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Influence of Unit Cell Repetition on Dimensional Precision of PEEK Honeycomb Auxetic Structures

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WHY IS THIS RELEVANT?

Auxetic structures [1] are architected materials characterized by a negative Poisson's ratio, which causes them to expand laterally under tensile loading and contract transversely under compression. This unconventional response provides enhanced energy absorption, indentation resistance, damping capacity and fracture tolerance, making auxetic lattices attractive for lightweight and high-performance applications. Additive manufacturing, and particularly Fused Filament Fabrication (FFF), enables the production of complex re-entrant geometries that would be difficult to manufacture using conventional processes. However, the functional response of these structures strongly depends on the accurate reproduction of their unit-cell geometry, including strut thickness, re-entrant angles, node dimensions and cell connectivity.

This work investigates the influence of unit-cell repetition and spatial layering symmetry on the dimensional accuracy of re-entrant honeycomb structures manufactured by FFF using high-performance PEEK. Specimens with different numbers and arrangements of unit cells were produced under identical processing conditions, allowing the effect of lattice configuration to be isolated from the influence of printing parameters. The manufactured geometries were compared with their nominal CAD models using three-dimensional optical scanning, while surface quality was evaluated by optical profilometry. Determining the minimum number of repeated cells required to obtain a stable and representative geometry is essential for the reliable design, mechanical characterization and future industrial application of additively manufactured auxetic structures

