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MECHANICAL RESPONSE OF ADDITIVE MANUFACTURED REGULAR CELLULAR STRUCTURES IN QUASI-STATIC LOADING CONDITIONS - PART I EXPERIMENTAL INVESTIGATIONS

Piotr Dziewit(*), Paweł Platek, Jacek Janiszewski, Marcin Sarzyński, Michał Grązka, Robert Paszkowski
Institute of Armament Technology, Military University of Technology, Warsaw, Poland
(*)*Email:* piotr.dziewit@wat.edu.pl

ABSTRACT

The aim of this paper is to present the results of experimental investigations concerning a mechanical response of 2D regular cellular structures with different topologies in an aspect of crashworthiness behaviour. Developed by the authors, genuine topologies of 2D regular cellular structures were built with using Fused Deposition Modelling (FDM) additive manufacturing method and afterwards they were subjected to uniaxial compression tests. A wide range of structure topologies made from three commercially available polymeric materials - ABSplus, Nylon12 and PC-10 were examined during carried out investigations. One of the commercially available CAD systems was used to define proposed structure topologies. It was found that the energy absorption depends on the elasticity of a structure, where high strength geometries represent linear crashworthiness behaviour with bending and cracking while flexible ones present exponential increase of deformation force due to densification of the structure.

Keywords: additive manufacturing, cellular structures, energy absorption, auxetic structure, fused deposition modelling

INTRODUCTION

A contemporary progress of new cutting-edge passive protective systems is associated with a development of a new multifunctional regular cellular structure materials (Ajdari, 2011; Nemat-Nasser, 2007; Li Yang, 2015). They indicate a high capacity of energy absorption with preserving a low relative density in comparison to solid materials (Ajdari, 2011; Nemat-Nasser, 2007; Li Yang, 2015). Observed in the last decade the progress in the area of regular cellular materials is caused due to the implementation of additive manufacturing methods which enable fabricating regular structures with complex topologies (Yan, 2012; Haghpanah, 2014; Wadley, 2006; Brenne, 2013). Based on research results presented in many scientific papers it was stated that geometrical features of topology strongly effects on crashworthiness behaviour of structures (Challis, 2014; Huang, 2008). Taking into consideration the possibility of application of various types of materials (metal powders, ceramic powders, polymers, resins) in structure manufacturing process as well as implemented topology it is available to programme the mechanical response of the regular cellular structure under static and dynamic loading boundary conditions (Mahshid, 2016; Tancogne-Dejean, 2016; Gao, 2015). Due to mentioned reasons numerous research development projects are undertaken in order to optimize the structure topology in view of their crashworthiness behaviour. The optimization process is usually realized by analytical, numerical as well as experimental approaches (Tancogne-Dejean, 2016; Gao, 2015; Gibson, 2010).

An interdisciplinary scientific group from the Military University of Technology started a research project in 2016. The main goal of this project is directed to optimize the crashworthiness behaviour of regular cellular structures manufactured from Ti-6Al-4V alloy powder by LENS system (Polanski, 2013) in static and dynamic loading conditions. Due to a wide spectrum of the problem concerning an investigation of the regular cellular structure crashworthiness behaviour, the authors focused their attention on the experimental approach in this paper. It presents the preliminary results of studies involving the mechanical response of 2D regular cellular structures with different topologies subjected to uniaxial compression tests under quasi-static loading boundary conditions. Cellular topologies developed by the authors were fabricated with the use of a FDM additive technology. The main advantage of proposed additive manufacturing method is its user-friendliness and relatively low cost of production (Chang, 2013; Croccolo, 2013; Smith, 2013; Dawoud, 2016). Developed specimens of investigated cellular structures were fabricated with the use of following materials: ABSplus, Nylon12 and Policarbonate-10. They indicate different mechanical properties and allow conducting the comparative analyse of energy absorption capacity.

DEFINITION OF CELLULAR STRUCTURE TOPOLOGIES

One of commonly available CAD system - SolidWorks - was used to develop the different type of 2D regular cellular structures (Fig. 1). The main assumption undertaken during this task refers to structure dimensions. They were designed as approximately 80 x 80 x 20 mm cuboids with 1 mm wall thickness. The size of a structure specimens was determined by a number of cells and technological possibilities of the implemented additive manufacturing system. The estimated values of relative density for the developed structures was in the range $0.20 < \rho_r < 0.41$. In order to extend the range of carried out studies, two groups of structures with positive Poisson's ratio (Fig. 1 - No.1÷2, 4÷5) and negative Poisson's ratio (Fig. 1 - No.3, 6). were examined.

The honeycomb structure topology presented in Fig. 1 - No.1 is well-known in the literature and tested repeatedly because of its excellent mechanical properties (which are used as fillers in engineering constructions, for example: racing car body, in order to minimize weight) (Gibson, 2010; Restrepo, 2016; Gao, 2015). Based on geometrical features of honeycomb structure the other topologies were designed.

