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MECHANICAL RESPONSE OF ADDITIVE MANUFACTURED REGULAR CELLULAR SCTRUCTURES IN QUASI-STATIC LOADING CONDITIONS - PART II: NUMERICAL INVESTIGATIONS

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ABSTRACT

The purpose of the paper is to present a research methodology used in order to predict the mechanical response of additive manufactured regular cellular structures subjected to quasistatic loading conditions. The authors' attention was focused on a numerical approach. The proposed method of investigation allows estimating crashworthiness behaviour of regular cellular structures under loading boundary conditions of uniaxial compression. The applied methodology is based on finite element analyses using an implicit solution. During the numerical analyses, selected topologies of 2D cellular structures were investigated. The validation based on correlation between numerical and experimental results was performed at the final stage.

Keywords: regular cellular structures, finite element method, additive manufacturing, crashworthiness,

INTRODUCTION

Contemporary development in leading-edge industry branches causes a growing demand for new multifunctional materials [1,2,3,4]. Scientists and engineers, inspired by nature, pay their attention to cellular structure materials which demonstrate specific mechanical properties with respect to low density [5,6,7,8]. Over the last two decades, a great number of studies have been undertaken in order to improve methods of their manufacturing [9,10,11]. Owing to additional studies on cellular materials [12], their mechanical properties and potential fields of application have been determined [13,14, 15, 16, 17,18,19]. Based on the conducted literature review, it could be stated that one of the significant group of cellular materials are regular 2D [6, 7, 8, 20] and 3D structures [13, 21, 22]. The recently observed increase of interest in this group of material is caused by new available methods their production based on additive manufacturing [23, 24, 25]. Application of various metal or ceramic powders [9, 11, 21, 22, 27] as well as different types of polymers [6] and resins [10] allows for determination of a desirable combination of material properties not possible to achieve in comparison to solid materials. An additional advantage of additive manufacturing is the design freedom it enables [24, 25]. The currently available methods allow building regular cellular structures with a complex topology tailored to specific applications. In recent years, this group of materials has begun to be used in many demanding branches of industry such as: automotive, aviation, railway, chemical and civil engineering as well as bioengineering [18, 24, 25, 28, 29, 30].

Moreover, regular cellular structure materials could be potentially implemented in military applications, especially in development of passive protective systems [31, 32].

An interdisciplinary scientific group from 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 (*Laser Engineering Net Shaping*) system in static and dynamic loading conditions. This paper presents the results of preliminary investigations performed in order to verify the correctness of the proposed numerical approach. During this stage of investigation, the concurrent engineering methodology was used.

RESEARCH METHODOLOGY

Estimation of the relationship between a cellular topology and crashworthiness behaviour of the cellular structure is potentially possible owing to analytical [8, 20], numerical [10, 11, 12, 34, 27] and experimental [6, 9, 21, 22, 29, 33] approaches. According to the results presented in a considerable number of papers, the analytical methodology could be implemented in cases where the topology of a cell is simple (e.g. circular, rectangular, triangle, hexagon) [9, 11, 12, 13]. Based on the experimental approach [9, 11, 14, 15, 21, 22, 33], it is possible to obtain accurate results, however, this method of investigation is time and cost consuming, especially when metal or ceramic powder is used in a manufacturing process of cellular structure samples. Considering both advantages and drawbacks of the numerical approach, it could be stated that this method is versatile and gives the possibility to perform studies for a complex cellular topology [6, 12, 20, 27, 34]. Moreover, it allows performing computer analyses, under both static and dynamic loading conditions. Nevertheless, it is crucial to verify the correctness of the proposed numerical model, accuracy of the applied constitutive model as well as the implemented contact model.

Taking into consideration the above mentioned reasons, the authors of the paper proposed numerical and experimental approaches in order to determine the crashworthiness of 2D regular cellular structures. The main idea of the applied methodology is presented in Fig.1.

