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PERFORMING COMPARATIVE ANALYSIS ON ADDITIVE MANUFACTURED HYBRID STRUT-BASED METAMATERIALS ON THE BASIS OF SPECIFIC ENERGY ABSORPTION

ABSTRACT

Architected metamaterials utilize unique geometries to enhance the mechanical and physical properties of structures. This study investigates the energy absorption capabilities of additively manufactured hybrid strut-based metamaterials, produced using Fused Deposition Modeling (FDM) with Polylactic Acid (PLA). Compression tests were conducted on six novel hybrid strut lattice designs to analyze their structure-property relationships. The designs integrated Kelvin cells, edge struts, octagonal shapes, hex trusses, face-centered components, and corner diagonal struts. The combination of "Kelvin Cell + Octagon" achieved excellent energy absorption efficiency, with the highest Specific Energy Absorption (SEA) of 1450 kJ/kg. Through the synergistic effect of octagonal geometry and Kelvin cell structure, controlled deformation and delayed buckling are realized to release the energy fully and maximize stress wave interaction. However, the configuration of the "Edge Struts + Hex Truss" configuration was not far away either, exhibiting an SEA of 1388.89 kJ/kg, owing to the effective load distribution provided by the hexagonal truss structure. Other configurations had much lower SEA values: 275 kJ/kg for "Kelvin Cell + Hex Truss" 185.71 kJ/kg for "Kelvin Cell + Edge Struts" 162.5 kJ/kg for "Edge Struts + Corner Diagonal" and 26.67 kJ/kg for "Edge Struts + Face Centre". Using microscopy to look at failed samples showed that shapes with hexagonal and octagonal parts increased SEA by making stress distribution more even and limiting deformation during compression. The unit cell geometry is the critical factor for deciding upon the energy absorption capacity of metamaterials. This work provides useful insights to design optimized additively manufactured metamaterials to achieve high energy absorption, which will be useful to applications such as automotive crash protection, aerospace components, personal protective equipment, and vibration damping systems. The "Kelvin Cell + Octagon" and "Edge Struts + Hex Truss" configurations emerge as highly effective designs, balancing strength, ductility, and energy absorption efficiency for advanced engineering applications.

Keywords: *additive manufacturing; fused deposition modeling; hybrid metamaterials; polylactic acid; tensile strength*

INTRODUCTION

Engineered materials known as architected metamaterials exhibit remarkable and peculiar characteristics not due to their composition but from purposefully designed micro- and nanoscale architectures [1]. By carefully organizing geometries and structures at micron or sub-micron scales, properties can be encoded into the architecture, producing responses beyond those seen in natural materials. Examples include anisotropic behavior tuned by

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geometric configurations and orientation, negative Poisson's ratios, and negative compressibility. The concept of repeating unit cells is scaled up to create larger functional structures and devices in architectural metamaterials [2]. Advancements in fabrication processes, such as 3D printing, enable the production of these complex and regulated designs. The emergence of 3D printing has allowed micro-lattice metamaterials to surpass the capabilities of conventional materials, making them highly advanced [3]. Designed metamaterials exhibit tailored mechanical, thermal, electrical, and acoustic properties for applications in biomedicine, photonics, soft robotics, and thermal regulation [4].

By utilizing architecture instead of composition, strut-based mechanical metamaterials demonstrate extraordinary features. A key challenge, however, is explaining how different geometries achieve optimal combinations of stability, stiffness, strength, and energy absorption [5, 6]. Periodic lattices allow for customized performance, but the relationship between failure mechanisms, mechanical behavior, and structure is yet unclear, complicating the creation of metamaterials tailored to specific needs [7, 8]. The porosity of open Kelvin-cell alumina-based metamaterials aligns closely with the Gibson-Ashby prediction for open-cell foams when struts are smooth, straight, and solid. However, due to fabrication limitations, such as reduced resolution and strut thinning, property values tend to be lower. Conversely, hollow struts yield higher property values [9]. This study investigates hybrid three-dimensional cubic lattices by integrating the benefits of octet and bending-dominated structures, manufactured using Fused Deposition Modelling (FDM) with Polylactic Acid (PLA) samples. Quasi-static uniaxial compression experiments assess the energy absorption capacity of these novel hybrid lattices, supported by computational simulations analyzing deformation patterns [10].

Lattices created using the sheet-networks approach exhibit deformation modes predominantly influenced by stretching, demonstrating superior structural efficiency with improved stiffness-to-weight and strength-to-weight ratios compared to strut-based designs. Functional grading has proven effective for engineering materials with desired properties [11]. A comparative analysis of sheet-based triply periodic minimal surfaces (TPMS), strut-based ordered lattice topologies, and plate-based lattice topologies offers insights for designing damage-resistant and tough structures [12].

Finite Element Analysis (FEA) evaluates the performance of eight different geometries, comparing octet and Kelvin cell designs dominated by bending and stretching. Specimens are engineered to fail in their middle regions to minimize edge effects, allowing assessment of relative density impacts on fatigue life [13]. The exceptional mechanical capabilities of these metamaterials result from the near membrane stress state of plate architectures and the outstanding ductility and strength of the base material [14]. A study revealed that increased resistance to compression requires higher strut density aligned with the applied force, whereas higher torsional resistance necessitates evenly distributed diagonal struts on the outer surface. Increasing unit cells from 1 to 64 significantly alters stiffness and global stress distribution. Metastructures with non-uniformity and reinforced vertical and diagonal struts on the outer surface exhibit enhanced stiffness under compressive or torsional loads [15].

Functionally graded lattice structures demonstrate improved mechanical properties over hybrid lattices. Beam-based graded structures show reduced stiffness and strength due to parameters like unit cell size, volume fraction, and structural buckling [16]. Lattices with gradients perpendicular to the load direction mitigate shear failure unpredictability, achieving high elastic modulus, yield strength, and compressive strength. Load-parallel gradient lattices provide superior energy absorption up to densification, attributed to layer-by-layer deformation and improved energy dissipation. FEA effectively simulates deformation behavior in lattice systems, enabling precise optimization of design variables at both meso (cell topology) and macro (gradient) scales for enhanced energy absorption properties [17]. Novel voxel lattice unit cells with symmetrical struts and graded density structures significantly improve SEA compared to uniform structures [18]. Gradient lattice structures optimize performance in dynamic applications, especially under substantial deformation and non-linear behavior [19].

This research systematically characterizes different unit cell geometries under compression, analyzing moduli, buckling, post-buckling responses, deformation modes, and strength. By correlating structural configurations with failure mechanisms and load-displacement trends, the study identifies design principles for customizing metamaterial characteristics. This comparative study aims to create an experimental knowledge foundation to guide future advancements in metamaterial creation and applications. The study introduces novel hybrid strut-based combinations by integrating well-known lattice structures, including Kelvin cells, octagons, and hex trusses, with edge struts and face-centered or corner diagonal elements. The systematic comparison of these hybrid designs offers valuable insights into how specific geometric features impact overall performance.

A key novelty of this study lies in its comparative analysis of Specific Energy Absorption (SEA) across a range of diverse hybrid lattice architectures. SEA, a critical metric for evaluating energy absorption capabilities, is quantitatively derived from load–displacement curve analysis, providing insight into structural efficiency under dynamic loading. This experimental work was conducted using Fused Deposition Modeling (FDM) with PLA as the base material. This included microscopic analysis and load–displacement curve evaluation, offering a practical assessment of real-life mechanical performance. This work holds significant implications across multiple industries due to the customizable mechanical behavior and high SEA values of the studied designs. Applications include structural support, sandwich panels, and space-filling materials. Controlled buckling and deformation mechanisms enable effective vibration damping and noise reduction through energy dissipation and unwanted noise minimization. PLA's biocompatibility makes PLA metamaterials suitable for use in the biomedical field, such as bone scaffolds and tissue engineering applications. Due to the design flexibility for controlling heat transfer in the lattice structures, they also find applications in thermal management, like heat exchangers and electronic cooling systems.

