Design and optimization of 3D fast printed cellular structures

Luca Collini1 | Chiara Ursini1 | Ajeet Kumar2

1Department of Engineering and Architecture, University of Parma, Parma, Italy
2Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

Abstract
This paper analyzes the effect of thin and thick walls on functional properties of 3D printed cell structures, designed from open cell structures inspired by the natural world. Different types of unit cells with the same density are introduced. The cells are studied in morphology and mechanical performance, in particular effective density, compressive stiffness, and energy absorption under cyclic loading. Material extrusion process with thermoplastic polyurethane filament is used as additive manufacturing technique, without any support structure. The designed printed cellular structures are studied numerically, using an advanced hyperelastic material model with hysteretic capacity, and experimentally by uniaxial compression testing for characterization of stiffness and energy absorption. The benefits and limitations of the method are highlighted.

KEYWORDS
additive manufacturing, shape optimization, supportless lattice structures

1 | INTRODUCTION

Cells of different shapes can cluster to form a cellular structure, in which if a repeated pattern is present it is generally referred to as a “lattice structure”.1-3 Three supportless lattice structures are designed from unit cells, inscribed in a cube having size of 8 mm, with a honeycomb criterion, namely open, thin-walled, and thick-walled (see Figure 1), and as all the cellular structures offer advantages in terms of light weight, high resistance to large stresses with great energy absorption. The open unit cell topology was designed with a bio-mimetic approach on the sea urchin shell, due to its excellent mechanical and functional properties in compression, stiffness and energy absorption respectively. Hence, closed cells are designed by closing the opening of open cell with thin or thick wall, which are compared to the equivalent open cell with the same density. The different unit cells are then repeated with the principle of periodic tessellation with unary type which ensure that unit lattice share complete edge with their neighboring lattice.4

Characterization and comparison of the structures’ behavior is then done both experimentally and by a numerical approach, which proves to be an effective virtual design tool. Therefore, in this work the behavior of thermoplastic polyurethane (TPU) molded with the additive process of Fused Deposition Modeling in lattice structures based on a biomimetic approach was analyzed and studied.

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ADDITIVE MANUFACTURING OF LATTICES

Design for additive manufacturing (DfAM) of the lattice structures was performed for the TPU filament with the MEX 3D printer Flashforge dreamer©. Important design considerations for the successful fabrication of self-supported structures are minimum feature size without any distortion noticed in 6×6×6 mm cube, minimum thickness of 0.6 mm, minimum overhang angle of 50° and parallel ledges are not fabricated.5–7 Since DfAM and environment temperature in a range of 20–24°C, three specimens for each type of lattice structures are printed through the additive process of Fused Deposition Modeling with the parameters of Table 1. As said, these lattice structures are designed for supportless printing, eliminating the needs for support material within the lattice, that is an undoubted advantage.8 Hence, also a closed cell lattice structure can be additively manufactured with the design concept of the supportless lattice structure.9

TESTING AND SIMULATION APPROACH

3.1 Experimental testing

The mechanical response of printed structures, characterized by the geometric parameters described in the Table 2, is determined by the application of repeated uniaxial compression tests at the same strain rate of 5 mm/min for three different strain levels, respectively 10%, 20%, and 30% of the specimen height, perpendicularly to print direction. Tests are performed on a servo-hydraulic MTS 810 material system equipped with 100 kN load cell, by keeping the temperature between 20°C and 24°C during the execution of the experimental tests. As it can be observed in Figure 2, 30% of compression causes a very large deformation of the lattice with principle of densification of specimens. To estimate the
energy absorption, due to the hysteretic behavior, the load must be cyclically repeated at least from 10 to 20 times,\textsuperscript{11,12} and the stabilized cycle has to be analyzed in terms of loss area in the load-deformation plot. In particular, the mechanical and functional properties are determined: the energy absorption as the integral of nominal stress–nominal strain curve; the loss area is evaluated after the application of 20 cyclic loads to reach the stabilized curve; the stiffness as the slope of the interpolating line over the loading curve.

From experimental load–displacement curves, it can be concluded that open cell and thin-walled cell structures behave very similarly in stiffness and energy absorption, while the thick-walled cell structure shows performances always about 20\% lower. However, stiffness always drops when the deformation increases.\textsuperscript{10}

\subsection*{3.2 Numerical approach}

The numerical approach to 3D printed lattice structures starts from the analysis of a unit cell virtually extracted from the structure which is assumed to behave as a representative volume element (RVE) of the entire structure, see Figure 3. In this way, given proper boundary and symmetry conditions to the cell, several geometrical solutions can be compared without need to print and test them experimentally and mechanical properties can be addressed more quickly. Moreover, the use of RVE was essential in order to guarantee a finer mesh by speeding up calculation times. In this study, given the cell size, shell thickness $T$ and wall thickness $T_w$ were considered as variable parameters, see Table 2. Numerical Finite Element (FE) models are generated in the ABAQUS/CAE\textsuperscript{©} 2020 code. Solid linear tetrahedral elements with hybrid formulation of type C3D4H are used, to manage incompressible behaviors, with an average size of 0.4 mm and the resulting number of nodes and elements shown in Table 2. Simulations are run by the explicit solver in the large deformation regime.
Simulation of the hysteresis loop is carried out by applying 20 consecutive compression and unloading cycles to ensure the achievement of the steady state of hysteresis. However, data related to the 21st cycle are used for the analysis and the numerical results are then elaborated in terms of reaction forces and displacement to obtain the cell stiffness, $K_0$, as a linear interpolation of the load curve. On the other hand, the energy absorption is determined via numerical integration of the load–displacement curve; in particular, the coefficient of absorbed energy in percentage through the Equation 1,

