INVESTIGATING THE LOAD-BEARING CAPACITY OF ADDITIVELY MANUFACTURED LATTICE STRUCTURES

Dr. János Péter Rádics and Levente Széles
Department of Machine and Product Design
Budapest University of Technology and Economics
Műegyetem rkp. 3., H-1111, Budapest, Hungary
E-mail: szeles.levente@gt3.bme.hu

KEYWORDS

Lattice structure, finite element method, compression test, auxetic, additive manufacturing

ABSTRACT

Additive manufacturing provides unprecedented design freedom from the product's external appearance to the internal structure. Additively manufactured parts, objects can be designed with cellular lattice structures as infills. The application of lattice structures can reduce the required amount of material and desired properties can be assigned to certain objects. There are several different lattice structures each with its own unique, exclusive property or properties. In this study a wide spectrum of so called 'auxetic' and standard lattice structures will be compared using finite element method and compression laboratory tests. The considered auxetic and non-auxetic cellular structures are based on the result of other researches. Along with the aforementioned existing lattices several new structures were proposed. Nine distinct additively manufactured specimens were compared.

INTRODUCTION

Nature inspired cellular structures such as wood and bone are widely used in countless areas of life. Metal foams, carbon fibre reinforced foams and honeycomb based structures are derived from natural cellular materials. (Hang et al. 2019). Owing to their promising mechanical properties, energy absorbing capabilities, impact resistance, high strength and favorable strength to weight ratio lattice structure filled parts and products are used in the automotive industry, aerospace exploration, packaging technology and biomechanics (Hang et al. 2019; Oyindamola and Behrad 2020). Cellular structures are made up from repeating cells, Cellular structures with open cell arrangement are referred to as lattice structures.

Recent advances in additive manufacturing enables the design and production of intricate 3D lattice structures. Knowing the behavior, mechanical, deformational and thermal properties of certain lattice structures we can design parts with prominent desired attributes.

In recent years several studies focused on the outstanding characteristics of lattice structures and their realization with additive manufacturing techniques. In particular, the creation of metamaterials gained outstanding attention. Metamaterial are materials which derives their properties form their structure and not form the actual material they are made from. The Greek word "meta" means "beyond", metamaterials can exhibit properties beyond the product's forming material.

Negative Possion's ratio (NPR) materials, structures and foams are of great interest in recent studies. Foams with negative Poisson's ratio were first created by Lakers in 1987 (Yongguang et al. 2019), Lakers named these materials 'auxetics'. Deformational response of auxetic materials to compression and stretching is ultimately different from traditional materials. Based on the definition of Poisson's ratio: the negative ratio of the transverse strain to the longitudal strain.

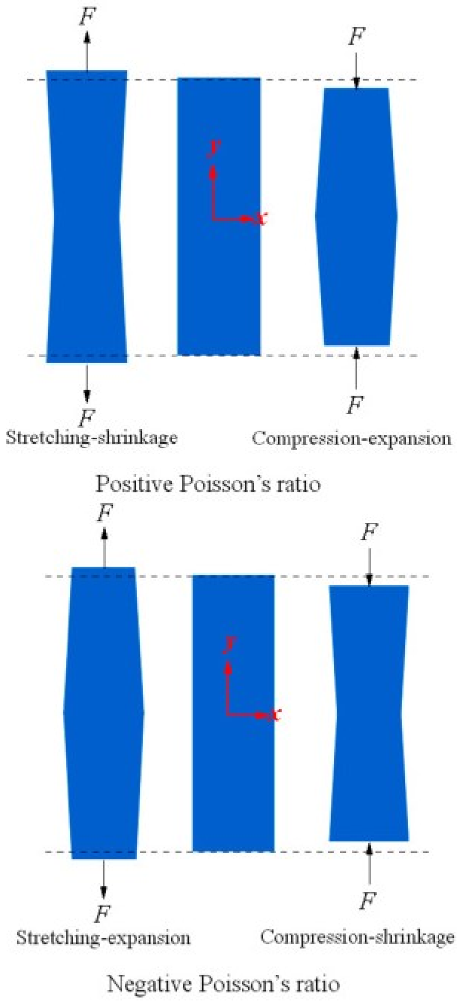

Figure 1: Deformational Response of Auxetic and Non-auxetic material (Chanfang et al 2020)