MATERIALS AND METHODS

A Fused Deposition Modelling (FDM) printer, specifically the Creality Ender 3-V2, was chosen for the fabrication of metamaterial samples because it possesses the optimal dependability, flexibility, accuracy, and versatility of all printheads. This printer offers a wide build volume of 220 × 220 × 250 mm, enabling the production of intricate and complex structures, including the strut-based geometries investigated in this study. The printer's precise 0.1 mm layer resolution allows for the accurate creation of detailed designs, crucial for maintaining the structural integrity of the tested geometries. The as-printed samples are shown in Figure 1.

The metamaterial designs examined in this study include six distinct configurations, each engineered to optimize mechanical performance and energy absorption. The Kelvin cell is a truncated octahedron composed of eight hexagonal faces and six square faces, with twenty-four vertices and thirty-six edges, known for its efficient space-filling and isotropic properties, which enhance load distribution across lattice structures [20]. Edge struts are linear components typically placed at structural corners, characterized by their length, cross-sectional shape (e.g., square or round), and a diameter of 0.5 mm in this study, which increases stiffness and load-bearing capacity by reinforcing connections between vertices or faces.

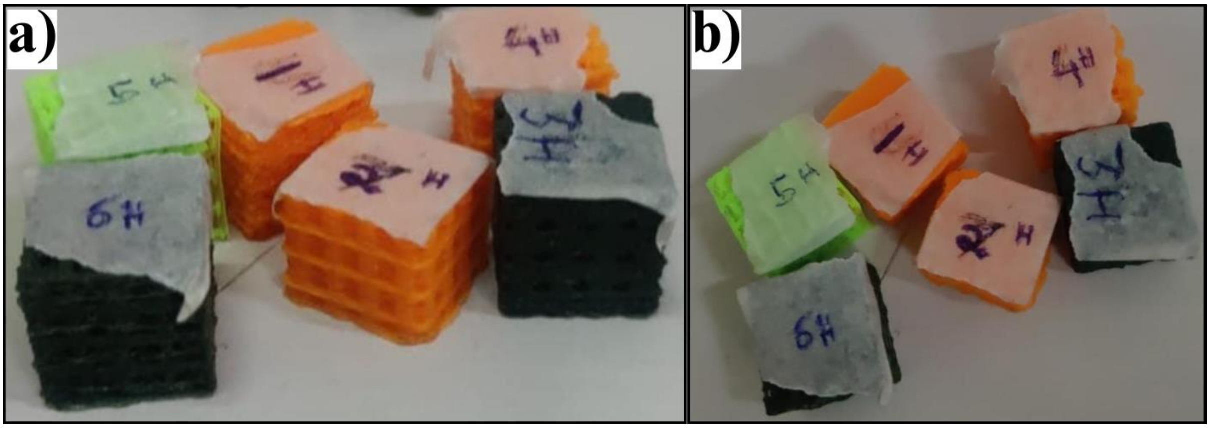


Fig. 1. As-printed samples. (a) front view (b) top view

The octagonal configuration features eight equal sides, vertices, and edges, improving mechanical stability and load distribution by increasing attachment points and load paths, thereby enhancing structural integrity. The hex truss shape consists of hexagon-shaped cells connected by struts, with each hexagon having six vertices and edges, offering superior load distribution and in-plane stiffness, making it suitable for applications like sandwich panels and core materials where lightweight and structural strength are critical [21]. Face-centered components incorporate additional struts that connect the centers of cubic cell faces, with internal struts linking each face's center to its opposite, improving load distribution, structural stability, and energy absorption by evenly distributing stress across the structure. Finally, the corner diagonal strut design connects non-adjacent vertices (corners) with diagonal struts positioned perpendicularly inside cubic or polygonal cells, adding extra edges to enhance shear resistance and reinforce the structure against shear stresses, further improving stability and energy absorption capacity.

For consistency across all designs, the same material—Polylactic Acid (PLA)—was used for all samples, ensuring identical weight and mechanical properties across all configurations. The use of a consistent 0.4 mm nozzle size further enhanced the precision and accuracy of the printed samples. Table 1 displays the printing parameters utilized in this study. These are concluded based on the pilot study. The Creality Ender 3-V2's compatibility with various filament types allows flexibility in material selection for specific application requirements, with PLA chosen in this study for its strength, ductility, and biocompatibility. Table 2 provides the mechanical properties of PLA filament used in this study.

Table 1. *Printing Parameters*

Parameter	Value
Nozzle temperature	210°C
Bed temperature	50°C
Layer height	0.2 mm
Print speed	50 mm/s
Infill density	100%
Infill pattern	Honeycomb
Retraction speed	50 mm/s
Cooling fan	100%
Wall thickness	0.8 mm

Table 2. *PLA Filament Mechanical Properties*

Property	Value/Range
Tensile strength	50-70 MPa or higher
Flexural strength	70-100 MPa
Elongation at break	3-8%
Density	1.24 g/cm^3
Glass transition temperature	55-65°C
Melting temperature	180-210°C
Print temperature	190-220°C
Bed temperature	40-60°C
Thermal expansion coefficient	60-70 × 10^{-6}/°C

Six distinct hybrid strut-based metamaterial designs were created using CAD software, as detailed in Table 3 and illustrated in Figure 2. The CAD models integrated combinations of the previously described components—Kelvin cells, edge struts, octagonal shapes, hex trusses, face-centered components, and corner diagonal struts—leveraging their synergistic effects to optimize SEA and structural performance. Experimental testing was performed for the resulting designs in order to evaluate their mechanical performance with an emphasis on load–displacement behavior and energy absorption characteristics.

Table 3. *Combination of Strut based metamaterials to get Hybrid Metamaterials*

Sample Number	Strut Diameter	Hybrid Strut based Combination
1.	0.5	Kelvin Cell + Edge Struts
2.	0.5	Kelvin Cell + Octagon
3.	0.5	Kelvin Cell + Hex Truss
4.	0.5	Edge Struts + Hex Truss
5.	0.5	Edge Struts + Face Centre
6.	0.5	Edge Struts+ Corner Diagonal

In this study, the hybrid strut-based combinations of this study were selected to take the complementary advantages of the several ways of geometric arrangement to improve the mechanical properties, like the energy absorption, the load distribution, and the structural stability. The designs are based on the integration of parts such as edge struts, hex trusses, octagons, and face-centered elements that tend to optimize performance over a broad range of applications. Recent research on hybrid architectures supports these configurations, providing clear proof that certain combinations may improve mechanical performance.

1. Kelvin Cell + Edge Struts (Figure 2 (a)): The Kelvin cell, or tetrakaidecahedron, is widely used as a cellular structure because of its space-filling efficiency and isotropic mechanical behavior that leads to uniform stresses on nodes, edges, and faces. Edge struts reinforce critical load-bearing edges and increase overall stiffness and strength. It is anticipated that this combination will lead to improved energy absorption since the Kelvin cell spreads loads evenly, and edge struts will prevent buckling under extreme stress. As a result, this combination provides mechanical efficiency where lightweight features are combined with high energy absorption capacity.