The second variant (Fig. 1 - No.2) is a regular structure which indicates the lower relative density. Due to adopted geometrical features it enables easy controlling size of a cell. The topology No.3 was inspired by interrogating mark. The elementary cell consists of four marks connected together and forming a regular square. Additional rounds are used to make the sharp angles more smooth. Moreover, they also effect on deformation process and enable the increase of the structure crashworthiness behaviour. The further samples of structure topologies No.4 to No.6 were elaborated based on elementary cell which consists of rounds connected together. Owing to proposed geometrical assumption the directional deformation of elementary cell should be transformed into twisting process. Additional spring elements added in topology No.5 and No.6 made it more flexible. No.6 is a modification of structure No.5. It is rotated by an angle of 45° which gives it the auxetic properties. The idea of using this kind of geometry was inspired by mesostructures developed by *Andreas Bastian*, who is one of the well-known engineers associated with the area of additive manufacturing.

The original structure topologies designed by the authors have different mass-inertia properties. The value of a relative density was determined for all of the studied topologies (1):

$$\rho_v = \frac{m}{V}, \qquad \rho_r = \frac{\rho_v}{\rho_m}, \tag{1}$$

where: ρ_v - density of the structure, m - model mass, V - model volume (approximately 80 mm x 80 mm x 20 mm), ρ_r - relative density of the cellular structure, ρ_m - material density (ABS, PA, PC).

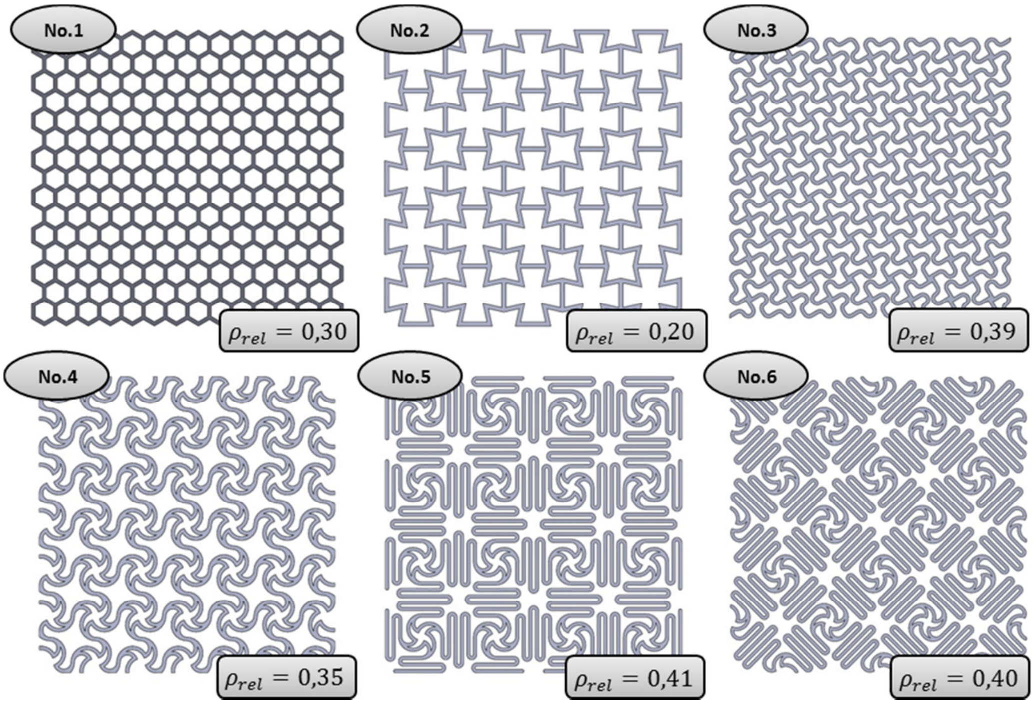

Fig. 1 - The view of developed regular cellular structures with different topologies: No.1÷2, 4÷5 with positive Poisson's ratio, No.3,6 with negative Poisson's ratio.

The FDM method was used to manufacture the elaborated structure topologies. The method was introduced to the public market in the vicinity of early 1990s (Chang, 2013; Labonnote, 2016; Vairis, 2016). It allows producing three-dimensional objects by extrusion of the thermoplastic filament from the nozzle onto the base table at a controlled rate. This technology enables building designed 3D models layer by layer from the bottom to the top (bottom up) until the part is finished. The manufacturing process is started from the definition of appropriate technological parameters such as: layer thickness, type of model and support materials infilling as well as model orientation on the base table. Afterwards, the 3D model is sliced in order to determine the code necessary to perform the manufacturing process. Both model and support materials are used in the technological process. The main role of additional support material is filling all kinds of holes, cut-outs and scaffolds which exist in the manufactured model. The support model is mechanically removed or it is dissolved from the model at the final stage of manufacturing process.