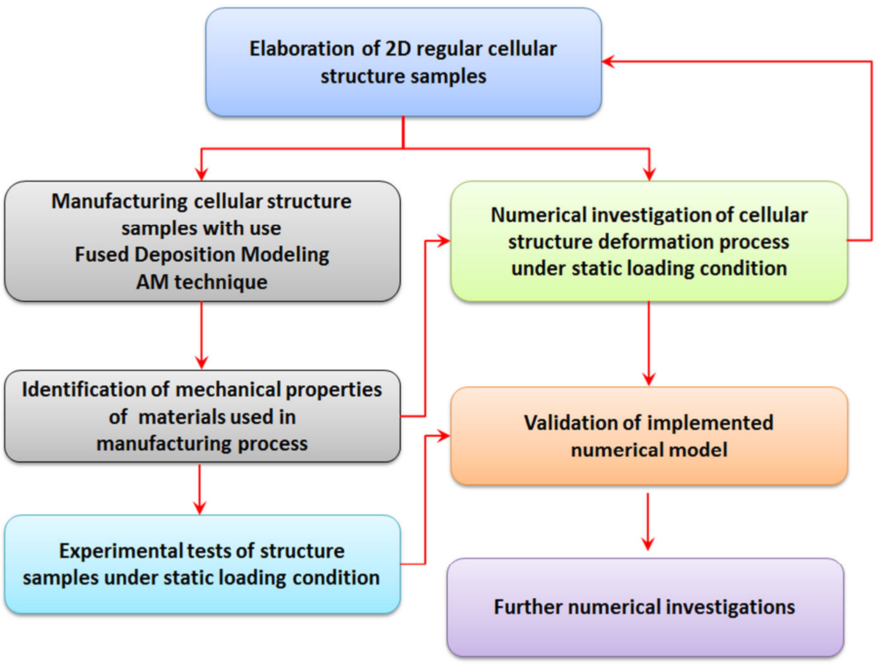

Fig. 1 - The scheme of the main stages of conducted investigations

The first stage of the carried out investigation was associated with a designing process in one of the commercial CAD systems. The main assumption undertaken during this task refers to structure dimensions. They were designed as 80x80x20 mm cuboids with 1 mm wall thickness. The size of a structure sample was determined by a number of cells and technological possibilities of the implemented additive manufacturing system. Fig.2 presents a view of initially developed structure topologies. In order to extend the range of the carried out studies, two groups of samples, taking into account auxetics, were examined. The estimated values of relative density for the developed structures was in the range of $0.3<\rho_r<0.4$.

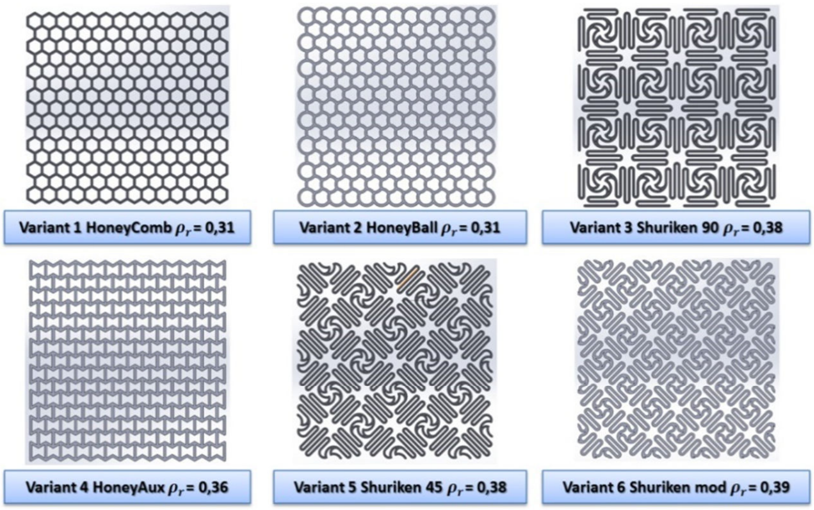

Fig. 2 - Samples of structure topologies applied during investigations

EXPERIMENTAL STUDIES OF STRUCTURE DEFORMATION PROCESS

Preliminary investigations conducted in order to predict a cellular structure deformation process were carried out with the experimental approach. For this reason, samples with different topologies were prepared using one of the commonly available additive manufacturing FDM *(Fused Depisition Modeling)* technique [24, 25]. The material used during this process was ABS*plus* (*Acrylonitrile Butadiene Styrene*) [35, 36]. This method has many advantages. First of all it is time and cost effective and enables applying a wide variety of commercially available materials. Moreover, the FDM technique allows obtaining a high accuracy of manufactured objects. Fig.3 presents the specimens of cellular structures manufactured by the FDM method. They were used for uniaxial compression tests performed to predict the mechanical response of cellular structures under quasi-static loading conditions.

The additional quality inspection of the manufactured structures was preceded the experimental investigations. The industrial computer microtomography Metrology XT H 255 device was used to acquire digital images of structures including their interior. Based on these data, it was possible to verify a presence of structural imperfections which could initiate a cracking process. Owing to the results of image inspection, the presence of some material imperfection was stated. Considering their shape, size, as well as location, it was found that they do not affect an initiation of cracking process. The subsequent stage of the conducted inspection was to control the structures geometric accuracy. Based on the results of the images reconstruction process, STL format file containing the three-dimensional surface' model of cellular structures were obtained. They were used to analyse the accuracy tolerance of the applied additive manufacturing technique (Fig.4). The average dimensional tolerance determined based on the comparison of the reconstructed and CAD models was in the range of ± 0.1 mm. The obtained results of geometrical accuracy inspection enabled the authors to assume that the CAD models of cellular structures without any dimensional changes can be used in further numerical investigations.