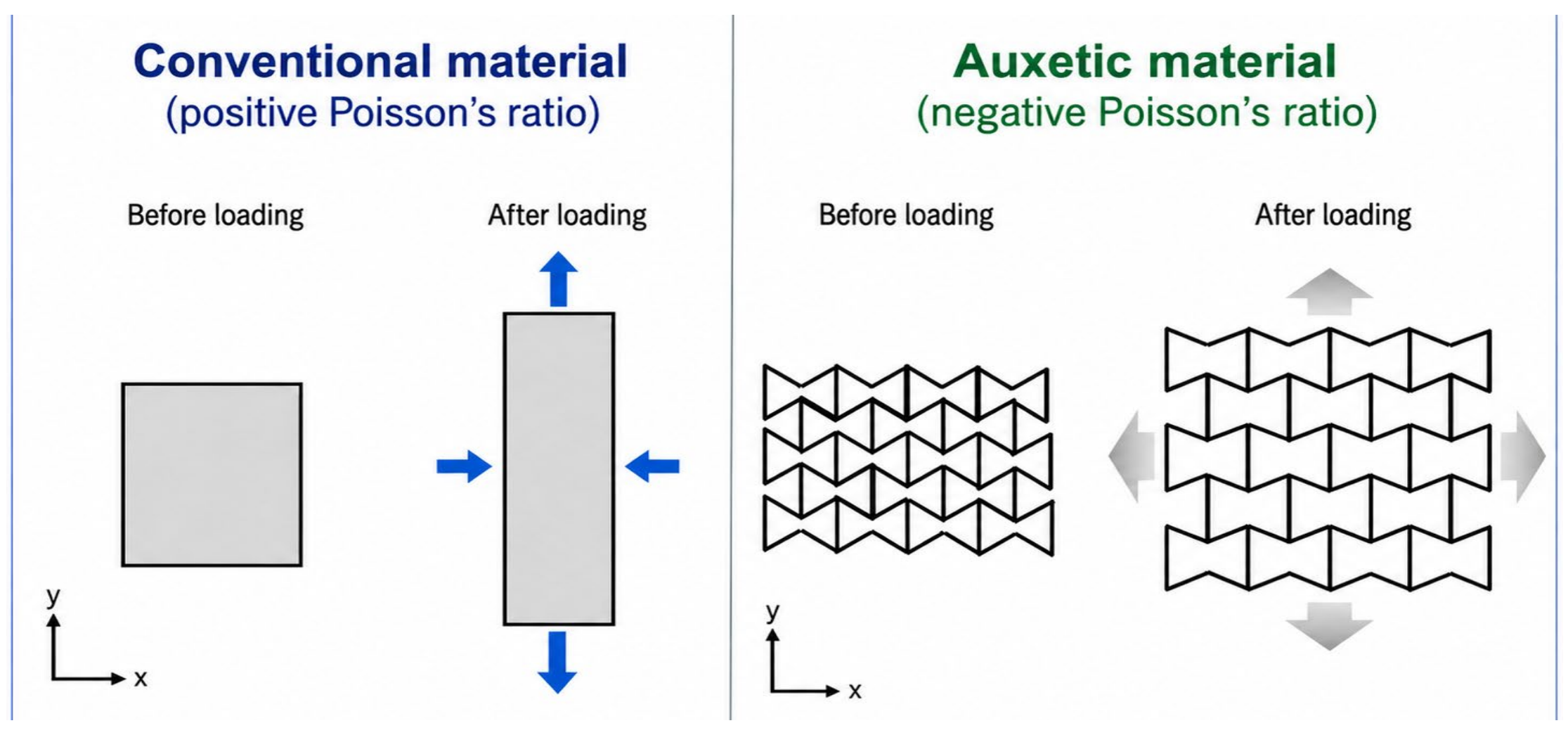


Fig 1. Schematic representation of Poisson's ratio and the deformation behaviour of conventional and auxetic materials.

OBJECTIVES & METHODOLOGY

The aim of this work is to evaluate how unit-cell repetition and spatial arrangement affect the dimensional accuracy of FFF-manufactured re-entrant Z-PEEK auxetic structures. First, the optimal thermo-mechanical printing conditions were identified using Digimat-AM® simulations and experimental validation. Then, lattices with different repetition patterns were manufactured and 3D scanned to quantify dimensional deviations and determine the minimum repetition required to achieve a stable and representative geometry.

Stage 1. Thermo-mechanical optimization of the FFF process

1 Experimental design: thermal DoE

A 3-factor / 3-level factorial design was defined to evaluate the influence of the main thermal variables governing Z-PEEK deposition and cooling.

27 combinations (3^3 design)

21 feasible printed conditions

Feasibility criterion: chamber temperature ≤ build-plate temperature.

Factor	Level 1	Level 2	Level 3
Extrusion temperature (°C)	375	400	425
Build-plate temperature (°C)	140	170	200
Build-chamber temperature (°C)	125	150	170

2 FFF manufacturing under controlled conditions

Z-PEEK specimens were manufactured on a Zortrax Endureal high-temperature FFF system. Only the thermal variables from the DoE were modified; remaining parameters were kept constant to isolate the effect of the selected processing temperatures.

Material: Z-PEEK

Printer: Zortrax Endureal

Constant settings: layer height · infill · speed · raster

Purpose of Stage 1: obtain a controlled processing window before comparing dimensional fidelity between auxetic lattice configurations.

Stage 2. Thermo-mechanical characterization and MCDM optimization

3 Mechanical characterization — Hoytom HM-D 100 kN

Tensile tests were performed on printed Z-PEEK specimens to quantify their load-bearing and deformation response. The key extracted variables were maximum tensile force / stress and maximum displacement / deformation.

Output 1: Fmax / σmax

Output 2: Dmax/ δmax

4 Dynamic mechanical analysis — Mettler Toledo DMA 1

Temperature-dependent stiffness was measured in DMA tensile mode. For Z-PEEK, the test was run from 25 °C to 225 °C at 3 °C/min and 1 Hz. Storage modulus values were extracted at 25 °C and 75 °C.

Output 3: E′ at 25 °C

Output 4: E′ at 75 °C

5 MCDM optimization: EWM + VIKOR

The four responses were jointly assessed to select the best global thermo-mechanical compromise. EWM provided objective criteria weighting and VIKOR ranked the printing conditions according to the compromise solution.

