

Article

Energy Absorption Behavior of Thickness-Dependent Functionally Graded Inconel 718 Auxetic Structures Produced by Laser Powder Bed Fusion

Orhan Gülcan ^{1,*} , Burak Özcan ² , Umut Çalışkan ^{2,3}  and Güher Pelin Toker ⁴

¹ Türkiye Technology Center, GE Aerospace, İstanbul 34880, Türkiye

² Advanced Composite Materials Research Group, Erciyes University, Kayseri 38030, Türkiye; ozcan.burak@outlook.com (B.Ö.); ucaliskan@erciyes.edu.tr (U.Ç.)

³ Faculty of Engineering, Department of Mechanical Engineering, Mechanics Division, Erciyes University, Kayseri 38030, Türkiye

⁴ Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, Construction and Manufacturing Division, Sivas University of Science and Technology, Sivas 58000, Türkiye; guhertoker@sivas.edu.tr

* Correspondence: orhan.gulcan@geaerospace.com

Abstract

Auxetic metamaterials have outstanding negative Poisson's ratio characteristics which can be beneficial in different industrial applications. The main aim of the present study is to investigate the effect of thickness-dependent functional grading (FG) on the mechanical response of two widely known auxetic geometries, namely re-entrant and anti-tetrachiral. Three different thickness-dependent FG versions of these geometries were compared against their counterparts without FG by using numerical simulations. The effect of thickness-dependent FG was also compared against non-auxetic geometry (honeycomb) to understand the effect of auxeticity. The validation experiments were performed by the production of sample geometries by laser powder bed fusion technology from Inconel 718 material and quasi-static compression testing. The results revealed that the grading direction is a key variable in design that significantly influences the deformation stability and stress distribution, and it was shown that thickness-dependent FG is a promising way to decrease the weight of auxetic structures without sacrificing SEA considerably.

Keywords: auxetic structure; energy absorption; re-entrant; anti-tetrachiral; honeycomb

1. Introduction

Metamaterials are artificially engineered materials that have unusual and extraordinary properties that cannot be observed in traditionally manufactured materials. These unusual properties include negative linear compressibility, negative thermal expansion coefficient and negative Poisson's ratio (NPR) [1]. Isotropic materials exhibit a Poisson's ratio between -1.0 and 0.5 based on elasticity theory and most of the bulk materials (metals, polymers etc.) show a positive Poisson's ratio [2]. On the other hand, auxetic metamaterials are a subtype of mechanical metamaterials that show an extraordinary deformation mechanism of NPR [3]. These structures show outstanding energy absorption behavior, shear stiffness, in-plane indentation resistance and fracture toughness when compared with conventional materials [4]. Due to these characteristics, they find their usages in different industrial applications like crashworthiness applications in the automotive industry [5],



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blast loading applications [6], medical and biomedical applications, protective devices, fasteners [7], sports accessories [8] and different energy absorption applications [9].

The most common and widely used auxetic metamaterials are re-entrant, trichiral, tetrachiral, hexachiral, anti-trichiral and anti-tetrachiral auxetic metamaterials. These different types of auxetic metamaterials show different effective moduli of elasticity, relative densities, Poisson's ratios and effective shear moduli [10].

A re-entrant auxetic metamaterial is a variation in the conventional honeycomb structure where the upper and bottom two walls in the conventional honeycomb structure move towards each other to form a bow-tie-like structure [11]. They have anisotropic cells which result in a higher shear modulus and transverse Young's modulus when compared with a conventional honeycomb structure [12]. It was stated in the literature that re-entrant structure usage decreases initial peak force and increases the mean plateau force which results in high energy absorption [13]. Re-entrant auxetic metamaterials undergo three deformation stages under compressive loads: elastic stage, plastic-plateau stage, and densification stage. In the elastic stage, the structure deforms elastically and cell walls bend. When the wall bending moment reaches the plastic bending moment, then the plastic-plateau stage starts at which each cell starts to collapse. When strain is increased, after some point, the densification stage starts where the structure behaves like a solid structure [14]. Re-entrant auxetic metamaterials show a long plastic-plateau stage which is an indication of high energy absorption [14]. During compressive loading, re-entrant auxetic metamaterials undergo ligament re-alignment, axial deformation and deflection of ligaments [15]. Jiang et al. investigated the compressive response of re-entrant and chiral auxetic metamaterials experimentally and numerically. Their results showed that re-entrant and chiral auxetic metamaterials can preserve auxetic effects up to 3–4% and 10–30% strains, respectively. The higher strain values for chiral auxetic metamaterials are due to their chirality-induced rotation behavior [16]. Related to tensile response, Zhang et al.'s study on the tensile behavior of re-entrant auxetic metamaterials revealed that the structure showed NPR in tension until the inclined cell walls became horizontal (until a strain value of 0.7), then a positive Poisson's ratio [17]. The compressive and tensile properties of re-entrant auxetic metamaterials are directly related to geometrical parameters. Hu et al.'s study revealed that the NPR effect of re-entrant structures increases when the cell wall angle increases and the cell wall length ratio decreases [18]. The thickness of walls in re-entrant auxetic metamaterials affects the deformation behavior. Thicker walls result in shrinkage deformation and fracture; on the other hand, thinner walls result in local shrinkage and expansion. This can be attributed to the friction effect at the boundaries where crushed walls resist friction more effectively and start to slip [19].

A chiral type of auxetic metamaterials, on the other hand, consists of a central cylindrical node and ligaments tangentially attached to the node [20]. These nodes can be on the opposite sides of a ligament (in trichiral, tetrachiral and hexachiral auxetic metamaterials) or on the same sides of a ligament (in anti-trichiral and anti-tetrachiral auxetic metamaterials) [21]. Chiral structures have unique geometries that cannot be superposed to their mirror images by just translation or rotation [22]. Trichiral, tetrachiral and hexachiral auxetic metamaterials have 3, 4 and 6 ribs per node, respectively. Due to the increasing rib number per node, compressive modulus values increase from trichiral to hexachiral configurations. Moreover, due to the lower cross-sectional area of anti-chiral auxetics when compared with their chiral equivalents, anti-chiral auxetic metamaterials show a higher compressive modulus than their chiral equivalents [23]. Alderson et al.'s study showed that hexachiral, tetrachiral and anti-tetrachiral auxetic metamaterials exhibit a Poisson's ratio of -1 at a low ligament-cylinder wall thickness/cylinder radius ratio. Poisson's ratio of trichiral auxetic metamaterials, on the other hand, changes from negative to positive

when ligament length/cylinder radius ratio increases [24]. These chiral types of auxetic metamaterials show ligaments folding around the node under compressive loading and ligaments unfolding under tensile loading which emerges from the rotation of the nodes when compressive or tensile loading is applied [21]. In chiral-type auxetic metamaterials, compressive loading generates a torque on the cylinders. Due to this torque, cylinders start to rotate and consequently ligaments connected to each cylinder start to bend. Bending of ligaments forms a half-wave ligament shape in anti-trichiral and anti-tetrachiral types of auxetic metamaterials. In trichiral, tetrachiral and hexachiral types of auxetic metamaterials, the rotation of cylinders is limited, and ligaments undergo flexure into a full-wave shape [24]. Mousanezhad et al. showed that anti-tetrachiral auxetic metamaterials exhibit NPR under small deformation [10]. However, the ligament's length ratio is very important in anti-tetrachiral auxetic metamaterials such that it can show a zero, positive or negative Poisson's ratio [25]. Günaydin et al.'s study showed that local buckling and plastic collapse of walls due to ligament bending and rotation of corner cylinders occur after the elastic stage in compression of anti-tetrachiral auxetic metamaterials [26].

To tailor mechanical properties, functional grading (FG) based on material, geometry and production methods has been investigated in scientific literature [27]. Kenan et al. investigated the effect of geometrical FG on re-entrant structures produced by fused deposition modeling and stated that FG increased the load-carrying capacity of re-entrant structures by 35% [28]. Dadashi et al. investigated the effect of geometric FG on mechanical behavior and energy absorption characteristics of fused deposition modeled double arrowhead auxetic geometries and stated that energy absorption can be increased by changing the angle of the auxetic double arrowhead unit cell [29]. Demirbas et al. investigated the effect of FG on negative Poisson's ratio characteristics of a novel double-cylindrical-shell-based re-entrant unit cell produced by fused deposition modeling and stated that both cell designs and material variations change the negative Poisson's ratio [30].

The literature review on the mechanical properties of different auxetic geometries and FG counterparts revealed that most of the studies focused on material grading and changing the struts of auxetic geometries with different types of struts. Moreover, in most of the scientific studies, experimental validations were based on polymeric materials. In engineering applications, metallic structures are widely used and to the best of the authors' knowledge, scientific literature has a gap in the mechanical properties and energy absorption characteristics of metallic FG auxetic materials. Nazeer et al. investigated the mechanical properties of anti-tetrachiral In718 materials with different cell sizes and relative densities produced by laser powder bed fusion (LPBF) [31]. Delcuse et al. investigated the mechanical properties of re-entrant In718 materials produced by LPBF with different process parameters [32]. However, the geometries used in these studies are non-graded specimens without any FG. To fill this gap, this study compares energy absorption characteristics and deformation behaviors of thickness-dependent FG re-entrant and anti-tetrachiral auxetic geometries against the honeycomb geometry. Numerical simulations were validated by quasi-static compression tests on LPBF-produced In718 geometries.

2. Materials and Methods

2.1. 3D CAD Model Preparation

Auxetic re-entrant and anti-tetrachiral geometries and non-auxetic honeycomb geometry were modeled by Siemens NX 12 software (Siemens AG, Munich, Germany). Due to the LPBF manufacturing constraints, the minimum wall thickness was selected as 1 mm at most and 0.6 mm at minimum. Wall angles, radii and other features are selected based on the most used configurations in the literature [15]. For each of the geometry types, one non-graded and three thickness-dependent graded specimens were designed.

Thickness-dependent geometries were designed such that thicknesses were decreased from top to bottom, from bottom to top and from middle to bottom and top. A 0.1 mm radius was used at the thickness transition regions. A total of 12 different geometries were used in the present study (Figures 1–3).

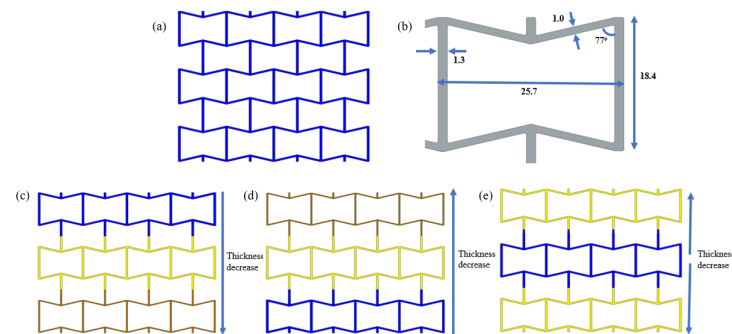


Figure 1. (a) Non-graded re-entrant geometry with overall dimensions of $98.9 \times 77.8 \times 15.0$ mm; (b) detail dimensions of one unit cell; (c) thickness-dependent FG: thickness decreases from 1 mm from top to 0.6 mm from bottom (FG-1); (d) thickness-dependent FG: thickness decreases from 1 mm from bottom to 0.6 mm from top (FG-2); (e) thickness-dependent FG: thickness decreases from 1 mm from middle area to 0.8 mm from bottom and top (FG-3). Blue, yellow and brown regions have 1 mm, 0.8 mm and 0.6 mm thicknesses, respectively.