$$\Omega_c = \frac{W_1}{W_2}(\%)$$

where $W_1$ is the absorbed energy and $W_2$ the total energy, absorbed and released, per cycle and per unit cell.

3.3 | Material model

TPU behaves as a viscoelastic, hyperelastic material.\textsuperscript{13} Hence, comparing the experimental nominal stress–strain curve obtained on standard dog bone specimens with the different strain energy potential models available in ABAQUS\textsuperscript{©}, it is here found that the best match, over the deformation range of interest, is reproduced by the Ogden model of the second order. Ogden material model parameters are provided by the finite element software, while the parameters characterizing the hysteresis curve of the TPU subjected to cyclic compression have been studied and identified, all shown in Table 3. Such hysteresis model, responsible for the dissipation of energy under repeated cyclic load, allows to: reproduce hysteresis cycles during the unloading paths depending on the level of deformation; reproduce the permanent series of deformation after each loading–unloading cycle; calculate the energy absorption per cycle.

4 | RESULTS AND DISCUSSION

4.1 | Functional response of the structures

Experimental and numerical results are summarized in Table 4. RVE of the lattices, that deform by periodic boundaries, behave very close to the experimental response within the stiffness and energy absorption, even if with a discrete gap at lower strain levels. In particular, the open cell and thin-walled closed cell shows similar mechanical response and functional property when compared to thick-walled closed cell structure.

4.2 | Mechanical properties

The open cell structure, among the others, concentrates all the material on the ribs, which apparently bear the compressive load more efficiently as the side walls bend easily from the very beginning of the deformation process, but this is not valid anymore at higher compression, due to the extreme deformation and the initiation of densification regime. Numerically, predicted values by the FE approach agree for the open cell structure but over-estimate the stiffness of the closed cell structures, especially when thick-walled. This may be due in part to the applied boundary conditions that

| Ogden material model parameters for TPU | Hysteresis parameters for TPU |
|---|---|
| Order | $\mu_i$ | $\alpha_i$ | $D_i$ |
| 2 | 6.1298 | -1.9004 | 0.0000 |

| S | A (s$^{-1}$ MPa$^{-m}$) | m | C | E |
|---|---|---|---|---|
| 2.2 | 0.556 | 4.0 | 0.0 | 0.01$^{2,4}$ |

Note: $K_0$, stiffness (N/mm); $\Omega_c$, coefficient of absorbed energy in percentage (%); $W_c$, energy absorption per unit volume (J/m$^3$).
### Table 4
Experimental and numerical stiffness and energy absorption of the lattice structures

| Lattice structure | $K_0^a$ (N/mm) | $W_c^b$ (J/m³) | $\Omega_c^c$ (%) |
|-------------------|----------------|----------------|-----------------|
|                   | 10 20 30 10 20 30 10 20 30 | Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM | Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM Exp FEM |
| Open              | 331.0 335.3 220.3 235.8 165.5 171.0 | 7.58 1.21 27.73 8.32 | 59.61 25.12 21.4 7.0 22.9 15.3 | 24.9 23.1 |
| Thin-w            | 336.0 264.6 219.2 212.3 161.7 161.4 | 6.84 1.08 32.72 13.33 | 61.52 48.23 20.0 4.3 23.1 15.4 | 24.6 26.7 |
| Thick-w           | 278.9 279.7 181.9 231.1 137.5 188.1 | 6.35 0.98 25.04 12.06 | 57.11 49.13 20.4 3.9 23.5 13.7 | 26.4 25.5 |

*aStiffness (N/mm).*

*bCoefficient of absorbed energy in percentage (%).*

*cEnergy absorption per unit volume (J/m³).*
probably over constrict the transversal dilatation of adjacent cells. In fact, by means of a radial dilatation of specimens, it has been found that the numerical simulation underestimates the experimental test by a factor of 1.5 for the open cell, is very close to the thick-walled cell and overestimates the thin-walled cell by a factor of 1.25. Discrepancies with the FE approach, which provides a much lower ability to disperse strain energy at low compression levels, are certainly due to the hysteretic material model, which is proven for a limited strain range, and which is not sensitive to other parameters, like temperature. Furthermore, being obtained by homogenizing the response of a single unit cell, the FE models are unable to recreate the contact condition between adjacent cell walls, that can drastically limit the deformation.

### 4.3 Effect of AM process

Fused Deposition Modeling (FDM) produces a non-isotropic, layered material structure that is mostly up to twice weak along the tangential direction than the transverse. Hence, samples obtained from the FDM process are typically non-uniform at different observation levels, while finite element software considers cells as isotropic cell solids.

