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Research Article / Araştırma Makalesi

Compression Characterization of Multi-Shore and Functionally Graded Silicone-Infilled Kelvin-Cell Lattices

Farklı Shore Sertliğine Sahip ve Fonksiyonel Derecelendirilmiş Silikon Dolgulu Kelvin Birim Hücreli Kafes Yapıların Basma Davranışının Karakterizasyonu

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Abstract

In this study, Kelvin-cell lattices fabricated via vat polymerization were combined with RTV-2 silicone infill to create hybrid and functionally graded architectures. Four silicone Shore hardness levels were investigated to quantify the influence of infill hardness, followed by functionally graded designs using the hardness level that yielded the highest mean compressive performance. Compression tests revealed monotonic increases in compressive force, maximum stress, and energy absorption with increasing Shore hardness, with Shore 50A silicone providing the highest performance. At 60% strain, the Shore 50A infilled lattice exhibited a ~704% increase in load capacity and a ~3.66 times improvement in energy absorption. Based on these results, functionally graded specimens with varying silicone filling heights (2–5 cells) were tested up to 60% strain using stress–strain analysis to capture the full deformation regime. The functionally graded lattices showed a sequential deformation mechanism, where Kelvin-cell collapse preceded silicone densification in partially filled configurations, enabling delayed densification and smoother stress evolution. The results demonstrate that silicone hardness and infill grading are effective design parameters for tuning the compressive properties of Kelvin-cell lattices.

Keywords: *Kelvin-cell lattice, Functionally graded materials (FGM), Compressive behavior, Energy absorption capacity, Additive manufacturing, Tunable mechanical properties*

Öz

Bu çalışmada, fotopolimerizasyon yöntemiyle üretilen Kelvin-cell kafes yapılar, hibrit ve fonksiyonel derecelendirilmiş mimariler elde etmek amacıyla RTV-2 silikon ile doldurulmuştur. Dolgu sertliğinin etkisini ortaya koymak için dört farklı Shore sertliği incelenmiş, ardından en yüksek ortalama basma dayanımı sağlayan silikon kullanılarak fonksiyonel derecelendirilmiş tasarımlar çalışılmıştır. Basma testleri, Shore sertliği arttıkça basma kuvveti, maksimum gerilme ve enerji sönümleme kapasitesinin doğrudan arttığını ve en yüksek performansın Shore 50A silikon ile elde edildiğini göstermiştir. %60 birim şekil değiştirme seviyesinde, Shore 50A dolgulu kafes yapının yük taşıma kapasitesinin yaklaşık %704 oranında arttığı ve enerji sönümleme kapasitesinin yaklaşık 3,66 katına ulaştığı belirlenmiştir. Bu sonuçlara dayanarak, farklı silikon dolgu yüksekliklerine (2–5 hücre) sahip fonksiyonel derecelendirilmiş numuneler %60 birim şekil değiştirmeye kadar test edilmiştir. Fonksiyonel derecelendirilmiş numuneler, kademeli deformasyon davranışı, ötelenmiş sıkışma ve daha kararlı bir gerilme değişimi sergilemiştir. Sonuçlar, silikon sertliği ve dolgu derecelendirmesinin Kelvin-cell kafes yapıların basma özelliklerini ayarlamak için etkili tasarım parametreleri olduğunu göstermektedir.

Anahtar Kelimeler: *Kelvin-cell kafes yapı, Fonksiyonel derecelendirilmiş malzemeler (FGM), Basma davranışı, Enerji sönümleme kapasitesi, Eklemeli imalat, Ayarlanabilir mekanik özellikler*

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1. Introduction

Kelvin-cell structures stand out as one of the most efficient lightweight lattice architectures due to their space-filling nature and their ability to achieve near-isotropic mechanical performance. Compared with conventional architectural topologies, they exhibit superior stiffness, enhanced energy absorption capability, and stable deformation characteristics [1]. These inherent geometric advantages make Kelvin-cell structures highly attractive structural elements for advanced engineering applications in which both mechanical efficiency and weight reduction are critical design requirements [2]. Especially following the advancements in additive manufacturing technologies, the Kelvin-cell geometry has become the subject of numerous studies investigating its performance across a wide range of application areas with different functional objectives [3,4].