2. Octagon + Kelvin Cell (Figure 2 (b)): The combination uses the Kelvin Cell's reliable and effective structural support with the Octagonal configuration's structural integrity and load distribution enhancement by increasing the number of faces and vertices. Some of the benefits associated with the octagonal shape include better energy absorption from the fact that impact forces are distributed more homogeneously, delaying stress concentrations. Furthermore, the increased resistance to deformation under loads improves structural stability, making it suitable for applications that require load-bearing capabilities.

3. Kelvin cell + Hex Truss (Figure 2 (c)): The load distribution of the Kelvin cell is enhanced together with increased load-bearing and directional rigidity in particular directions from the hex truss design. This combination provides multiple load channels, increases the contact area in compression, and thereby enhances energy absorption and dissipation. This configuration also enhances the directional stiffness, making it suitable for applications that require precise load carrying in specific directions.

4. Edge Struts + Hex Truss (Figure 2 (d)): For this combination, the edge struts mainly support the structure at the edges, while the hex truss creates an internal reinforcement and rigidity to the cell. The benefits include overall rigidity and stability, which would significantly reduce the deformation under load. Additionally, the hex truss design also results in the expectation of better energy absorption as forces from impact are better distributed across a wider area, leading to the structure being better able to absorb and dissipate energy.

5. Edge Struts + Face-Centered Components (Figure 2 (e)): The edge struts provide robust load-bearing, but also the face-centered components allow better connection between cell faces as well as distribute the load more evenly across the structure. Also, the benefits of this combination are anticipated to be improved load distribution, less stress concentration, and improved durability. Enhanced load dispersion leads to good energy absorption under impact conditions, and it also enables the structure to withstand extreme loading without losing stability.

6. Corner Diagonal Struts + Edge Struts (Figure 2 (f)): The major load-bearing elements, but also for the increase of shear forces and overall stability—switching adjacent vertices of cubic or polygonal cells with corner diagonal struts. It is anticipated that this configuration will enhance the shear resistance for the structure for more efficient shear stress resistance, and it will also increase the ability to absorb energy. This combination is very effective in dynamic loading conditions, transporting shear forces, and increasing structural stiffness and strength while being useful in applications of high stability and dissipation of energy under extreme stresses.

These hybrid combinations of struts base their concept on improving the mechanical performance of these structures by combining a complementary set of geometries, which provide, of course, superior energy absorption, better load distribution, and higher structural stability for a set of engineering purposes.

Systematic compression testing on the metamaterial samples was possible due to the accuracy, capacity, and control of the TUE C-400 system. The force rating of the device at 400 kN exhibits outstanding robustness with respect to the variety of strut-based geometries investigated in this work. Figure 3 shows the compression testing of the printed sample. Uniaxial quasi-static compression tests were conducted on the as-fabricated lattice structures at a constant velocity of 0.02 mm/s. During the testing, the lattice specimens were placed on a fixed lower platen, while the upper platen moved downward, compressing the specimens to 75% of their original height. The applied load was aligned with the building direction of the lattices to simulate realistic loading conditions.

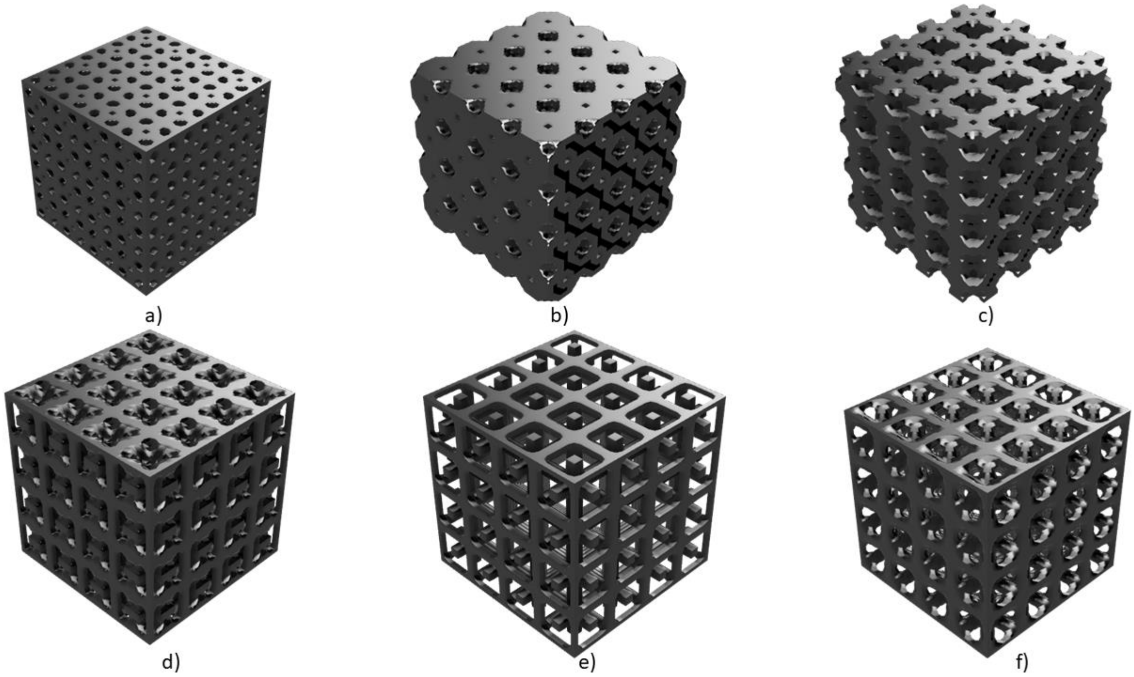


Fig. 2. Proposed design of hybrid strut-based metamaterials in the present work (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4, (e) Sample 5, and (f) Sample 6

To ensure the repeatability and reliability of the data, each test was repeated three times for every lattice design. The variations in results were less than 10%. The crosshead's 0.1 mm movement was divided into smaller increments, and a high-resolution 0.04 kN load cell was utilized for precise measurement of mechanical responses. These capabilities to extract elastic moduli and buckling, as well as post-buckling, transition, and strengths from load displacement curves were used. Further, it was possible to image the fracture surfaces of the deformed materials with high detail using a Radical RTM 500 microscope for microstructural analysis.

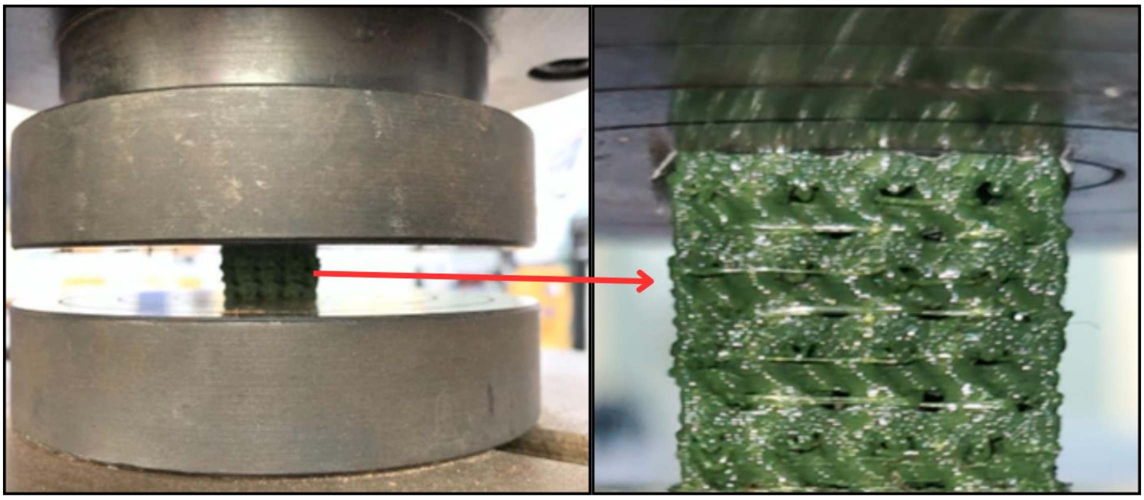


Fig. 3. Compression test setup used in this study with sample

The microscope had an efficient method of specimen illumination using a 3X eyepiece and adjustable substage oblique lighting, which highlighted these failure and deformation features more clearly. The technologies are capable of combining precise mechanical testing with advanced microscopy to undertake a thorough study in order to elucidate structure–

property–performance relationships of these metamaterials. Lastly, the compression rig and the customized features of the microscope were key technical instruments for the execution of these comparative geometrical and microstructural investigations on the metamaterials.