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Based on the definition, when the Possion's ration is positive the material's deformation is stretching-shrinkage and compression-expansion. On contrary, when the Poisson's ration is negative the deformation is stretching-expansion and compression-shrinkage (Changfang et al. 2020). Figure 1 illustrates the deformational response of standard and auxetic materials.

Energy absorption, load bearing and deformational capacity can be obtained from compression tests, hence in this study compression tests and simulations were adopted.

The realization of additively manufactured specimens and subsequent laboratory testing is time-consuming and costly. Employing finite element simulations, the effect of certain lattice parameters can be obtained more efficiently. Finite element simulation results must be verified by a series of measurements conducted on real specimens. In this study the result of FEM simulations and laboratory compression tests are compared.

MATERIALS AND METHODS

In this section the reasoning and the process of creating comparable specimens is presented.

Structure of the proposed specimens

In total nine different specimens were created, each built with different elements. Being a comparative study, the specimens were designed from many aspects so that the result of the laboratory tests and FEM result can be compared among specimens.

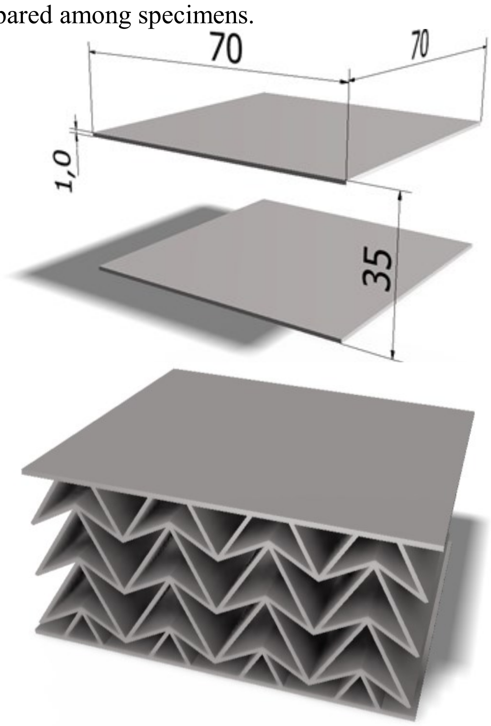


Figure 2: Overall Dimensions of the specimens and one example Specimen with Lattice structure

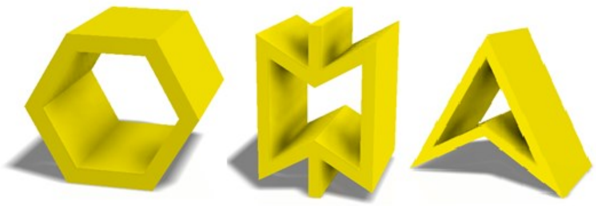
The overall dimensions are equal among test pieces; the overall height of a specimen is 35 mm, the top and bottom plates are 70 mm by 70 mm and 1 mm in thickness.

As illustrated in figure 2 the space in-between the two planes is filled with different lattice structures. Each specimen is built up using only one structure, there were no combinational experiments considered in this study. Figure 2 illustrates the hollow specimens with general dimensions and an example specimen made up from concave arrow cells.

Specimens were designed to have the same weight thus results are more clearly comparable. More precisely the weight of the test pieces consisting of 2.5 and 3 dimensional elements are the same.