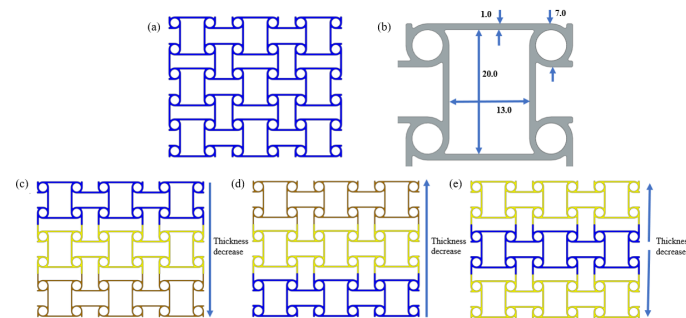


Figure 2. (a) Non-graded anti-tetra chiral geometry with overall dimensions of $99.0 \times 80.0 \times 15.0$ mm; (b) detail dimensions of one unit cell; (c) thickness-dependent FG: thickness decreases from 1 mm from top to 0.6 mm from bottom (FG-1); (d) thickness-dependent FG: thickness decreases from 1 mm from bottom to 0.6 mm from top (FG-2); (e) thickness-dependent FG: thickness decreases from 1 mm from middle area to 0.8 mm from bottom and top (FG-3). Blue, yellow and brown regions have 1 mm, 0.8 mm and 0.6 mm thicknesses, respectively.

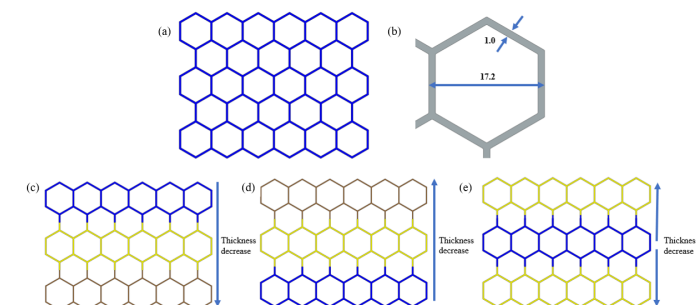


Figure 3. (a) Non-graded honeycomb geometry with overall dimensions of $98.2 \times 75.9 \times 15.0$ mm; (b) detail dimensions of one unit cell; (c) thickness-dependent FG: thickness decreases from 1 mm from top to 0.6 mm from bottom (FG-1); (d) thickness-dependent FG: thickness decreases from 1 mm from bottom to 0.6 mm from top (FG-2); (e) thickness-dependent FG: thickness decreases from 1 mm from middle area to 0.8 mm from bottom and top (FG-3). Blue, yellow and brown regions have 1 mm, 0.8 mm and 0.6 mm thicknesses, respectively.

2.2. Numerical Analysis

2.2.1. Model Description and Boundary Conditions

In this study, the quasi-static compression behavior of twelve different lattice geometries was numerically investigated in the ANSYS Mechanical 2023 R2 environment using a nonlinear implicit solver. Due to the geometric complexity and the high number of parameters inherent in lattice structures, a two-dimensional plane stress approach was preferred. This approach was selected to keep the computational cost at a reasonable level and to ensure the efficient execution of parametric analyses.

Each lattice specimen was modeled between two steel plates to represent experimental compression tests. The bottom plate was defined as a fixed support, with all translational degrees of freedom constrained. No additional kinematic constraints were imposed on the lateral edges of the specimens, allowing free in-plane deformation throughout the compression process. A controlled displacement was applied to the top plate in the direction of compression, mimicking the experimental crosshead motion. A total displacement loading of 30 mm was utilized in the analyses (Figure 4).

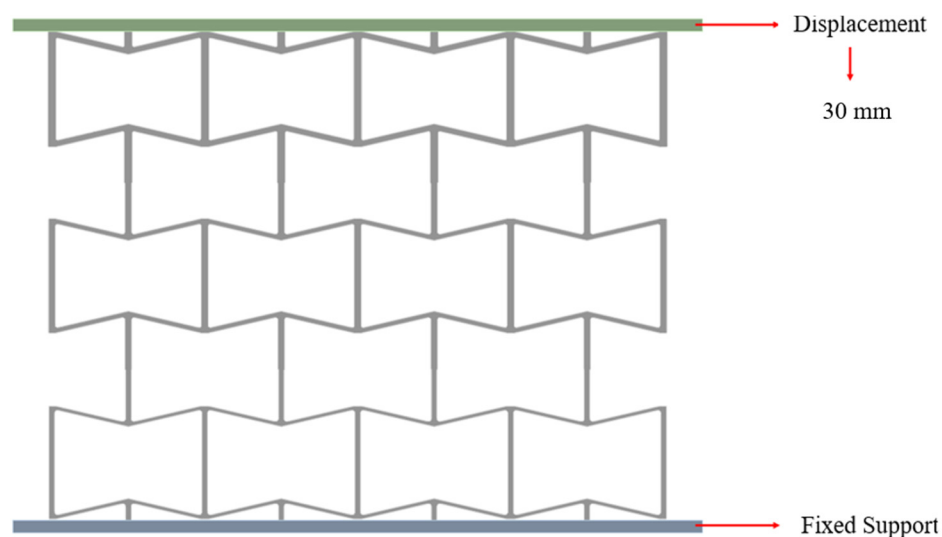


Figure 4. Boundary conditions for the re-entrant FG lattice structure test setup.

Since lattice structures involve large deformations, contact, and local folding mechanisms, geometric nonlinearities (large deformation effects) were incorporated into the analysis. Automatic time stepping was employed during the solution process to ensure numerical stability in regions of high deformation and contact. Furthermore, a Nonlinear Adaptive Region was defined to enhance solution accuracy in zones characterized by high plastic strain.

Although lattice structures are inherently three-dimensional, the geometries investigated in this study possess a uniform prismatic cross-section along the build direction (15 mm depth) with no out-of-plane loading or kinematic constraint. Under these conditions the deformation field is dominated by in-plane ligament bending, node rotation and self-contact mechanisms; therefore, a 2D plane stress idealization has been adopted. This idealization enabled the parametric assessment of twelve geometries within a feasible computational time while preserving the dominant physics of the problem. Furthermore, high-resolution imaging of the experimental specimens throughout compression revealed no appreciable out-of-plane deformation, lateral buckling or twisting along the 15 mm depth direction, providing direct experimental support for the plane stress idealization. The favorable agreement between numerical and experimental stress–strain curves and deformation patterns presented in Sections 3.1–3.3 further confirms the validity of this assumption.

2.2.2. Material Model

The lattice structures were modeled using Inconel 718 (In718). The elastic properties of the material were defined with a Young's modulus of 177 GPa, a Poisson's ratio of 0.273, and a density of 8.17×10^{-6} kg/mm³. The compression plates were modeled as steel, with an assigned modulus of elasticity of 200 GPa and a Poisson's ratio of 0.3.

To represent the material behavior under quasi-static loading conditions, a Multilinear Isotropic Hardening model based on stress–plastic strain data was employed (Figure 5). This approach was selected to accurately capture the high levels of plastic deformation that lattice structures undergo during crushing.

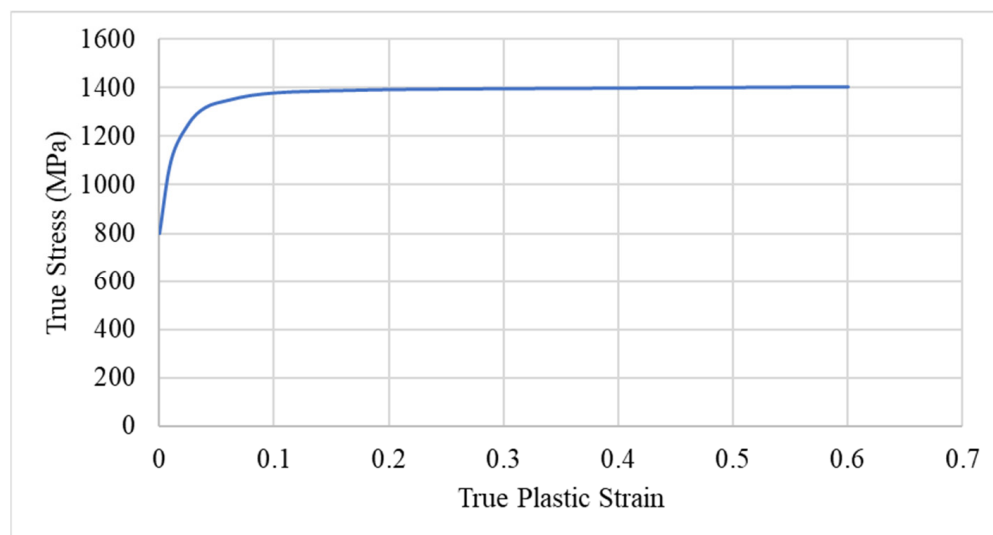


Figure 5. True stress-true plastic strain data for In718.

Due to the low loading rate, strain-rate-dependent effects were neglected, and a rate-independent material behavior was assumed [33,34]. Furthermore, damage and fracture behaviors were not explicitly modeled; instead, the progression of deformation was represented through geometric nonlinearity and contact interactions.

2.2.3. Contact Definition

The interaction between the lattice wall surfaces and the steel plate surfaces was represented using a frictional contact model defined with the Augmented Lagrange formulation. This formulation is a widely preferred method in terms of penetration control and convergence stability [35,36].

The frictional coefficient for all contact interfaces, including both the specimen–plate interaction and the self-contact within the lattice, was set to 0.5. This value is consistent with the typical ranges reported in the literature for metal-to-metal contact between as-built Inconel 718 surfaces in similar lattice structure compression studies. The contact stiffness was updated at each Newton–Raphson iteration, and an aggressive stiffness update algorithm was employed to ensure that the contact behavior was accurately captured during large deformations.

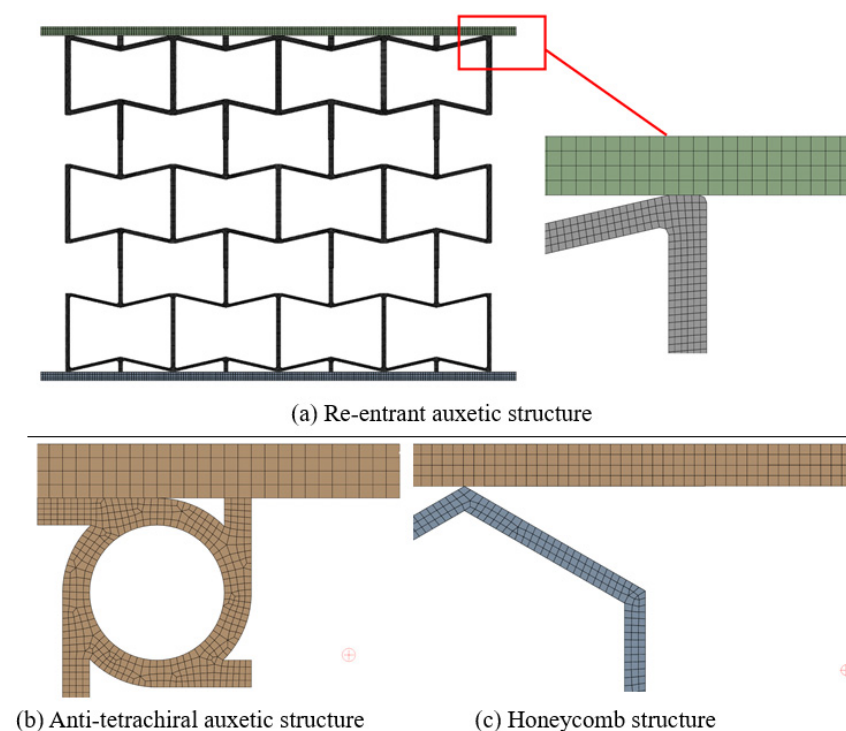
To model the wall-to-wall contacts occurring during the crushing process, self-contact was defined within the lattice structure. This allowed for the realistic representation of progressive folding and cell collapse mechanisms. The contact parameters used in the study are summarized in Table 1.

Table 1. Contact parameters.