RESULTS AND DISCUSSION

Hybrid strut-based metamaterials are also analyzed in terms of their ability to absorb energy, using Specific Energy Absorption (SEA) as the critical metric. SEA is defined as a measure that quantifies the energy a material can absorb and is a critical property for materials that could be used for applications where both weight and energy dissipation are important, such as automotive crash protection, aerospace structures, and personal protective equipment [22]. Higher SEA values signify enhanced energy absorption efficiency, enabling the design of structures that are lighter, safer, and more structurally sound. Table 4 presents the comparative analysis of specific energy absorption in additively manufactured hybrid strut-based metamaterials from this study. Consequently, comparing the specific energy absorption for each set of structural combinations provides valuable insights into the energy absorption abilities of various geometries. It appears that the highest SEA of 1450 kJ/kg comes from the "Kelvan Cell + Octagon" configuration, which is significantly better than other configurations. The excellent performance of the structure is attributed to the fact that the unique octagonal geometry, combined with the Kelvin cell structure, aids in a highly effective energy absorption mechanism. The octagonal shape clearly promotes the deformation and buckling processes, allowing the structure to effectively absorb energy during impact situations. Close behind it is "Edge Struts + Hex Truss" with a SEA of 1388.89 kJ/kg. The inherent structural strength of the hexagonal truss and added struts surrounding the perimeter of the structure make this configuration a forceful contender. This design has a balance between rigidity and flexibility, which allows for efficient energy absorption without destroying structural integrity. This combination indeed has high SEA and could be used as a robust alternative in applications in which both strength and energy dissipation are required [23].

The "Kelvin Cell + Hex Truss" combination results in a moderate SEA level of 275 kJ/kg. The hexagonal truss contributes to energy absorption, but its effectiveness is clearly inferior to the "Edge Struts + Hex Truss" setup. The reduction in performance may result from less optimal load distribution or deformation pathways in the Kelvin cell when applied in conjunction with the hexagonal truss. Additionally, the "Kelvin Cell + Edge Struts" also results in an SEA of 185.71 kJ/kg, which is off just from the hex truss combination. However, edge struts provide some support and energy dissipation, but they are not as effective in improving the Kelvin cell’s absorption characteristics. The SEAs of the "Edge Struts + Corner Diagonal" and "Edge Struts + Face Centre" configurations are 162.5 kJ/kg and 26.67 kJ/kg, respectively. However, a face-centered strut arrangement provides little energy dissipation, while the corner diagonal elements provide moderate structural support and energy absorption. These suggested configurations witness a stark contrast in their performance, pinching out the significance of the unit cell geometry on energy absorption efficiency. Furthermore, the unit cell geometry significantly influences a structure's energy absorption capability. Hexagonal and octagonal elements incorporated into the "structures" always result in a higher SEA, which certainly suggests their ability to efficiently dissipate energy through controlled deformation and buckling mechanisms [24]. In particular, for the Kelvin cell structure, good performance is shown when combined with optimized geometry, such as an octagon, whereas its performance varies with other secondary elements. Energy absorption structures are also equally important from mass consideration points of view. However, for weight-sensitive applications, the high mass of the "Kelvin Cell + Octagon" combination at 0.1 kg may be considered a negative point. Alternatively, when the mass is 0.03 kg, the SEA decreases to its lowest value of 2.44 J/g, which undergoes a trade-off with the energy absorption capacity. These factors must be balanced by designers when choosing materials and configurations for a particular application.

By virtue of their high SEA, the "Kelvin Cell + Octagon" and "Edge Struts + Hex Truss" configurations are attractive candidates for applications in which energy absorption is desired with high efficiency. These structures can be used in the automotive industry to improve passenger safety through the reduction of impact forces during collisions. These configurations could be used to safeguard sensitive components from impact and vibration in aerospace structures that are required to maintain the integrity of spacecraft and aircraft systems. These designs could be integrated into personal protective equipment like helmets and body armor to provide improved safety while providing good comfort. Furthermore, such structures are quite appropriate for vibration damping in machinery and structural systems to reduce noise and to prolong machine life.

The findings highlight the significant role of geometry in optimizing energy absorption capabilities, particularly with hexagonal and octagonal elements. To enhance the designs further, investigating hybrid geometries or multi-material structures could yield higher SEA values while managing weight constraints. Additionally, exploring the fatigue resistance of these metamaterials under multiple impact scenarios is crucial, as real-world applications often involve repeated stresses. Environmental considerations, such as the sustainability of materials and additive manufacturing techniques, are vital for large-scale production. Furthermore, integrating damping mechanisms or phase-change materials could offer advanced energy dissipation properties. While the "Kelvin Cell + Octagon" combination excels in SEA, its weight might limit its use in certain applications, prompting a need for optimization in mass-to-performance ratios. Tailoring these structures for specific applications, such as aerospace or automotive industries, requires a careful balance between energy absorption, structural integrity, and weight efficiency.

Specific energy absorption (SEA) characteristics of each metamaterial design are analyzed based on the data, including the hybrid strut combinations and microscope image of failed samples (Figure 4). All six samples have the uniform strut diameter of 0.5 so that the structural variations can be compared to the performance [25].

Table 4. *Comparative analysis of specific energy absorption in additively manufactured hybrid strut-based metamaterials*

Hybrid Strut based Combination	Total Energy Absorbed (kJ)	Mass (kg)	Specific Energy Absorption (kJ/kg)
Kelvin Cell + Edge Struts	13	0.07	185.71
Kelvin Cell + Octagon	145	0.1	1450
Kelvin Cell + Hex Truss	22	0.08	275
Edge Struts + Hex Truss	125	0.09	1388.89
Edge Struts + Face Centre	0.8	0.03	26.67
Edge Struts + Corner Diagonal	6.5	0.04	162.5

Combining the Kelvin Cell with edge struts results in a "strengthened edge" failure mode (Figure 4 (a)), which implies that edge struts effectively distributed stress, enhancing the overall structural integrity and, perhaps, by delaying failure, leading to higher SEA (Sample 1). Sample 2, with the Kelvin Cell and octagon combination, benefits from "more vertices," which enhances load distribution and stability, potentially improving SEA by providing more pathways for stress dissipation (Figure 4 (b)).

Sample 3, featuring the Kelvin Cell and hex truss, exhibits "many load channels," indicating a complex internal structure that likely absorbs more energy by distributing loads through multiple paths, enhancing SEA performance (Figure 4 (c)).