Examined lattice structures

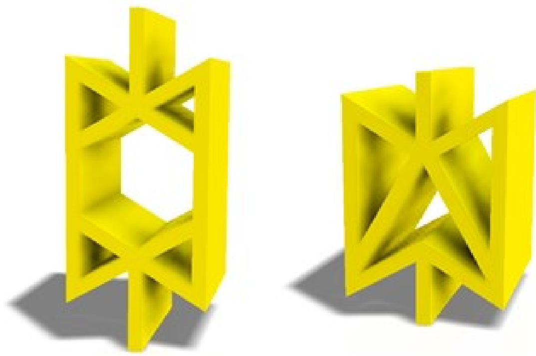
As mentioned in the introduction alongside the existing lattice structures three unique, newly created structures will be compared in this study. Figure 3 represent three existing 2.5 dimensional and broadly examined unit cell geometries. The Regular Honeycomb structure unlike the other two structure on Figure 3 does not demonstrates auxetic behavior.



a) b) c)

Figure 3. a) Regular Honeycomb unit cell; b) Vertical Auxetic honeycomb unit cell; and c) Arrowhead unit cell

Based on the research result of the unit cell types shown on Figure 3 two new 2.5 dimensional structures were proposed. The created lattice structures are combinations of existing cell structures; a combined honeycomb unit cell and a combined auxetic unit cell was created. Figure 4 illustrates the aforementioned unit cell structures.



a) b)

Figure 4. a) Combined Honeycomb unit cell; b) Combined Auxetic unit cell

Besides 2.5 dimensional unit cell types 3 dimensional ones were considered as well. The so called Octahedron unit cell and the auxetic Double-V and Double-U hierarchical structures (Hang et al.) were studied.
A new unit cell geometry called "Semi Auxetic Octahedron", based on the combination of the Octahedron unit cell and two Vertical Auxetic Honeycomb unit cells is introduced and investigated in this paper.

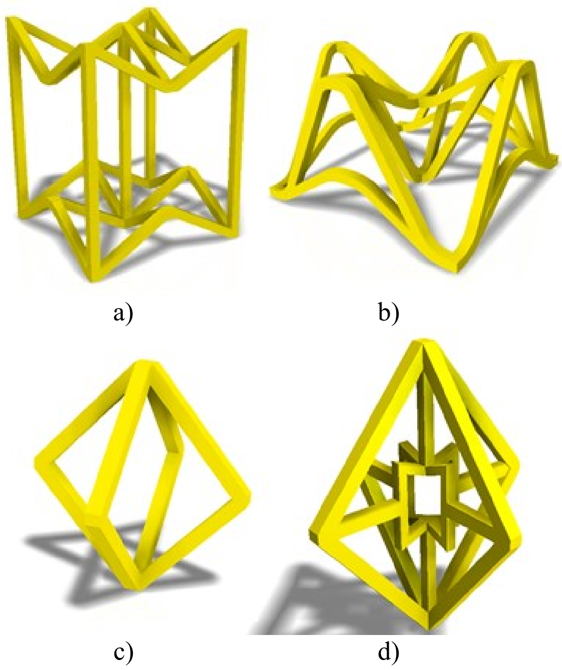


Figure 5. a) 3D Double-V unit cell; 3D Double-U unit cell; c) 3D Octahedron unit cell; and d) Semi-Auxetic Octahedron unit cell structures

Specimens were created using parametric adaptive computer aided modelling. The previously introduced unit cell geometries can be specified by a series of dimensions, parameters as Figure 6 illustrates. Adaptive modelling enables rapid creation of new specimens for future parameter based investigations.

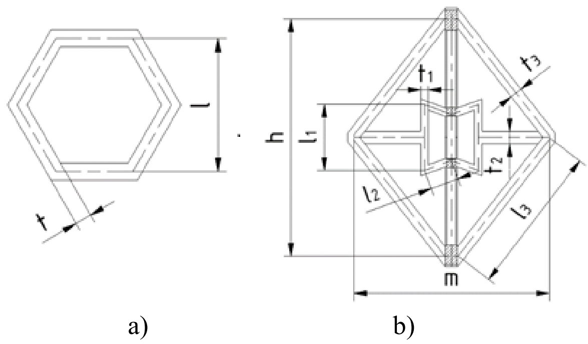


Figure 6. Examples of Parametric Drawings for a) traditional honeycomb unit cell; and b) semi-auxetic octahedron unit cells

The above listed nine structures form the basis of the present study.

