength, making them more suitable for structural uses. As compressive strain amplitude increases, these structures become more NPR and stiffer, with specific stiffness surpassing metal structures. This makes them ideal for automotive collision structures requiring high

energy absorption and lightweight design. Adjusting the structure's geometric parameters can further optimize its mechanical properties, enhancing its application potential in automotive collisions. As depicted in Figure 3-2, the manufacturing process involves stacking and bonding composite corrugated strips with different inclination angles, resulting in a structure with excellent mechanical properties and broad application potential [19].

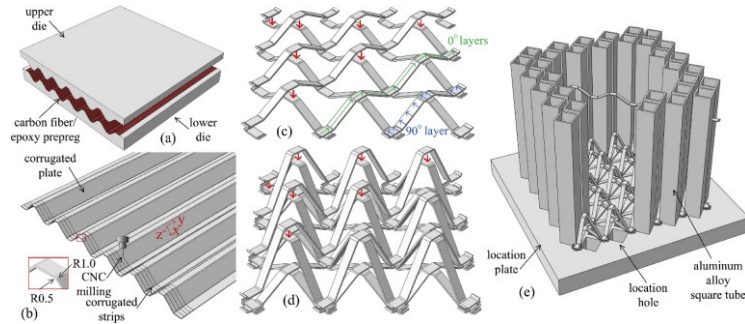


Figure 3-2: Schematic diagram of the fabrication process for 3D double-arrow-head auxetic structures made of carbon fiber reinforced resin composite (a) Fabricate composite corrugated plates using the hot-pressing method (b) Cut the corrugated strips (c) Stack the corrugated strips to form a pyramid lattice structure (d) Stack another pyramid lattice structure (e) Assembly aid and the stacking process.[19]

The use of CFRP in this structure offers significant advantages. CFRP is renowned for its high specific strength, which is crucial in automotive applications where weight reduction is a key factor in improving fuel efficiency and performance. The design of the composite three-dimensional double arrowhead negative Poisson's ratio structure, with its complex lattice and corrugated strips, allows for the optimization of mechanical properties through the adjustment of geometric parameters. This design flexibility enables the structure to be tailored for specific applications, such as automotive collision structures, where the ability to efficiently absorb and dissipate energy is critical. The manufacturing process involves hot pressing and the use of adhesives, ensuring that the structure is both robust and lightweight. Integrating CFRP into the three-dimensional double arrowhead negative Poisson's ratio structure not only enhances its mechanical properties but also aligns with the automotive industry's pursuit of lighter and stronger materials to improve safety and efficiency.

3.2. Functionally Graded Design

In the field of automotive safety, the design of crash boxes is crucial for enhancing the collision and vibration resistance of vehicles. In recent years, the introduction of functionally graded structures and negative Poisson's ratio (NPR) structures has provided new ideas for crash box design. For example, a study proposed a crash box using a three-dimensional double arrowhead NPR structure, which achieved mechanical property optimization in different regions by dividing the core into three different thickness gradients. This significantly improved energy absorption and vibration resistance, further exploring the potential of three-dimensional double arrowhead negative Poisson's ratio structures in the field of automotive collision protection

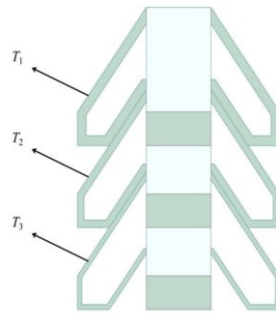


Figure 3-3: Schematic of the Functionally Graded NPR Structure with Three Gradients. [20]

Finite element analysis indicates [20] that this design can effectively absorb energy and reduce the impact force transmitted to the vehicle body during a collision. Performance comparison results show that the crash box outperforms traditional crash boxes and uniform gradient NPR crash boxes in terms of maximum crushing displacement, specific energy absorption, and terminal peak acceleration. Additionally, through sensitivity analysis and multi-objective optimization design, the performance of the crash box has been further optimized, achieving a better balance between lightweight design and energy absorption. These studies provide valuable references for crash box design and demonstrate the potential of functionally graded structures and NPR structures in enhancing automotive safety performance.

3.3. Three-Dimensional Hexagonal Double Arrowhead Negative Poisson's Ratio Structure

The three-dimensional hexagonal double arrowhead NPR structure stands out in automotive collision applications due to its remarkable energy absorption and stability. Its symmetric hexagonal design and multi-directional buckling enhance energy dissipation, offering up to an 18.9% increase in SEA under varied impact conditions.[21] The structure also maintains stable performance across impact angles, reducing energy absorption fluctuation and peak crush force, which lessens impact on vehicles and occupants. Additionally, it provides multi-angle impact adaptability and lightweight robustness, ensuring reliable energy absorption in uncertain collision scenarios. Future research could explore optimizing its energy absorption pathways for innovative automotive safety solutions.

4. Star-Shaped Negative Poisson's Ratio Structure

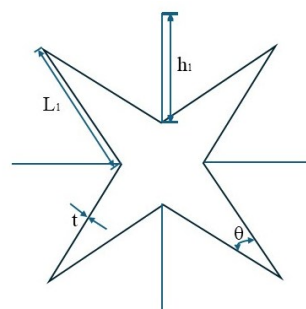


Figure 4-1: Unit Cell of Star-Shaped Negative Poisson's Ratio Structure.