Parameter	Value/Setting
Contact type	Frictional
Formulation	Augmented Lagrange
Friction coefficient	0.5
Stiffness update	Each iteration, Aggressive
Stabilization damping factor	5×10^{-2}
Behavior	Program Controlled
Interface treatment	Add Offset, No Ramping

2.2.4. Mesh Structure and Independence Analysis

All specimen geometries were defined with a global element size of 0.5 mm, while a first-order element size of 0.25 mm was utilized for the lattice structure. The mesh for the plate bodies was generated using the Prime Quad Dominant method, which produces quadrilateral-heavy elements suitable for the thin-walled planar geometry of the lattice structures. For the FG re-entrant specimen where the thickness decreases from 1 mm at the top to 0.6 mm at the bottom, selected as a representative sample, the mesh structure consists of 22,741 nodes and 18,455 elements. The numerical mesh generated for this specimen along with anti-tetrachiral and honeycomb structures is presented in Figure 6.

**Figure 6.** Finite element mesh configurations for three distinct lattice designs.

To verify the adequacy of the selected element size, a systematic mesh independence study was performed on the non-graded re-entrant specimen. Three successive element sizes were tested from coarse to fine (1.0 mm, 0.5 mm and 0.25 mm), and the resulting load–displacement responses were compared. A noticeable difference in the plateau stress was observed between the 1.0 mm and 0.5 mm meshes, whereas the response obtained with the 0.25 mm mesh exhibited only a negligible deviation from that of the 0.5 mm mesh, indicating that the numerical results had converged at this refinement level. This study justified the use of the 0.25 mm element size in all subsequent analyses. Furthermore, the favorable agreement between the numerical and experimental stress–strain curves of the

non-graded specimens provides an a posteriori confirmation of the accuracy of the chosen mesh resolution.

2.2.5. Solution Settings

The analyses were conducted using a single-step static structural solution approach. The loading was defined by incrementally increasing a total displacement of 30 mm applied to the top plate throughout the analysis duration. Large deformation effects were activated to ensure the accurate representation of the significant geometric changes exhibited by the lattice structures during crushing.

During the solution process, automatic time stepping was utilized, and the load increment was controlled through adaptive substeps. This approach was preferred to enhance solution stability in regions characterized by nonlinear behaviors such as contact, local folding, and sudden cell wall collapse. Equilibrium conditions were satisfied at each substep via Newton–Raphson iterations, and convergence was monitored based on both force and displacement residuals.

A direct solver was selected for the analysis. This choice was made because direct solvers provide more stable and reliable convergence behavior compared to iterative solvers, particularly in problems involving high nonlinearity and intensive contact interactions. Weak springs and inertia relief were not utilized; the solution was based entirely on static equilibrium conditions.

The primary physical justification for choosing an implicit solver is the very low experimental loading rate (0.5 mm/min). Under these conditions, inertial effects are negligible, and the solution can be reliably obtained under a quasi-static assumption. Consequently, methods commonly used in explicit dynamic analyses, such as mass scaling or artificial loading rate increases, were not required. Similarly, the use of implicit solvers under quasi-static conditions is widely preferred in numerous lattice structure compression studies in the literature [37–39]. Table 2 summarizes the numerical solution settings and solver parameters employed in this study.

Table 2. Summary of numerical solution settings.

Parameter	Value/Setting
Number of steps	1
Step end time	1 s
Auto time stepping	On
Initial substeps	400
Minimum substeps	400
Maximum substeps	9×10^8
Solver type	Direct
Large deflection	On
Quasi-static solution	On
Inertia relief	Off
Weak springs	Off

2.3. Validation Experiments

For validation purposes of numerical analysis with quasi-static test results, our previous research results were used [40] where non-graded geometries were manufactured by using the Concept Laser M2 machine (Colibrium Additive, Lichtenfels, Germany) with process parameters of 160 W laser power, 680 mm/s laser scan speed, 80 μ m laser spot size and 50 μ m layer thickness. The meander scanning strategy was used during the build and in each of the new layers, the scan direction was rotated 67°. Inconel 718 powder material was used during production. After production, the powder evacuation process was

performed by using the Solukon SFM AT800 depowdering system. Then, the specimens were removed from the substrate by using the GF Agiecharmilles wire electrical discharge machine (Agie Charmilles Ltd., Biel, Switzerland). No heat treatment was performed; the specimens were left in as-built condition, and all the validation tests were performed in this condition. Three repetitions for each of the three geometries (re-entrant, anti-tetrachiral and honeycomb) were manufactured and tested to show the repeatability of tests.

An Instron 5985 universal testing machine (Instron Inc., Norwood, MA, USA) was used during quasi-static compression tests. A top crosshead velocity of 0.5 mm/min was used during the tests. The Canon EOS 650D camera (Canon Inc., Tokyo, Japan) was used to capture deformation characteristics of graded and non-graded auxetic and non-auxetic geometries. The testing machine recorded the applied force F and the crosshead displacement Δ . To enable a fair comparison between specimens of different overall dimensions and masses, these data were converted into nominal (engineering) stress and nominal strain at the structural level using $\sigma = F/A_0$ and $\epsilon = \Delta/H_0$, where A_0 is the initial gross cross-sectional area of the specimen perpendicular to the loading direction and H_0 is its initial height. The resulting nominal stress represents the load-carrying capacity per unit footprint area of the lattice as a whole and is not intended to describe the local stress field within individual cell walls, which is reported separately through the von Mises distributions obtained from the finite-element model. The geometries were compressed into a densification regime with a total displacement of 40 mm.

By using applied force and crosshead displacement data of different specimens, energy absorption values were calculated as specified by Equation (1).

$$EA(z) = \int_0^z P(x)dx \quad (1)$$

Here, z is the total crosshead displacement, P is the applied force, and x is the crosshead displacement. Then, by dividing energy absorption values by specimen weights, specific energy absorption values were found as specified in Equation (2).

$$SEA = \frac{EA}{m} \quad (2)$$

The weights of the specimens were calculated by using Siemens NX (version 12) software from their 3D CAD models and the Sartorius GC 1603 SOCE model weight measuring device (Sartorius AG., Göttingen, Germany) was used to validate the measurements on the produced specimens.

3. Results and Discussion

This section presents the mechanical response and energy absorption characteristics of thickness-dependent FG re-entrant, anti-tetrachiral, and honeycomb geometries. The results are evaluated through a comparative analysis of numerical simulations and experimental data obtained from In718 specimens produced via laser powder bed fusion (LPBF). To validate the accuracy of the finite element models, the stress–strain curves and deformation modes of non-graded structures were initially compared against quasi-static compression test results. Subsequently, the influence of three distinct thickness-grading strategies, decreasing from top-to-bottom, bottom-to-top, and middle-to-ends, was investigated to determine their impact on load-carrying capacity and deformation stability. The following subsections detail the localized stress distributions, densification regimes, and specific energy absorption (SEA) values for each lattice configuration.

3.1. Re-Entrant Structures

3.1.1. Comparison of Experimental and Numerical Results

The stress–strain responses of the re-entrant auxetic structures obtained from experimental tests and numerical simulations are presented in Figure 7. All curves exhibit a characteristic deformation behavior consisting of three distinct regions: an initial elastic regime, a plateau region associated with progressive cell collapse, and a densification stage which is consistent with the experimental results in the literature [41].

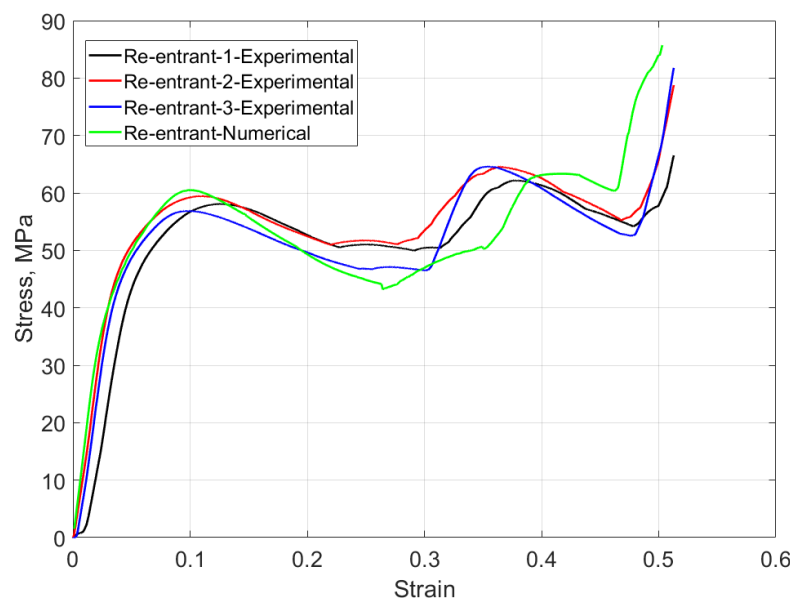


Figure 7. Comparison of the experimental and numerical stress–strain curves of the re-entrant auxetic structure under quasi-static compression.

In the initial region ($\varepsilon < \sim 0.1$), a rapid increase in stress is observed for all specimens, indicating the elastic bending-dominated response of the re-entrant cell walls. The numerical model slightly overpredicts the initial stiffness compared to the experimental results, which can be attributed to the idealized geometry and the absence of manufacturing-induced imperfections in the simulations. Following the elastic region, a stress drop and subsequent plateau behavior are observed between $\varepsilon \approx 0.1$ – 0.3 . This region corresponds to the onset of plastic deformation and progressive folding of the inclined ligaments. The relatively stable plateau stress (~ 45 – 60 MPa) indicates efficient energy absorption capability, which is a well-known characteristic of re-entrant auxetic structures.

At higher strain levels ($\varepsilon > \sim 0.3$), the stress increases again, marking the transition to the densification regime. In this stage, the collapsed cell walls come into contact, leading to a rapid increase in load-carrying capacity. The numerical model predicts an earlier and more pronounced densification response, reaching higher stress values (~ 85 MPa) compared to experimental results (~ 80 MPa). This discrepancy is likely due to the simplified contact definitions and the lack of damage or fracture modeling in the simulations. A good agreement is observed between experimental and numerical results in terms of deformation stages and general trend. However, differences in peak stress levels and densification behavior highlight the influence of real manufacturing effects such as surface roughness, geometric deviations, and local defects, which are not captured in the numerical model.

Figure 8 presents the comparison between numerical predictions and experimental observations of the deformation behavior of the re-entrant auxetic structure under quasi-static compression at different displacement levels (10 mm, 20 mm, 30 mm, and 40 mm).

A consistent deformation mechanism is observed in both approaches, confirming the reliability of the numerical model in capturing the overall collapse behavior.