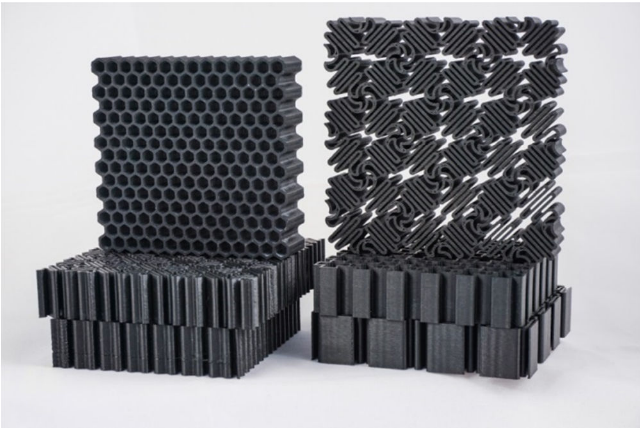

Fig. 3 - Specimens of the cellular structures manufactured by FDM method

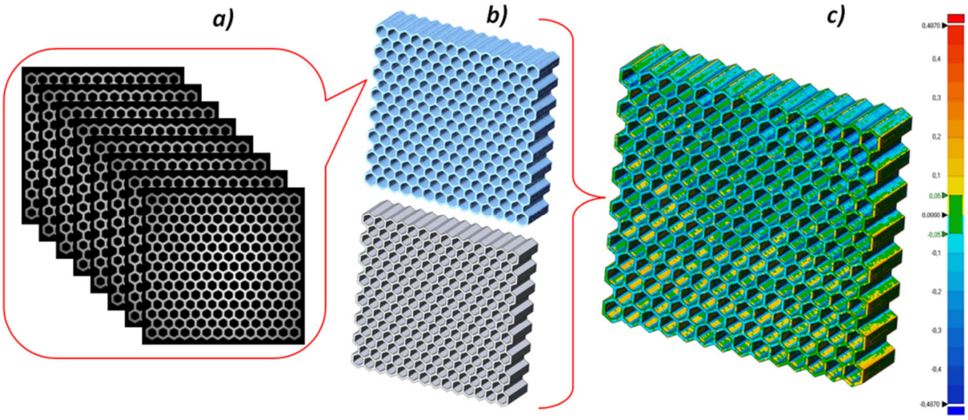

Fig. 4 - The scheme of dimensional accuracy inspection procedure:
a)- sequence of images acquired by computer microtomography, b) - model obtained after images reconstruction process (upper) and CAD model (lower), c) - comparison between native and reconstructed models

The experimental investigations of the cellular structures deformation process were performed under the uniaxial quasi-static loading boundary conditions at the velocity of 1 mm/s. The main goal of this approach was to obtain data necessary to validate the correctness of numerical models described in this paper. Two of the proposed structure topologies were used to conduct the compression tests with application of MTS Criterion C45 strength machine. Due to the geometrical features of structures, the authors proposed analysis of the specimens deformation process in the orientation presented in Figs. 5÷6. Moreover, these figures contain the plots of the registered loading force versus the displacement of crosshead. The results of the tests presented in Fig.5 demonstrate the deformation process of a honeycomb structure topology. In this case, the cracking mechanism is the main issue responsible for the progressive destruction of the structure. Moreover, it affects the loading force history presented on the chart. The next diagram (Fig.6) presents the process of deformation registered for an auxetic structure. In this case, it is possible to observe densification of the structure during its compression. The cracking mechanism arrived just at the final stage of the compression. Based on the plot of the loading force, specific features of the auxetic structure were proved.

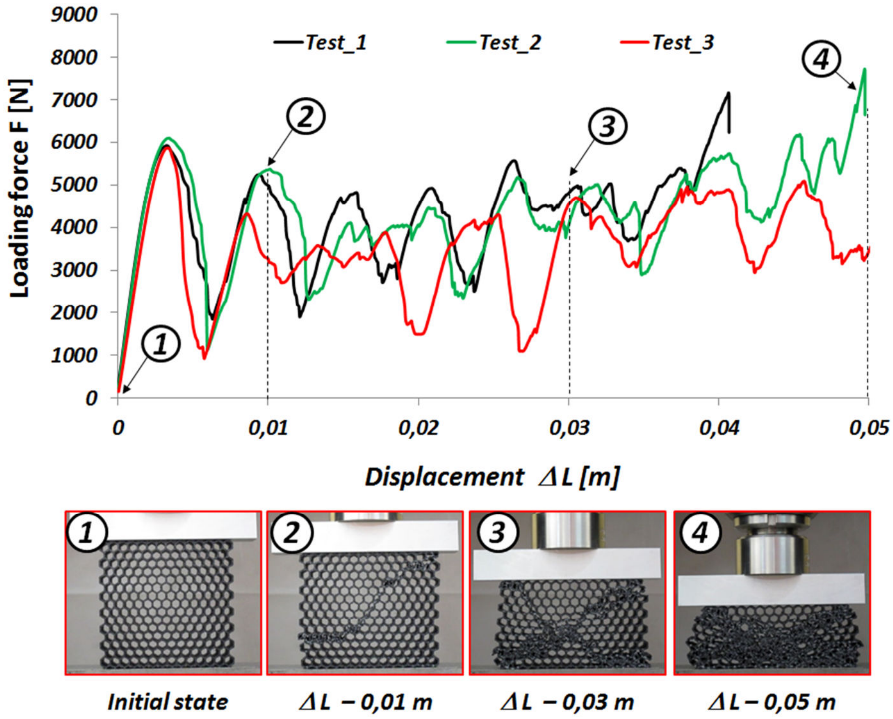

Fig. 5 - The loading force plot registered for a honeycomb topology structure and selected images illustrated its compression process