Sample 4 combines edge struts with a hex truss, where the "internal support" provided by the hex truss appears to play a crucial role in reinforcing the structure, likely improving its ability to absorb energy before failure (Figure 4 (d)). Sample 5, with edge struts and a face-centre configuration, displays an "edge-to-edge connection," which may influence failure by creating localized stress concentrations, possibly reducing SEA by promoting early failure at specific points (Figure 4 (e)). Lastly, Sample 6, incorporating edge struts and corner diagonal elements, shows the presence of a "diagonal strut," which typically enhances bracing and stability (Figure 4 (f)). This design likely contributes positively to SEA by resisting deformation and delaying structural collapse under compression.

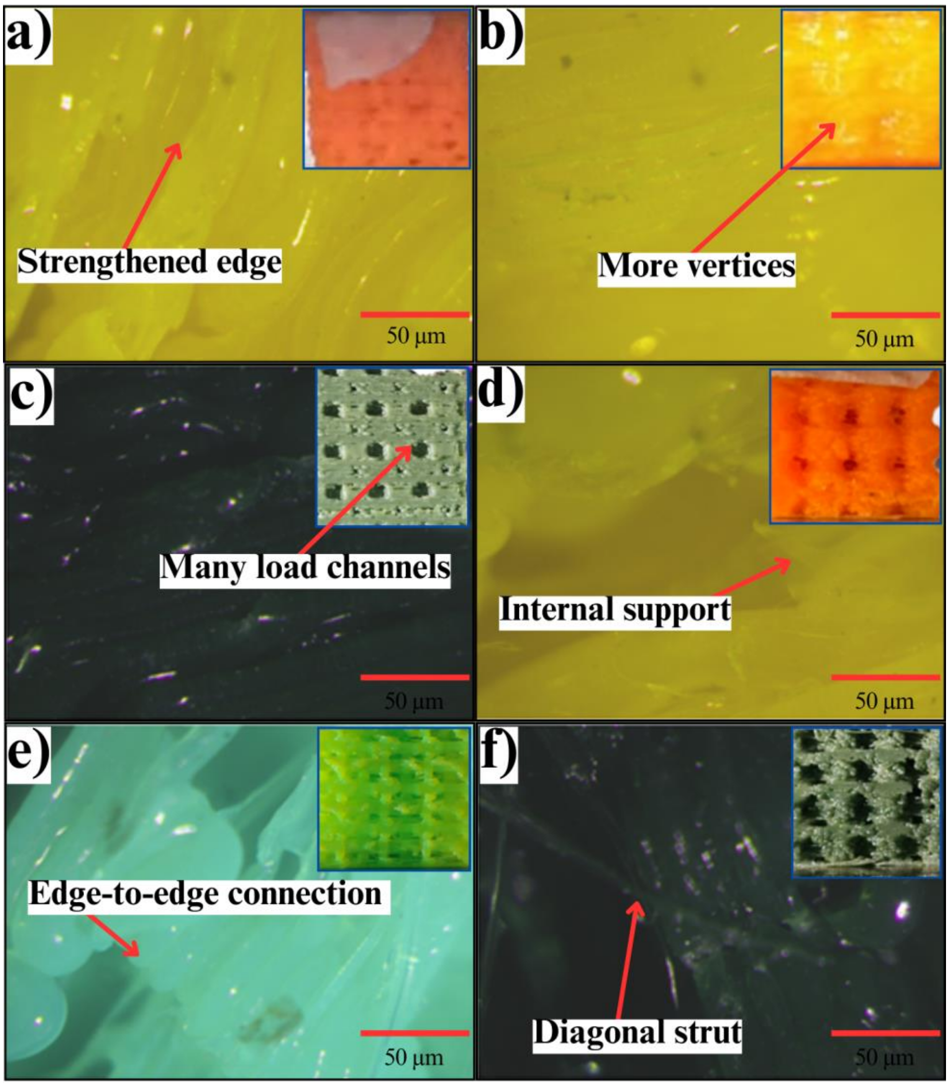


Fig. 4. Microscopic analysis of the failed samples (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4, (e) Sample 5, (f) Sample 6

In general, the failure mode and energy absorption characteristics depend on the specific structural design variations among these hybrid strut combinations. Structures that are more complex and well-reinforced have better SEA characteristics. This study has resulted in and discussed a strong relationship between the specific energy absorption (SEA) values and the failure modes of the different structural configurations. Through the analysis of microscope images, the structural geometry and connectivity of cellular structures influence their energy absorption behavior during compression. Hence, Sample 2 (Kelvin Cell + Octagon) shows the highest SEA of 1450 kJ/kg, as its structural connectivity is superior. The microscope image reveals "more vertices," indicating a high degree of structure connectivity. This complex network of vertices seems to help give a more uniform stress in the structure, delaying buckling locally, and allowing more energy to be taken by the material before failure [26]. The octagonal geometry leads to enhanced connectivity with the Kelvin cell structure, and this synergy with the Kelvin cell structure brings to bear the highest energy absorption capacity over all tested samples. The performance of Sample 4 (Edge Struts + Hex Truss) is a close second to Sample 2 in specific energy absorption, which is 1388.89 kJ/kg. This sample's microscope image shows evidence of "internal support," indicating that the hexagonal truss structure provides substantial reinforcement of the overall system. It is likely that this internal support mechanism allowed the structure to withstand higher stress levels before failure and thus improve the energy absorption capability [27]. The hexagonal truss's ability to distribute load efficiently across the structure seems to be a crucial factor in its high SEA performance, making it an excellent choice for energy absorption applications.

Sample 3 (Kelvin Cell + Hex Truss) shows a moderate SEA of 275 kJ/kg, which is considerably lower than the top-performing configurations. The image description notes "many load channels," indicating a complex internal structure designed to distribute loads throughout the material. While this complexity aids in energy absorption to some extent, it does not match the effectiveness of the internal support seen in Sample 4. The load distribution pathways in this configuration may lead to early localized failure points, reducing the overall SEA compared to the more robust "Edge Struts + Hex Truss" design.

Lower than 185.71 kJ/kg SEA is illustrated by Sample 1 (Kelvin Cell + Edge Struts). This "strengthened edge" (as seen in the microscope image) provides limited reinforcement compared to hexagons. Edge struts provide structural integrity but do not offer an energy absorption that is made as good as the hexagonal or octagonal elements. Its relatively lower SEA highlights the effects of the internal support and connectivity on its better performance for energy absorption. Sample 6 (Edge Struts + Corner Diagonal) shows an SEA of 162.5 kJ/kg, where the energy absorption capabilities are rather limited. It can be seen in the microscope image that the "diagonal strut" design offers some structural reinforcement but does not significantly improve energy absorption alone. It appears that the corner diagonal elements provide little load distribution benefits as well as early failure and lower energy absorption efficiency. This result implies that hexagonal or octagonal beams are more effective energy dissipaters than corner diagonal ones.

The microscope image of sample 5 (Edge Struts + Face Centre) shows the "edge to edge connection" design, and it records the lowest SEA of 26.67 kJ/kg. The presented pattern of this connectivity appears to be inefficient in the distribution of the load and dissipation of the energy while the material is being compressed. This configuration provides only minimal structural support and leads to early failure under load, pointing out the industrial importance of connectivity and support to enhance SEA. It is shown that the geometry is essential for determining the energy absorption capabilities of hybrid structures. The Samples 2 and 4 geometries, also hexagonal and octagonal, exhibit much higher performance than other configurations, indicating that they are more efficient at energy dissipation. Furthermore, internal support and connectivity are critical. Both Sample 2's high connectivity and Sample 4's internal support also give rise to improved energy absorption; hence, both of these structural attributes are important. Microscope imaging makes the explicit relationship between failure modes and SEA. Directly, the failure mechanisms, namely buckling, load channel distribution, and support reinforcement, affect SEA values. Understanding these failure modes will aid in fruitful metamaterial design optimization toward behavior in which energy absorption is the critical component of an application.