The mechanical behavior of Kelvin-cell structures and its dependence on unit cell size, strut cross-sectional characteristics, and relative density have been extensively investigated in the literature through analytical, experimental, and numerical approaches [5–7]. Another major research focus for Kelvin-cell structures concerns the evaluation of their load-carrying capacity and energy absorption characteristics. For instance, the mechanical properties and energy absorption performance of Kelvin-cell structures fabricated from PLA using the fused filament fabrication technique have been experimentally examined as a function of infill density [8]. The results demonstrated that variations in infill density led to changes in the dominant deformation mechanisms, which in turn resulted in distinct energy absorption responses. In a similar study, Duan et al. [9] reported that the initiation location of deformation under dynamic loading varies with the deformation rate, and that Kelvin-cell structures exhibit superior energy absorption capability under dynamic loading conditions compared with conventional structures. Furthermore, the deformation behavior of functionally graded Kelvin-cell structures fabricated via resin-based additive manufacturing under different impact loading conditions, as well as the controllability of this behavior, has been investigated by Montgomery et al. [10]. Their study demonstrated through experimental and numerical analyses that resin-based functionally graded Kelvin-cell structures composed of hard and soft regions with different curing degrees exhibit superior energy absorption performance. Using the same manufacturing approach, Guerra Silva [11] examined the effects of specimen size and aspect ratio on the compressive behavior of Kelvin-cell polymer lattices through static compression tests supported by finite element analyses, evaluating elastic modulus, compressive strength, and energy absorption capacity. The results revealed that the mechanical properties and energy absorption performance of Kelvin-cell structures are strongly dependent on specimen size and aspect ratio, with samples possessing a 1:1 aspect ratio exhibiting more balanced deformation and a more stable energy absorption response. Other studies have also reported that Kelvin-cell structures fabricated from elastomeric materials exhibit competitive performance relative to metallic counterparts, owing to their low cushioning factor and effective energy absorption capacity [12,13].

Various strategies aimed at controlling and/or enhancing the mechanical properties and deformation behavior of Kelvin-cell structures for different application fields have been extensively investigated in the literature. One such approach involves filling the cell cavities of Kelvin-cell structures with different materials. Carlsson et al. [14] examined the influence of epoxy-filled cell cavities in Kelvin-cell structural elements on their mechanical response using static compression tests in combination with finite element analyses. Their results indicated that the presence of epoxy filler promotes more stable collapse lobes and leads to a smoother and more stable force–displacement response. In a similar study, the effect of foam filling in stainless steel Kelvin-cell structures was investigated, demonstrating that foam filling significantly improves both the energy absorption capacity and the multiaxial load-bearing performance of the structure [15]. Furthermore, under impact loading conditions such as shock, Kelvin-cell-based hybrid structures incorporating foam fillers and used in protective helmet systems were shown to exhibit competitive and functional protective performance compared with conventional honeycomb structures and uniform lattice topologies (e.g., BCC, octet) [13]. Beyond foam fillers, the effects of filling cell cavities with silicone-based materials on structural performance have also been investigated in the literature across different architectural topologies. For instance, Xue et al. [16] investigated the effects of silicone rubber filling on the compressive behavior and load-bearing capacity of Ti-6Al-4V BCC lattice structures through quasi-static compression tests combined with finite element analyses. Their findings revealed that silicone rubber infill enhances the compressive strength of the lattice structures, mitigates stress fluctuations and localized deformation, and promotes a more homogeneous crushing mode. In another study examining open-cell aluminum foam materials, the influence of filling the cell cavities with silicone-based materials on energy absorption performance was evaluated [17]. The results indicated that silicone infill significantly increases plateau stress and total absorbed energy. Furthermore, it was reported that the infill stabilizes the deformation process by suppressing layer-by-layer collapse; however, it also introduces a drawback in terms of specific energy absorption due to the additional mass contribution. It has been demonstrated that, in regular photopolymer cellular specimens fabricated using the PolyJet process, silicone infill effectively suppresses layered and irregular fracture, significantly reduces stress fluctuations, and enables a more stable plateau response [18]. Moreover, particularly under dynamic loading conditions, these silicone-filled structures exhibit markedly higher energy absorption capacity, offering a promising solution for controlled impact mitigation and cushioning applications. Yin et al. [19] reported that filling the cell cavities of composite lattice structures with appropriately selected elastomeric materials suppresses local buckling and damage propagation, thereby significantly enhancing energy absorption and vibration damping performance while providing a tunable and multifunctional design strategy dependent on infill placement.

To the best of the authors' knowledge, no comprehensive and systematic study has examined the combined design space of silicone infills with different Shore hardness values and spatially graded filling heights in Kelvin-cell lattices. Accordingly, the present study systematically investigates how silicone Shore hardness and the number of silicone-filled cell layers affect stress response, load-bearing capacity, energy absorption, and deformation modes.

