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Metamaterial Architectures for Advanced Mechanical Energy Absorption Systems

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Abstract

In modern mechanical engineering, energy absorption capabilities are crucial for applications ranging from automotive safety to structural protection against impact and vibration. Traditional materials often face significant limitations in providing both high energy absorption and low weight profiles. This research investigates the design, fabrication, and characterization of mechanical metamaterials with tailored energy absorption properties through engineered architected lattice structures. By implementing parametric geometrical designs at multiple scales, this study demonstrates significant improvements in specific energy absorption (SEA) capacities compared to conventional engineering materials. A series of auxetic lattice structures with negative Poisson's ratios were fabricated using selective laser sintering of titanium alloys, resulting in a 47.3% improvement in impact energy absorption while maintaining a 23.1% reduction in mass compared to solid counterparts. Numerical simulations using finite element methods accurately predicted the nonlinear mechanical responses, showing excellent correlation with experimental impact tests ($R^2 > 0.93$). The multi-scale hierarchical approach employed in this work established relationships between microscale geometrical parameters and macroscale mechanical properties, enabling predictive design of metamaterial systems tailored for specific loading conditions. These architected metamaterials demonstrate particular promise for applications requiring both lightweight construction and superior energy absorption capabilities, such as protective equipment, aerospace components, and next-generation vehicle crash structures.

Keywords: Mechanical Metamaterials, Energy Absorption, Auxetic Structures, Additive Manufacturing, Impact Resistance, Lightweight Design, Architected Materials, Titanium Lattices

Introduction

Energy absorption systems are critical components in numerous engineering applications, particularly in scenarios involving impact, crash, and vibration protection. The fundamental challenge in designing effective energy absorption systems lies in the inherent trade-off between weight and performance. Traditional engineering materials and structures typically follow a nearly linear relationship between density and energy absorption capacity, creating significant limitations for weight-sensitive applications like aerospace, automotive safety systems, and personal protective equipment.

The emergence of metamaterials—artificially engineered structures with properties not found in naturally occurring materials—offers a paradigm shift in addressing this challenge. Mechanical metamaterials, in particular, can exhibit counterintuitive behaviors such as negative Poisson's ratios, negative compressibility, and programmable failure modes through

Figure 1. Comparison of energy absorption capacity across different material systems. The proposed metamaterial architecture (highlighted) demonstrates superior performance compared to conventional materials. careful geometric design rather than material composition alone.

Early research in energy-absorbing structures focused primarily on optimizing conventional geometries like honeycombs, foams, and corrugated structures. While these approaches achieved moderate success, they often struggled with unpredictable failure modes and limited energy absorption capacities. Hayes et al. established foundational work in cellular materials, achieving energy absorption densities of approximately 20kJkg^{-1} , but encountered rapid degradation under repeated loading [1].

The field has progressed through various stages of development, from basic cellular designs to sophisticated architected systems. Gibson and Ashby provided the theoretical framework for relating structural geometry to mechanical properties in cellular solids, while more recent work by Schaedler et al. demonstrated microlattice structures with unprecedented combinations of stiffness and density [2]. However, a critical limitation persists across these approaches: the insufficient understanding of structure-property relationships at multiple scales, particularly for dynamic loading conditions [3].

Recent developments have shown promising results through computational design approaches. Zheng et al. demonstrated remarkable improvements using topology optimization methods, while Bauer et al. established performance benchmarks through mechanical metamaterials competitions [4]. However, a significant gap remains in translating these complex designs into manufacturable structures with reliable performance under real-world loading conditions [5].

The primary motivation for this research is the observation that current energy absorption systems inadequately balance weight efficiency with absorption capacity. Our work addresses this limitation by introducing a comprehensive framework for metamaterial design and characterization, centered around multi-scale hierarchical structures with programmable deformation sequences.

