EAN 2024 62th annual conference on experimental stress analysis

Modeling the Compression Behavior of Additively Manufactured Lattice Structure and Energy Absorption

A. Boualleg [1,a], J. Fiori [2], D. Cirkl [1]

[1] *Technical University of Liberec, Czech Republic*
[2] *Universidade Estadual Paulista,Brazil*
[a] *abdelmadjid.boualleg@tul.cz*

Abstract: Lattice structures have garnered significant attention due to their lightweight nature and favorable mechanical properties. They find widespread application across various industries and engineering fields, such as automotive, aerospace, marine, and medical. Notably, the deformation of lattice structures allows the dissipation of substantial amounts of energy. In this work, we need to understand the mechanical behavior of the lattice structure. To do that, we need to design the structure in the software and then choose the right flexible material for printing the model thereafter the model is subjected to the experiments. The finite element method is included for comparison of the experiment and simulation.

Keywords: lattice structure; TPU; viscohyperelastic; 3D printing.

1 Introduction

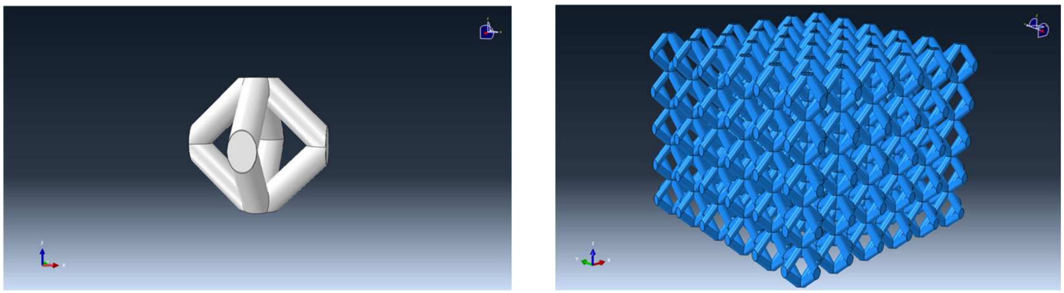
The lattice structures, characterized by their intricate network of interconnected struts, have gained prominence across various engineering domains due to their lightweight nature and unique mechanical properties [1]. Additive manufacturing technologies have enabled the precise fabrication of lattice structures with complex topologies, paving the way for advanced design and production of such structures [2]. These structures often manufactured through advanced techniques like additive manufacturing (AM), present an innovative approach to design challenges. The lattice geometry, with its high surface area and low material volume, offers an excellent compromise between structural integrity and weight efficiency [3]. Lattice structures have been employed in various industrial applications, including scaffolds for tissue and bone replacement, automotive and aerospace components for noise isolation and weight reduction, and a range of protective uses [4]. This work proposes the study of thermoplastic polyurethane (TPU) lattices under loading and unloading cycle compression, along with numerical analysis through FEA. A face-centered cube (FCC) unit cell was selected to design and build the lattice configurations. A commercially available TPU was chosen as the base material due to its flexibility and high support of the load on the structure while avoiding its failure. The tensile test samples of the parent material were manufactured via and later tested under seven cycles of loading, while the lattices were assessed under loading and unloading compression conditions. The mechanical characterization of the base material was used to fit with the Parallal Reological Framework (PRF) to determine the hyperelastic and viscoelastic material constant, which was later used as the input for the numerical simulation of the structure. The experiment and the simulation provided a good agreement. Additionally, the dissipation energy was investigated.

2 Materials and Methods

2.1 Design

The lattice structure sample was designed in Abaqus Software with (10 x10 x .9,6) mm cells with a strut diameter size of 2 mm see Fig. 1(a) and a cube size with a base (60 x 60) and height of 48 mm as presented in

Fig. 1(b). This cube was printed using a 3D printer with selected TPU material. For the material characterization, three dog bone samples were printed and subjected to tensile tests.

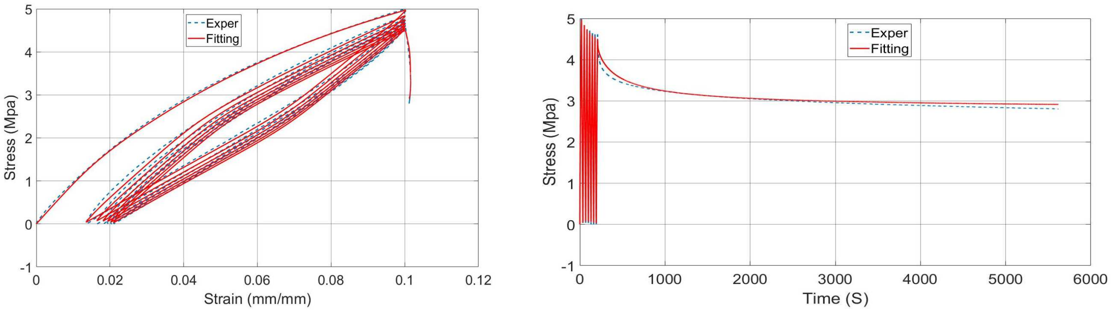


a) One unit cell b) FCC structure

Fig. 1: The design of the lattice structure: (a) unit cell, (b) FCC structure.