2. Materials and Methods

2.1. Materials

The primary structures were fabricated using a high-performance photopolymer, Anycubic Tough Resin 2.0. This material was selected specifically for its balance between high tensile strength (30-42 MPa) and superior elongation at break (60–72%), which helps reduce the risk of brittle failure often observed in standard resins when subjected to high-strain compressive loads [20]. The 405 nm UV-curable resin provides the necessary structural integrity to support the silicone infill without premature fracture at the lattice nodes. For the infill phase, a high-performance RTV-2 (Room Temperature Vulcanizing) E-Series addition-cure silicone was selected. This silicone is characterized by high tear strength, low linear shrinkage, and excellent flowability, properties that are critical for penetrating the narrow channels of the Kelvin-cell architecture. To investigate the influence of the infill hardness on the hybrid system, four distinct hardness levels were utilized: Shore 20A, 30A, 40A, and 50A.

2.2. Additive Manufacturing of Kelvin-cell Structures

The lattice scaffolds were fabricated using a Phrozen Sonic Mighty 8K MSLA 3D printer. This device utilizes an 8K resolution monochrome LCD screen to mask UV light from a linear projection LED module, enabling the production of microscale features with a high XY resolution of 22 μm.

The Kelvin-cell lattice specimens were designed using nTopology software. The unit cell was defined with dimensions of 10 mm x 10 mm x 10 mm. All lattice struts had a circular cross-section with a diameter of 1.5 mm. For the fully silicone-infilled specimens used to investigate the effect of Shore hardness, the lattice structure consisted of a 5 x 5 x 2 repetition of Kelvin unit cells, resulting in specimen dimensions of 50 mm x 50 mm x 20 mm. For the silicone-infilled functionally graded Kelvin-cell specimens, the lattice structure consisted of a 5 x 5 x 5 repetition of Kelvin unit cells, corresponding to total specimen dimensions of 50 mm x 50 mm x 50 mm. Before 3D printing, all designed specimens were imported into CHITUBOX slicing software, sliced according to the selected printing parameters, and prepared for fabrication.

The printing process was conducted at a controlled ambient temperature of 25 °C to maintain suitable resin viscosity. After printing, the specimens were washed for 10 min in 95% isopropyl alcohol (IPA) to remove uncured resin. The printing parameters, which were established through preliminary optimization to minimize dimensional deviation and improve interlayer adhesion, are summarized in Table 1. Owing to geometry, supports were applied only to the build-plate-facing surface, as shown in Figure 1.

Table 1. Printing parameters

Parameter	Value
Layer Thickness	50 µm
Normal Exposure Time	2.5-3.5 s
Bottom Exposure Time	35-45 s
Bottom Layer Count	5-6
Lifting Distance	6-8 mm
Lifting Speed	60 mm/min
Retract Speed	150 mm/min

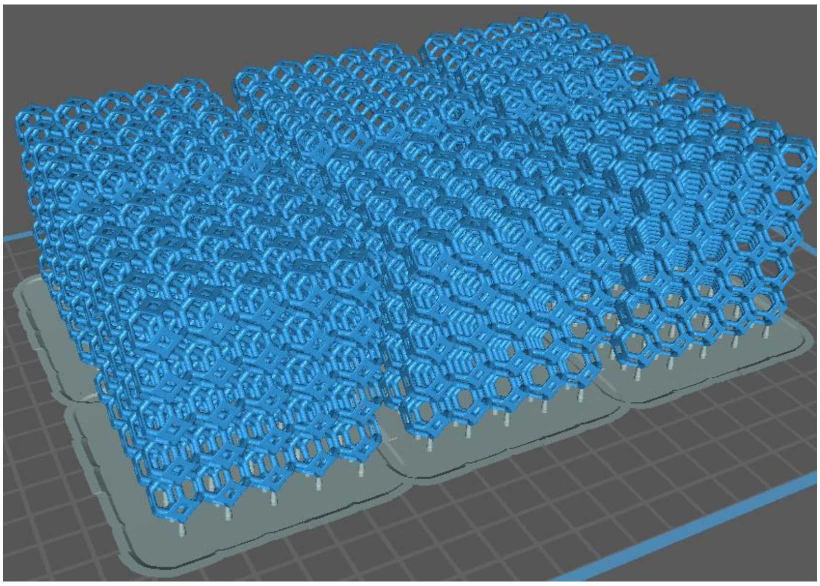
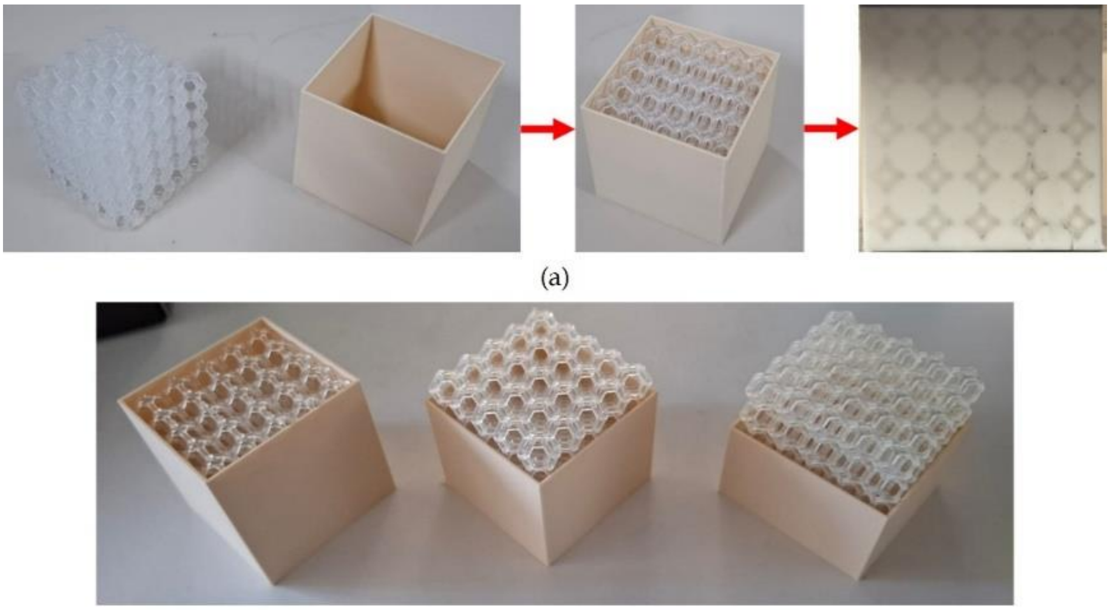


