MECHANICAL BEHAVIOUR OF 3D-PRINTED METAMATERIALS WITH TUNABLE STIFFNESS

MIRCEA CRISTIAN DUDESCU , CRISTIAN VILĂU

Abstract. The concept of mechanical metamaterials has received special attention during the last years due to the advances in additive manufacturing techniques that allows fabrication of structures with complex architectures. The special design of metamaterials micro architecture offers the possibilities to obtain unprecedented mechanical properties that could be exploited to create advanced materials with novel functionalities. This paper presents the design, fabrication and testing of cellular metamaterials obtained by fused deposition molding, an affordable additive technology. Cellular structures with comparative cell dimensions but different geometries have been printed out and subjected to uniaxial compression test. The understanding of mechanical behavior of proposed structures leads to the possibility to create metamaterials with tunable compressive or bending stiffness. For the designed cellular metamaterials the results of experimental investigations are compared with those obtained by finite element analysis.

Key words: metamaterials, additive manufacturing, tunable compressive stiffness.

1. INTRODUCTION

Recently, researchers started to engineer not only the outer shape of objects, but also their internal microstructure. Such objects, typically based on 3D cell grids, are also known as metamaterials. Metamaterials are structured materials consisting of periodically arranged blocks that exhibit properties and functionalities that differ from those of their constituent materials rather than simply combining them. There are different types of metamaterials with applications in optics, acoustics and thermal fields and that have extremely unusual properties, such as a negative refractive index.

Originally, the field focused on achieving unusual (zero or negative) values for familiar mechanical parameters, such as density, Poisson's ratio or compressibility [1], but more recently, new classes of metamaterials – including shape-morphing, topological and nonlinear metamaterials – have emerged. These

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materials exhibit exotic functionalities, such as pattern and shape transformations in response to mechanical forces, unidirectional guiding of motion and waves, and reprogrammable stiffness or dissipation [2]. Acoustic metamaterials can manipulate and control sound waves in ways that are not possible in conventional materials. Metamaterials with zero, or even negative, refractive index for sound offer new possibilities for acoustic imaging and for the control of sound at subwavelength scales. The combination of transformation acoustics theory and highly anisotropic acoustic metamaterials enables precise control over the deformation of sound fields, which can be used, for example, to hide or cloak objects from incident acoustic energy [3]. Han and others [4] employ one identical sensu-unit with facile natural composition to experimentally realize a new class of thermal metamaterials for controlling thermal conduction (e.g., thermal concentrator, focusing/resolving, uniform heating), only resorting to positioning and locating the same unit element of sensu-shape structure. The thermal metamaterial unit and the proper arrangement of multiple identical units are capable of transferring, redistributing and managing thermal energy in a versatile fashion. Numerous researches have been dedicated to metamaterials and their unusual proprieties and applications.

A series of review papers [2–5] present the state of the art in the field of metamaterials. Other trends are the metamaterial mechanisms. Such metamaterial mechanisms consist of a single block of material the cells of which play together in a well-defined way in order to achieve macroscopic movement [6–9]. The metamaterial door latch, presented in [9], transforms the rotary movement of its handle into a linear motion of the latch. The key element behind the metamaterial mechanisms is a specialized type of cell, the only ability of which is to shear. Other application are the metamaterial textures which are integrated into 3D printed objects and allow designing how the object interacts with the environment and the user's tactile sense [10]. Inspired by foldable paper sheets ("origami") and surface wrinkling, the proposed 3D printed metamaterial textures consist of a grid of cells that fold when compressed by an external global force [11].

The paper analyses the mechanical behavior under compression forces of cellular metamaterials with similar cell dimensions but different geometrical structure. When a force is applied the cells are designed to deform, mostly to shear which allows for directional movement. The structures of the metamaterials were realized by 3D printing technology using a thermoplastic elastomer in order to obtain models with low stiffness that undertake big displacement of single cells. In the first part of the paper are presented the materials and the methods employed for the fabrication and analysis of the created metamaterials, the compression test results and a finite element analysis of the investigated structures. The numerical stiffness was compared with the experimentally obtained values. The paper ends with the conclusions and some idea for future work.