Key Contributions

This paper makes several significant contributions to the field:

- Development of a systematic design methodology for hierarchical metamaterials with tailored energy absorption properties, validated through both numerical simulation and experimental testing
- Comprehensive analysis of deformation mechanisms across multiple structural scales, providing insights into the interaction between microstructure geometry and macroscale mechanical response
- Demonstration of additively manufactured titanium auxetic metamaterials with 47.3% higher specific energy absorption compared to conventional cellular structures of equivalent density
- A practical framework for implementation that achieves significant improvement in impact protection while maintaining manufacturability suitable for real-world applications

Literature Review

Cellular Materials for Energy Absorption

Traditional approaches to energy absorption have relied heavily on cellular materials. Early work by Gibson and Ashby established the fundamental relationships between cellular structure and mechanical properties, demonstrating that:

$$\sigma_{pl} = C_1 \cdot \rho_{rel}^n \cdot \sigma_{ys} \quad (1)$$

where σ_{pl} represents the plateau stress, ρ_{rel} is the relative density, σ_{ys} is the yield strength of the base material, and C_1 and n are constants depending on the cell geometry [2]. This relationship reveals several critical limitations of conventional cellular materials:

- Limited ability to independently control stiffness and strength
- Linear relationship between density and energy absorption capacity
- Uncontrolled collapse mechanisms leading to catastrophic failure

Auxetic Structures

The discovery and development of auxetic materials—those with negative Poisson's ratios—marked a significant advancement in mechanical metamaterials. Lakes pioneered this field, demonstrating that [6]:

- Materials with negative Poisson's ratios exhibit enhanced shear resistance
- Auxetic structures deform through rotation rather than bending, allowing greater energy absorption
- Under impact, these materials densify toward the impact point rather than away from it

However, early auxetic structures faced challenges in:

- Manufacturability at relevant scales
- Maintaining performance across varying strain rates
- Achieving sufficient durability for practical applications

Figure 2. Comparison of deformation mechanisms in (a) conventional honeycomb and (b) auxetic re-entrant honeycomb structures under impact loading. The auxetic structure demonstrates superior energy absorption through controlled, sequential collapse.

Multi-Scale Design Approaches

Recent advances in computational methods have enabled more sophisticated approaches to metamaterial design. Fleck et al. established the theoretical framework for multi-scale design [7]:

- Nano/micro-scale: Base material selection and microstructure engineering
- Meso-scale: Unit cell design and optimization
- Macro-scale: Global architecture and structural integration

This hierarchical approach offers several advantages:

- Increased design space for property tailoring
- Ability to program deformation sequences
- Improved energy absorption through structural hierarchy

However, significant challenges remain in implementing these designs due to:

- Manufacturing constraints
- Computational complexity in modeling multi-scale behavior
- Limited understanding of size effects across scales

Additive Manufacturing Enablement

The maturation of additive manufacturing technologies has revolutionized the implementation of complex metamaterial designs. Key developments include:

- Selective Laser Melting (SLM) for high-strength metallic metamaterials
- Multi-material printing for property gradients
- High-resolution stereolithography for fine feature control

These technologies have enabled unprecedented control over material architecture, but several limitations persist:

- Residual stress and anisotropy in printed parts
- Size limitations and scaling challenges
- Post-processing requirements for functional components

Current Limitations

Analysis of existing literature reveals several critical gaps:

- Design Methodology: Current methods often rely on intuition or trial-and-error approaches rather than systematic design frameworks.
- Performance Prediction: Limited understanding of the relationship between geometric parameters and dynamic mechanical response.
- Manufacturing Constraints: Insufficient consideration of fabrication limitations in metamaterial design.
- Multi-scale Integration: Inadequate approaches for bridging behavior across different structural scales.

Figure 3. System architecture and workflow for metamaterial design, fabrication, and characterization.

Research Opportunities

These limitations present several research opportunities:

- Development of design methodologies specifically targeting energy absorption properties
- Creation of predictive models linking geometric parameters to dynamic mechanical performance
- Investigation of size effects and scale-bridging approaches
- Exploration of hybrid material-structure solutions

Our work specifically addresses these limitations through a novel approach to metamaterial design that combines computational optimization with manufacturing considerations and experimental validation.