Figure 1. Printing orientation and support placement for the Kelvin-cell lattice specimens

2.3. Silicone Infiltration and Molding Process

To contain the liquid silicone during the infiltration process, custom molds were fabricated via fused deposition modeling (FDM) using polylactic acid (PLA) filament. The internal dimensions of these molds were designed to match the external boundaries of the Kelvin-cell scaffolds with high precision. This tight interface ensured that the peripheral struts of the lattice effectively sealed against the mold walls, preventing lateral leakage and confining the silicone to the internal voids of the structure. The Kelvin-cell scaffolds were seated within the molds, and the RTV-2 silicone was poured to specific heights corresponding to 2, 3, 4, or 5 cell layers to obtain the desired spatial filling configurations. After a 24-hour curing period at room temperature, the PLA molds were disassembled to retrieve the hybrid specimens, ensuring the vertical faces remained flush and the silicone-resin bond remained intact.



(a)

(b)

Figure 2. Silicone molding process of Kelvin-cell lattice structures; (a) stages of the molding process and (b) molds for different cell heights.

2.4. Mechanical Testing

Uniaxial compression tests were conducted to investigate the mechanical performance and deformation mechanisms of the hybrid Kelvin-cell structures. The experiments were performed using an Instron 3382 universal testing machine equipped with 100 kN load-cell. To maintain quasi-static conditions and minimize dynamic effects, all tests were conducted in displacement-controlled mode at a constant crosshead speed of 5 mm/min. The procedure was based on ASTM D1621, with the tests extended to 60% engineering strain to characterize the plateau and densification regimes. For each experimental group, at least three specimens were tested, and the mechanical responses were reported as mean ± standard deviation. During the quasi-static compression tests, the force and displacement data were continuously recorded at a sampling rate of 100 Hz and subsequently used to obtain the force–displacement curves and calculate the energy absorption capacity. Owing to the exploratory mechanical-characterization scope of the study and the limited number of replicates per group, no formal inferential significance testing was performed. Accordingly, the comparisons among the experimental groups are interpreted descriptively on the basis of the mean responses, experimental variability, force–displacement and stress–strain curves, and the observed deformation mechanisms.

Fully infilled specimens containing Shore 20A, 30A, 40A, or 50A silicone were tested first to identify the hardness level that provided the highest measured compressive performance. Specimens with silicone filling heights of 2, 3, 4, and 5 cell layers were then tested to evaluate the effect of spatial filling height. The mechanical properties and energy absorption capacity were derived from the resulting curves. Energy absorption was calculated by integrating the force–displacement curve over the recorded displacement interval up to 60% strain. Accordingly, the absorbed energy can be expressed as:

$$EA=\int F(x)dx \tag{1}$$

where EA represents the absorbed energy, F(x) is the force during the compression, and x is the displacement during compression.

3. Results and Discussion

3.1. Compression Tests with Different Hardness Values

The effects of the Shore hardness of the infill material on mechanical behavior of silicone-infilled Kelvin-cell lattices were examined with compression tests. The mechanical test results indicated a monotonic improvement in the measured compressive response with increasing Shore hardness. Mean specimen masses and their standard deviations are presented in Table 2.