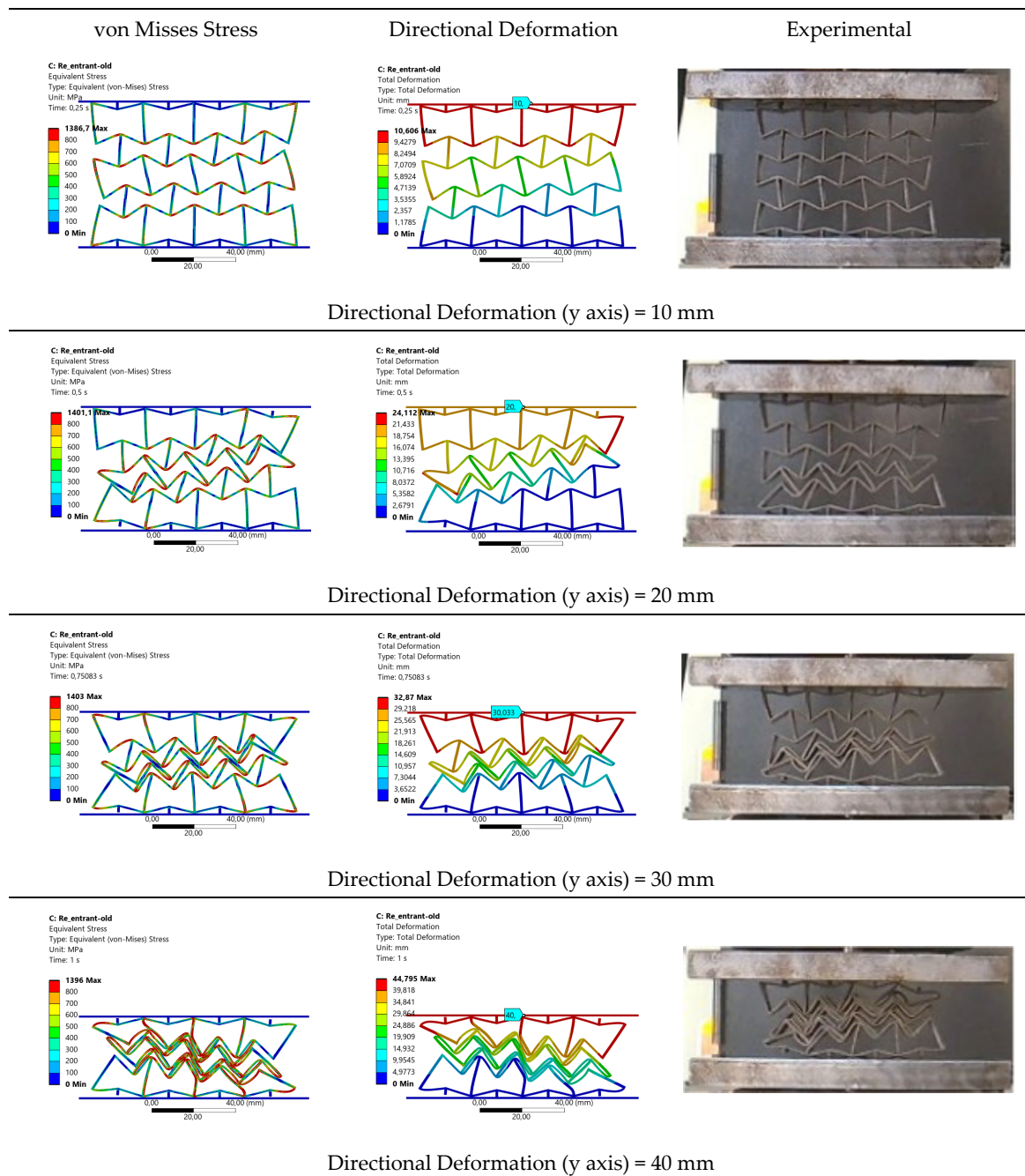


Figure 8. Comparison of numerical and experimental deformation behavior of the re-entrant auxetic structure under quasi-static compression.

At the early stage of deformation (10 mm), the structure exhibits a predominantly elastic response characterized by bending of the inclined ligaments. The von Mises stress distribution indicates that stress concentrations initiate at the junction regions and inner corners of the re-entrant cells, which act as critical locations for the onset of plastic deformation. The deformation pattern is relatively uniform across the height, suggesting stable load transfer.

As the displacement increases to 20 mm, the structure transitions into the plastic collapse regime. Progressive folding of the ligaments becomes evident, accompanied by

localized buckling in the middle layers. Both numerical and experimental results show that deformation starts to localize in specific rows, indicating the initiation of layer-by-layer collapse rather than a fully homogeneous deformation. Due to the plastic deformation at connections of struts, diagonal struts start to rotate which causes a sudden stress drop. Due to the touching of struts to the next struts, layer-by-layer collapse of struts and fluctuations in the stress–strain curve can be observed [42].

At 30 mm displacement, the collapse mechanism becomes more pronounced, with significant plastic hinging and rotation of the re-entrant cell walls. The numerical results capture the formation of plastic hinges and stress redistribution along the inclined struts, while the experimental images confirm similar folding patterns. The deformation becomes increasingly asymmetric, which is typical for auxetic structures due to geometric imperfections and manufacturing-induced irregularities.

In the final stage (40 mm), densification dominates the response. The collapsed cell walls come into contact, leading to a sharp increase in stress and a highly compacted structure. The numerical model predicts a more regular and symmetric densification pattern, whereas the experimental results exhibit slight irregularities and misalignments. This difference can be attributed to surface roughness, residual stresses from LPBF manufacturing, and minor geometric deviations not accounted for in the simulations. The numerical model successfully reproduces the key deformation mechanisms, including ligament bending, progressive collapse, and densification. However, minor discrepancies in deformation symmetry and localization highlight the importance of manufacturing imperfections in governing the real structural response.

The three-stage stress–strain response can be rationalized as follows. In the elastic regime, the inclined ligaments of the re-entrant cells respond in a bending-dominated manner due to their inward bow-tie configuration, which is the underlying mechanism of the auxetic negative Poisson's ratio behavior; the initial stiffness therefore exhibits a strong, highly nonlinear sensitivity to ligament thickness and decreases markedly with increasing ligament length.

The transition to the plateau regime is initiated when the bending moment at the inner corners, where inclined and horizontal struts intersect, exceeds the plastic moment capacity of the cross-section. The resulting plastic hinges convert the unit cell into a kinematic mechanism with negligible incremental stiffness, which directly explains the abrupt stress drop and the subsequent plateau. Because the plateau stress is governed by the plastic hinge moment rather than by the bulk yield strength of the material, it scales strongly with ligament thickness and decreases with ligament length.

Densification occurs when the collapsed ligaments come into contact, with the onset strain controlled by the relative density. The inward strut geometry of the re-entrant cell requires an additional closure stroke, which delays densification compared with conventional honeycombs of equivalent relative density. The slightly higher initial stiffness and the sharper densification predicted by the numerical model are consistent with its reliance on idealized geometry and with the omission of LPBF-induced surface roughness, micro-notch effects and sub-surface porosity from the formulation.

3.1.2. The Effect of Thickness-Dependent FG

The stress–strain responses of the non-graded and thickness-dependent FG re-entrant structures are presented in Figure 9. The non-graded specimen exhibits the highest initial peak stress (~60 MPa), indicating a relatively higher stiffness and load-carrying capacity. In contrast, all FG configurations show reduced initial peak stresses, with the most pronounced decrease observed in the FG-2 specimen, suggesting that thickness grading leads to a softer initial response.

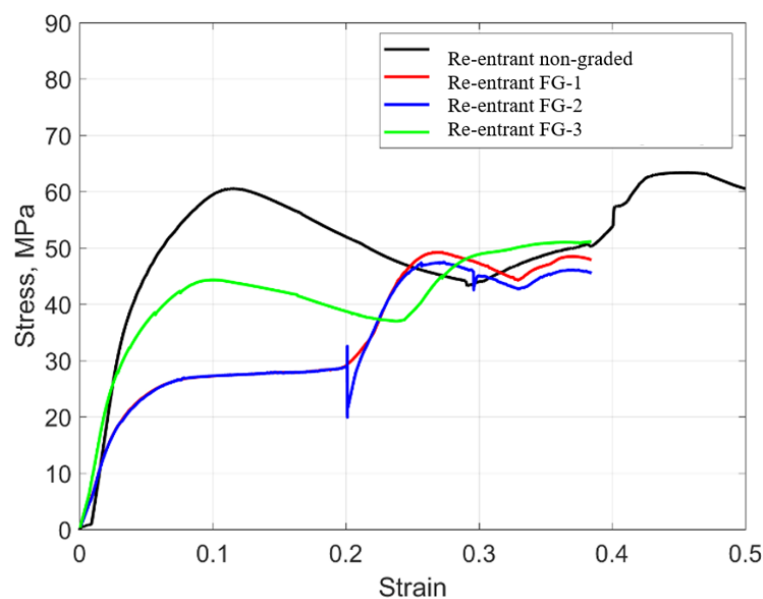


Figure 9. Stress–strain responses of the non-graded and thickness-dependent FG re-entrant auxetic structures under quasi-static compression.

Following the initial peak, the graded structures demonstrate a more stable plateau region compared to the non-graded configuration. Particularly, FG-1 and FG-3 exhibit relatively smooth and sustained stress levels within the strain range of $\epsilon \approx 0.2$ – 0.35 , indicating a more controlled and progressive collapse mechanism. This behavior is associated with improved energy absorption capability, as the structure deforms in a more stable manner without sudden load drops.

On the other hand, the non-graded structure shows a sharper stress drop after the initial peak and a less stable plateau, followed by an earlier transition into the densification regime, as evidenced by the rapid stress increase at higher strain levels. In contrast, the graded structures delay the onset of densification, extending the plateau region and enhancing deformation stability. Thickness-dependent FG modifies the mechanical response by reducing peak stress while promoting a more stable collapse behavior, which is advantageous for energy absorption applications.

The deformation behaviors of the thickness-dependent FG re-entrant structures are comparatively presented in Figure 10 for different displacement levels. At the initial stage (10 mm), all grading configurations exhibit predominantly elastic bending of the ligaments; however, FG-1 shows higher stress concentration in the upper regions, whereas FG-2 and FG-3 display a more distributed stress field along the height, indicating a more uniform load transfer.

As the deformation progresses to 20 mm, distinct collapse patterns begin to emerge depending on the grading strategy. FG-2 demonstrates earlier and more localized buckling in the middle layers, leading to a less stable deformation pattern. In contrast, FG-1 and FG-3 exhibit a more gradual and layer-wise collapse mechanism, where deformation spreads progressively through the structure rather than concentrating in a single region.

At higher deformation levels (30 mm), these differences become more pronounced. FG-1 and FG-3 maintain a relatively stable folding mechanism characterized by progressive ligament bending and rotation, while FG-2 shows more irregular and asymmetric deformation, associated with localized stress accumulation and premature collapse of specific cell rows. The results indicate that the grading direction significantly influences the deformation stability and stress distribution. Configurations such as FG-1 and FG-3 promote a more uniform and controlled collapse behavior, whereas FG-2 leads to localized deformation

and reduced structural stability. This highlights the critical role of thickness distribution in tailoring the mechanical response of auxetic structures. As stated by Shao et al., increasing or decreasing the thickness along the FG re-entrant structures affects the mechanical responses [43].