The Dimension 1200es SST and Fortus 900mc (Stratasys Corp.) 3D printers were applied to manufacture specimens with different cellular structure topologies. Application of both devices with different technological specifications enables extending the range of conducted experimental investigations. The Dimension 1200es SST 3D printer allows fabricating objects with preserving the single layer thickness equal 0.254 mm or 0.33 mm. Comparing to commonly available low-cost 3D printers it operates in the closed workspace with an additional heating system which ensures the invariable working conditions. In turn, the Fortus 900mc 3D printer is a professional industrial additive manufacturing system which allows using a wider variety of materials in comparison to the Dimension SST 1200es 3D printer. It was decided to apply a three commercially distributed by Stratasys Corp. materials such as: ABSplus, Nylon12 and PC-10 to manufacture specimens of studied regular cellular structures. Proposed materials have different mechanical properties and they are dedicated to various range of applications (Smith, 2013; Dawoud, 2016, stratasys.com). The material specification provided by producer was presented in Tab. 1.

Table 1 - The comparison of physical-mechanical properties of filaments used to manufacture cellular structures provided by Stratasys, Inc. (stratasys.com)

Material	Density [g/mm^2]	Tensile Strength	Young's Modulus	Tensile Elongation
ABSplus (ABS)	1.04	31	2200 MPa	6%
Nylon 12 (PA)	1.00	46	1282 MPa	30%
PC-10 (PC)	1.20	57	1944 MPa	4.8

The crashworthiness behaviour studies of developed structure topologies of were preceded by uniaxial tensile tests. The main purpose of carried out studies was verification of facilitated material specifications. Five dog-bone tensile samples were fabricated and tested for each material. The dimensions of samples used during tests are presented in Fig.2a. Moreover, adopted direction of the manufacturing process (on 0XY plane) enables to make an assumption that samples do not indicate the orthotropic mechanical properties.

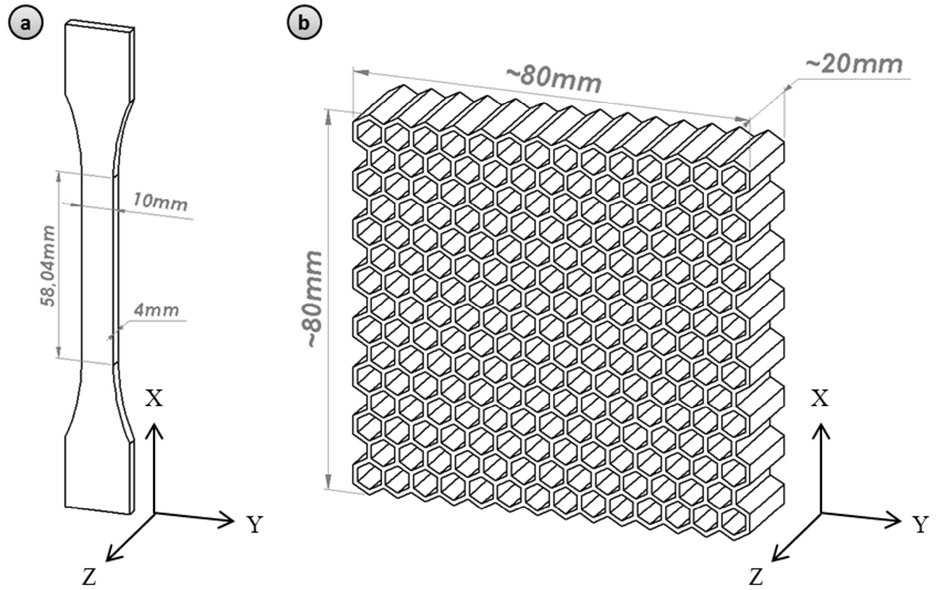

Fig. 2 - Manufacturing orientation (0XY - plane base table, 0Z - direction of slicing) and dimensions of specimens: (a) flat tensile specimen and its reference dimensions; (b) structure example (Honeycomb) and its dimensions

Both tensile testing of dog-bone samples and compression strength tests of fabricated cellular structure samples were performed on a testing machine MTS Criterion C45. The entire process was monitored and recorded using the TW-Elite software. The tensile tests were conducted with deformation velocity of 0.1 mm/s, whereas the structures are compressed with traverse velocity of 1 mm/s and in a perpendicular direction to the direction specimens building. The process of deformation was stopped after the rapid growth of the stress curve, which indicates densification of the structure.

RESULTS AND DISCUSSION

The uniaxial tensile tests were conducted in order to determine the mechanical properties of applied filaments in the manufacturing process of cellular structure specimens. Based on obtained results it was possible to define the material strength under applied loading boundary conditions. These tests were performed to estimate the mechanical properties of FDM filaments, for which there is no information about defined layer thickness during the manufacture process. Moreover, the producer of filaments claims that the information included in the specification sheet are typical values intended for reference and comparison purpose only (startasys.com).