Criterion	Meaning
Fmax / σmax	Load-bearing capacity
δmax	Deformation capability
E'25	Room-temperature stiffness
E'75	Stiffness retention at elevated temperature

Optimal FFF condition
400 °C Extrusion / 200 °C Plate / 150 °C chamber

Purpose of Stage 2: select the processing condition that maximizes the combined thermo-mechanical response before printing the auxetic lattices.

S1 **Thermo-mechanical optimization of the FFF process**

A three-factor, three-level experimental design was used to identify the printing conditions that maximize the thermo-mechanical performance of Z-PEEK. The analysed parameters were extrusion temperature, build-plate temperature and chamber temperature, while the remaining printing settings were kept constant.
Based on previous analyses, the layer height was set to 0.1 mm; infill density 100% and an orthogonal raster configuration to perpendicular, and the physically feasible combinations were reduced to 21 conditions. These were simulated in Digimat-AM® to evaluate dimensional response and thermal behaviour and to identify the most suitable processing window.

S2 **Thermo-mechanical characterization and multi-criteria optimization**

The simulated conditions were experimentally assessed by tensile and DMA tests. Tensile tests provided maximum force and deformation capacity, while DMA supplied storage modulus values at 25 °C and 75 °C.
The four response variables were combined using an MCDM methodology based on Entropy Weight Method and VIKOR. This approach enabled the identification of the processing condition that provided the best overall balance between mechanical strength, deformation capability and thermal performance.

S3 **Influence of unit-cell repetition on dimensional accuracy**

After defining the optimal processing parameters, a second study analysed the effect of unit-cell repetition on dimensional accuracy. Re-entrant honeycomb structures with the same unit-cell geometry based on [2] were manufactured while progressively modifying the number of repetitions along the X and Y directions.
The printed specimens were digitized by optical 3D scanning and compared with their nominal CAD models. Full-field deviation maps were used to quantify geometric differences and to determine the minimum repetition size at which dimensional deviations became homogeneous, and the printed structure accurately reproduced the original design.

Stage 3. Influence of unit-cell repetition on dimensional accuracy

6 Lattice configurations: unit-cell number and symmetry

Re-entrant auxetic structures were manufactured with different unit-cell numbers and with symmetric or non-symmetric X–Y repetition. Here, symmetry refers to regular repetition of the unit-cell topology along both in-plane directions.

Different cell numbers

Symmetric / non-symmetric

Same unit-cell geometry

Optimized FFF parameters fixed

7 3D optical scanning — Steinbichler COMET L3D®

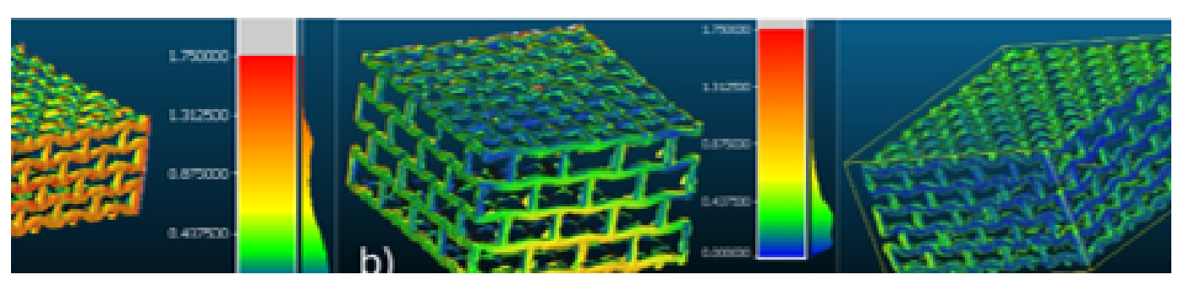
Each printed lattice was digitized using a real optical 3D scanning system. High-resolution point clouds were obtained to reconstruct the manufactured geometry and compare it with the CAD model.