Fabrication of specimens

Specimens were realized using selective laser sintering (SLS) technology with an HP Multi Jet Fusion 4200 type printer.
The material used was HP's PA 12 (MJF), material properties are listed in Table 1.

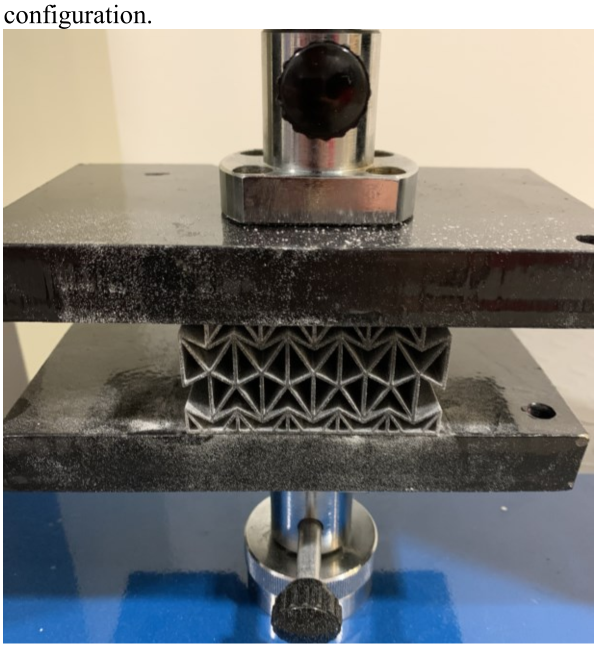
Table 1. Material Properties of PA12

Material constants	**Value**
Density [kg/m^3]	1130
Poisson's ratio [-]	0.35
Tensile modulus [MPa]	1800
Tensile strength [MPa]	49
Elongation at break [%]	20

The printed test pieces were removed from the build unit and also the powder from the lattice structures followed by sandblasting.

Methodology of laboratory testing

Load bearing capacities, deformational response and the absorbed amount of energy can be obtained by subjecting the specimens to compressive load.
Each specimen is compressed by a dual-column (twin-ball screws) tensile testing machine (KINSGEO KJ-1066A type). The conducted measurements were load controlled; force is measured by the S-beam load cell of the testing machine. Displacement is measured via the rotary encoder mounted to the motor.
The measurements are ended when rapid failure begins or when the measurement limit of 5000 N is reached. Force – displacement curves are plotted for each measurement. Figure 7 illustrates the measurement configuration.


Figures 7: Measurement Configuration for Compression tests

The measured values are adjusted by the weight of the black steel plate placed on top of the test samples.

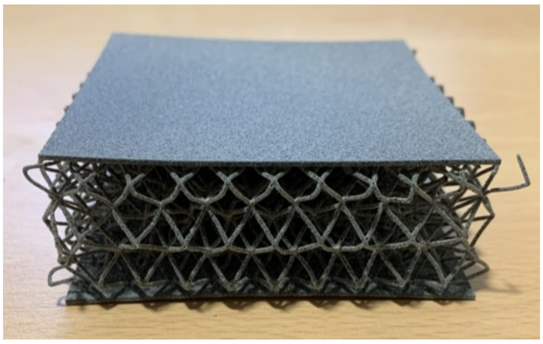


Figure 8: The beginning of Rapid Failure in the octahedron based specimen

Figure 8 illustrates a specimen in which several unit cells broke, resulting in rapid failure.
Figure 9 on the other hand represents a test piece which withstood the measurement limit without any significant failure.