The average stress versus strain plots obtained during carried out tensile tests are presented in Fig. 3 and Tab. 2.

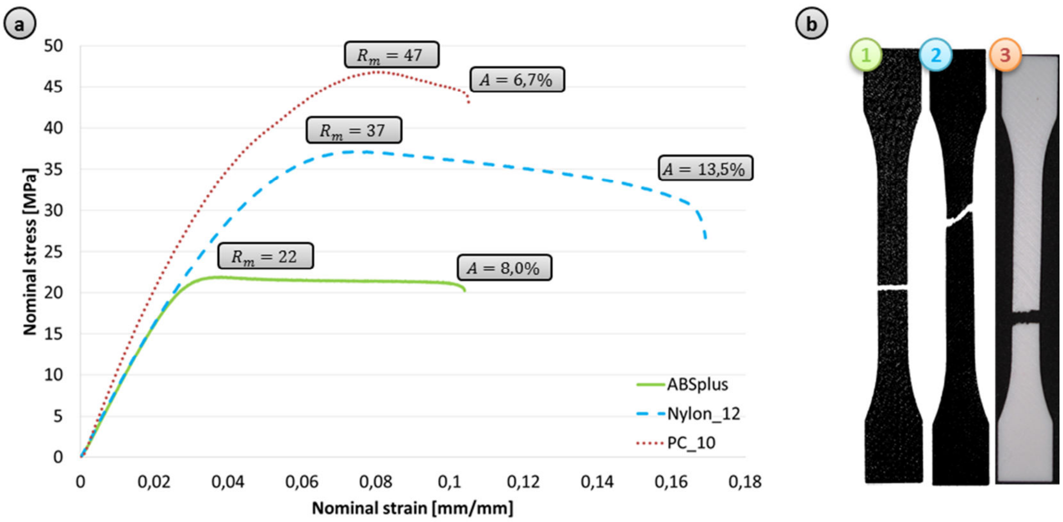

Fig. 3 - Tensile stress-strain curves for additive manufactured samples made of ABS(1), PA(2) and PC(3) (a); view of the fractured tensile test specimens (b)

Table 2 - The comparison of the additive manufactured test samples tensile properties

Material	Tensile Strength	Tensile Elongation
ABSplus (ABS)	22	8%
Nylon 12 (PA)	37	12.5%
PC-10 (PC)	47	6.7%

The relative densities of structure specimens fabricated from different materials are shown in Tab. 3. Obtained values were determined based on measured structure dimensions and defined densities. Comparing this data with estimated values on the basis of CAD model (Fig. 2) some disagreements between relative density values were noticed. It could be explained by the particular features of the technological process. Although the parameters of the process are controllable, the printing accuracy depends on how fast the output nozzle can change its directions and how precise the curves can be obtained, which results in wall thickness. Moreover, the density of base material provided to the 3D printer and the fabricated object could be different due to the preciseness of the layer connection.

Table 3 - Comparison of estimated relative density values obtained through different materials and structure topologies

Material	ABSplus	Nylon 12	PC 10
Structure No.1	0.30	0.32	0.31
Structure No.2	0.19	0.20	0.19
Structure No.3	0.36	0.38	0.36
Structure No.4	0.30	0.31	0.30
Structure No.5	0.37	0.38	0.37
Structure No.6	0.36	0.38	0.36

In Figs. 4 ÷ 9 the results of uniaxial compression test obtained for developed regular cellular structures are collected. It can be seen that polycarbonate structures (PC 10) indicates the highest strength properties than nylon and ABS. It corresponds to the results of tensile strength test (Tab. 1, Fig. 2).

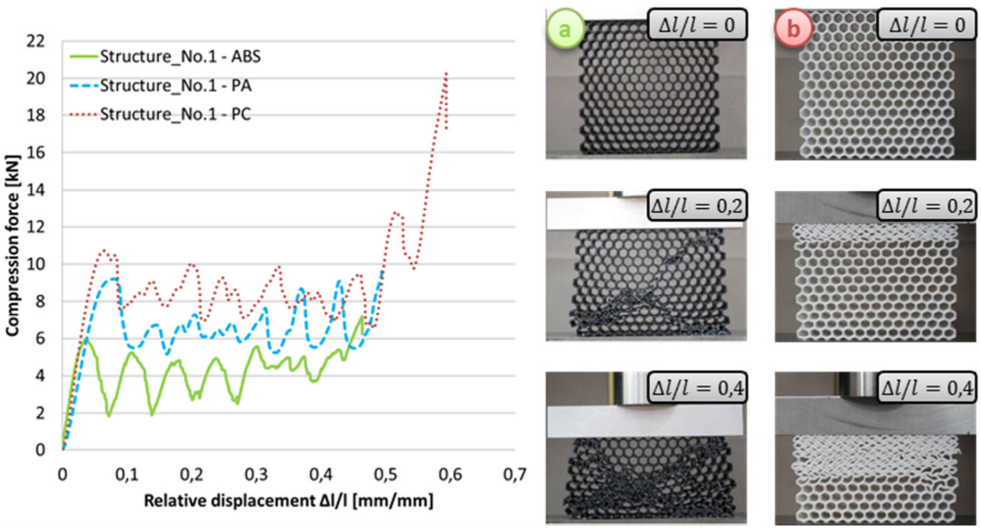

Fig. 4 - Uniaxial force-relative displacement curves for structure No.1; successive stages of structure deformation made of (a) ABS, (b) PC