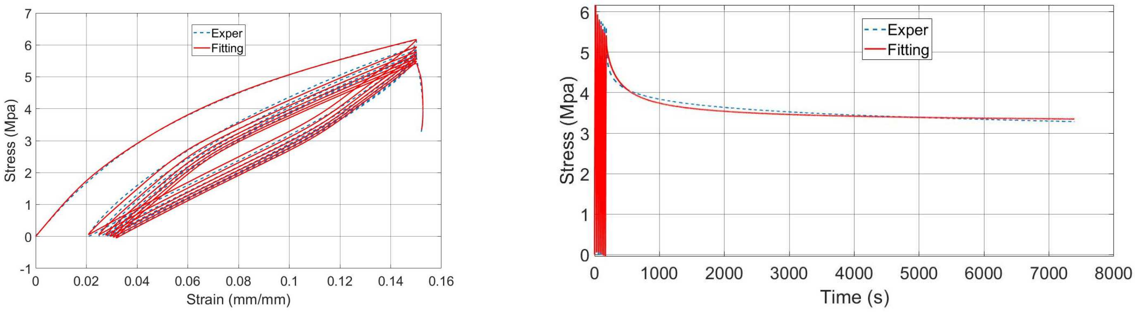
2.2 Experiment and Fitting

For printing the lattice structure the TPU material is used. The mechanical properties of the material were performed on the three bone shape samples. The cyclic tension tests were carried out through loading-unloading cycles followed by a final loading phase where the strain was kept constant for a period, allowing the stress relaxation. The cycles were applied at three different strain levels: 0.1 and 0.15, with various strain rates: $0.5\ 10^{-2}$ and $0.9\ 10^{-2}\text{s}^{-1}$. The experiment and fitting results are presented in Figs. 2 and 3.



a) Stress-strain curve fitting b) Stress-time curve fitting

Fig. 2: The fitting result at strain 0.1 and strain rate $0.5\ 10^{-2}\ \text{s}^{-1}$.



a) Stress-strain curve fitting b) stress-time curve fitting

Fig. 3: The fitting result at strain 0.15 and strain rate $0.9\ 10^{-2}\ \text{s}^{-1}$.

Tab. 1: Hyperelastic parameters (two-terms Mooney).

C1	C2
7.24467	0.34267

Tab. 2: Viscoelastic parameters.

Viscoelastic parameters	Bergstrom-Boyce (Chain B)	Bergstrom-Boyce (Chain C)
nkt	6.38584	9.76011
N	30.2971	21.2684
C_1	6.49168e-05	0.158953
C_2	-0.217285	-9.39227e-06
m	2.18651	3.6405

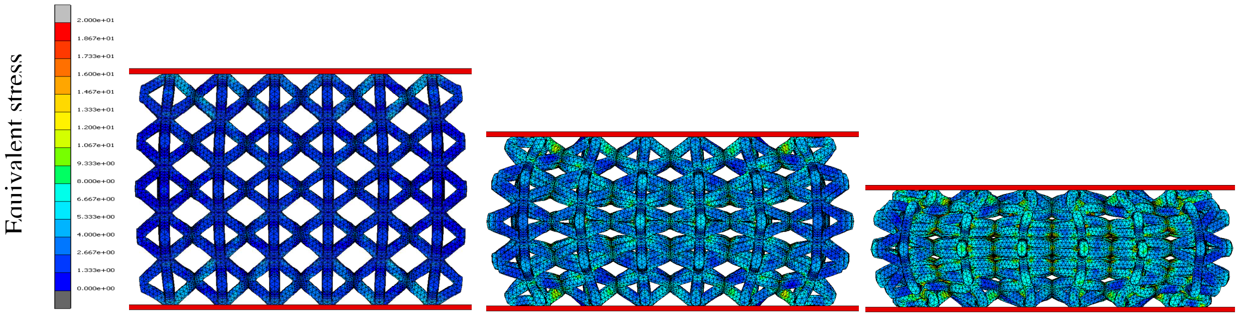
Tab. 3: Mullins effect model parameters two-terms.