Table 2. Masses of fully silicone-infilled Kelvin-cell specimens for different Shore values

	Empty	Shore 20A	Shore 30A	Shore 40A	Shore 50A
Mass (g)	11.76 (0.38)	77.89 (0.17)	82.17 (0.90)	86.82 (0.45)	90.93 (2.32)
Increase (%)	-	562	599	638	673

The mean specimen mass increased from 77.89 g for Shore 20A to 90.93 g for Shore 50A. The standard deviations remained low for all hardness levels (≤ 2.32 g), demonstrating good repeatability of the molding and infiltration process. Compared to the empty lattice, the mass increase ranged from 562% to 673%, reflecting the increasing stiffness and density of the silicone phase.

The average force-displacement curves for each sample obtained from the compression test are given in Figure 3. The corresponding mechanical properties, reported as mean (standard deviation), are summarized in Table 3. From Table 3, the results show that increasing Shore hardness was associated with improved compressive performance. For instance, the maximum force increased sharply with Shore hardness, from 4797.6 N (Shore 20A) to 11352.6 N (Shore 50A). Relative to the empty lattice (1411.8 N), the improvement reached ~239% for Shore 20A and increased to ~704% for Shore 50A, highlighting the dominant role of silicone stiffness in load transfer and deformation resistance. Similarly, the maximum compressive stress increased monotonically with Shore hardness, rising from 1.92 MPa (Shore 20A) to 4.54 MPa (Shore 50A), compared to 0.565 MPa for the empty lattice structure. This behavior indicates that stiffer silicone more effectively constrains cell wall bending and delays localized buckling, allowing the lattice to sustain higher stresses before densification [16].

Table 3. Mechanical properties of samples with different silicone Shore hardness values

Sample	Maximum Force (N)	Improvement in Maximum Force (%)	Maximum Stress (MPa)	Energy Absorption (J)
Empty	1411.8 (5.9)	-	0.565 (0.0024)	13.23 (0.18)
Shore 20A	4797.6 (80.2)	239	1.92 (0.032)	31.81 (0.86)
Shore 30A	5106.2 (312.3)	261	2.04 (0.12)	32.64 (0.78)
Shore 40A	8451.9 (498.7)	498	3.38 (0.069)	42.96 (0.79)
Shore 50A	11352.6 (185)	704	4.54 (0.074)	48.39 (1.49)

The energy absorption capacity also showed a pronounced dependence on Shore hardness. While the empty lattice absorbed only 13.23 J, silicone infill increased energy absorption to 31.81 J and 32.64 J for Shore 20A and Shore 30A, and further to 42.96 J and 48.39 J for Shore 40A and Shore 50A, respectively. The increase at higher Shore values reflects the greater force sustained over the imposed displacement range, which is desirable for energy-absorbing, load-carrying, and cushioning applications. Overall, increasing the Shore hardness of the silicone infill led to systematic increases in compressive force, maximum stress, and energy absorption, without introducing excessive scatter between samples. These results demonstrate that Shore hardness provides an effective and easily tunable parameter for tailoring the mechanical response of hybrid Kelvin-cell lattices under compressive loading, enabling controlled transitions from compliant, energy-dissipative behavior to stiffer, load-bearing performance [19,21].

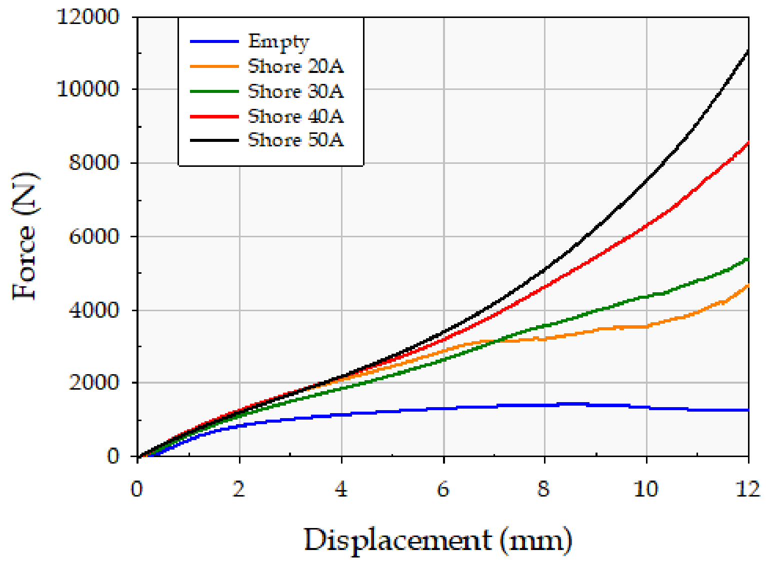


Figure 3. Force displacement curves of fully infilled Kelvin-cell samples at different Shore hardness

3.2. Compression Tests of Functionally Graded Samples

Based on the results presented in Section 3.1, Shore 50A silicone was selected for the functionally graded (FG) configurations because it provided the highest measured compressive force and energy absorption among the tested hardness levels. As in Section 3.1, the specimens were evaluated up to 60% engineering strain. For the FG specimens, the response is presented as stress versus strain curves rather than force versus displacement curves (Figure 4), thereby normalizing force and displacement by the initial specimen dimensions and facilitating visualization of the elastic, plateau, and densification regimes.