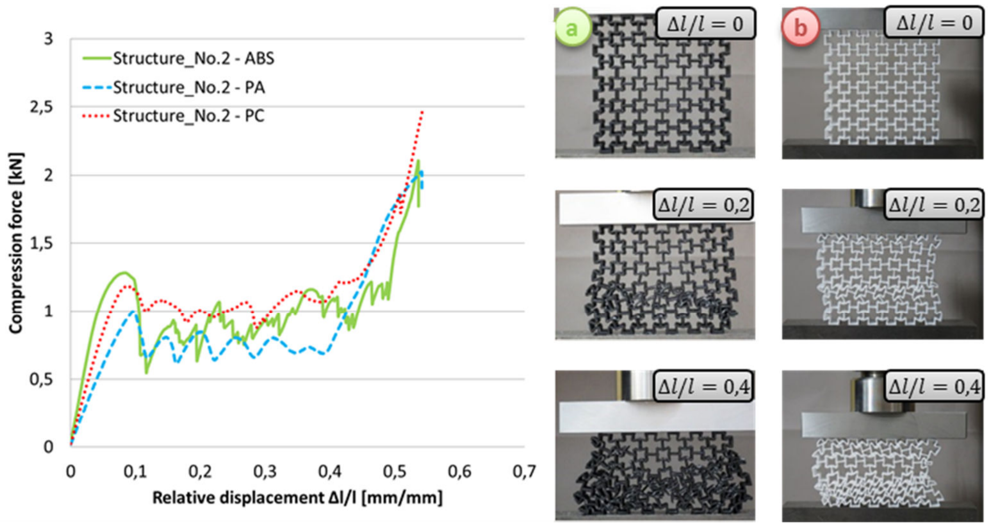

Fig. 5 - Uniaxial force-relative displacement curves for structure No.2; successive stages of structure deformation made of (a) ABS, (b) PC

The results shown in Fig. 4 and 5 represent cellular topologies with high stiffness. As it can be seen, structure under quasi-static loading tends to behave initially like solid material followed by the elastic deformation up to stress peak. The slope angle of the linear fragment of the curves depends mainly on the stiffness of the structure. After overcoming the yield strength of the structure the plateau region is reached in which the stress fluctuates. This phenomenon is caused by cracking of the structure at the exceeding point of the tensile strength of the material. Afterwards the force decreases until the whole array of the cells is collapsed and densification of the structure occurs. That process repeats subsequently for remaining cells array until the total densification occurs.

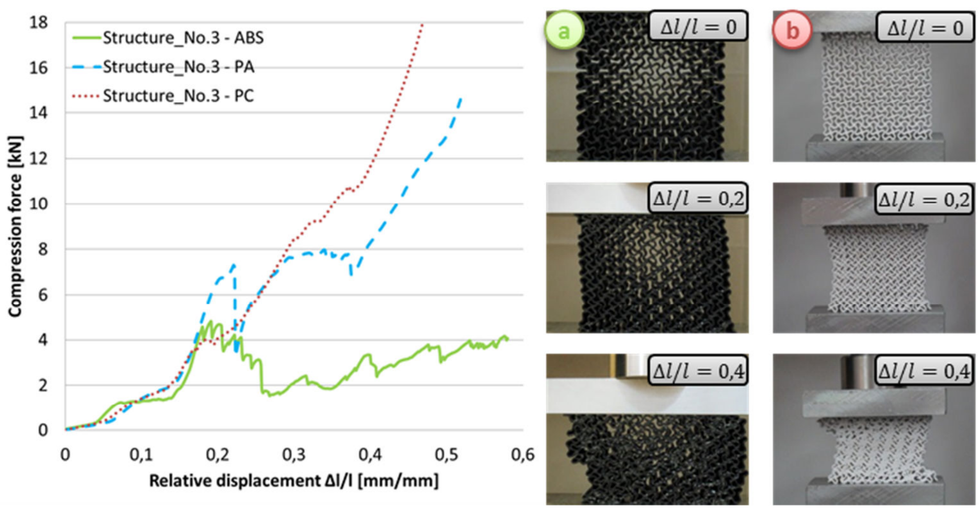

Fig. 6 - Uniaxial force-relative displacement curves for structure No.3; successive stages of structure deformation made of (a) ABS, (b) PC