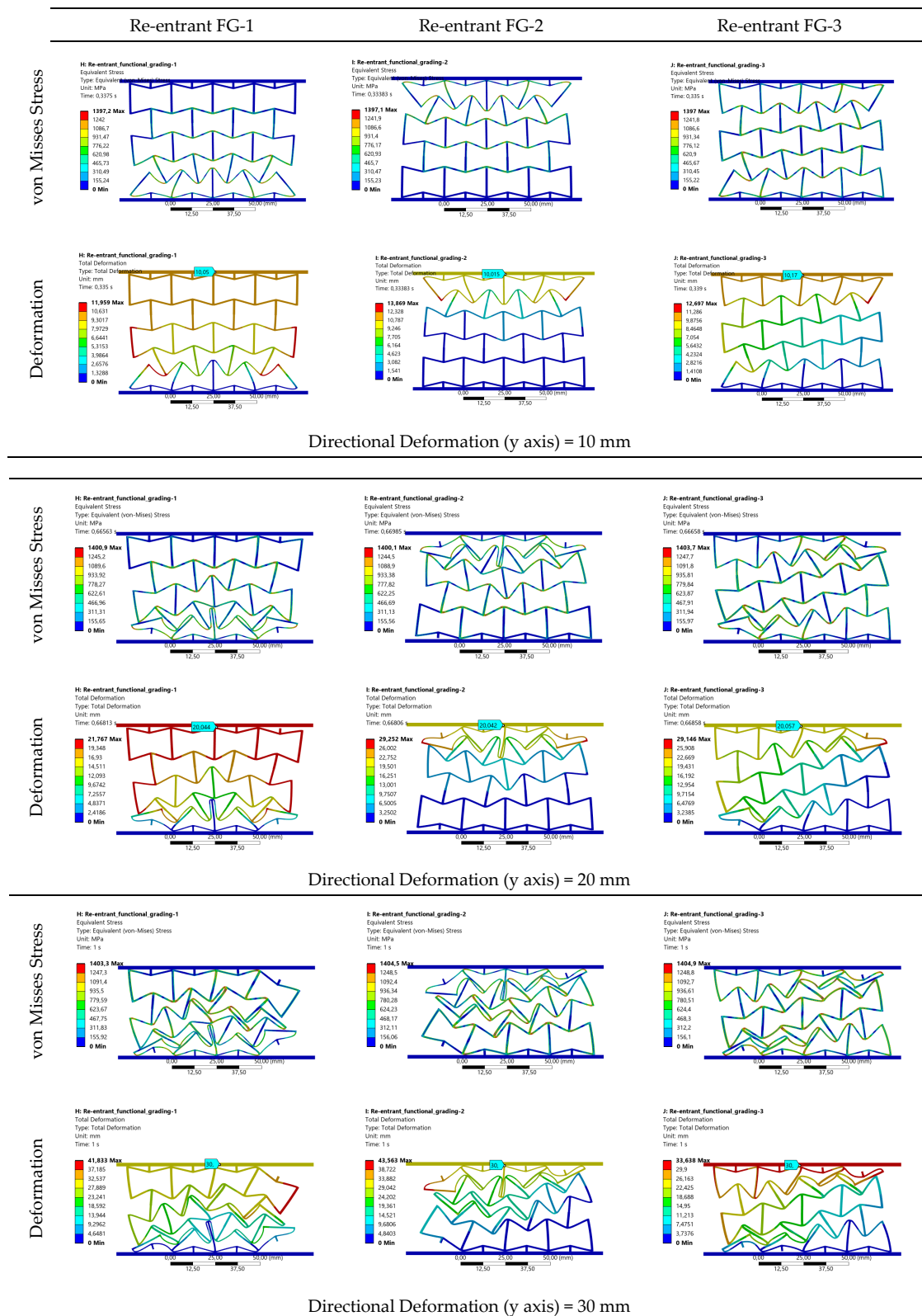


Figure 10. Numerical comparison of deformation behavior for thickness-dependent FG re-entrant auxetic structures under quasi-static compression.

The observed behavior can be explained by the directional effect of the thickness gradient on the load path. In a re-entrant unit cell, the local bending stiffness and plastic hinge moment are highly nonlinear functions of wall thickness, so the thinnest ligaments form the weak link that governs the initial response. The non-graded specimen, with uniform thickness throughout, therefore reaches the highest peak stress, whereas the thinned regions of the FG configurations promote early plastic hinge formation and substantially lower the initial peak.

Although FG-1 and FG-2 share the same total mass and gradient magnitude, their collapse behaviors differ markedly. In FG-1 the thinnest layer lies adjacent to the fixed support; the first plastic hinges form there and the collapse front propagates upward through progressively thicker ligaments, providing a continuously increasing resistance ahead of the front and producing a uniformly distributed, layer-by-layer collapse. In FG-2 the thinnest layer lies directly beneath the loaded top plate; this region yields immediately upon loading, and the local softening prevents the thicker underlying layers from reaching their plastic hinge capacity. Deformation therefore localizes near the top while the rest of the structure remains largely elastic, leading to a shorter plateau and reduced energy absorption.

The FG-3 configuration, with a thick mid-layer and thinner ends, generates a symmetric collapse front: plastic hinges develop almost simultaneously at the top and bottom, while the stiffer middle behaves as a quasi-rigid block that distributes the deformation equally toward both ends. This mechanism preserves the load-carrying capacity, delays densification and extends the plateau region.

From a stress redistribution standpoint, once a plastic hinge forms the load is transferred to neighboring cells. In a graded structure this redistribution is anisotropic and is preferentially channeled toward regions of increasing thickness; in FG-1 and FG-3 this guidance promotes a uniformly progressing collapse front, while in FG-2 the redistributed load path returns to the same weak upper region, reinforcing localization.

3.2. Anti-Tetrachiral Structures

3.2.1. Comparison of Experimental and Numerical Results

The stress–strain responses of the anti-tetrachiral structures obtained from experimental tests and numerical simulations are presented in Figure 11. All experimental curves exhibit an initial elastic region followed by a relatively stable plateau around ~90–100 MPa up to $\epsilon \approx 0.2$, indicating bending-dominated deformation of the ligaments. Beyond this region, a noticeable increase in stress is observed, associated with the onset of plastic collapse and rotation of the circular nodes.

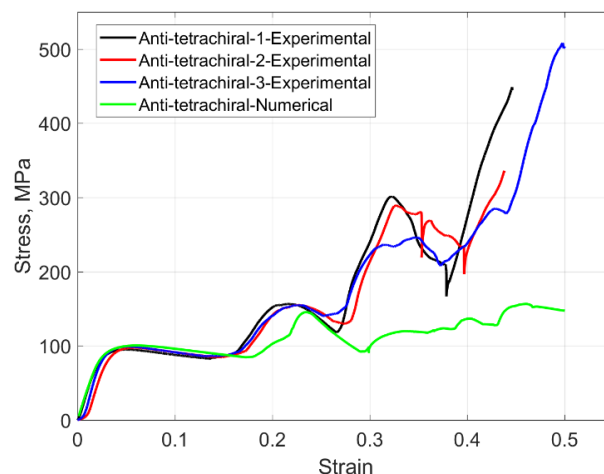


Figure 11. Experimental and numerical stress–strain responses of the anti-tetrachiral auxetic structures under quasi-static compression.

Compared to the experimental results, the numerical model significantly underpredicts stress levels, particularly in the post-yield and densification regions. While the experiments reach stress values exceeding 400–500 MPa at higher strains, the numerical results remain limited to approximately 150 MPa. This discrepancy suggests that the numerical model does not fully capture the complex deformation mechanisms of anti-tetrachiral structures, such as node rotation, contact interactions, and localized stiffening during densification. The experimental curves show fluctuations and sudden drops in stress, which can be attributed to progressive layer collapse and instability effects during deformation. These features are not well reproduced in the numerical results, which display a smoother and more uniform response. Although the numerical model captures the general trend of the initial response, it fails to accurately represent the nonlinear deformation and densification behavior of anti-tetrachiral structures under quasi-static compression.

The deformation behavior of the anti-tetrachiral auxetic structure under quasi-static compression is presented in Figure 12 through a comparison of numerical predictions and experimental observations at different displacement levels. At the initial stage (10 mm), deformation is dominated by elastic bending of the ligaments and the onset of rotation of the circular nodes, with stress concentrations forming at the ligament–node connections. As the displacement increases to 20 mm, the rotation of nodes becomes more pronounced, leading to significant ligament bending and the initiation of localized buckling, particularly in the central regions. At 30 mm displacement, the structure exhibits a highly nonlinear response characterized by extensive node rotation, ligament folding, and increased interaction between adjacent cells, resulting in a more compact and irregular deformation pattern. In the final stage (40 mm), densification dominates the response, where the collapsed ligaments and rotated nodes come into contact, forming a highly compressed configuration. While the numerical results successfully capture the overall deformation mechanism, including node rotation and progressive collapse, the experimental observations reveal more pronounced asymmetry and irregularity due to manufacturing imperfections, friction effects, and local geometric deviations inherent to the LPBF process. The anti-tetrachiral structure demonstrates a rotation-dominated deformation mechanism, distinct from bending-dominated auxetic geometries, which governs its mechanical response under compression [44].

The deformation mechanics of anti-tetrachiral structures are fundamentally different from those of bending-dominated re-entrant cells and exhibit a rotation-dominated character. Because the ligaments are tangentially attached to the same side of each nodal cylinder, axial compression causes every ligament to exert a torque on its neighboring node, which in turn rotates about its axis. This rotation forces the ligaments into a half-wave bending shape and simultaneously pulls adjacent cells toward one another, producing the characteristic negative Poisson's ratio response. Stress therefore concentrates at the ligament–node junctions, which act as the cantilever roots of the rotating nodes.

In the elastic regime the ligaments undergo small-amplitude half-wave bending while node rotation remains negligible, and the response is governed by the ligament bending stiffness. The plateau regime is initiated by the onset of plastic yielding at the ligament–node roots, after which the nodes begin to rotate steadily; this rotation amplifies the half-wave deflection of the ligaments and converts the structure into a kinematic mechanism with low incremental stiffness. Densification begins once the rotated nodes and folded ligaments come into contact with neighboring cells.

The pronounced underprediction of post-plateau stress by the numerical model is attributable to several superposed mechanisms. First, the three-dimensional contact and frictional interactions that develop between rotated nodes and ligaments are only partially represented within a 2D plane stress formulation. Second, the absence of damage and fracture criteria, together with the idealized geometry, eliminates the mechanical interlocking

of rotated nodes and the local strain hardening at ligament–node junctions, both of which contribute substantially to the experimental post-plateau stress. Third, the LPBF process introduces build-direction microstructural anisotropy, grain-boundary hardening and high dislocation density in the as-built condition, which raises the experimental post-yield hardening rate above the level captured by the numerical material model. Finally, the friction developing at the loading interfaces during the experiments imposes a lateral confinement on the structure that further elevates the apparent stress, an effect that is more limited in the idealized contact formulation.

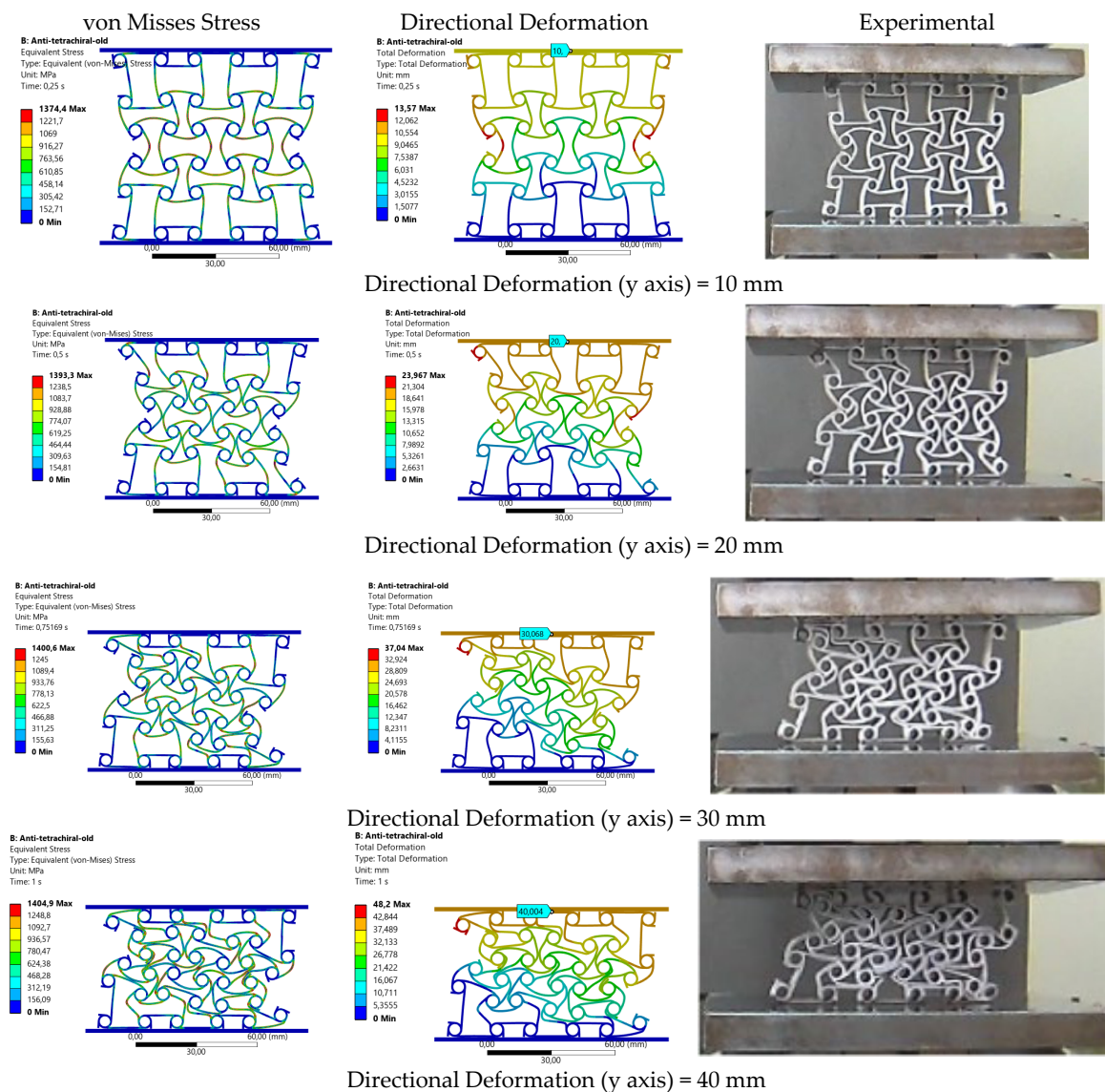


Figure 12. Comparison of numerical and experimental deformation behavior of the anti-tetrachiral auxetic structure under quasi-static compression.