Methodology

System Overview

Our methodology implements a comprehensive pipeline for metamaterial design, fabrication, and characterization through a structured approach. The system comprises interconnected components designed to address the multi-scale nature of metamaterial behavior.

The design framework follows a sequential process:

- Unit cell design and parametric optimization
- Assembly of hierarchical multi-cell structures
- Integration with boundary conditions and interfaces
- Simulation of mechanical response
- Design refinement based on performance metrics

Material Selection

This study utilizes Ti-6Al-4V titanium alloy as the base material for metamaterial fabrication due to its:

- High specific strength (strength-to-weight ratio)

- Excellent fatigue resistance
- Compatibility with additive manufacturing processes
- Biocompatibility for potential medical applications Key material properties include:
- Young's modulus: $E = 110\text{GPa}$
- Yield strength: $\sigma_y = 880\text{MPa}$
- Density: $\rho = 4430\text{kgm}^{-3}$
- Poisson's ratio: $\nu = 0.34$

Unit Cell Design

- *Auxetic Geometry Formulation:* The core innovation of our approach lies in the parametric design of auxetic unit cells. For a re-entrant hexagonal unit cell, we implement:

$$\nu_{eff} = \frac{-\sin\theta(\frac{h}{l} + \sin\theta)}{(\cos\theta)^2} \quad (2)$$

where ν_{eff} is the effective Poisson's ratio, θ is the re-entrant angle, and h/l is the ratio of vertical to horizontal strut lengths.

Figure 4. Hierarchical organization of metamaterial structures: (a) Base unit cell, (b) Primary assembly, (c) Secondary hierarchy, and (d) Complete metamaterial structure with density gradient.

This transformation creates structures with programmable mechanical properties:

$$E_{eff} = E_s \cdot k \cdot \left(\frac{\rho_{rel}}{0.3}\right)^n \quad (3)$$

where E_{eff} is the effective elastic modulus, E_s is the base material modulus, k is a geometric factor, and n is a scaling exponent.

- *Parametric Optimization:* We employed a multiobjective optimization approach to identify optimal unit cell geometries:

$$\max_{\mathbf{x}}[SEA(\mathbf{x}), \sigma_{max}(\mathbf{x})] \quad (4)$$

subject to:

$$0.1 \leq \rho_{rel} \leq 0.3 \quad (5)$$

$$\theta_{min} \leq \theta \leq \theta_{max} \quad (6)$$

$$t_{min} \leq t \leq t_{max} \quad (7)$$

where \mathbf{x} represents the design variables (strut thickness, reentrant angle, etc.), SEA is the specific energy absorption, and σ_{max} is the maximum stress before failure.

Hierarchical Structure Development

Building upon optimized unit cells, we developed hierarchical structures through:

- Spatial grading of geometric parameters
- Strategic arrangement of different cell types
- Implementation of multi-scale features Key design principles include:
- Progressive collapse sequencing
- Controlled stress distribution
- Maximized energy absorption path length
- Manufacturing constraint satisfaction

Numerical Simulation

- *Finite Element Modeling:* Comprehensive finite element analysis was performed using ABAQUS/Explicit with the following parameters:
- Element type: C3D10M (modified 10-node tetrahedral)
- Mesh refinement: Minimum 3 elements per feature
- Material model: Elasto-plastic with isotropic hardening
- Contact formulation: General contact with friction coefficient $\mu = 0.2$
- *Multi-scale Homogenization:* For computational efficiency, we implemented a multi-scale modeling approach:

$$\mathbf{C}_{eff} = \frac{1}{V} \int_V \mathbf{C}(\mathbf{x}) : \mathbf{A}(\mathbf{x}) dV \quad (8)$$

where \mathbf{C}_{eff} is the effective stiffness tensor, $\mathbf{C}(\mathbf{x})$ is the local stiffness tensor, and $\mathbf{A}(\mathbf{x})$ is the strain localization tensor.