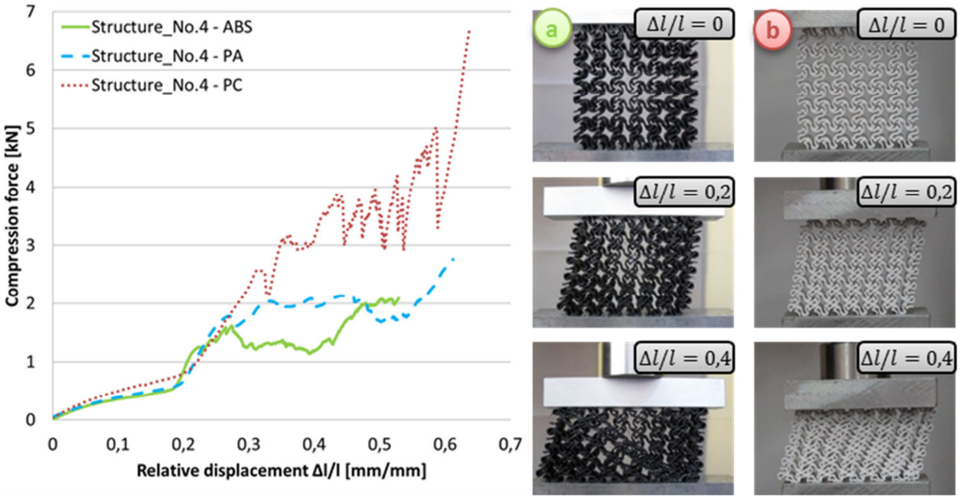

Fig. 7 - Uniaxial force-relative displacement curves for structure No.4; successive stages of structure deformation made of (a) ABS, (b) PC

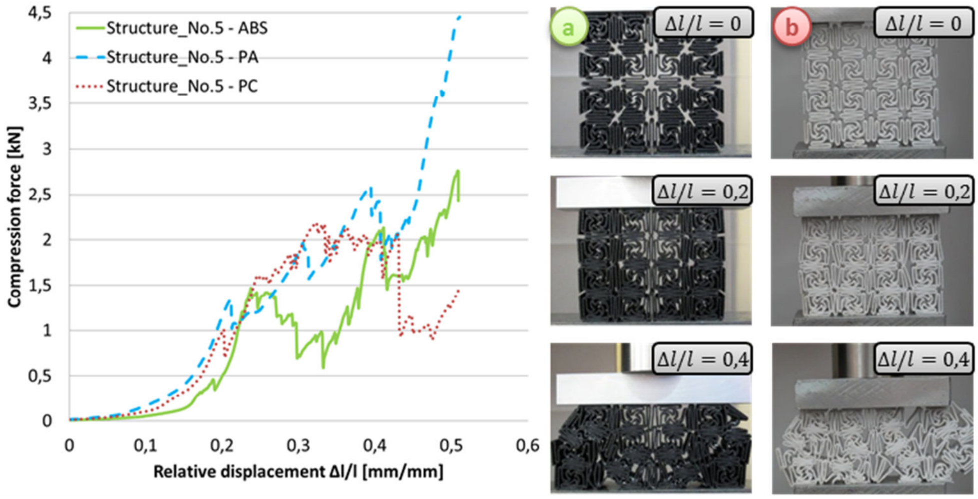

Fig. 8 - Uniaxial force-relative displacement curves for structure No.5; successive stages of structure deformation made of (a) ABS, (b) PC

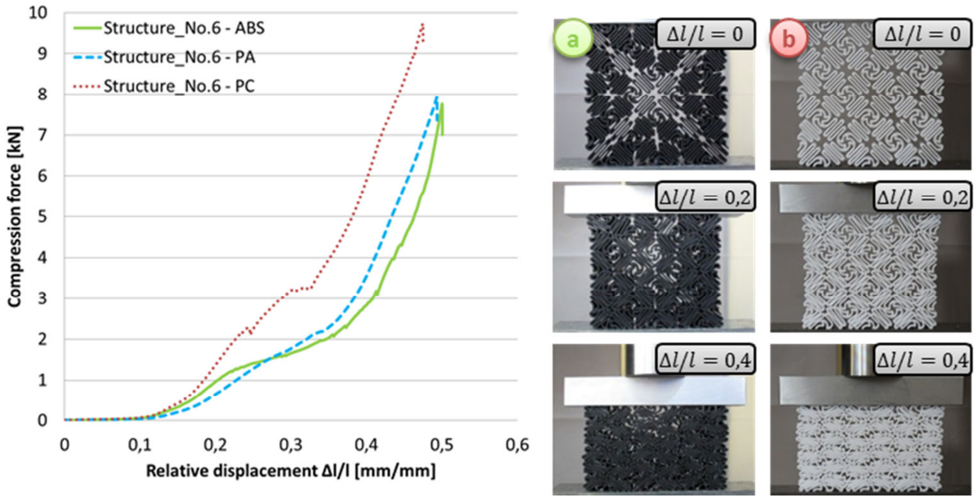

Fig. 9 - Uniaxial force-relative displacement curves for structure No.6; successive stages of structure deformation made of (a) ABS, (b) PC