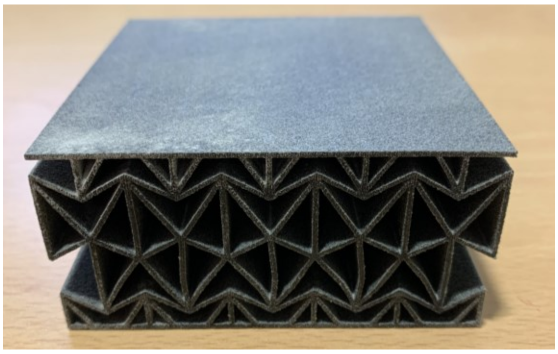


Figure 9. The combined auxetic cell based specimens withstood the measurement limit

Results of the compression test

Measured force-displacement diagrams are shown on figure 10, 11 and 12 for the Regular Honeycomb, the Octahedron and the Vertical Auxetic Honeycomb lattice based specimen respectively.

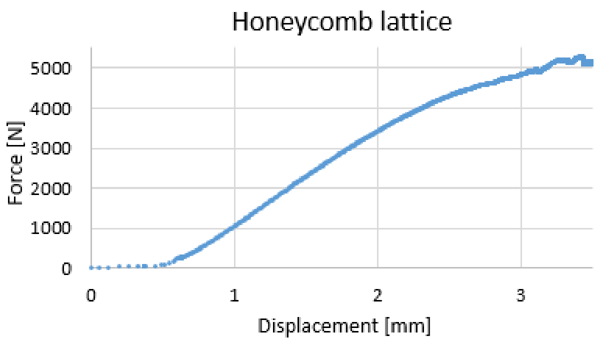


Figure 10. Measured Force – Displacement Curve of the Standard 2.5D Honeycomb lattice.

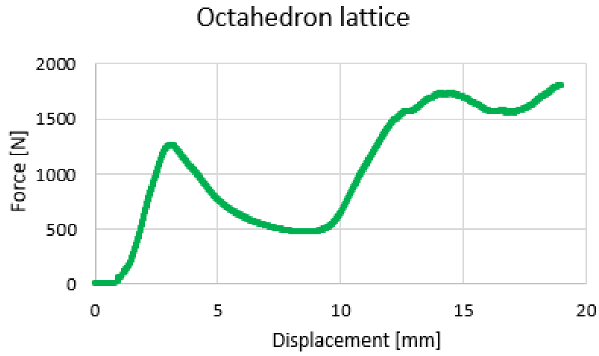


Figure 11. Measured Force – Displacement Curve of the 3D Octahedron lattice

In this study the load-bearing capacity of specimens of the same size and weight were tested. The value of the greatest force endured by the nine examined specimen variations is listed in Table 2. The measurement limit was 5000 N, thus specimens with 5000 N (5300 N) load-bearing capacity have even greater load bearing capabilities.

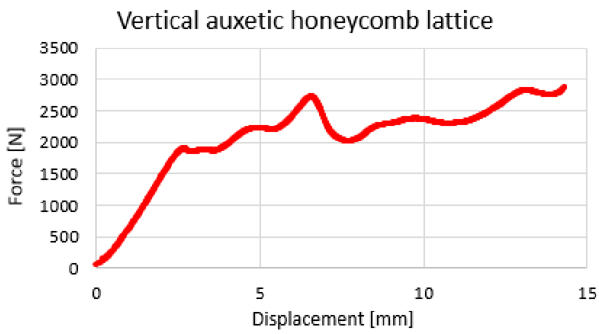


Figure 12. Measured Force – Displacement curve of the Vertical Auxetic Honeycomb lattice

Table 2. The value of the Greatest Force Endured by specific lattice types

Lattice structure type	Greatest force endured	Maximum displacement
Standard Honeycomb (2.5D)	5300 N	2.5 mm
Vertical Auxetic Honeycomb (2.5D)	4770 N	13.5 mm
Arrowhead (2.5D)	2700 N	12.7 mm
Combined Auxetic (2.5D)	5300 N	12.5 mm
Combined Honeycomb (2.5D)	5300 N	11.5 mm
Octahedron (3D)	2600 N	7.5 mm
Semi-Auxetic Octahedron (3D)	4000 N	6 mm
Double-V (3D)	2400 N	14 mm
Double-U (3D)	750 N	24 mm

The load bearing capacity is just one of the many properties a certain lattice structure can be characterized by. Energy absorption and the shape, characteristics of the force – displacement curve are also important features.
In order to increase the reliability of the laboratory tests three specimens were additively manufactured from each lattice type.