3.2.2. The Effect of Thickness-Dependent FG

The stress–strain responses of the non-graded and thickness-dependent FG anti-tetrachiral structures are presented in Figure 13. The non-graded specimen exhibits higher initial stiffness and reaches an early peak stress, followed by a noticeable stress drop, indicating an unstable collapse behavior. In contrast, the FG structures display lower initial stiffness but a smoother and more gradual stress evolution, suggesting a more stable deformation mechanism.

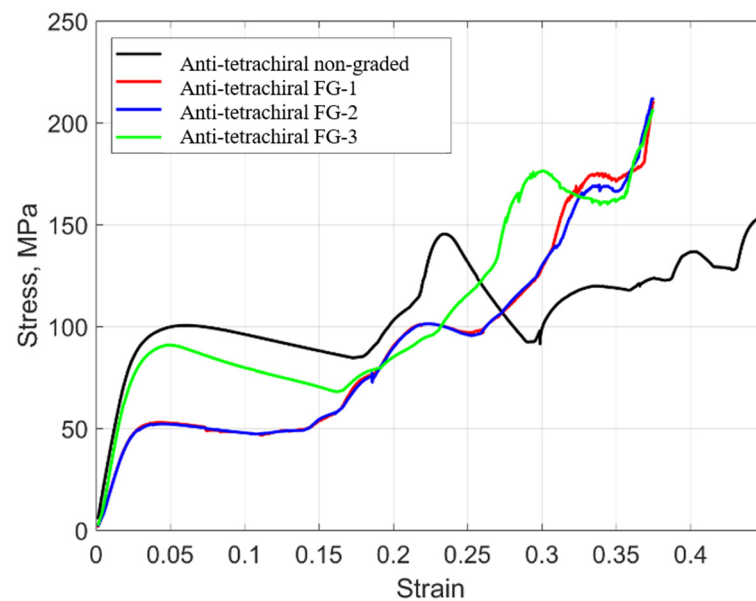


Figure 13. Stress–strain responses of the non-graded and thickness-dependent FG anti-tetrachiral auxetic structures under quasi-static compression.

As the strain increases, the graded configurations show a more consistent load-carrying response without significant fluctuations. Particularly, FG-3 demonstrates relatively higher stress levels in the mid-strain region, indicating improved load distribution and delayed localization of deformation. At higher strain levels, all graded structures surpass the non-graded specimen in terms of stress, reaching higher values and indicating a delayed onset of densification. Thickness-dependent FG reduces the initial peak stress while significantly improving deformation stability and enhancing load-carrying capacity in the later stages of compression.

The numerical deformation behavior of the thickness-dependent FG anti-tetrachiral structures is presented in Figure 14 for different displacement levels. At the initial stage (10 mm), all configurations exhibit elastic bending of ligaments accompanied by the onset of node rotation, with stress concentrations forming at the ligament–node connections. Among the grading types, FG-1 shows slightly higher stress localization near the upper regions, whereas FG-2 and FG-3 display a more distributed stress pattern.

As the deformation increases to 20 mm, the rotation of nodes becomes more pronounced, leading to progressive ligament bending and the initiation of localized collapse. FG-2 exhibits earlier and more concentrated deformation in the central region, indicating less stable behavior, while FG-1 and FG-3 show a more gradual and distributed collapse mechanism.

At 30 mm displacement, the deformation becomes highly nonlinear, characterized by extensive node rotation, ligament interaction, and increasing contact between adjacent cells. FG-1 and FG-3 maintain relatively more uniform deformation patterns, whereas FG-2 shows more irregular and asymmetric collapse. The results demonstrate that thickness grading significantly influences deformation stability, with FG-1 and FG-3 promoting more controlled and homogeneous collapse compared to FG-2.

The response of anti-tetrachiral structures to thickness grading is directly linked to their rotation-dominated character: the torque required to rotate each node depends on ligament bending stiffness and length, so thinner regions act as local initiators of node rotation and lower the initial peak stress.

In FG-1 the weak ligaments lie near the fixed support, so rotation initiates there and propagates upward through progressively thicker ligaments, producing a distributed rotation pattern. In FG-2 the weak ligaments lie beneath the loaded plate; the upper

nodes rotate immediately, and the resulting local softening prevents adequate torque from developing in the layers below, confining rotation to the top rows. In FG-3 the thick mid-layer behaves as a quasi-rigid spine that channels lateral pulling loads between cells and supports symmetric collapse from both ends, raising the plateau in the mid-strain range and producing the observed SEA improvement.

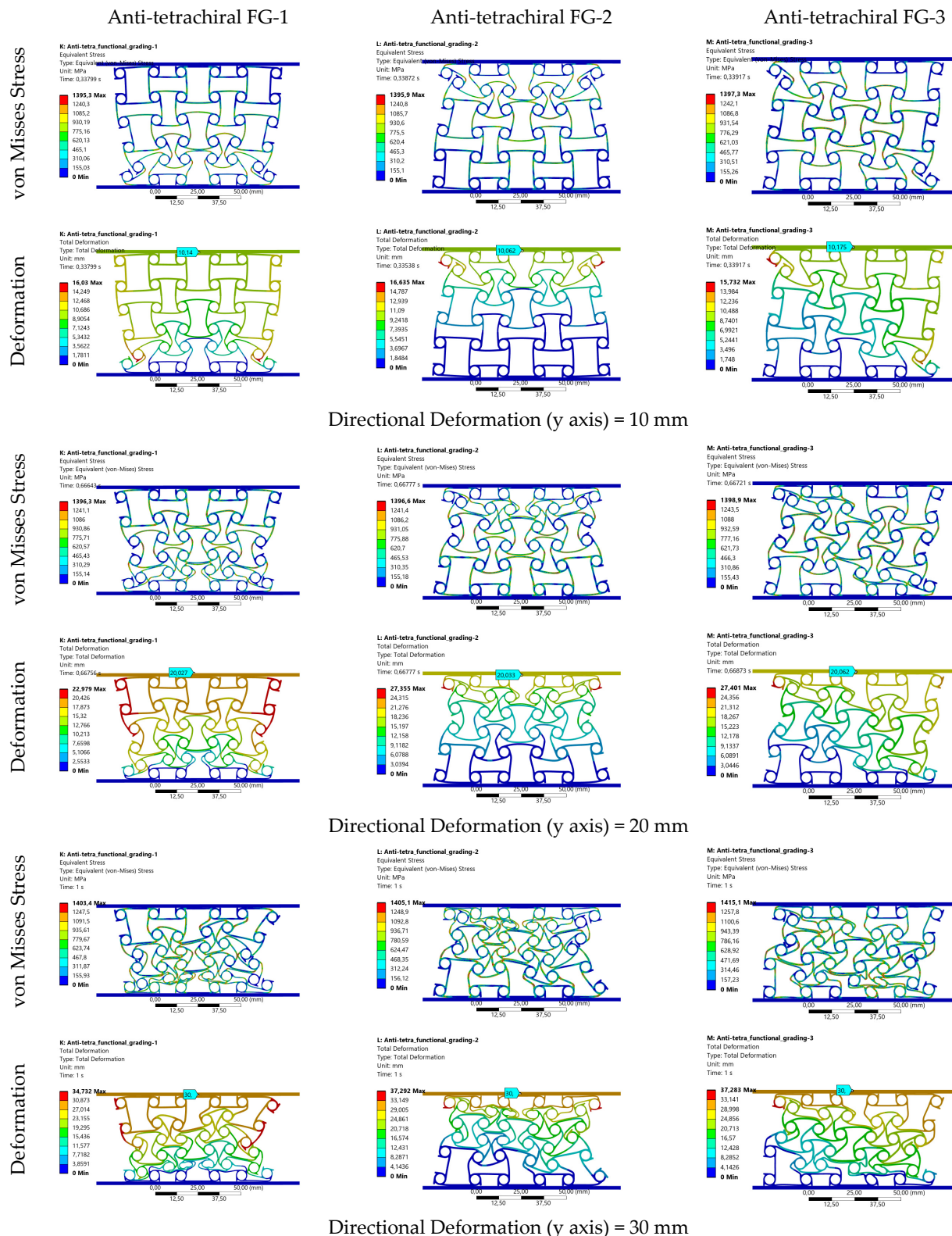


Figure 14. Numerical comparison of deformation behavior for thickness-dependent FG anti-tetrachiral auxetic structures under quasi-static compression.

Stress redistribution here is both local and long-range, because yielding in one ligament also triggers coordinated rotation of neighboring nodes; the symmetric distribution of FG-3 conveys this redistribution equally to both halves of the structure, while in FG-2 it returns to the same weak upper region and restricts the auxetic effect to a small portion of the structure. Ligament thickness remains the dominant geometric parameter, while node radius and ligament length, held constant in this study, would otherwise govern the torque arm and the rotation onset stress.

3.3. Honeycomb Structures

3.3.1. Comparison of Experimental and Numerical Results

The stress–strain responses of the honeycomb structures obtained from experimental and numerical analyses are presented in Figure 15. All curves exhibit a similar initial elastic region, reaching a plateau around ~120–130 MPa up to $\epsilon \approx 0.15$, indicating a typical bending-dominated response of honeycomb cell walls. Following this region, a noticeable stress drop is observed in all experimental curves, corresponding to the onset of local buckling and progressive cell collapse.

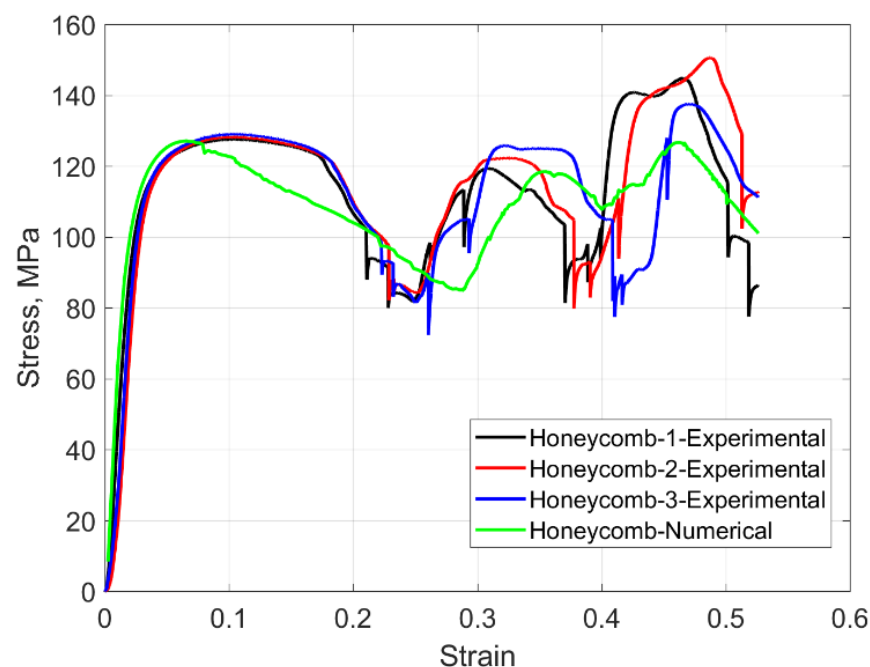


Figure 15. Experimental and numerical stress–strain responses of honeycomb structures under quasi-static compression.