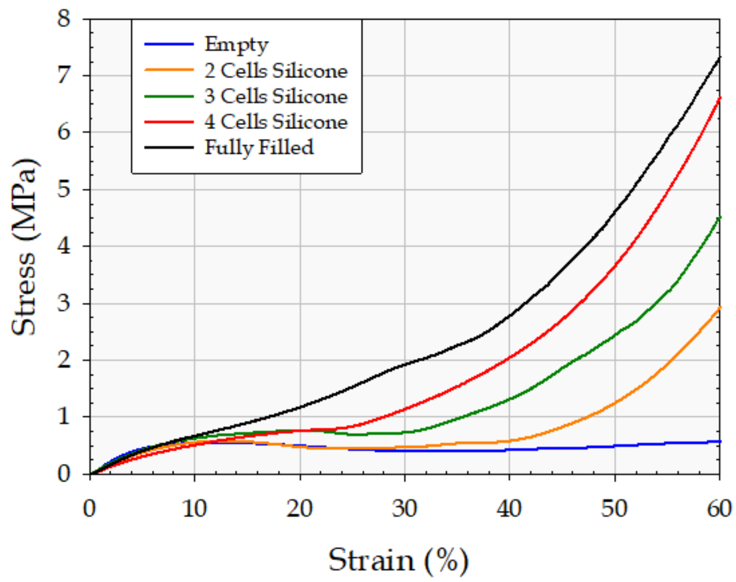


Figure 4. Stress–strain curves of functionally graded (FG) samples with different numbers of silicone-filled cell layers

The mean compressive responses exhibited a clear dependence on the number of silicone-filled cell layers within the investigated experimental conditions (Table 4). The empty lattice exhibited a low stress response with an extended plateau-like region, reaching only 0.58 MPa at 60% strain, with limited energy absorption (35.14 J). Introducing silicone infill led to a pronounced increase in stiffness and load-bearing capacity [17–19]. Specimens with 2 and 3 silicone-filled cell layers showed moderate stress levels of 3.35 MPa and 3.87 MPa, respectively, accompanied by gradual densification and steadily increasing energy absorption (70.0 J and 90.25 J). A substantial change in deformation behavior was observed for the 4-cell and fully filled specimens. These configurations exhibited a much steeper stress increase beyond approximately 30%–40% strain, indicating the onset of densification. The fully filled lattice showed the most abrupt transition, reaching 7.66 MPa at 60% strain with an energy absorption of 174.6 J. This earlier and steeper progression highlights the dominance of the stiff silicone phase, which rapidly suppresses cell wall bending and void collapse [17]. In contrast, reducing the number of filled cells delayed densification, resulting in a more extended plateau region and a smoother stress evolution. Overall, the functionally graded designs enabled a controlled tuning of the compressive response. Fully filled structures maximized stiffness and energy absorption but densified rapidly, while partially filled lattices exhibited a more progressive deformation with lower peak stresses.

Figure 5 presents representative images recorded during the compression tests, highlighting the deformation and densification mechanisms of empty, partially filled, and fully silicone-infilled Kelvin-cell lattices. The empty lattice deforms solely through Kelvin-cell wall bending and collapse, resulting in progressive cell densification without any contribution from a secondary phase. For the partially filled specimens (2, 3, and 4-cell infill), deformation proceeds in a two-stage sequence. At lower to intermediate strains, compression is dominated by Kelvin-cell collapse in the unfilled or partially constrained regions, leading to localized cell densification. As strain increases, the deformation progressively transitions to silicone densification, where the infilled regions begin to carry the majority of the load. In the 2- and 3-cell silicone-filled specimens, the silicone phase remains largely intact throughout the test, acting as an energy-absorbing medium that delays global densification and promotes a smoother stress–strain response. In contrast, the 4-cell specimen marks a critical transition in behavior. While Kelvin-cell collapse still initiates the deformation process, the subsequent silicone densification becomes dominant at higher strains, leading to localized silicone rupture under confinement. This transition explains the sharper stress increase observed in the stress–strain response compared to lower filling heights. The fully filled lattice exhibits a fundamentally different mechanism (Figure 5). Due to the absence of unfilled cells, deformation is governed almost entirely by silicone densification from the early stages of loading, with minimal contribution from Kelvin-cell bending. This results in an earlier onset of densification, accompanied by extensive silicone rupture and extrusion at high strains, consistent with the steep stress rise and highest energy absorption measured for this configuration. Such two-stage deformation mechanisms, characterized by an initial lattice collapse followed by infill densification, as well as the transition toward infill-dominated behavior at higher filling ratios, have been consistently reported for elastomer and silicone filled lattice structures in the literature [16,17].