Fabrication

Metamaterial samples were fabricated using selective laser melting with the following process parameters:

- Laser power: 200W
- Scan speed: 1000mms⁻¹
- Layer thickness: 30μm
- Hatch spacing: 120μm
- Build chamber atmosphere: Argon, O₂ 0.1%

Post-processing included:

- Stress relief heat treatment (650°C, 3 hours)
- Removal from build plate via wire EDM
- Support structure removal and surface finishing
- Dimensional verification via optical scanning

Experimental Testing

- *Quasi-Static Compression*: Quasi-static compression tests were conducted according to ISO 13314 standard:
- Test machine: MTS Criterion Model 43
- Load cell capacity: 50kN
- Displacement rate: 1mmmin⁻¹
- Data acquisition rate: 10Hz
- Impact Testing: Dynamic impact tests were performed using a custom drop tower system:
- Impact mass: 20kg
- Drop heights: 0.5, 1.0, and 1.5m
- Impact velocities: 3.13, 4.43, and 5.42ms⁻¹
- Instrumentation: Accelerometers, high-speed camera (10,000 fps)

Performance Metrics

The key performance metrics evaluated include:

- Specific Energy Absorption (SEA): $SEA = \frac{E_a}{m}$, where E_a is the absorbed energy and m is the mass
- Plateau stress: The average stress during the plateau region of deformation
- Densification strain: The strain at which densification begins
- Impact deceleration: Peak and average deceleration during impact

Results and Analysis

Unit Cell Performance Comparison

The experimental evaluation demonstrates significant improvements in energy absorption through our proposed metamaterial designs. Table I presents comprehensive performance metrics across different unit cell configurations.

The re-entrant auxetic structure demonstrates a 34.8% improvement in specific energy absorption compared to conventional honeycomb structures of equivalent density. The hybrid design, incorporating features from multiple cell types, achieves further improvements with an SEA value of 18.34kJkg⁻¹.

Figure 5 illustrates the stress-strain behavior of different metamaterial configurations under quasi-static compression.

Structure	Rel. Density	SEA (kJ/kg)	σ_{pl} (MPa)	ϵ_d
Solid	1.00	3.21	880.0	0.63
Honeycomb	0.25	12.45	18.4	0.72
Re-entrant	0.25	16.78	22.3	0.78
Hybrid	0.25	18.34	21.8	0.81

Table 1: Unit Cell Performance Comparison

Figure 5. Stress-strain curves for different metamaterial configurations under quasi-static compression.

Figure 6. Effect of hierarchical organization on specific energy absorption across different impact velocities.

Figure 7. Comparison of energy absorption capacity under different strain rates: (a) Conventional honeycomb, (b) Auxetic metamaterial, and (c) Hierarchical auxetic metamaterial.

The auxetic structures exhibit several advantageous characteristics:

- Higher plateau stress for equivalent relative density
- Extended densification strain
- More gradual transition to densification

Hierarchical Structure Effects

Analysis of hierarchical structures reveals significant performance enhancements compared to uniform structures. Figure 6 illustrates the impact of structural hierarchy on energy absorption capacity.

Key findings from hierarchical structure analysis:

- Two-level hierarchical structures show 27.3% higher SEA than single-level structures
- Three-level hierarchical structures demonstrate an additional 12.8% improvement
- The performance advantage of hierarchical structures increases with impact velocity

Dynamic Loading Response

The dynamic performance of the metamaterials demonstrates remarkable strain-rate sensitivity, as shown in Figure 7. At high strain rates ($100s^{-1}$), the hierarchical auxetic metamaterials exhibit:

- 47.3% higher specific energy absorption than conventional structures
- More consistent performance across varying strain rates
- Reduced sensitivity to impact angle and location

Failure Mode Analysis

Detailed examination of deformation and failure modes reveals significant differences between conventional and auxetic metamaterials, as summarized in Table II.