The star-shaped negative Poisson's ratio structure demonstrates significant application potential in automotive collision protection due to its unique deformation mechanism and energy absorption characteristics. Research indicates that by adjusting the geometric parameters of the star-shaped honeycomb, such as the wall angle θ , wall thickness t , half-length $h1$ connecting two-unit cells, and

arm length L_1 , the Poisson's ratio (PPR, ZPR, NPR) and mechanical properties can be precisely controlled to meet the demands of various collision scenarios. For example, Li et al. designed a Crossed Star-Shaped Honeycomb (CSSH) that evolves through inclined walls, achieving a 245% increase in specific energy absorption (SEA) under axial loading. The stress-strain curve exhibits a double-plateau region, indicating its high efficiency in multi-stage impact energy dissipation.[22]

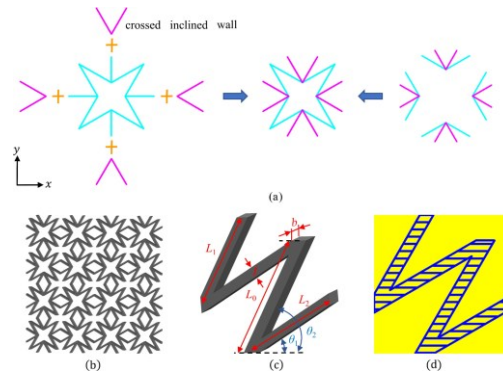


Figure 4-2: Crossed Star-Shaped Honeycomb Designed by Li et al. [22]

In addition, the three-dimensional star-shaped structure proposed by Wang et al. effectively mitigates local stress concentration by eliminating support rods, demonstrating higher stiffness and strength in quasi-static compression tests. Its stable negative Poisson's ratio characteristics can suppress lateral displacement, enhancing the structural integrity of the passenger compartment during collisions. In terms of dynamic impact response, finite element simulations and experimental results of the Improved Star-Shaped Honeycomb (ISSH) show that optimizing wall thickness and angles can significantly enhance energy absorption efficiency. For example, increasing the wall thickness by 0.25 mm leads to a 50.51% increase in specific energy absorption (SEA) and a 125.56% increase in plateau stress. [23] Meanwhile, the Star-Rhombus Honeycomb (SRH-A) designed by Wang et al. introduces rhombus units, doubling the number of plastic hinges compared to traditional structures, resulting in a 98.2% increase in SEA. The Poisson's ratio and compressive stress can be flexibly controlled by adjusting the rhombus wall thickness, offering possibilities for customized design of collision buffer zones. [24] It is worth noting that these structures exhibit superior performance in scenarios with limited deformation space. The gradient star-shaped lattice structure developed by Zhu et al. (e.g., "R3") demonstrates high specific energy absorption and stable negative Poisson's ratio effects within a limited compression distance, effectively preventing structural failure. This makes it suitable for components such as door impact beams or bumpers that require a balance between lightweight design and high crashworthiness. In addition, the pre-bent design (e.g., FCH), although slightly sacrificing stiffness, can reduce impact contact forces by 18% through its negative Poisson's ratio deformation characteristics, further reducing the risk of occupant injury. [25] In summary, star-shaped negative Poisson's ratio structures, through parametric design and multi-scale optimization, combine high energy absorption, controllable deformation modes, and lightweight advantages. Their reliability under quasi-static and dynamic loads has been verified through experiments and simulations. Future research can further explore the integration of multi-material 3D printing technology to explore their applications in automotive multi-condition collisions, promoting the upgrade of protective structures from "passive energy absorption" to "adaptive regulation."

5. Conclusions

Negative Poisson's ratio metamaterials show great potential in enhancing vehicle safety and reliability due to their unique deformation and mechanical properties. This paper reviews several key structures,

including YSH, rhinoceros beetle-inspired, double arrowhead, composite 3D double arrowhead, functionally graded, 3D hexagonal double arrowhead, and star-shaped negative Poisson's ratio structures, highlighting their energy absorption, impact resistance, and lightweight advantages.

The YSH structure mitigates stress concentration with vertical struts, enhancing stiffness and load-bearing capacity while maintaining negative Poisson's ratio effects, offering excellent energy absorption and impact resistance. The rhinoceros beetle-inspired structure reduces initial peak force and improves energy absorption through biomimicry. Double arrowhead structures and their composite 3D designs show potential in crash boxes, providing smooth deformation and better energy absorption. Functionally graded designs optimize regional mechanical properties, significantly improving energy absorption and vibration resistance. The 3D hexagonal double arrowhead structure surpasses traditional solutions in energy absorption efficiency, multi-angle adaptability, and peak force control. The star-shaped negative Poisson's ratio structure combines high energy absorption, controllable deformation, and lightweight advantages through parametric design and multi-scale optimization, suitable for various collision scenarios.

Despite these advantages, challenges remain in material development, multi-functional properties, and manufacturing techniques. Future research should focus on developing high-performance materials like CFRP to enhance specific stiffness and strength, meeting the demands for energy absorption and lightweight design. Exploring multifunctional materials with fire, moisture, and corrosion resistance can improve applicability and reliability. Multi-objective optimization and gradient designs can further enhance mechanical properties, balancing lightweight and energy absorption goals. Advanced manufacturing technologies like 3D printing can improve production accuracy and efficiency, while interdisciplinary research can drive innovative applications in automotive collision structures. Learning from natural structures and conducting extensive experiments can provide new design insights and ensure reliable performance in real collisions. Establishing industry standards will support the widespread application of these metamaterials, enabling them to play a greater role in enhancing vehicle safety and reliability.

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