Surface digitization

Point-cloud generation

8 CAD-to-part comparison

The scanned geometry was aligned and superimposed onto the nominal CAD geometry. Full-field deviation maps were generated to evaluate local and global dimensional differences throughout the lattice.



Point-cloud alignment

Surface overlap

Deviation maps

Goal: identify the minimum number of unit cells required to obtain the highest dimensional accuracy and the best agreement with the original CAD geometry.

RESULTS

The scanned geometries were aligned and superimposed onto their corresponding nominal CAD models to generate full-field dimensional deviation maps. All three specimens were represented using the same deviation scale, allowing a direct comparison of the magnitude and spatial distribution of the dimensional discrepancies. The colour scale indicates the distance between the manufactured surface and the original CAD geometry, with warmer colours corresponding to larger deviations and cooler colours indicating closer agreement. The 4 × 4 non-symmetric configuration (a) presents the widest distribution of yellow and orange regions, particularly around the external struts and lower areas of the lattice, revealing a heterogeneous dimensional response. In the 4 × 4 symmetric specimen (b), the deviation field becomes more uniform, although localized discrepancies remain near the lower and peripheral regions. The 5 × 5 symmetric configuration (c) exhibits a predominantly green–blue distribution across the complete structure, with fewer localized high-deviation areas and a more homogeneous correspondence between the scanned geometry and the CAD model.

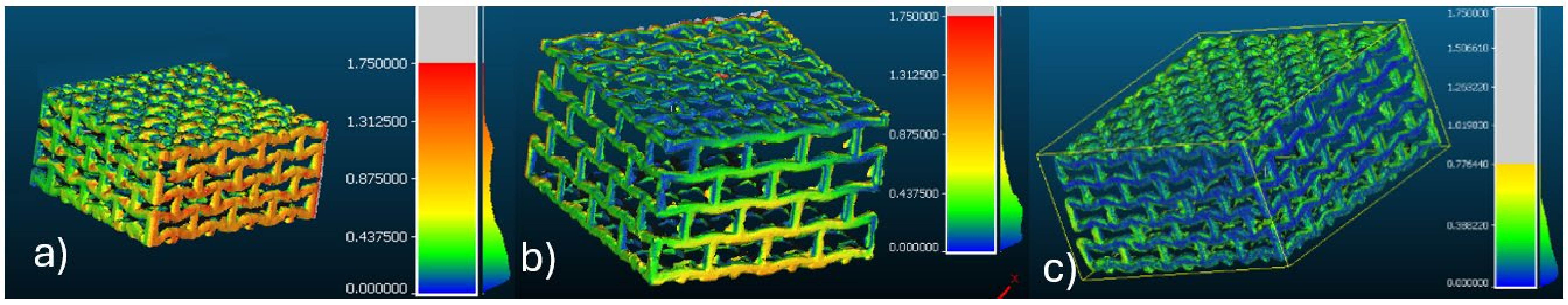


Fig 2. a) Sample with no layering symmetry and 4x4 re-entrant unit cells. b) Sample with layering symmetry and 4x4 re-entrant unit cells. c) Sample with layering symmetry and 5x5 re-entrant unit cells.

CONCLUSIONS

1. SYMMETRY EFFECT
For the same 4 × 4 unit-cell configuration, the symmetric lattice exhibited a more homogeneous dimensional deviation field than the non-symmetric specimen. Regular cell repetition along the X and Y directions therefore improves geometric consistency.

2. UNIT-CELL NUMBER EFFECT
Increasing the symmetric lattice from 4 × 4 to 5 × 5 cells further reduced the spatial variability of the dimensional deviations. The 5 × 5 configuration showed the most uniform agreement with the nominal CAD geometry. A minimum number of 5 repeated cells in each spatial direction is required before the printed geometry can be considered dimensionally stable.

KEY TAKEAWAY
Spatial layering symmetry and unit-cell repetition are decisive design variables in FFF-manufactured Z-PEEK auxetic structures.

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