Finite element simulation

Finite element method is used to simulate the response of the specimens under quasi-static compression load using Ansys Workbench. The material properties are listed in Table 1. Isotropic elasticity material model was used for the FEM simulations.
The finite element boundary conditions were set according to the actual compression test; fixed support was used at the bottom plane of the test pieces.
To compare specimens load force of 2550 N was applied on the top plane of the specimens. To achieve uniform results, the force was applied only in the middle 50 mm by 50 mm surface area. Solid element type with 0,3 mm element size was applied for all studies resulting in a fine mesh. Figure 13 and 14 illustrates the deformation and the Von Mises stress distribution in the Vertical Auxetic Honeycomb cell based specimen.

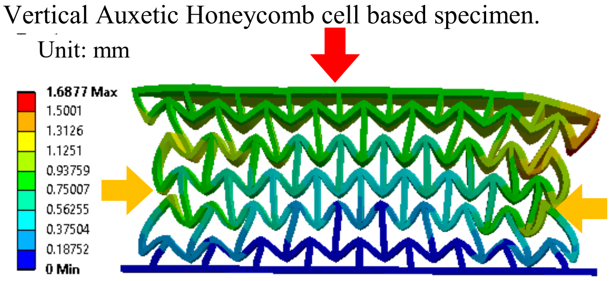


Figure 13. FEM Resulting Displacement

As its name suggests the Vertical Auxetic unit cell shows auxetic properties; the characteristic compression-shrinkage behavior can be obtained on Figure 13. Based on the FEM deformational result, simulations can be deemed acceptable.
Distribution of the Equivalent (Von-Mises) stress was considered in each simulation. Peak mechanical stresses can indicate possible failure segments on the specimens.

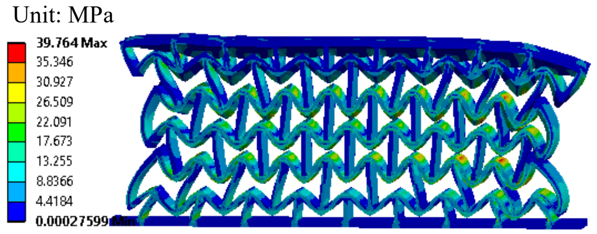


Figure 14. FEM von-Mises Stress Distribution

Results of the FEM simulations are listed in Table 3.

Table 3. Results of the FEM Simulation

Lattice structure type	Maximum displacement	Maximum stress.
Standard Honeycomb (2.5D)	0.96 mm	43.82 MPa
Vertical Auxetic honeycomb (2.5D)	1.69 mm	39.76 MPa
Arrowhead (2.5D)	7.72 mm	123.3 MPa
Combined Auxetic (2.5D)	2.42 mm	50.74 MPa
Combined Honeycomb (2.5D)	1.50 mm	73.98 MPa
Octahedron (3D)	2.59 mm	109.9 MPa
Semi-Auxetic Octahedron (3D)	2.45 mm	160.4 MPa
Double-V (3D)	23.8 mm	490 MPa
Double-U (3D)	33.9 mm	840 MPa

In specimens with maximum Von-Mises stress values greater than the tensile strength of PA12 the high stress areas had a significant extent, thus the specimens are prone to brake during laboratory tests.