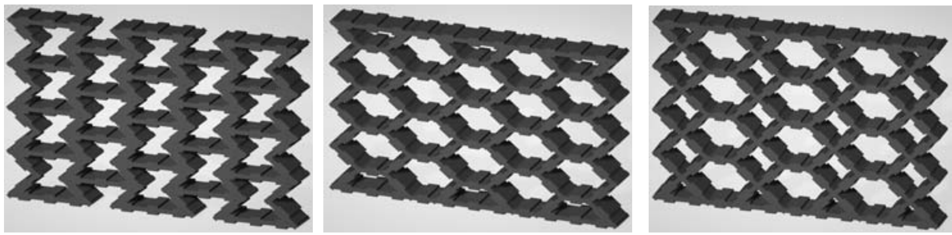
2. MATERIALS AND METHODS

Fused Deposition Modeling (FDM) is an additive manufacturing process (material addition), which belongs to material extrusion technology. Through FDM technology, an object is constructed by depositing molten material on a work table, layer by layer. The materials used are thermoplastic polymers and have a filament shape. A coil (roller) with thermoplastic filament is loaded into the printer and is fed to the extrusion head and passed through a nozzle. The nozzle is heated and once the nozzle has reached the desired temperature (melting of the filament), the filament melts and is passed through the nozzle. The extrusion head is attached to a 3-axis system that allows it to move in X, Y and Z directions. The molten material is extruded into thin filaments and is deposited layer by layer in predetermined places, where it cools and solidifies. To fill a region (or layer), multiple passes are necessary. When a layer is completed, the construction platform moves down (or the extrusion head rises) and a new layer is deposited. This process is repeated until the completion of the part (model).

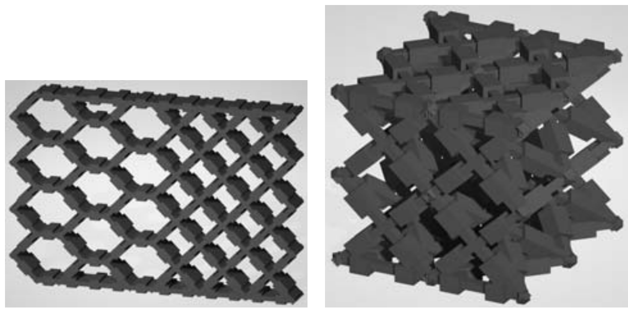
Investigation of cellular metamaterials with high elasticity fabricated by additive manufacturing technologies, particularly by Fused Deposition Modeling (FDM) implies use of elastomers as basic materials to achieve the desire mechanical behavior. Elastomers are polymer networks, which have low crosslinking density and have high molecular weight polymer chains between their links. A typical elastomer can be stretched up to 10 times its initial length, reaches an extremely high elongation at break (400–1000%) and recovers its shape when tension is released. The most commonly used flexible materials suitable for FDM technology are thermoplastic materials, namely thermoplastic elastomer (TPE) and thermoplastic polyurethane (TPU) [12]. For the 3D models, using the FDM manufacturing technology, a flexible filament (Spectrum Filaments, Poland) with a diameter of 1.75 (+/refractive index for sound 0.05) mm and a print temperature from 245 °C to 275 °C was used.

The 3D models were build using the free metamaterial editing software provided by Hasso Plattner Institute, Germany [13]. Figure 1 presents the created geometrical structures, based on cells grid. It can be noticed that the cells are a specialized type of cell with ability to shear under an in–plane force. Unlike rigid cell, this shear cell is designed to deform (shear) when a force is applied and consists of elements (beams) with different width and constant thickness especially at the joining points. Practically, the joining points take the role of a flexible hinge. Five types of structure were proposed to be analyzed, named hourglass, hexagonal, hexagon-rhombus, hexagon-square and cube.