Terms	Scalar factors	Relaxation parameters
1	0.34267	0.189211
2	0.385533	3.68207

3 Results and Discussion

The lower plate compression was constrained in X, Y, and Z axis directions. In contrast, the upper plate was free to move in all directions and allowed to descend along the Z-axis direction of the sample till the desired displacement. The boundary conditions were established in correspondence to the testing conditions used in the experiments. This included matching the step size, time settings, and sample size.

The deformation behavior of different strain levels and stress zones under compression is shown in Fig. 4. For example, in displacement U=4.5 mm it is observed that the higher stress acts on the strut located near the lower and bottom plates, the struts begin to bend and buckle, afterword can be seen when the displacement at U=14.5 the unit cells begin to collapse by elastic buckling and crushing. In the final stage U=24, the lattice cells impinge upon each other.



U=4.5 mm U=14.5 mm U=24 mm

Fig. 4: Compressive deformations of FEM lattice structure at different strain levels.

The cyclic stress-strain curves for a maximum compression displacement of 24 mm were obtained at a strain rate of 0.01 s^{-1}. Figure 5 compares the experimental results with the simulations. Qualitatively, the results are satisfactory, as the FEM simulations captured the experimental behavior well. However, the FEM results are slightly higher than the experimental data.

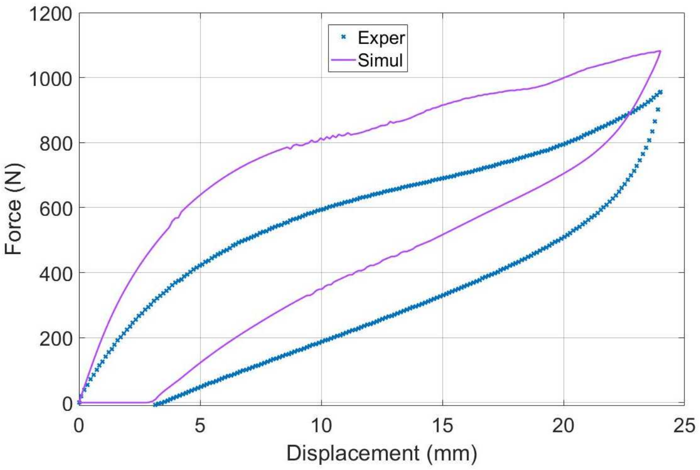


Fig. 5: Comparison of force-displacement the experiments and simulation at strain rate 0.01 s^{-1}.

This discrepancy is likely due to the influence of the printing process on the dog bone tensile sample used for identifying the material parameters. Figure 6 presents the damping force from the experiments, the comparison of damping force between the experiment and the simulation demonstrates a good agreement, as illustrated in Fig. 7. This damping force is caused by the material's viscoelastic properties.

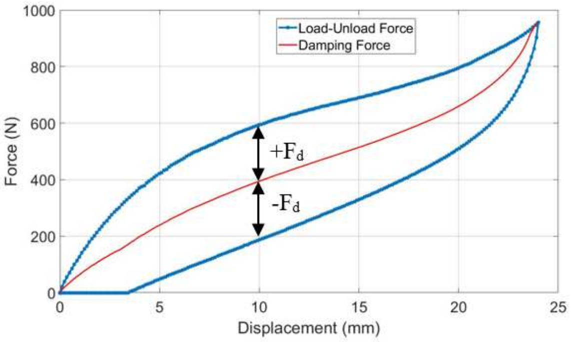


Fig. 6: Presenting the damping force from experiments.

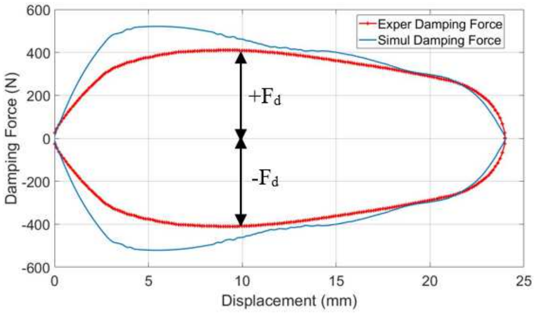


Fig. 7: Compare the damping force of the experiments and simulation.

4 Conclusion

In conclusion, the experiment was conducted on lattice structures under uniaxial compressive force using both experiment and simulation. The TPU material used for printing the samples exhibits characteristics of viscoelasticity with damage. A comparison between the simulation and experimental data revealed a good in force-displacement relationships. Overall, the study highlights the importance of considering material properties and energy absorbed by the structure, which are increasingly being utilized in various engineering applications for their lightweight and efficient design.

Acknowledgment

This publication was written at the Technical University of Liberec as part of the project "Research of advanced materials, and application of machine learning in the area of control and modeling of mechanical systems" nr. SGS-2022-5072 with the support of the Specific University Research Grant, as provided by the Ministry of Education, Youth and Sports of the Czech Republic in the year 2022.

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