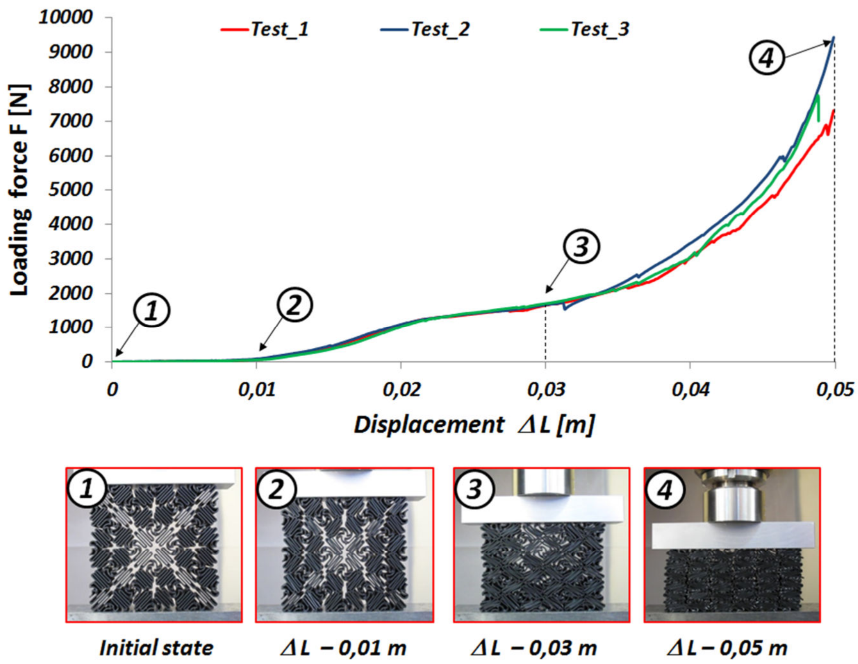

Fig. 6 - The loading force plot registered for an auxetic topology structure and selected images illustrated its compression process

NUMERICAL STUDIES OF STRUCTURE DEFORMATION PROCESS

Finite element analyses with an implicit integration scheme implemented in LS-Dyna code [37] were used at this stage of investigations. Based on the developed topologies of cellular structures, proper numerical models were elaborated. Owing to these models, it was possible to predict the crashworthiness behaviour of the analysed structures subjected to quasi-static load. Numerical simulations were conducted under assumptions which reflected uniaxial compression test conditions. Fig.7 presents an exemplary numerical model developed to perform numerical simulations of such a process.

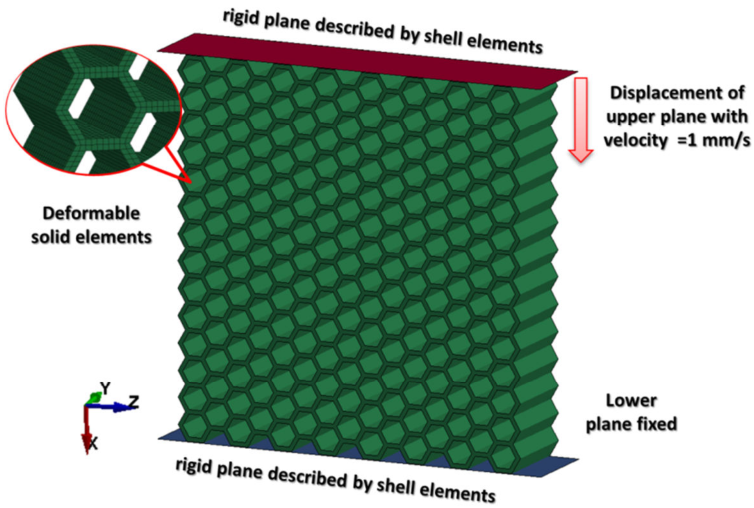

Fig. 7 - Initial boundary conditions defined during computer simulations

The implemented model consists of three parts: a cellular structure described by 8-node deformable solid elements and two rigid planes described by 4-node shell elements. The upper plane has one degree of freedom, a possibility of motion in 0X direction, the other one is defined as a fixed one. The applied displacement of the upper plane at a velocity of 1 mm/s enables prescribing the load boundary conditions. Mutual interaction between the structure and planes is determined by proper contact definitions. The first one AUTOMATIC_SURFACE_TO_SURFACE_MORTAR is established to define the relations between structure and planes, the other one AUTOMATIC_SINGLE_SURFACE_MORTAR allows prescribing the self-interaction between the structure cells [37].

The further stage of model pre-processing was associated with a description of material properties. A plastic-kinematic material model was used to define the mechanical properties of the cellular structure material. Non-deformable properties of planes were determined using a rigid material model.

Based on the literature review, the authors found a few different characteristics describing mechanical properties of ABSplus material [35, 36], which indicates that proper material parameters identification is fundamental to obtain accurate numerical results. For this purpose, additional studies on material parameters identification were undertaken. They were realized both experimentally and numerically through uniaxial tensile tests at a velocity of 1 mm/s. The experimental tests were carried out with the use of standard tensile test specimens manufactured with FDM technique. Application of different orientations of the specimen model during the manufacturing process enabled the authors to verify orthotropic mechanical properties of the material. Taking into consideration the fact that the analysed structures are two-dimensional, it was possible to make an assumption that there is no need to define the orthotropic material properties. The subsequent stage of material parameters identification was realized numerically. The computer simulations were carried out in LS-Dyna code with the same initial-boundary conditions. The plastic-kinematic material definition was used to define the material properties. The process of material parameters identification depended on modification of material properties such as: Young's modulus, Poisson ratio, yield stress, tangent modulus in order to adjust the convergence of force versus displacement plots (Fig.8). Based on the conducted attempts, the parameters of material properties were determined. They are presented in Tab.1.