The dimensions of the 3D models, presented in Fig. 1 (a–d) have the following values: height 40 mm, length 55 mm, thickness 5 mm and the wall thickness of the cell elements is 2 mm. The 3D model presented in Fig. 1e represents a cube with a side of 40 mm, the thickness of its internal single elements of 2 mm and the length of one side of a cell is 5 mm.



a) hourglass structure b) hexagon structure c) hexagon–rhombus structure



d) hexagon-square structure e) cube structure

Fig. 1 – Virtual 3D models of the metamaterials.

2.1. Filament characterization

Thermoplastic materials can be easily extruded, but require careful attention when printing parts, due to their flexibility. The characteristics of the filament used to fabricate the models are presented in Table 1.

Table 1

Filament characteristics

Material	Rubber (thermoplastic elastomer)
Diameter	1.75 mm
Dimensional tolerance	+/– 0.05 mm
Print temperature	from 245 °C to 275 °C
Printing speed	20 mm/s
Color	Black

Future mechanical analyses imply the known of mechanical constants of the raw material. There is a lack of material data for such filaments, reason why a standard tensile test was performed on a specimen of filament. An Instron 3366

(10kN) universal testing machine was used for mechanical test. The obtained strain–stress curve is presented in Fig. 2 and the measured material *E*–modulus was 36,5 MPa.

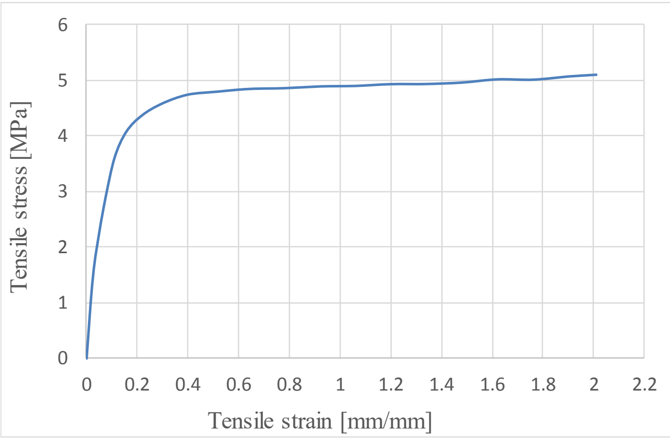


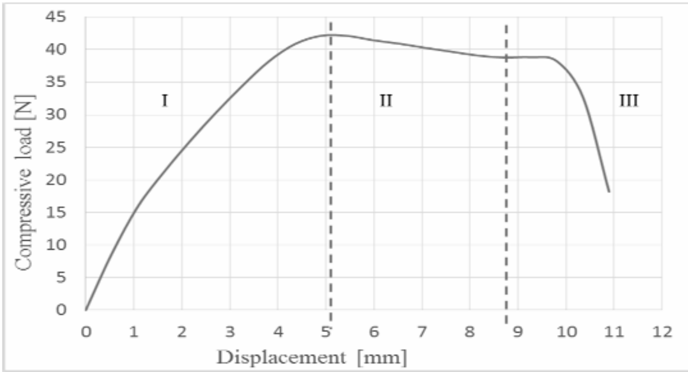
Fig. 2 – Strain–stress curve of the filament material.

It can be observed in Fig. 2 that the characteristic curve is a typical curve for an elastomeric material with an elastic zone followed by a large yield domain.

The above described cellular metamaterials have been printed out and subjected in an as it is state to a compression test using the same universal testing machine. The tests were carried out until the models start to collapse. After realization the tests, on the machine presented above, the compression behavior of the metamaterials made of flexible material with different structures were obtained. These characteristic curves are shown in Figs. 3 to 7. In these figures are represented the compressive load versus transverse displacement for each structure and in addition some picture with the deformed shape at certain moments.

For all analyzed structures we can distinguish three intervals of the characteristic curve in compression. The first interval (I) is characterized by an elastic behavior in which the deformation increases proportionally with the force. The second domain (II) is similar with the yielding, where the force remains approximately constant while the deformation increases. The third interval, for the hourglass structure, has a rapid decrease in force (Fig. 3), the structure collapsed, and the internal elements are strongly deformed. A different behavior in the last part (III) could be noticed for the hexagon, hexagon–rhombus, hexagon-square and cube type models, the third range has a rapid increase in compressive force.