The results for structures with flexible geometry are shown in Figs. 6 to 9. The first plateau occurs due to the elastic feature of the structure. Subsequently, when the stress caused by the compression force exceeds the elasticity limit of the structure, growth of the stress occurs and the second plateau is reached. Afterwards the process is similar to deformation of high stiffness structures. In turn, Figs. 8 and 9 present the specific elastic deformation of auxetic structures. It can be found that the curves for auxetic structure (Fig. 9) are smooth, i.e. the cracking do not occur. The reason for this phenomenon is that the auxetic structure deforms mostly in the elastic range. Plastic deformation of the structure material dominate at the final stage of compression, when the structure densification occurs. Taking into consideration the exponential character of plots obtained for the auxetic structure it could be stated that these type of structures maintain better crashworthiness behaviour under cycling loading conditions within the elastic range of deformation.

It is noticeable that critical stresses of the honeycomb structure (Fig. 4) compared to the other geometries are different. Honeycomb structure reaches its fractured stress value at 6 kN (ABS material), whereas the remaining structures resist to about 1.5 kN. It is caused by the fact that the honeycomb has high regularity with 120° angles and constant wall length so it deforms at the entire range and does not have a preferred direction of fracture.

From the mechanical material property point of view, ABS and PC are brittle in comparison to PA. It can be seen that the peak force changes for the ABS and PC topologies are sharp, while curves profiles for PA structures are smooth, i.e. the cohesion of the material is maintained. However, it was stated that the material cohesion was also retained for PC. In this case the strength of the PC material exceeds structure strength capacity, which leads to its folding.

Based on performed uniaxial compression tests on the regular cellular structure the plots of energy absorption capacity were obtained. Energy curves were calculated

$$E = \sum_{i=0}^{n} F_i \, x_i \tag{2}$$

where: $F(x)$ - compression force, x - compression

As discussed above, cellular structures were separated into two groups: high stiffness and flexible. The energy absorption efficiency results for the first group is shown in Fig. 10a, b, whereas the other in Fig. 10c ÷ f. The value of the absorbed energy rises up linearly with constant increment. The flexible group of material are represented by the parabolic curve for energy absorption. The process of energy absorption could be divided into two stages: non-linear at the beginning, and linear afterwards.

High strength structures compared to flexible group deform through cracks and plastic bends of the structure walls, what causes damage of the structure geometry making it unusable. In this case deformation energy of structure is dissipated by plastic deformation and fractures of structure walls. It can be concluded that, their ability to deform in the plastic range has a prevailing significance in energy dissipation. In turn, flexible structures do not dissipate energy at the initial stage of deformation (approximately up to 0.1 relative displacement). The energy dissipation takes place when the elastic limit of the structure is exceeded and the elastic - plastic deformation occurs.