An analysis of the energy absorption capability leads to the most promising designs of "Kelvin Cell + Octagon" and "Edge Struts + Hex Truss". Since they have high SEA values, they are good candidates for applications such as automotive crash protection, aerospace structures, and personal protective equipment. Regardless of the optimal choice of material and configuration, they will still face application-specific requirements such as mass, cost, and manufacturing feasibility. It shows how the unit cell geometry and structural configuration of metamaterials are important factors in deciding their energy absorption capacity. Future designs can be made more efficient with energy dissipation by optimizing structural geometry and connectivity in order to achieve higher efficiency energy dissipation.

The findings underscore the critical importance of both geometry and connectivity in optimizing energy absorption. The "Edge Struts + Face Centre" configuration's poor SEA performance highlights how inefficient load distribution and limited internal support hinder energy dissipation. In contrast, the "Kelvin Cell + Octagon" and "Edge Struts + Hex Truss" configurations demonstrate superior SEA, thanks to their geometrically optimized strut arrangements and enhanced connectivity. Future research could explore hybrid configurations that combine the best aspects of various designs, potentially leading to even more efficient energy absorption. Additionally, the role of failure mechanisms, such as buckling and load channeling, should be more deeply studied to understand how different geometries respond under stress. The scalability of these designs for mass production, particularly in industries like automotive and aerospace, will require balancing material costs, manufacturability, and weight considerations. Ultimately, fine-tuning geometry and structural connectivity will be key to enhancing the real-world performance of these metamaterials.

Table 5 outlines the critical failure mechanisms of all the metamaterial designs and provides corresponding targeted recommendations to enhance their energy absorption capacity and performance.

Table 5. *Summary of the failure types, observed issues, and recommendations for each sample*

Sample	Failure type	Observed issues	Recommendations
1 (Strengthened edge)	Edge crack resistance	Reinforced edges prevent early crack initiation but may lead to layer delamination if interlayer bonding is weak.	Enhance interlayer bonding during fabrication; ensure uniform material density at edges to avoid delamination.
2 (More vertices)	Stress concentration at junctions	Increased vertices improve load distribution but introduce stress concentration at nodes, leading to crack initiation.	Optimize vertex design to reduce stress concentration; reinforce junctions with additional material or improved bonding techniques.

3 (Many load channels)	Progressive failure	Parallel load channels allow gradual energy absorption, but thin struts may shear off sequentially under cyclic loading.	Increase strut thickness where possible; use materials with higher shear strength; improve strut alignment to minimize shear forces.
4 (Internal support)	Delayed global collapse	Internal supports stiffen the lattice and resist buckling, but localized cracking may occur at weak joints due to load redistribution.	Strengthen joint areas with enhanced bonding; use higher-stiffness materials for internal supports; optimize support placement to evenly distribute loads.
5 (Edge-to-edge connection)	Shear-induced delamination	Direct edge-to-edge connections improve load transfer but create shear stress at interfaces, risking delamination if adhesion is weak.	Improve layer adhesion during manufacturing; modify connection design to distribute shear stress more evenly across the structure.
6 (Diagonal strut)	Buckling failure	Diagonal struts enhance load transfer, but insufficient material stiffness leads to buckling and torsional collapse under compression.	Use stiffer materials for diagonal struts; optimize strut angle and cross-section to resist buckling; increase overall structural stiffness.

Load vs. displacement curves of six hybrid strut-based metamaterial samples are presented in Figure 5, and it gives great insight into its mechanical deformation under compression. The overall comparison graph and these curves can be used to directly evaluate how each sample is strong, stiff, ductile, and energy absorbent. An understanding of the behavior of each sample is provided through the connection of these curves to the specific energy absorption data in Table 4. The highest mechanical performance is demonstrated in Sample 2 (Kelvin Cell + Octagon), as seen in the load vs. displacement curve (Figure 5 (b)); the peak load is highest, and the greatest displacement is prior to failure. Therefore, Sample 2 is the stiffest and strongest sample tested and can support the largest forces as well as undergo considerable deformation before structural collapse. This finding is confirmed by the overall comparison graph (Figure 6), as Hybrid 2 has the highest and farthest curve to the right, which implies higher load-carrying capacity and ductility. Table 4 reports the highest SEA of 1450 kJ/kg for this sample and that it has an extraordinary energy absorption efficiency. This configuration makes it an ideal candidate for applications requiring high energy absorption, such as automotive vehicle impacts and aerospace structures, due to its high stiffness, strength, and ductility. Sample 4 (Edge Struts + Hex Truss) comes close to Sample 2 in terms of its mechanical performance. According to the load vs. displacement curve (Figure 5 (d)), which shows a high load peak and high displacement, just slightly lower than Sample 2, it can be inferred that Sample 4 is a highly ductile and strong sample as well. The curve of Hybrid 4 ranks second in overall comparison (Figure 6), nearly reaching the maximum displacement of

Sample 2. Table 4 corroborates this high performance with an SEA of 1388.89 kJ/kg, confirming its ability to absorb considerable energy before failure. The robust internal support provided by the hexagonal truss structure enhances load distribution, enabling the sample to maintain its integrity under significant compression. Sample 4's combination of strength and ductility makes it a strong contender for similar high-performance energy absorption applications.

Sample 3 (Kelvin Cell + Hex Truss) exhibits moderate mechanical behavior. The load vs. displacement curve (Figure 5 (c)) shows a moderate peak load and displacement, indicating a balanced performance between strength and ductility. In the overall comparison (Figure 6), Hybrid 3's curve occupies the middle range, reflecting its moderate performance relative to other samples. With an SEA of 275 kJ/kg as reported in Table 4, this configuration offers decent energy absorption but does not match the higher-performing configurations of Samples 2 and 4. The "many load channels" structure allows for good energy distribution but lacks the reinforcement provided by internal support, resulting in reduced efficiency.

Sample 1 (Kelvin Cell + Edge Struts) shows a similar mechanical behavior to Sample 3. The load vs. displacement curve (Figure 5 (a)) indicates a moderate peak load and displacement, aligning closely with Sample 3's performance. The overall comparison graph (Figure 6) places Hybrid 1 near Hybrid 3, confirming its moderate mechanical behavior. Table 4 shows an SEA of 185.71 kJ/kg, which is lower than Sample 3 but still acceptable for applications where moderate energy absorption is sufficient. The "strengthened edge" design provides some reinforcement but does not significantly enhance the overall energy absorption capacity, limiting its effectiveness in high-stress applications.

Sample 6 (Edge Struts + Corner Diagonal) exhibits poor mechanical performance. The load vs. displacement curve (Figure 5 (f)) reveals a low peak load and limited displacement, indicating weaker structural integrity and lower ductility compared to higher-performing samples. In the overall comparison (Figure 6), Hybrid 6's curve ranks among the lowest, confirming its subpar performance. Table 4 reflects this with an SEA of 162.5 kJ/kg, suggesting that the corner diagonal structure does not effectively dissipate energy or distribute load, leading to early failure under compression. This configuration would be unsuitable for high-energy absorption applications.