In Fig. 3a a peak value of the compressive force that corresponds to a value of 5 mm deformation can be seen. After that the load remains approximately constant until a 9 mm deformation, after which the value of the compression force decreases rapidly.

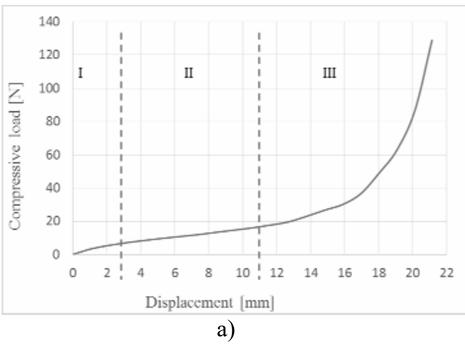


a)

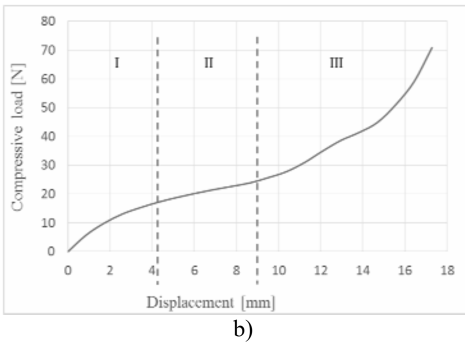
b)

Fig. 3 – Compressive test of the hourglass structure: a) load–displacement diagram; b) deformed shape of the structure at different stages.

A similar test was done on all structures. It can be seen in Fig. 4 that hexagon, hexagon-rhombus, hexagon-square structures and for the cube on the third interval the value of the compressive force increases rapidly. It can be also observed that the compressive strength increases during the first interval, for the mentioned structures at a value of 20 N and then remains approximately constant.



a)



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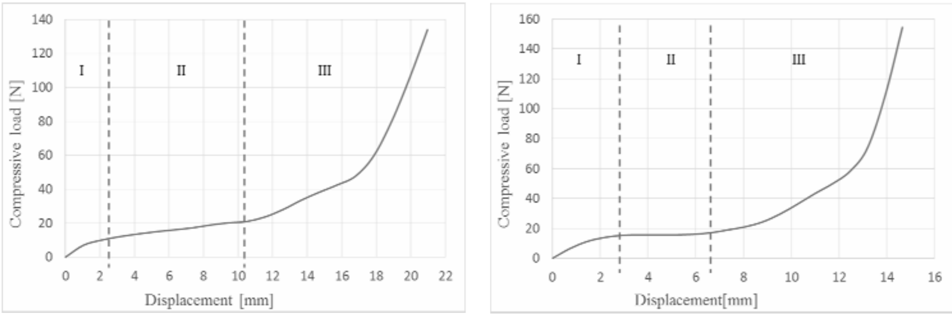
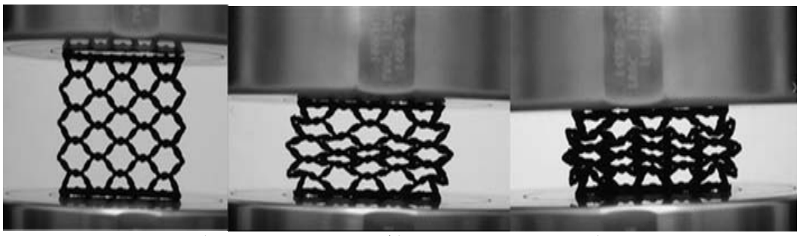


c) d)

Fig. 4 – Compressive test: a) hexagon structure; b) hexagon-rhombus structure; c) hexagon-square structure and d) cube structure.

In Fig. 5 are presented the three stages for a compression-tested structure.



a) b) c)

Fig. 5 – Compressive test of the hexagon structure: a) first interval; b) second interval; c) third interval.

A comparative analysis of the obtained compression load–displacement curves is presented in Fig. 8.