Table 1 - The plastic-kinematic parameters determined for ABSplus material

Mass density [m/kg^3]	**Young's modulus [Pa]**	**Poisson's ratio**	**Yield stress [Pa]**	**Tangent modulus [Pa]**	**Hardening parameter**	**Strain rate parameter**
971	$2.1 \cdot 10^9$	0.35	$30 \cdot 10^6$	$22 \cdot 10^6$	0	0

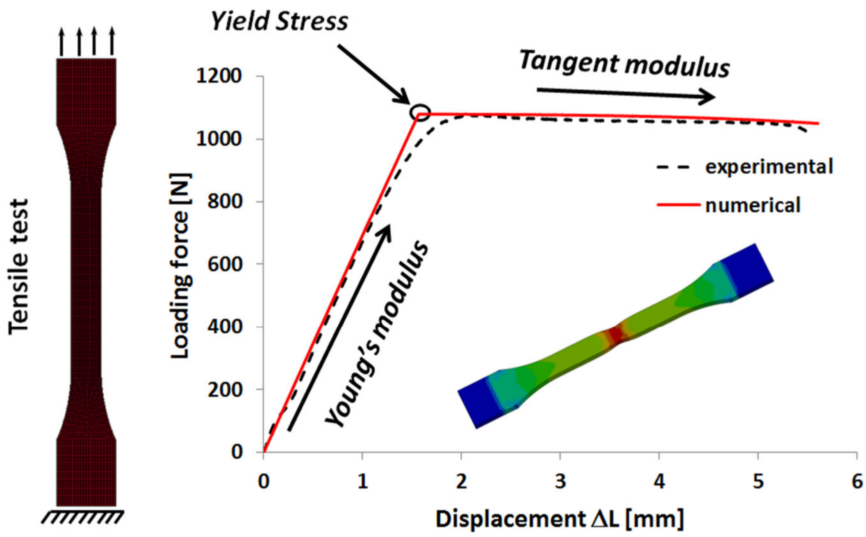

Fig. 8 - The results of mechanical properties identification of ABS material

RESULTS OF NUMERICAL INVESTIGATIONS

Based on the applied numerical model and the adopted initial boundary conditions, the computer simulations of regular cellular structure deformation were performed. The exemplary topologies presented in Fig.2 were investigated. The first referential topology was a classic honeycomb. The results achieved for this case were presented in Figs.9÷10. The differences between experimental and numerical results (Fig.9) are caused by the adopted material definition without consideration of the failure criteria for the material model as well as eroding of elements. However, the results related to energy absorption, presented in Fig. 10, indicate a good agreement between numerical and experimental approaches.