Sample 5 (Edge Struts + Face Centre) performs the worst among all configurations. The load vs. displacement curve (Figure 5 (e)) shows the lowest peak load and the smallest displacement, indicating minimal strength and ductility. The overall comparison (Figure 6) confirms this poor performance, with Hybrid 5's curve being the lowest and shortest. Table 4 reports the lowest SEA of 26.67 kJ/kg, highlighting this configuration's inefficiency in energy absorption. The "edge-to-edge connection" design fails to distribute load effectively or enhance structural support, resulting in early structural failure and minimal energy dissipation. Sample 5's performance indicates it is unsuitable for any application requiring significant energy absorption.

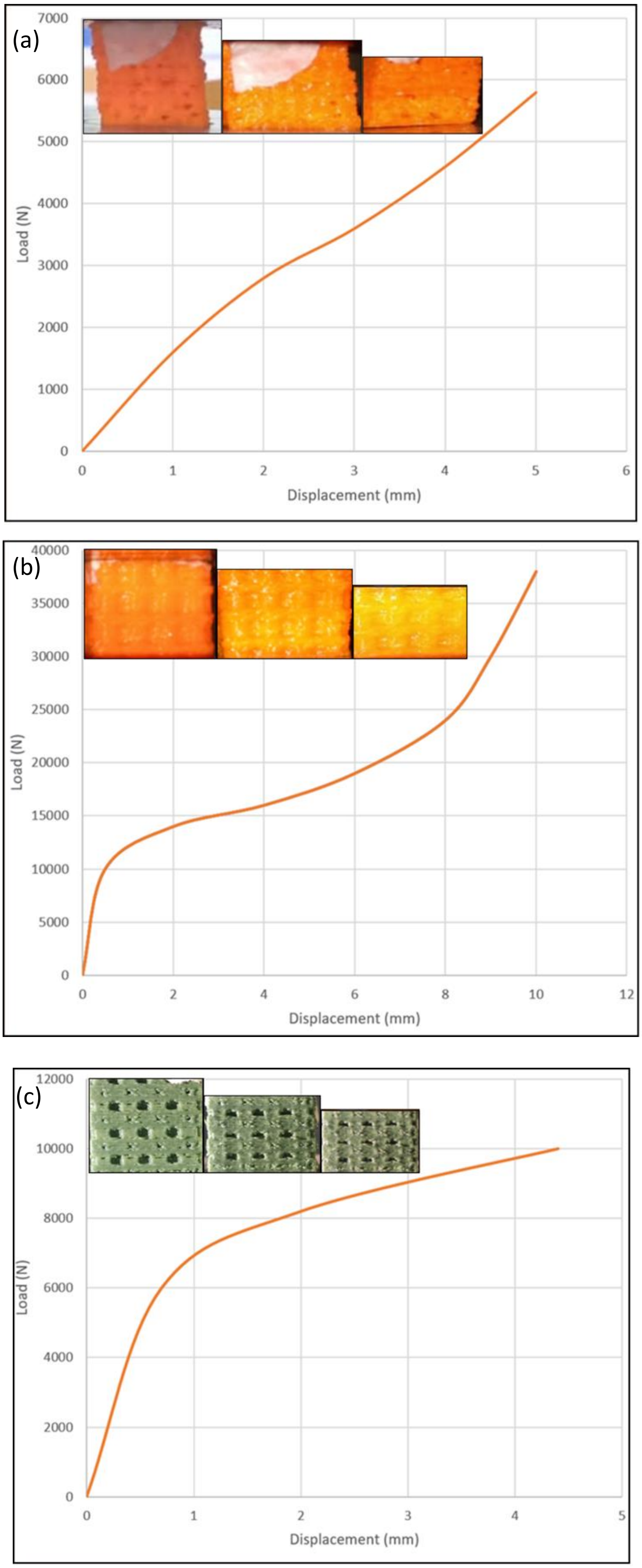
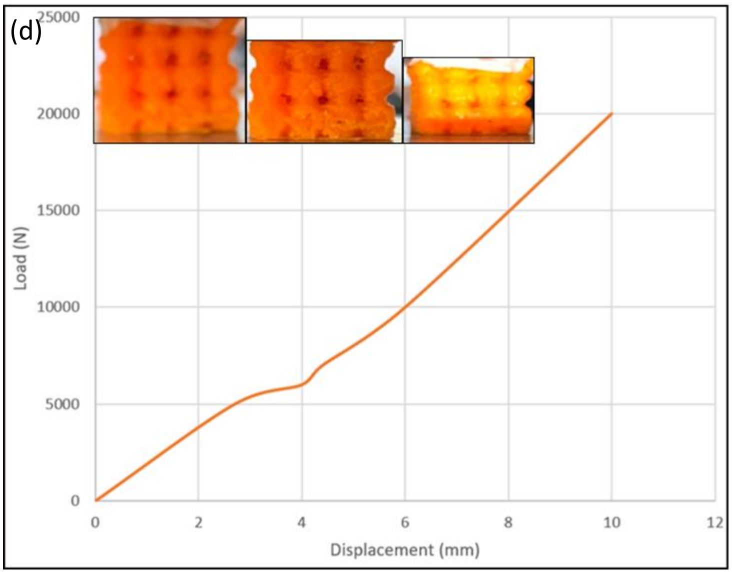
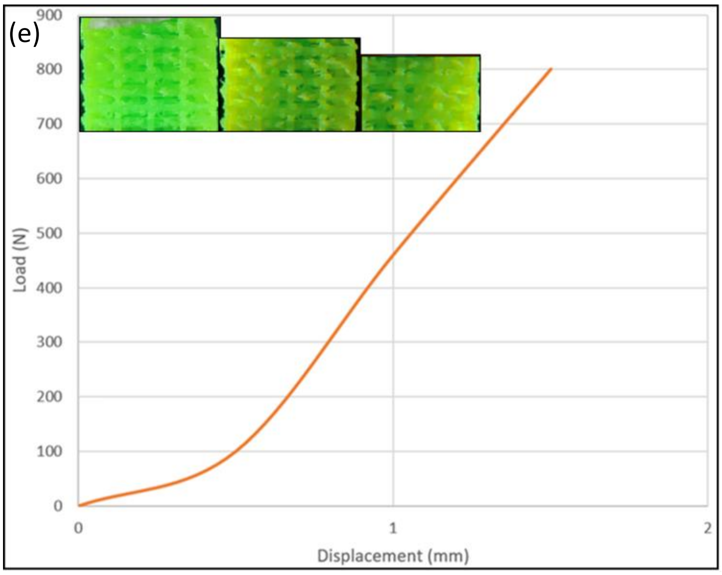


Fig. 5. Load vs displacement curve (a) sample 1, (b) sample 2, (c) sample 3





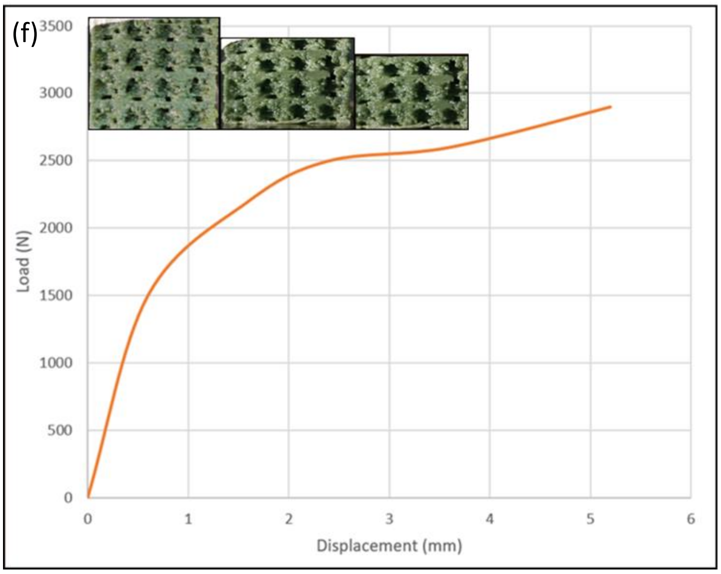


Fig. 5 (continued). Load vs displacement curve (d) sample 4, (e) sample 5, (f) sample 6

A clear correlation exists between the load vs. displacement curves and the SEA results. Samples 2 and 4, which exhibit the highest SEA values, also demonstrate superior load-bearing capacity and ductility, as indicated by their high peak loads and large displacements. Conversely, Sample 5, with the lowest SEA, shows the weakest performance across both load and displacement metrics.