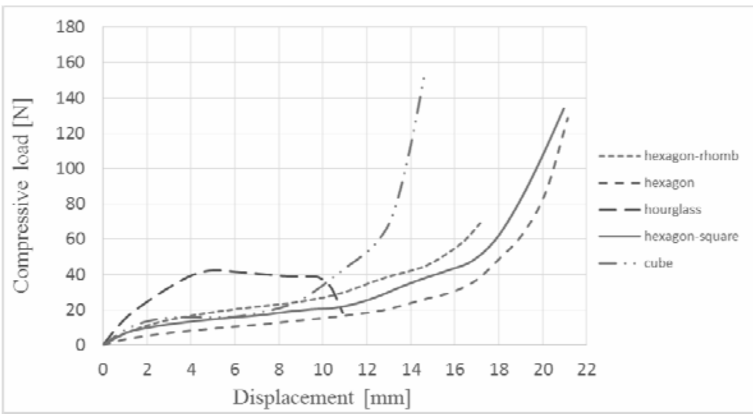
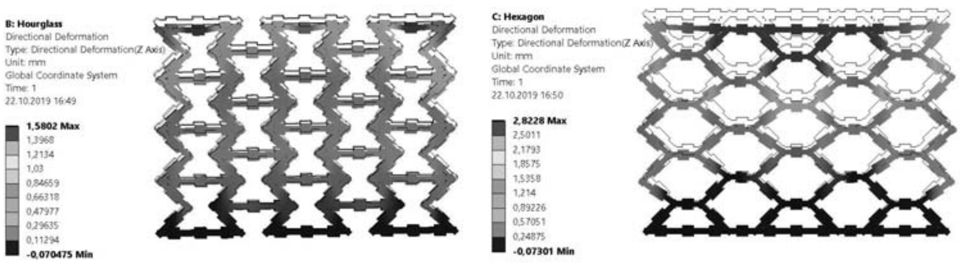


Fig. 8 – Comparative analysis of the load–displacement curves.

It can be noticed that the only structure with different behavior is the type hourglass which is much stiffer, and it collapses by buckling of the hole structure having a visible lateral deflection. The other structures will behave similarly, and the collapses are done by excessive deformation of the internal elements rather than the complete structure deformation. From the point of view of the expected results the deformation way in which internal elements and successive layers are compressed and collapses is more desirable from the structural point of view instead of whole structure buckling.

A finite element (FE) study was performed for each structure to get the numerical stiffness. The same 3D models obtained previously and used for the 3D printing process were imported in ANSYS Workbench 2019R2 simulation software. The material was defined by its elastic constant and for nonlinear part the experimentally measured strain-stress data of the filament was imported as uniaxial test. In case of big displacements using of real strain-stress data will ensure proper results. Figure 9 presents the FE results (directional deformation) for the investigated structures. Computation of the structure's stiffness as the ratio between the applied force and the corresponding displacement revealed good agreement with the experimental test. Thus, the hourglass structure has a measured compression stiffness of 14.55 N/mm and a simulated one of 15.7 N/mm. For the hexagon structure the experimental stiffness was 2.25 N/mm and the computed value 1.96 N/mm.



a) b)

Fig. 9 – Simulated displacements of the investigated metamaterials: a) hourglass structure and b) hexagon structure.

3. CONCLUSIONS

In the present paper we have presented some models of flexible structures used for metamaterials, made from theomoplastic elastomeric materials. These structures were made using FDM manufacturing technology. Additive manufacturing or 3D printing reduces the cost and time of manufacture of a product or part. Analyzing the mechanical behavior of the analyzed structures three intervals of the characteristic curve in compression can be distinguished. The first interval is characterized by an elastic behavior in which the deformation increases proportionally with the force. The second one is similar with the yielding, where the force remains approximately constant while the deformation increases. The third interval has a rapid decrease in force (hourglass structure) followed by the collapse of the structure due to buckling of the entire structure. A different behavior in the last part could be noticed for the hexagon, hexagon–rhombus, hexagon-square and cube type models, the third range has a rapid increase in compressive force, the collapse are done by excessive deformation of the internal elements rather than the complete structure deformation. FE studies complete the analysis and the obtained results will be considered for future numerical investigations of such structures with different internal geometry and variable stiffness.

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