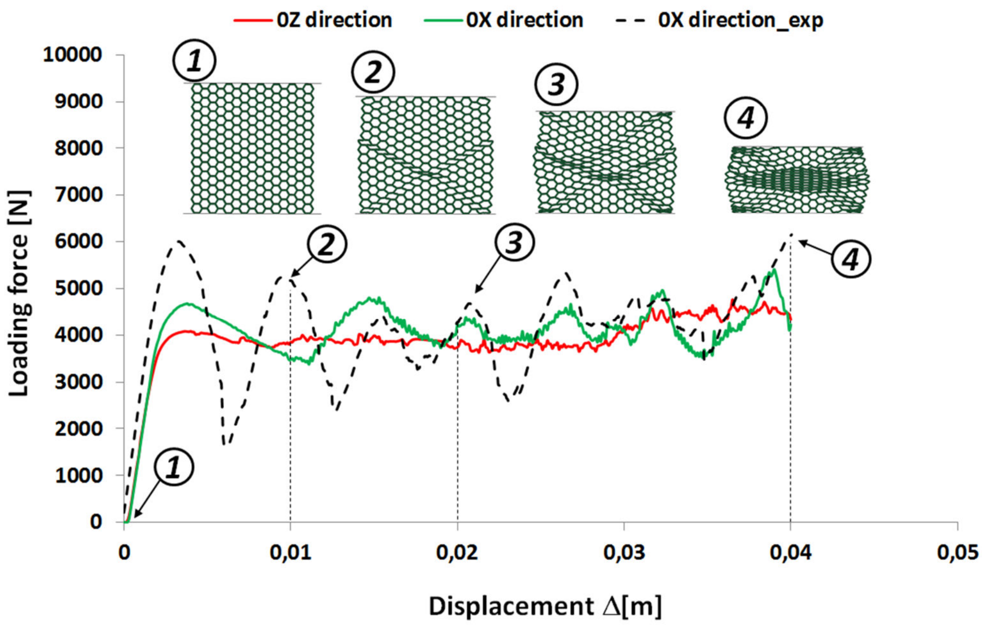

Fig. 9 - The compression curves obtained for a honeycomb topology

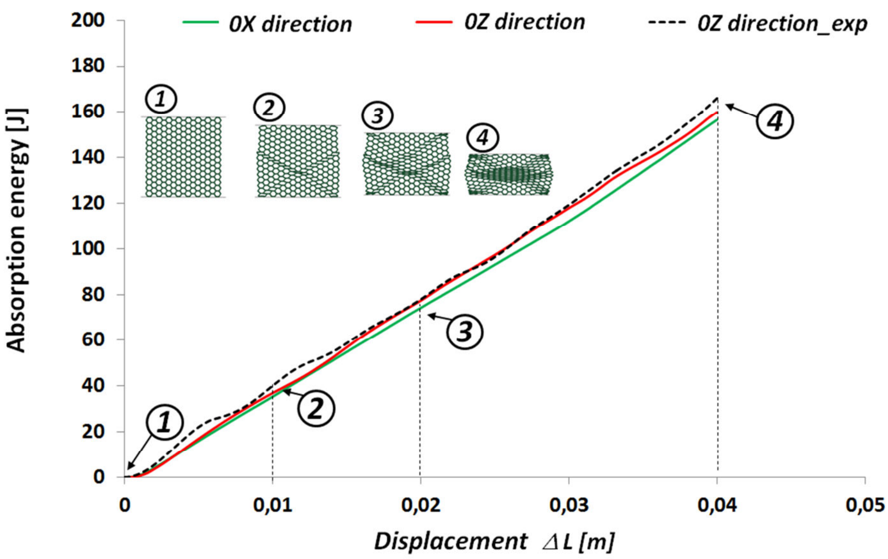

Fig. 10 - The energy absorption curves obtained for a honeycomb topology structure

Another numerical analyse was performed to verify the correctness of the auxetic structure topology. The proposed topology of the cell consists of the spring linking elements which are twisted under compression. It results in the fact that the cracking mechanism appears in the final stage of the deformation process. High ability to structure densification enables obtaining a high value of absorption energy in the final stage. These results are presented in Figs.11÷12. Based on that, it was found out that the process of structure deformation could be divided into two stages: the first one is associated with elastic deformation whereas the other with plastic deformation. The presented results of numerical studies indicate a good convergence with the experimental data. Due to this reason, the numerical model was validated positively and is possible to be used in further investigations.

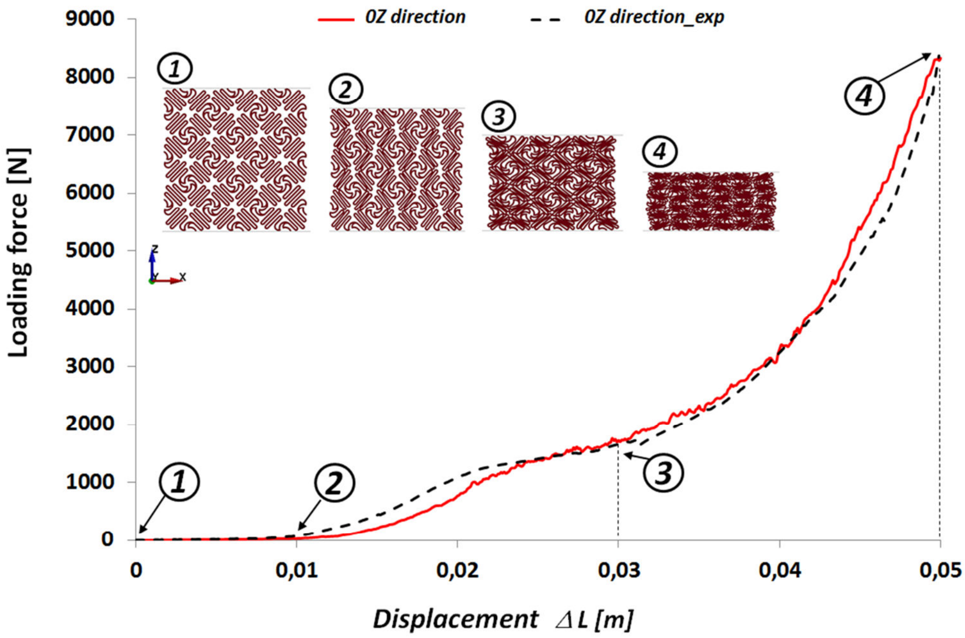

Fig. 11 - The compression curves obtained for an auxetic topology structure

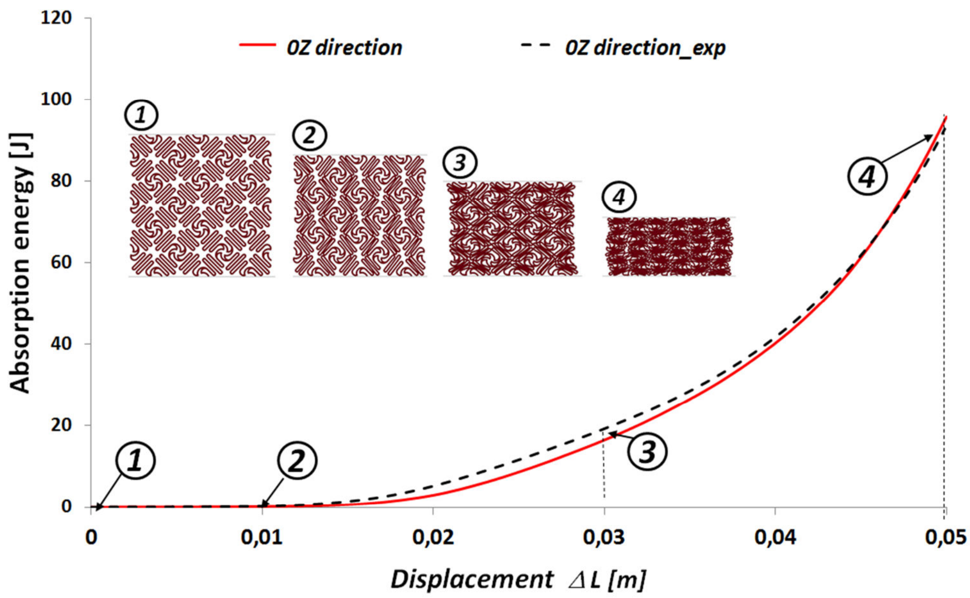

Fig. 12 - The energy absorption curves obtained for an auxetic topology structure