The stiffness of each sample is inferred from the initial slope of the load vs. displacement curves. Samples 2 and 4 show the steepest initial slopes, indicating higher stiffness, which is crucial for applications where minimal deformation under load is desired [28]. The peak load reflects material strength, with Samples 2 and 4 enduring the highest forces before failure.

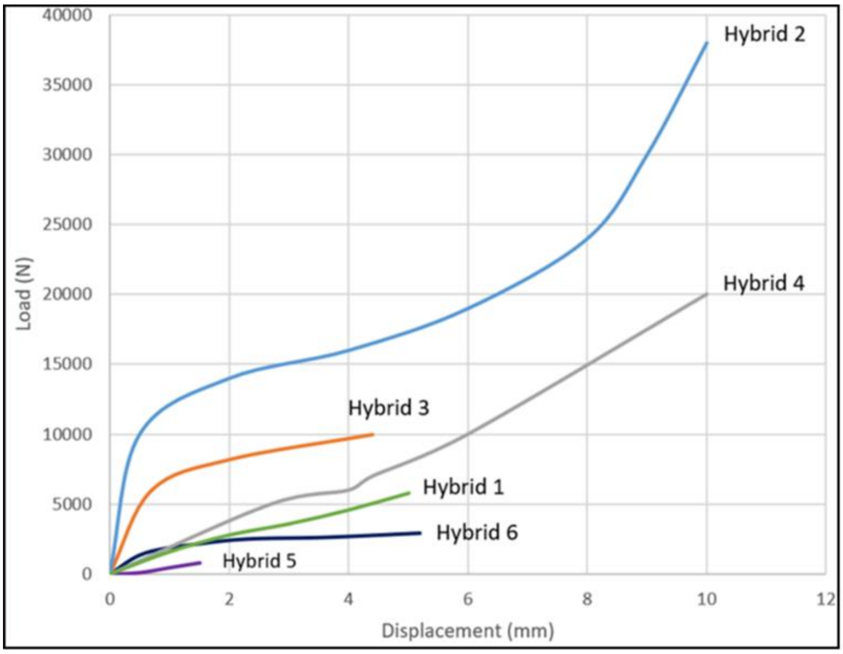


Fig. 6. Load vs displacement curve of overall comparison

The ductility and overall energy absorption capability are represented by the area under each curve. Samples 2 and 4 exhibit the largest areas, confirming their high energy absorption capacity. The curves also show the presence of failure mechanisms: sharp load drops imply brittle failure, whereas gradual decreases of the load signify ductile behavior. The ductility and controlled failure mode of samples 2 and 4 is also evident in the more gradual decrease shown by the samples. Among the samples, those of Sample 2 (Kelvin Cell + Octagon) and Sample 4 (Edge Struts + Hex Truss) exhibit the best mechanical performance in terms of high load-bearing capacity, ductility, and energy absorption, respectively. The performance of Sample 5 (Edge Struts + Face Centre) is unsatisfactory in all metrics and is therefore not well suited for high energy absorption applications.

The pull provides a basis for complementing the SEA analysis with the curve load vs. displacement, which allows getting a full picture of the mechanical behavior and confirming the value of the geometrical sample cell block and structural topology in metamaterial design. "Kelvin Cell + Octagon" and "Edge Struts + Hex Truss" combinations turn out to be the better configurations, especially for applications involving high strength, high ductility, and energy absorption, for example, automotive crash protection and aerospace structural components. The load vs. displacement curves provide a comprehensive understanding of the mechanical performance of hybrid strut-based metamaterials, revealing key insights into their strength, stiffness, ductility, and energy absorption. The superior performance of "Kelvin Cell +

Octagon" (Sample 2) and "Edge Struts + Hex Truss" (Sample 4) in terms of load-bearing capacity and ductility confirms their potential for high-performance applications, such as automotive crash protection and aerospace structures. These configurations exhibit high stiffness, strength, and ductility, ensuring they can withstand significant loads and absorb energy efficiently. On the other hand, the poor performance of "Edge Struts + Face Centre" (Sample 5) emphasizes the importance of effective load distribution and internal support. The gradual failure modes in the best-performing samples highlight their energy-dissipative nature, which is crucial for applications requiring controlled energy absorption. Further optimization of connectivity and internal reinforcement could enhance the performance of weaker configurations, improving their applicability in diverse engineering fields.

CONCLUSIONS

A comparative analysis of six hybrid strut-based metamaterial designs was executed in the study of their energy absorption capabilities. The production process employed Fused Deposition Modeling (FDM) with Polylactic Acid (PLA). The key findings and conclusions are as follows:

With 1450 kJ/kg specific energy absorption, the "Kelvin Cell + Octagon" configuration performed best among all the configurations. It is due to the synergistic effect of octagonal geometry and Kelvin cell structure, leading to controlled deformation and delayed buckling, which maximizes energy dissipation.

The "Edge Struts + Hex Truss" configuration trailed closely behind, with a SEA of 1388.89 kJ/kg. Through this, it can be noted that there is effective load distribution and reinforcement by using the hexagonal truss structure.

SEA for other configurations was significantly lower, demonstrating the inherent importance of unit cell geometry in determining the energy absorption capacity for metamaterials.

The analysis of failed samples by microscopy showed geometries with edges of hexagons and octagons allowed the SEA to be higher since uniform stress and controlled deformation were promoted during compression.

It is suggested that the geometry of the unit cell represents an important geometric characteristic responsible for determining energy absorption ability in hybrid structures.

Finally, it is shown that through a suitably modified (easily constructed) steel octagon and adapter structure, these designs offer high energy absorption in comparison to their original, and the "Kelvin Cell + Octagon" and "Edge Struts + Hex Truss" designs are identified as the most promising for use in high energy absorption applications, including automotive crash protection, aerospace structures, and personal protective equipment.

SEA analysis is complemented by the load vs. displacement curves, which provide a complete picture of the mechanical behavior and validate the significance of unit cell geometry and structural configuration in the design of metamaterials.

Findings of this study point to future research on hybrid strut-based metamaterials. In the future, future work can innovate with advanced polymers, metals, and composites that would improve mechanical properties and energy absorption. Genetic algorithms and machine learning can be used to optimize geometry to achieve improved strength-weight ratios and multiplicity. Precision and microstructural features can be further incorporated through advanced manufacturing. Further research into these applications may include heat transfer, acoustic damping, and electromagnetic shielding. Furthermore, biomimetic designs based on natural structures may enable the design of adaptive metamaterials with improved capabilities in terms of energy absorption.

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