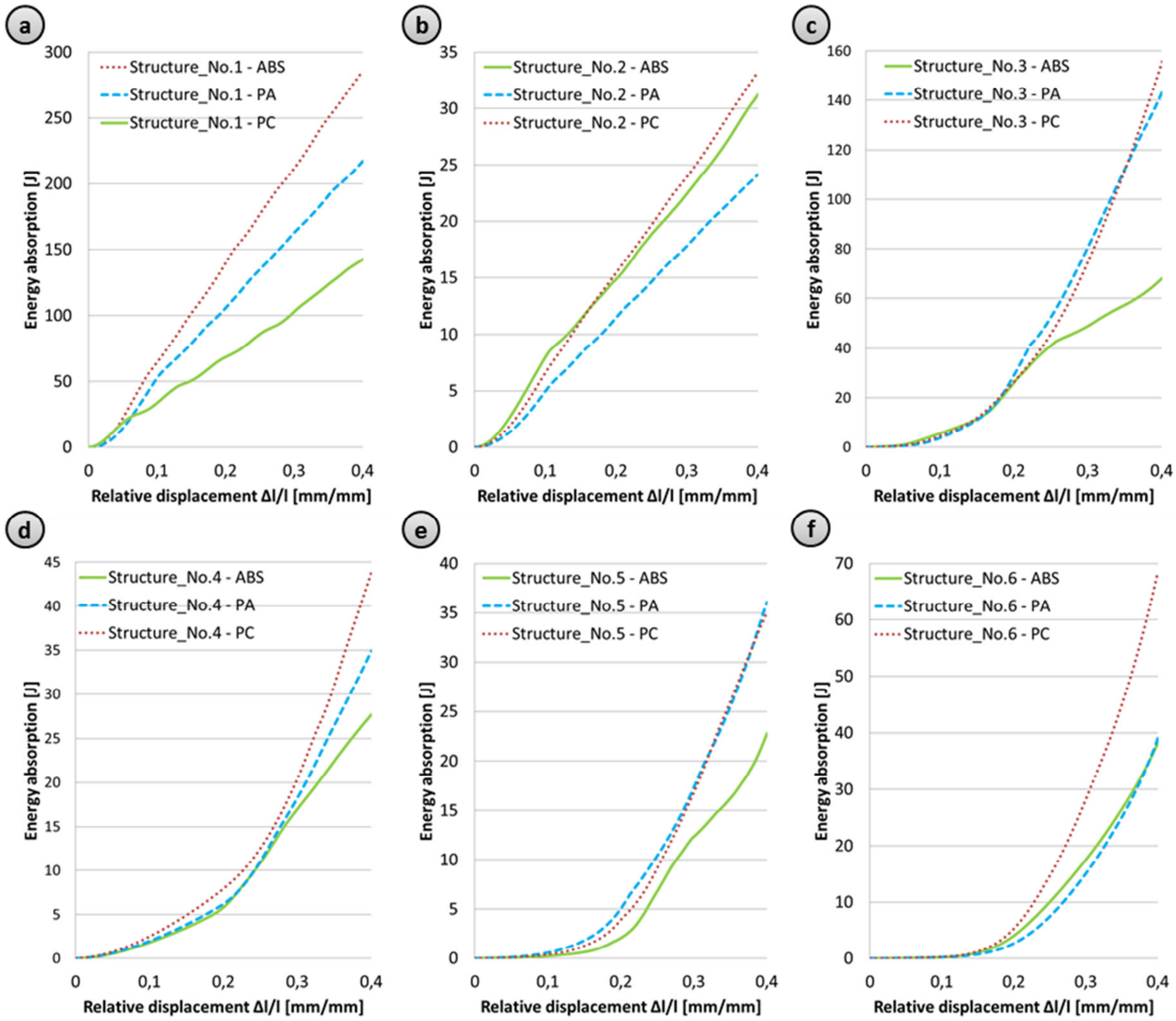

Fig. 10 - Energy absorption curves of different cellular structures and materials at 40% of deformation

Table 4 - Relative absorption energy for tested structures

Material	ABSplus	Nylon 12	PC 10
Structure No.1	473	678	**923**
Structure No.2	166	120	**174**
Structure No.3	189	382	**433**
Structure No.4	93	113	**147**
Structure No.5	62	**97**	92
Structure No.6	106	103	**189**

In order to perform comparative analysis of tested structures crashworthiness behaviour the absorption energy related to relative density was collected in Tab. 3. Considering the material issue, it is worth notice the best-behaved material is polycarbonate, which represent the highest strength. In turn, the geometry analysis shows that the topologies with high cells concentration and structure regularity show better energy dissipation ability. The best energy absorption properties are demonstrated by Honeycomb structure.

The capacity of energy absorption can also be evaluated from another perspective. For cellular materials which could be potentially used as the packaging materials (damper and body armour) the peak force during the dynamic crushing should not exceed the maximum stress of the protected item (Wangyu, 2016). From this point of view, our flexible structures seem to be suitable.

CONCLUSIONS

Presented in this paper experimental approach enables to estimate the crashworthiness behaviour of developed 2D regular cellular structures. Proposed additive manufacturing technique facilitated the process of their production. Moreover, it allowed fabricating structure specimens with different polymer materials. Owing to the conducted uniaxial compression tests the results of the structure deformation process investigation were determined. Based on them, it was possible to analyse the influence of structure topology and mechanical properties of the material on energy dissipation efficiency.

The authors found that mechanical response of regular 2D structures is mainly associated with two parameters: the strength of material applied in the manufacturing process and adopted geometrical features of the elementary cell, which define the structure properties. Based on obtained results it was found that samples with higher stiffness indicate more efficient energy absorption properties. Bending and cracking mechanisms that occurred during deformation process are the main justification of this phenomena. In turn, structures with flexible topology indicate different deformation mechanism.

The initial stage of deformation is mainly elastic and it does not result in energy absorption. This process last until the structure condenses and the bending/cracking mechanisms is observed. This phenomenon (these phenomena) is generally observed for auxetic structures. The plot of loading force versus displacement increases exponentially in these cases.

Taking into consideration the crashworthiness results of developed structure topologies the structure topology and its relative density are noticeable to be optimised. Geometrical features of the single cell should guarantee the high value of loading force necessary to exceed the structure stiffness while the mass should be minimised.

For further investigation, the authors plan to extend the material issue of metallic Ti6Al4V alloy manufactured by LENS technology and add experimental studies concerning deformation of the structures in dynamic loading condition using Split Hopkinson Pressure Bar technique.

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