The compressive response of non-filled lattice structures is generally governed by the progressive collapse of the unit-cell architecture, which may involve strut bending, buckling, fracture, layer-by-layer deformation, shear band formation, and final densification depending on the lattice topology, material, relative density, and manufacturing method [22]. In the present silicone-infilled Kelvin-cell structures, however, the deformation behavior cannot be attributed solely to the collapse of the lattice. Instead, the mechanical response is governed by the coupled interaction between the Kelvin-cell lattice and the silicone infill. During compression, the lattice provides the main structural skeleton, while the silicone phase contributes to load transfer, local constraint, and deformation resistance. Therefore, increasing Shore hardness or varying the filled height modifies not only the stiffness and maximum stress but also the onset and progression of densification. This behavior indicates that the silicone infill can be used as an additional design parameter to tune the quasi-static compressive response of Kelvin-cell lattice structures.

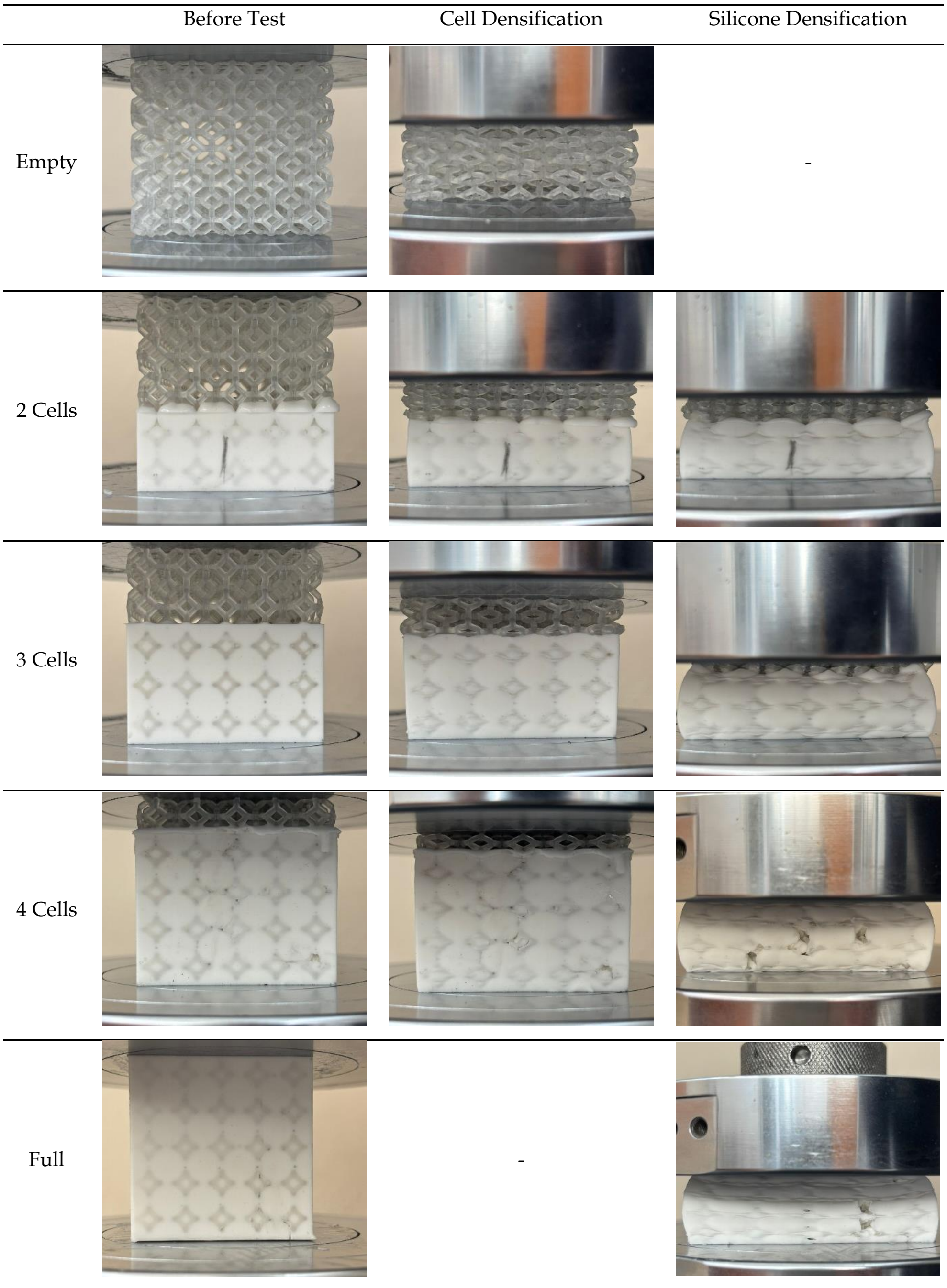


Figure 5. Representative images of Kelvin-cell specimens during compression testing

Table 4. Mechanical properties of functionally graded (FG) samples at different numbers of silicone-filled cell layers.

Sample	Force (N) at 60% Strain	Stress (MPa) at 60% Strain	Energy Absorption (J) at 60% Strain
Empty	1450.5 (64.1)	0.58 (0.026)	35.14 (8.1)
2 cells	8372.6 (1017.6)	3.35 (0.407)	70 (10.73)
3 cells	9668.5 (1686.8)	3.87 (0.67)	90.25 (9.77)
4 cells	17363.5 (734.3)	6.94 (0.29)	150.8 (10.63)
Full	19155.3 (787)	7.66 (0.31)	174.6 (8.85)

4. Conclusion

This study systematically investigated the compressive behavior of silicone-infilled Kelvin-cell lattices, focusing on the effects of silicone Shore hardness and functional grading along the lattice height. The results demonstrate that both parameters provide effective means of controlling stiffness, densification behavior, and energy absorption capacity.

Among the hardness levels investigated, Shore 50A silicone delivered the highest mechanical performance, showing monotonic increases in compressive force, maximum stress, and energy absorption with increasing hardness. The within-group mass measurements showed limited scatter, supporting the repeatability of specimen preparation. Within the investigated conditions, the groupwise changes in mechanical response were therefore associated primarily with silicone hardness; however, mass measurements alone cannot confirm spatially uniform infiltration.