Compared to the experimental results, the numerical model predicts a smoother response with lower stress fluctuations, as it does not capture instability effects such as sudden cell wall buckling and imperfections. In the elastic strain region ($\epsilon \approx 0.2$ – 0.4), the experimental curves show significant oscillations, indicating unstable and layer-wise collapse behavior, whereas the numerical curve maintains a more stable trend.

At higher strain levels, the stress increases again, marking the densification stage where collapsed cell walls come into contact. The experimental results reach higher peak values compared to the numerical model, highlighting the limitations of the simulation in capturing complex contact interactions and local stiffening effects.

While the numerical model captures the general deformation trend, the experimental results reveal more pronounced instability and fluctuation behavior inherent to honeycomb structures under compression.

The deformation behavior of the honeycomb structure under quasi-static compression is presented in Figure 16 through numerical and experimental comparisons at different displacement levels. At the initial stage (10 mm), deformation is dominated by elastic bending of the cell walls, with stress concentrations forming along the inclined ligaments. As the displacement increases to 20 mm, localized buckling initiates in the middle layers, leading to the onset of progressive collapse.

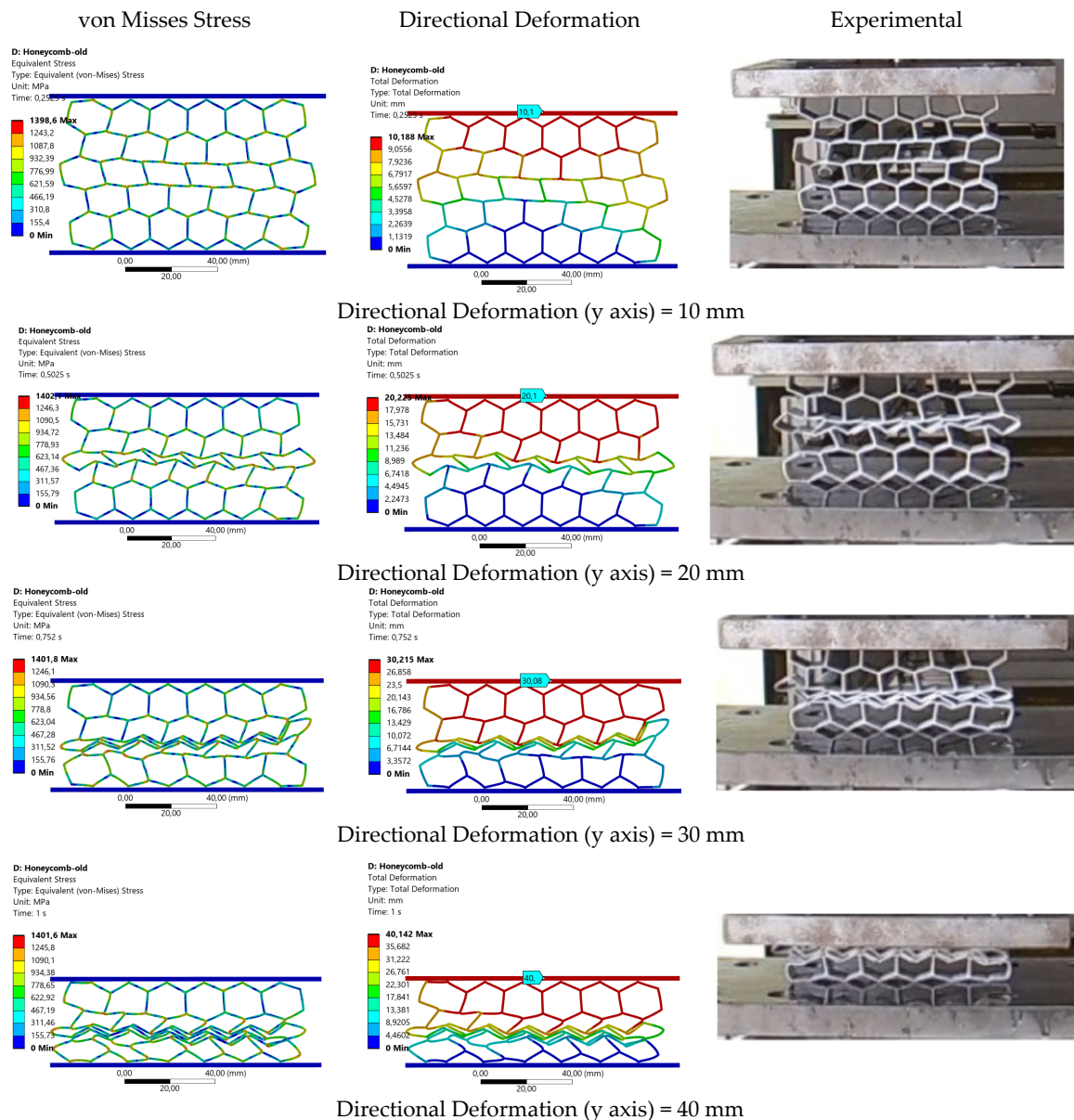


Figure 16. Comparison of numerical and experimental deformation behavior of the honeycomb structure under quasi-static compression.

At 30 mm displacement, a distinct layer-by-layer collapse mechanism is observed, where deformation localizes within specific rows, forming a characteristic folding band. This behavior is consistently captured in both numerical and experimental results, although the experimental images show slightly more irregular and asymmetric deformation due to manufacturing imperfections.

At the final stage (40 mm), densification becomes dominant, with collapsed cell walls coming into contact and forming a compact structure. The numerical model captures the general deformation pattern and collapse progression; however, the experimental results

reveal more pronounced instability and local distortions. The honeycomb structure exhibits a buckling-dominated deformation mechanism with progressive layer collapse, differing from the rotation-dominated behavior observed in anti-tetrachiral structures.

The deformation mechanics of honeycomb structures are bending-dominated as in the re-entrant case, but the absence of inward struts makes their collapse fundamentally buckling-controlled. In the elastic regime the inclined walls undergo small-amplitude bending while the horizontal walls remain in axial compression, so the initial stiffness is governed by the bending stiffness of the inclined walls and is highly sensitive to wall thickness.

The transition to the plateau is initiated when the inclined walls reach their critical buckling load: one or a few cell rows suddenly buckle and plastic hinges form at the cell vertices. Unlike the coordinated, relatively stable collapse of the re-entrant geometry, buckling is intrinsically unstable; each row collapse produces a momentary stress drop before the next row is fully engaged, and the resulting sequential events are reflected as the pronounced oscillations in the experimental curves and as a clear layer-by-layer collapse band.

The smoother numerical response stems from the idealized geometry, which lacks the small row-to-row thickness and alignment variations that act as critical buckling triggers in the real specimens. The higher post-plateau experimental peak is consistent with the local strain hardening and friction developing within the densely contacting collapsed walls, together with LPBF-induced build-direction hardening, none of which are fully captured by the idealized contact model. Honeycomb therefore exhibits a buckling-dominated collapse mode, distinct from the rotation-dominated anti-tetrachiral and the coordinated bending-dominated re-entrant mechanisms, and this is the underlying source of its plateau-stage stress fluctuations and intermittent energy absorption.

3.3.2. The Effect of Thickness-Dependent FG

The stress–strain responses of the non-graded and thickness-dependent FG honeycomb structures are presented in Figure 17. The non-graded specimen exhibits higher initial stiffness and reaches a peak stress of approximately 120–130 MPa, followed by a gradual softening, indicating an early onset of local buckling and unstable collapse behavior. In contrast, the FG structures show reduced initial stiffness and lower peak stresses, particularly for FG-1 and FG-2, suggesting a softer initial response.

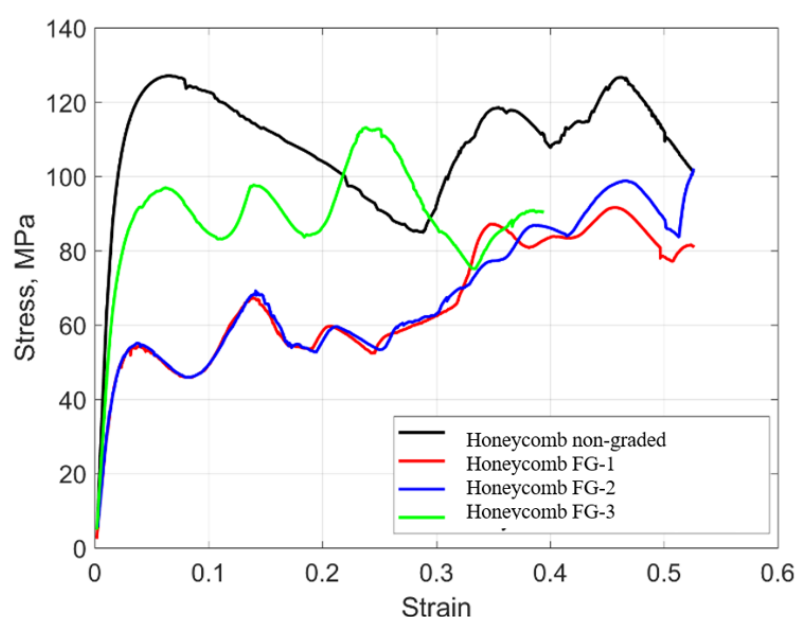


Figure 17. Stress–strain responses of non-graded and thickness-dependent FG honeycomb structures under quasi-static compression.

As deformation progresses, the graded configurations display a more gradual stress evolution. Among them, FG-3 demonstrates relatively higher stress levels in the mid-strain region, indicating improved load redistribution and delayed localization of deformation. However, compared to auxetic geometries, the plateau region in honeycomb structures remains less stable and exhibits noticeable fluctuations due to buckling-driven collapse.

At higher strain levels, the non-graded structure shows earlier densification, while the graded structures delay this transition and maintain a more extended deformation region. Thickness-dependent FG reduces the initial peak stress while improving deformation stability and slightly enhancing the load-carrying behavior at higher strain levels.

The numerical deformation behavior of the thickness-dependent FG honeycomb structures is presented in Figure 18 for different displacement levels. At the initial stage (10 mm), all configurations exhibit elastic bending of the cell walls, with stress concentrations primarily forming in the lower regions where collapse initiates. FG-1 shows more localized deformation at the bottom layers, whereas FG-2 and FG-3 exhibit a more distributed stress pattern along the structure height.

As the displacement increases to 20 mm, localized buckling becomes more pronounced. FG-2 demonstrates earlier deformation localization in the upper layers, indicating less stable collapse behavior. In contrast, FG-1 and FG-3 show a more progressive layer-by-layer collapse, where deformation spreads gradually through the structure.

At 30 mm displacement, the collapse mechanism becomes fully developed, characterized by folding of cell walls and increased interaction between adjacent cells. FG-1 and FG-3 maintain relatively more uniform deformation patterns, while FG-2 exhibits more localized and asymmetric collapse. The results indicate that thickness grading significantly influences the deformation mode, with FG-1 and FG-3 promoting more stable and distributed collapse behavior compared to FG-2.