COMPARING AND EVALUTAING THE RESULTS

The study focused on determining and comparing the load bearing capacity of different additively manufactured lattice structures. Another aim of this research was to compare the results of the finite element method with the results of the compression laboratory tests. Existing and newly proposed lattices were considered.
The behavior characteristic (compressive shrinkage) of auxetic materials is displayed by the laboratory tests and FEM simulations as well. Among the lattice samples examined the maximum load bearing capacity of non-auxetic lattices is greater. On the other hand, having compared the force-displacement curves of auxetic and non auxetic lattices (Figure 12 and Figure 10) it can be stated that auxetic structures in general have greater energy absorption capabilities.
FEM simulation results and laboratory test results are comparable based on Table 2. and Table 3 the following statements can be made. Those specimens which failed at lower load levels showed greater stress values at FEM simulations next to equal loads (for example 2.5D arrowhead lattice failed at 2700N and the greatest stress value in FEM simulations was 123.3 MPa).
Relative (maximum) displacement shows comparable results on the simulations and measurements as well; auxetic and non-auxetic behaviors can be recognized.
Among the newly proposed lattice structures the “Combined Honeycomb (2.5D)” and the “Semi-Auxetic Octahedron (3D)” geometries exhibited outstanding load-bearing capabilities, next to significant deformation values.

The "Combined Auxetic (2.5D) lattice still presented expressive load-bearing capability; the relatively great enclosed area under the curve characterizes the preeminent total absorb energy (Jianjun et al. 2020).

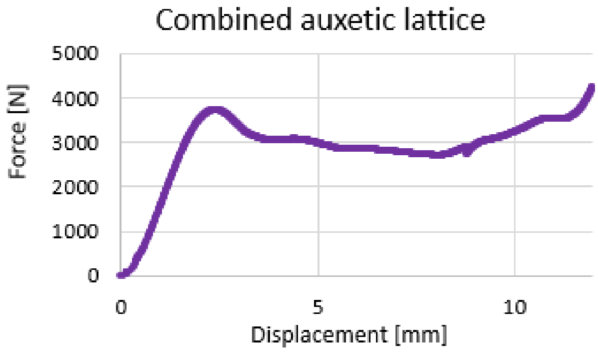


Figure 15 Measured Force-Displacement Curve of the Combined auxetic lattice

Comparing the results of the simulation and the laboratory tests advocates that the behaviors and characteristics of lattice structures can be obtained using finite element computer simulation.

CONCLUSIONS

Based on the Von-Mises stress distribution obtained from FEM simulations we can predict with high confidence the possible failure points. Comparing the stress distribution of FEM simulation especially the high stress areas it can be stated that failure will occur at these regions in real life applications. The finite element simulation method can be applied to study the behavior of existing and newly created lattice structures.

In this study three newly proposed lattice structures were examined. The "Combined Auxetic cell" in our simulations and laboratory tests presented auxetic properties. On the other hand, the two structures combined from auxetic and non-auxetic geometries did not represented auxetic properties. Based solely on our research it can be declared that the combination of auxetic stucutres will result in auxetic behavior, however, further comprehensive research is recommended. In summary the newly created lattice structures proved to be promising, further study and development is recommended.

In further stages of the research it is advised to consider the effect of geometrical parameters on the behavior of specimens. Figure 6 illustrates the geometrical parameters for certain lattice structures, changing geometrical parameters will affect the mechanical properties of a lattice structures. Establishing relationships between geometrical parameters and physical properties can provide a decision preparation basis for choosing the most adequate structure and parameter for a certain application.

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AUTHOR BIOGRAPHIES

DR. JÁNOS PÉTER RÁDICS is an assistant professor and deputy head at the Department of Machine and Product Design BME. His research area is Design for Additive Manufacturing (DfAM), soil CHG emission, soli-tool wear and DEM simulation of agricultural material behavior. His email address is: radics.janos@gt3.bme.hu.

LEVENTE SZÉLES was born in Balassagyarmat, Hungary. He is PhD student at the Department of Machine and Product Design BME. Levente graduated from BME with BSc and MSc degrees in 2016 and 2020 respectively. His research field is additive manufacturing, specifically creating design guidelines for additive manufacturing. His email address is: szeles.levente@gt3.bme.hu.