This type of 3D printing is very demanding due to low viscosity and low elastic modulus of TPU filament. Common printing problems with flexible filament, which being TPU is also hygroscopic in nature, have been studied using scanning electron microscopy (SEM) (JOEL JSM -6390LV), as they can affect the mechanical and functional properties of the printed structures. Although microscopic pores are present along the longitudinal and transverse directions, these have been found to have no major effect on the structural properties of the lattices. But in general, several process parameters have been found to influence the final mechanical properties of the molded polymer, such as presence of pores, building orientation and temperature. Moreover, an extensive literature review from 1996 to 2018, shows how compressive mechanical response of the samples is influenced by many other process parameters.

It can be concluded that the combination of all these process parameters, but also of the material and external conditions, has a great influence on the mechanical properties of the printed lattice structures. This must be taken into consideration in the design phase, since the results obtained analytically must be suitably analyzed in relation to the combined effect of all the possible conditions influencing and acting on the printed part. About that, the consideration of an anisotropic material model will be the subject of future studies, precisely to investigate the discrepancies obtained between the numerical and the experimental.

![Figure 4](image-url)  
(A) Unit cells; (B) optimized unit cells
Shape optimization is part of optimal control theory and is the most general of all parametric optimizations. Here, the shapes of the unit cells are varied by identifying suitable design variables since the shape of a component can play a significant role on its cyclic load response.

As a first step the «Tet–3D stress» elements used for the meshes are selected as variables for optimization, allowing the FE software to arrange them in an optimal way to maximize mechanical and functional response. By defining the quality level of the mesh target, level of convergence and frequency of evaluation of the geometric restrictions as “Medium” in a range from Low to High, to have a trade-off between accuracy of the results and computational complexity, objective function and constraint are defined: respectively, minimization of the maximum value of strain energy density and constant volume constraint. The optimal shape is identified among 10 optimization cycles, such as the shape with the lowest strain energy density. From the optimization processes, it was found that the open cell has material reinforcements along the ribs, the thick one shows reinforcements along the wall and the thin-walled remains almost the same, thus showing a geometry that is somewhat optimized, as shown in Figure 4.

These shape changes show a different trend especially in compressive strains, $\varepsilon_{22}$, Figure 5. This supports what the authors themselves have identified in previous works,\textsuperscript{13} that is, it is even more evident how the walls and the ribs support unevenly the bending. In fact, with the rearrangement of the material, the new unitary morphologies maximize their mechanical and functional properties, working mostly by compression.

A comparison between optimized and non-optimized cells shows that in the optimized cells the bending component on ribs and walls is reduced.

The graph in Figure 6 shows all the percentage increase values of the FE optimized models’ properties, subjected to the same boundary and load conditions. As said, the open and thick-walled closed cell types show considerable

**FIGURE 5** Optimized unit cells 30% deformed: Compressive strains, $\varepsilon_{22}$

**FIGURE 6** Percentage optimization values on unit cells
increases in both values of stiffness and energy absorption per unit volume compared to the thin-walled cell, as expected from the major changes made.

As a matter of fact, the thin-walled closed cell type, among the others, shows minor percentage increases in mechanical and functional properties, highlighting a shape that is already somewhat optimized for the same properties. The volume of non-optimized lattice structures was used for the analysis as the volume varies in a centesimal range. It must be said that these new morphologies have not yet been experimentally tested, so in-depth studies will follow in this regard. However, the unit cells are numerically optimized in terms of stiffness and energy absorption.

6 | CONCLUSIONS

This study tries to understand the effect of thin and thick wall on functional and mechanical property which can be used for designing closed cell from the topologies of open cell lattice structure. It has been found how stiffness and energy absorption behave in a non-intuitive way and how they can be influenced by the shape of the unitary cells. The conclusions of the study can be summarized as follows:

- possibilities of supportless printed lattice structures are investigated with excellent results;
- thin-walled closed cell lattice structures maximizes the relative stiffness and energy absorption when compared to thick-walled closed cell lattice structure, showing a shape that is already somewhat optimized in structural properties;
- manufacturing uncertainties are revealed by the numerical simulation, that is, the TPU structures do not behave as isotropic cellular solids, and anisotropy depend on deformation level;
- design of lattice structures obtained by FDM process should consider the strong effect that the deposition process has on the mechanical properties of the molded polymer;
- shape optimization reveals how mechanical and functional properties can be increased through appropriate modifications in cell geometries, especially when open and thick-walled cells;
- trade-offs and limits have to be carefully taken into account when comparing the optimization findings with technological possibilities.

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CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest. “No competing financial interests exist.” The design of a sea urchin closed cell lattice structure is applied for United states patent and trademark office (62/953327) and Taiwan patent (109137416).

DATA AVAILABILITY STATEMENT

Data are available on request due to privacy/ethical restrictions.

ORCID

Luca Collini @ https://orcid.org/0000-0002-1497-9470
Chiara Ursini @ https://orcid.org/0000-0002-0185-0790

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