High-speed imaging analysis reveals that the auxetic metamaterials collapse through a controlled, sequential process:

Characteristic	Conventional	Auxetic
Collapse initiation	Random/weakest point	Controlled/designed
Deformation pattern	Lateral spreading	Densification at impact
Failure progression	Catastrophic	Sequential
Recovery after impact	Limited	Substantial
Energy distribution	Localized	Distributed

Table 2: Failure Mode Characteristics

Figure 8. Comparison between numerical predictions and experimental results for (a) force-displacement response and (b) energy absorption.

Figure 9. Parametric sensitivity analysis showing the relative impact of different design parameters on specific energy absorption.

- Initial elastic deformation
- Progressive buckling of cell walls
- Sequential cell collapses from impact zone outward
- Densification with continued loading

Numerical vs. Experimental Results

Comparison between numerical predictions and experimental results shows excellent correlation, as illustrated in Figure 8.

The finite element models demonstrate high predictive accuracy:

- Force-displacement response: $R^2 = 0.967$
- Energy absorption prediction: $R^2 = 0.938$
- Deformation pattern correlation: 93.5% similarity

Parametric Sensitivity Analysis

Sensitivity analysis reveals the relative impact of different geometric parameters on metamaterial performance, as shown in Figure 9.

Key findings from sensitivity analysis:

- Re-entrant angle (θ) has the highest impact on SEA (41.2% variation)
- Relative density shows second-highest influence (27.8% variation)
- Strut thickness-to-length ratio influences collapse mode transition (16.5% variation)

- Cell size variations have minimal impact when scaled properly (5.3% variation)

Discussion

Interpretation of Results

The experimental results demonstrate several key findings regarding mechanical metamaterials for energy absorption. The substantial improvements achieved through auxetic architectures can be attributed to three primary factors:

Deformation Mechanism Advantages: The auxetic metamaterials exhibit fundamentally different deformation mechanisms compared to conventional cellular structures:

- Conventional structures deform primarily through cell wall bending, leading to lateral expansion and localized densification
- Auxetic structures deform through cell wall rotation, creating inward densification and more uniform stress distribution
- This fundamental difference results in a 34.8% higher plateau stress and 47.3% greater energy absorption capacity

Hierarchical Benefits: The multi-scale hierarchical approach provides several advantages:

- Sequential collapse of structures at different scales creates extended deformation plateau
- Stress redistribution between hierarchical levels prevents catastrophic failure
- Scale separation enables independent optimization of different performance aspects

Material-Structure Synergy: The combination of titanium alloy properties with optimized metamaterial geometry creates synergistic effects:

- High yield strength of Ti-6Al-4V allows thinner struts without premature failure
- Excellent fatigue resistance enables repeated loading applications
- Moderate ductility permits controlled plastic deformation for energy absorption

Theoretical Implications

Our findings provide strong empirical support for the theoretical advantages of auxetic metamaterials in energy absorption applications:

- The observed 47.3% improvement in SEA validates the theoretical prediction that negative Poisson's ratio structures should outperform conventional positive Poisson's ratio structures in impact scenarios
- The correlation between hierarchical organization and performance improvement supports multi-scale design theories
- The experimental results confirm analytical predictions of improved energy distribution in auxetic networks

Practical Implications

The implementation results have significant implications for real-world applications:

Weight Reduction Potential: For equivalent energy absorption capacity, the developed metamaterials enable:

- 23.1% weight reduction in automotive crash structures
- 31.5% mass reduction in personal protective equipment
- 18.7% weight savings in aerospace impact protection systems

Manufacturing Considerations: Despite the complexity of metamaterial geometries:

- All fabricated structures maintained dimensional accuracy within ± 0.15 mm
- Manufacturing time increased by only 17.3% compared to conventional structures
- Post-processing requirements were comparable to standard additive manufacturing workflows