The response of honeycomb structures to thickness grading is closely tied to their buckling-dominated collapse character. Since the critical buckling load of the inclined walls is a strongly nonlinear function of wall thickness, the thinnest walls form the local weak link that initiates the first buckling event and substantially reduces the initial peak stress. However, because buckling itself is intrinsically discontinuous, even graded configurations cannot produce a plateau as smooth as in auxetic geometries, and oscillations persist throughout this regime.

The performance difference between FG-1 and FG-2 follows the propagation direction of the buckling front. In FG-1 the thinnest walls lie near the fixed support, so buckling initiates there and the front advances upward through progressively thicker rows that impose an increasing critical load, enabling a sequential layer-by-layer collapse and extending the plateau. In FG-2 the weak walls lie beneath the loaded plate; the upper row buckles immediately and the local softening prevents the thicker layers below from reaching their critical load, confining buckling to the top rows. The FG-3 configuration, with a thick mid-layer, produces a symmetric buckling front from both ends while the stiff core acts as a quasi-rigid block, raising the plateau in the mid-strain range and delaying densification.

Stress redistribution after a row buckle is anisotropic and is preferentially channeled toward thicker regions, supporting a uniformly progressing front in FG-1 and FG-3 and reinforcing localization in FG-2. This redistribution is less coordinated than in the auxetic geometries because honeycomb cells lack the lateral coupling that auxetic contraction provides, so the load is transferred almost exclusively along the loading direction. Wall thickness is again the dominant geometric parameter, while cell wall angle and cell size, kept constant in this study, would otherwise influence the plateau level and the non-auxetic Poisson response.

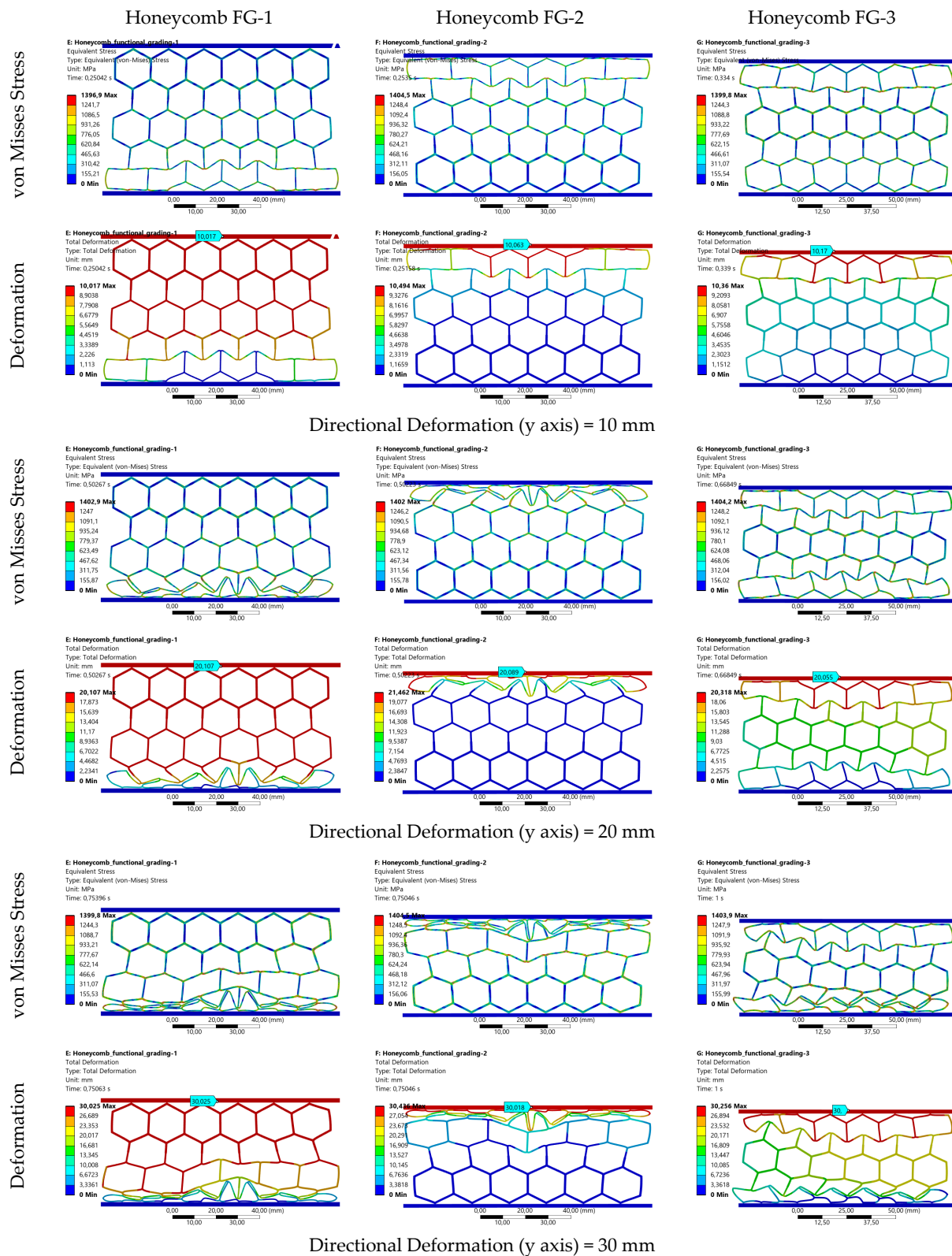


Figure 18. Numerical deformation behavior of thickness-dependent FG honeycomb structures under quasi-static compression.

3.4. Energy Absorption and Specific Energy Absorption Results

Figures 19–21 show mass, energy absorption (EA) and specific energy absorption (SEA) values for non-gradient and thickness-dependent FG re-entrant, anti-tetrachiral and honeycomb structures. From Figure 21, it is clear that SEA of FG-3 outperforms FG-1 and

FG-2 (both of them are nearly identical) for re-entrant, anti-tetrachiral and honeycomb structures. Using thickness-dependent FG re-entrant structures decreases the weight of the FG-3 structure from 138.4 gr to 122.8 gr (nearly 11%) but decreases the SEA from 0.93 J/gr to 0.91 J/gr (nearly 2%) which means that thickness-dependent FG is a promising way to decrease the weight of re-entrant structures without sacrificing SEA considerably. For the honeycomb structure (FG-3), the weight of the specimen can be reduced 13% (from 117.6 gr to 102.6) by just sacrificing SEA by nearly 4% (from 2.46 J/gr to 2.35 J/gr). Moreover, the situation for anti-tetrachiral structure (FG-3) is more promising where using thickness-dependent FG can both decrease the weight (from 186.1 gr to 164.3 gr, nearly 12%) and increase SEA (from 1.48 J/gr to 1.76 J/gr, nearly 19%).

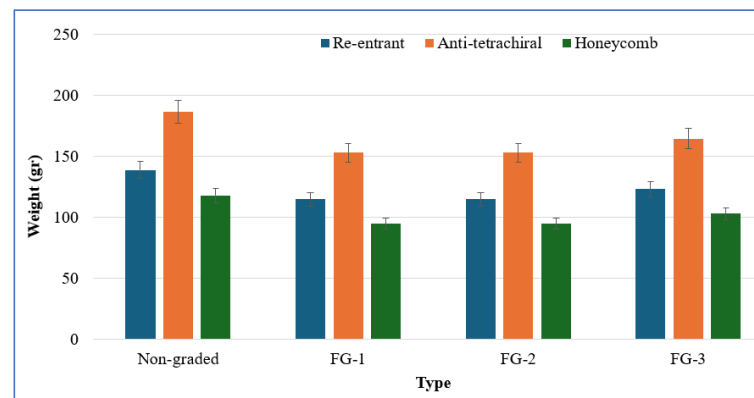


Figure 19. Weight comparison of different lattices with different FG types.

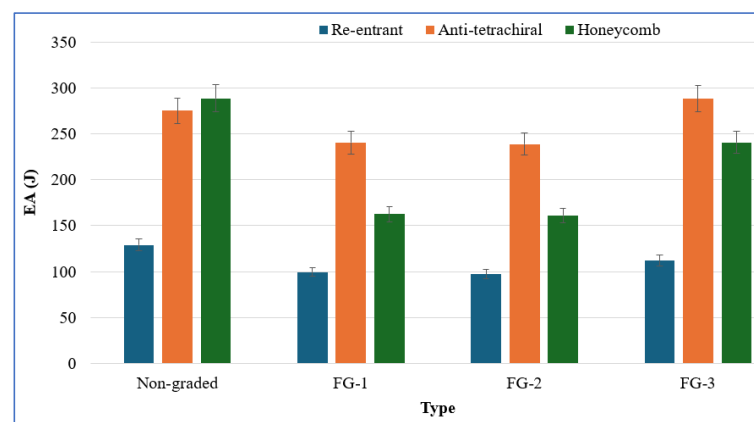


Figure 20. EA comparison of different lattices with different FG types.

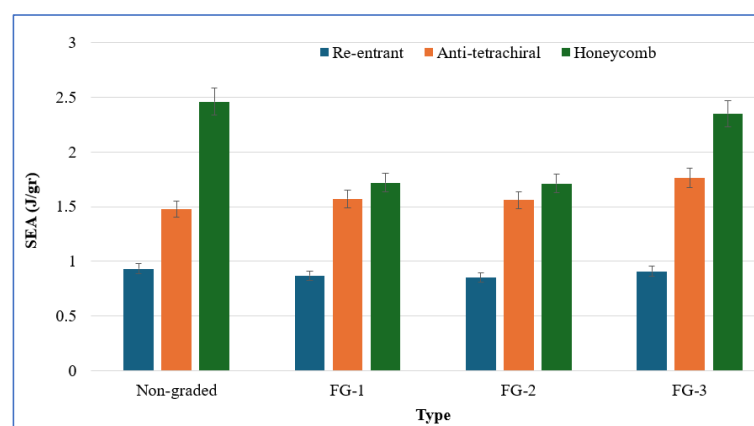


Figure 21. SEA comparison of different lattices with different FG types.

4. Conclusions

The present study focused on the feasibility of using thickness-dependent FG on two types of auxetic structures (re-entrant and anti-tetrachiral) and one non-auxetic structure (honeycomb). The numerical studies were compared with experimental results and the main findings can be summarized as follows:

- Grading direction is a key variable in design that significantly influences the deformation stability and stress distribution.
- For all the structures (re-entrant, anti-tetrachiral and honeycomb), initial peak stress values are reduced when thickness-dependent FG is used which also improves deformation stability and enhances load-carrying capacity in the later stages of compression. Compared to non-graded structures, using thickness-dependent FG re-entrant, anti-tetrachiral and honeycomb structures decreased the initial peak stress values from 60 MPa to 28 MPa (for FG1 and FG2) and 45 MPa (for FG3), from 100 MPa to 50 MPa (for FG1 and FG2) and 90 MPa (for FG3) and from 120 to 130 MPa to 55 MPa (for FG1 and FG2) and 95 MPa (for FG3), respectively.
- For all the structures (re-entrant, anti-tetrachiral and honeycomb), FG-1 and FG-3 structures show more uniform and controlled collapse behavior, whereas FG-2 leads to localized deformation and reduced structural stability.
- Comparison of SEA values for both non-graded and thickness-dependent FG structures revealed that thickness-dependent FG is a promising way to decrease the weight of structures without sacrificing SEA considerably. Compared to non-graded structures, using thickness-dependent FG re-entrant and honeycomb structures decreased SEA by 2% and 4%, respectively, but decreased the weight 11% and 13%, respectively, and the anti-tetrachiral FG structure decreased the weight by 12% and increased SEA by 19%.

Future studies can consider thickness-dependent FG based on loading scenarios. Different auxetic geometries have different deformation behavior and mechanical characteristics. Therefore, based on the requirements and loading conditions for specific applications, hybrid auxetic geometries consisting of two or more different auxetic topologies can also be studied. Moreover, to quantify the discrepancies between experimental and numerical results, microstructural analysis and surface and sub-surface defect characterizations can be performed as a future study.

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