The other cellular topology based on honeycomb structure was the next subject of numerical investigation (Fig.2, variant - 2). The authors proposed some geometrical modifications in order to minimize the effects of a cracking mechanism during the deformation process. The results of the conducted computer simulation are presented in Figs.13÷14. Curves illustrating the loading force history are convergent. However, the deformation process realized in 0X direction is more smooth in comparison to the honeycomb structure. Regardless of the loading force direction, this topology indicates similar mechanical properties.

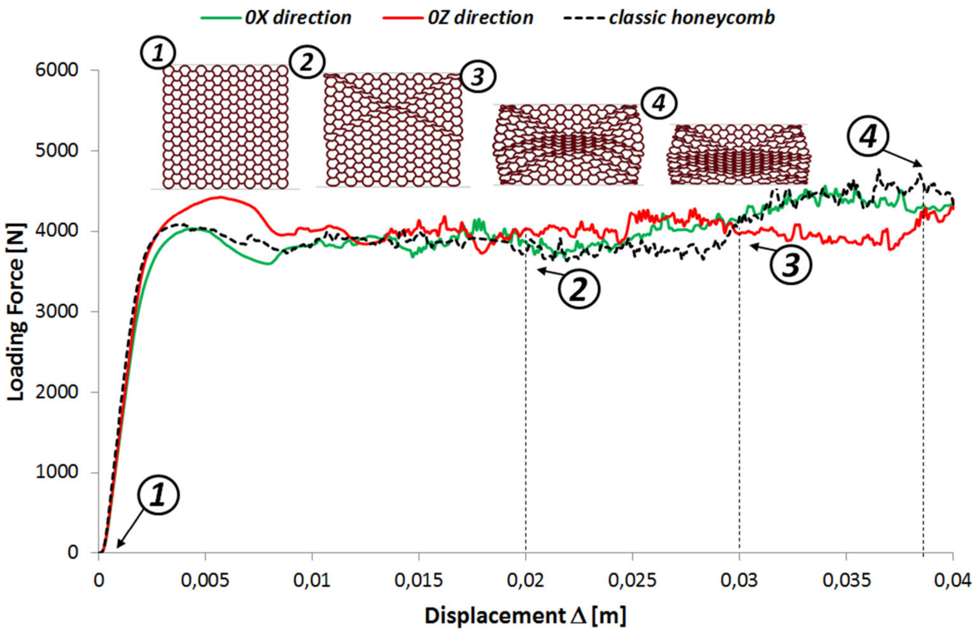

Fig. 13 - The compression curves obtained for variant 2 topology

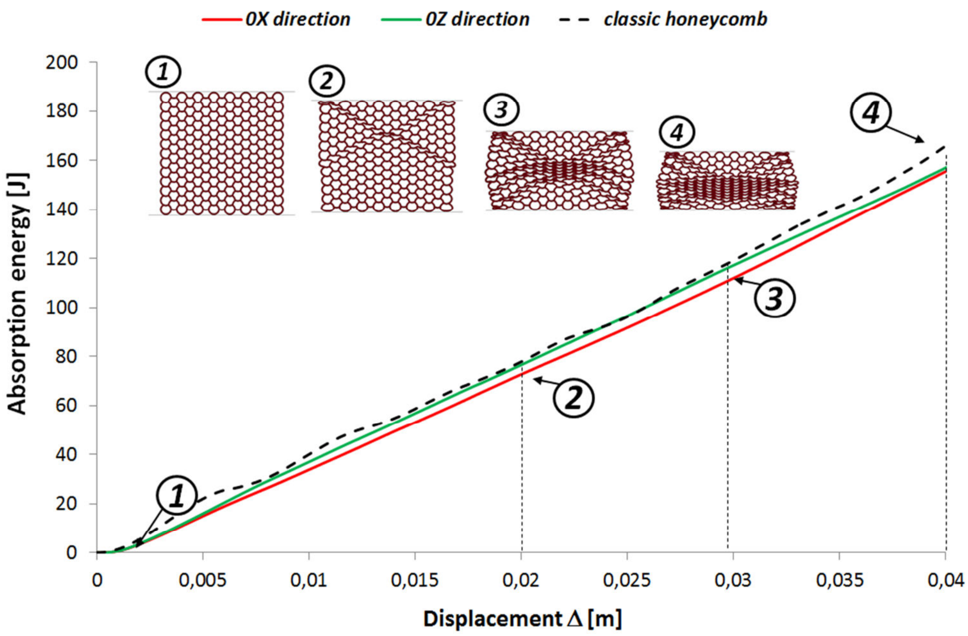

Fig. 14 - The absorption energy curves obtained for variant 2 topology

The third topology subjected to numerical investigations was developed on the basis of the above presented auxetic structure. The adopted geometrical modifications caused considerable changes in the deformation process of the structure. The perpendicular direction of the loading force action on spring elements of the cells initiates a buckling and cracking mechanisms. Based on Figs.15÷16, it was observed that modification of the cells orientation, when the same relative density was considered, caused an appreciable decrease of structure ability to energy absorption. Moreover, lower ability to densification during the deformation process is the main reason leading to decline in crashworthiness capabilities of the structure. Due to a tendency of the structure to buckling and cracking, additional experimental tests under uniaxial compression conditions were performed. The recorded data were compared with the results of numerical investigations. Deprivation of failure criteria for the adopted material model results in discrepancies in the initial stage of plastic structure deformation.