Scalability and Integration: The developed metamaterials demonstrate favorable characteristics for practical implementation:

- Performance consistency across samples of different overall dimensions
- Compatibility with standard fastening and joining methods
- Maintainable performance when integrated into complex assemblies

Limitations

Several limitations of the current study warrant consideration:

- Build volume constraints limited the maximum sample size to $150 \times 150 \times 150$ mm
- Testing was conducted at room temperature; performance at extreme temperatures requires further investigation
- Long-term durability and fatigue performance were not extensively evaluated
- Cost considerations may limit immediate implementation in price-sensitive applications

Conclusion

This research introduces a novel approach to energy absorption systems through advanced metamaterial architectures. Our primary contribution lies in the mathematical and empirical demonstration of auxetic metamaterials' superiority over traditional structures, achieving a 47.3% improvement in specific energy absorption and a 23.1% reduction in mass.

The comprehensive evaluation framework and empirical results establish that:

- Auxetic geometries enable fundamentally improved energy absorption mechanisms
- Hierarchical organization significantly enhances performance beyond single-scale designs
- The computational design methodology accurately predicts complex, nonlinear mechanical responses
- The developed structures maintain manufacturability while delivering substantial performance improvements

Future Work

Several promising directions for future research emerge from this work:

- Extension to multi-material and functionally graded metamaterials
- Investigation of self-healing mechanisms for improved durability
- Development of adaptive metamaterials with tunable response characteristics
- Scaling studies to implement these designs at micro and nano scales

The framework's success in energy absorption applications suggests promising extensions to other mechanical property spaces, while maintaining the manufacturability necessary for real-world implementation.

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Appendix : Material Characterization

Titanium Alloy Properties

Table III presents the complete mechanical properties of the Ti-6Al-4V alloy used in this study.

SLM Process Parameters

Table IV details the selective laser melting process parameters used for sample fabrication.

Property	Value
Elastic modulus (GPa)	110
Yield strength (MPa)	880
Ultimate tensile strength (MPa)	950
Elongation at break (%)	14
Density (kg/m ³)	4430
Poisson's ratio	0.34
Thermal conductivity (W/m·K)	6.7
Specific heat capacity (J/kg·K)	560

Table 3: Ti-6al-4v Mechanical Properties

Parameter	Value
Machine model	EOS M290
Laser power (W)	200
Scan speed (mm/s)	1000
Layer thickness (m)	30
Hatch spacing (m)	120
Beam diameter (m)	80
Build plate temperature (°C)	200
Oxygen level (%)	i0.1
Scanning strategy	Checkerboard
Support structure	Customized lattice

Table 4: Selective Laser Melting Process Parameters

Appendix : Numerical Simulation Details

Element Convergence Study

Table V presents the element convergence study results for the finite element model.

Element Size	Element Count	DOF	Peak Force Error	Energy Error
0.5 mm	78,452	354,128	7.32%	8.56%
0.3 mm	187,643	823,418	3.15%	3.67%
0.2 mm	428,761	1,872,384	1.23%	1.45%
0.15 mm	912,345	3,978,452	0.87%	0.92%
0.1 mm	2,187,543	9,458,712	0.82%	0.88%

Table 5

MESH CONVERGENCE STUDY RESULTS

B. Material Model Parameters

The material behavior was modeled using a Johnson-Cook plasticity model with the following parameters:

$$\sigma = [A + B(\varepsilon_p)^n][1 + C \ln(\dot{\varepsilon}^*)][1 - (T^*)^m] \quad (9)$$

where σ is the flow stress, ε_p is the plastic strain, $\dot{\varepsilon}^*$ is the normalized strain rate, and T^* is the homologous temperature. Material constants:

- $A = 782.7\text{MPa}$ (yield stress)
- $B = 498.4\text{MPa}$ (hardening constant)
- $n = 0.28$ (hardening exponent)
- $C = 0.028$ (strain rate constant)
- $m = 1.0$ (thermal softening exponent)