Building on these findings, functionally graded configurations using Shore 50A silicone revealed that the filling height governs the deformation sequence. Stress–strain analysis up to 60% strain enabled clear identification of elastic response, plateau behavior, and densification. Partially filled lattices (2 and 3 cells) exhibited a sequential deformation mechanism, where Kelvin-cell collapse preceded silicone densification, resulting in smoother stress evolution and delayed densification. Increasing the filled height to 4 cells introduced a transition toward silicone-dominated behavior, marked by a sharper stress rise and localized silicone rupture. Fully filled lattices exhibited the earliest densification response, achieving the highest stress (7.66 MPa) and energy absorption (174.6 J), but with reduced compliance.

Visual observations during compression were consistent with the mechanical data and indicated that functional grading enables deliberate control over whether deformation is cell-dominated, silicone-dominated, or sequential. This tunability allows designers to balance stiffness, peak stress, and energy absorption according to application-specific requirements. From an application perspective, these hybrid lattices show potential for load-carrying structures, protective cushioning, and compact energy-absorbing components. Partially filled designs are particularly attractive where progressive collapse and controlled load transfer are required, while fully filled configurations are suitable for high-load, compact energy-absorbing applications. Overall, the combination of additive manufacturing and silicone-based functional grading offers a versatile platform for designing tailorable, high-performance architected materials under compressive loading.

The main limitation of this study is that the mechanical behavior of the silicone-infilled Kelvin-cell lattice structures was investigated only under quasi-static compression loading. Therefore, the results should be interpreted within the scope of quasi-static mechanical response and should not be directly extended to dynamic, impact, or cyclic loading conditions. In addition, the cyclic and fatigue behavior of the photopolymer material was also beyond the scope of this study. Future investigations should address dynamic loading, fatigue behavior, finite element analysis and interface characterization to further clarify the long-term, temperature-dependent and rate-dependent performance of silicone-infilled Kelvin-cell lattice structures as well as other lattice topologies. In addition, the comparisons among the investigated configurations were based on descriptive statistics contains, and no formal statistical significance testing was conducted. Therefore, the differences observed between the group means should be interpreted as experimental trends within the investigated specimen set rather than as statistically confirmed population-level differences. Future studies involving larger sample sizes could employ inferential statistical analyses to quantify the significance and effect size of the observed differences.

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Contribution Statement

All authors contributed equally.

Conflict of Interest Statement

The authors of this article declare that they have no personal or financial conflicts of interest with any institution, organization, or individual.

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