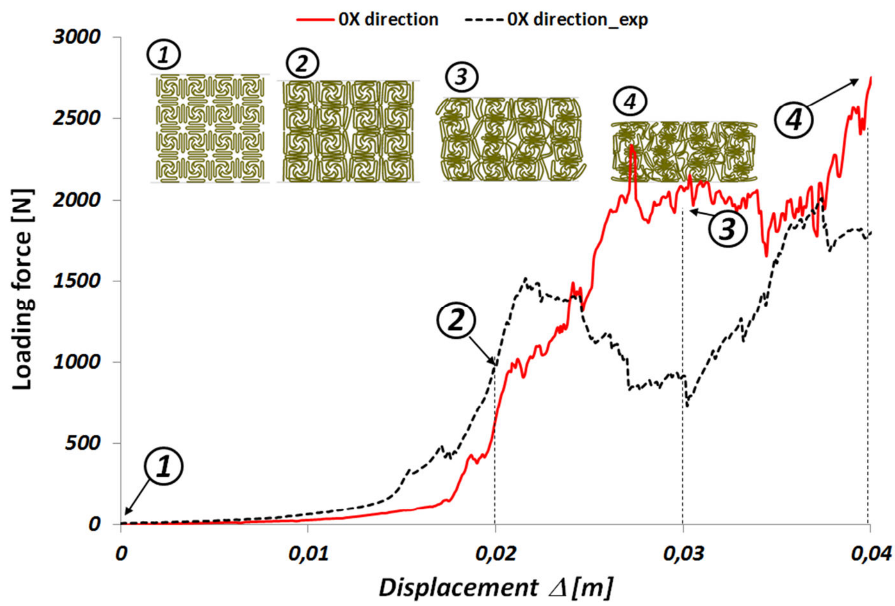

Fig. 15 - The compression curves obtained for variant 3 topology

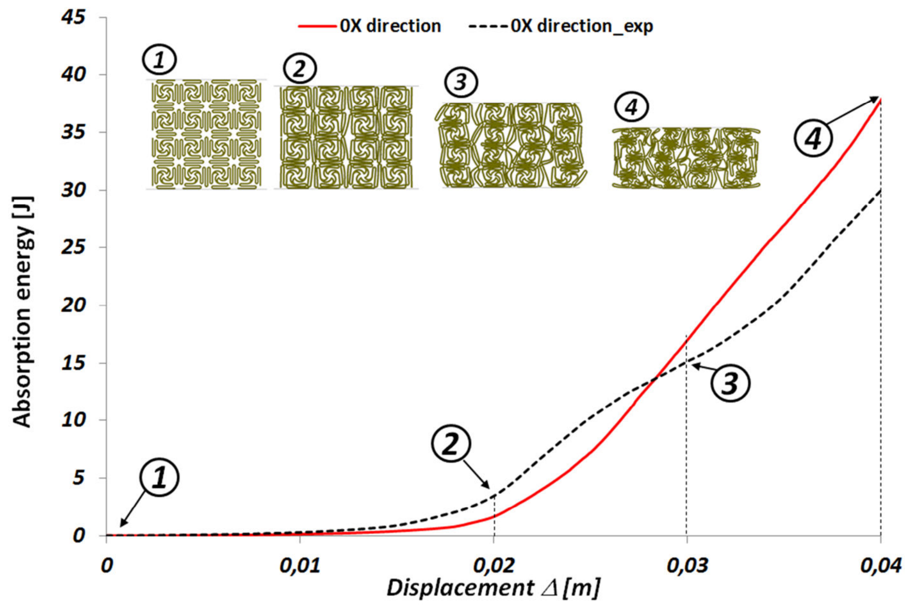

Fig. 16 - The energy absorption curves obtained for variant 3 topology

The next topology used in numerical investigations was an auxetic structure (Fig.2 variant - 4) developed on the basis of a classic honeycomb. Modification introduced in the structure topology resulted in an increase in the relative density. The results of computer simulations obtained in this case study are presented in Figs.17÷18. Additionally, they were compared with the classic honeycomb data in order to evaluate efficiency of the proposed modifications. It was noticed that the main discrepancy between both topologies is caused by a buckling effect. Before buckling point. (marker No.3) both curves (the red and black dotted) are in a good convergence, afterwards the longitudinal stability is disturbed and the decline in a force value was observed. The further increase in a loading force value is caused by the densification process (marker No.4). The other 0Z direction of the loading force action indicates a high tendency to buckling. This sensitivity of the structure topology leads to an appreciable oscillation of the loading force value.

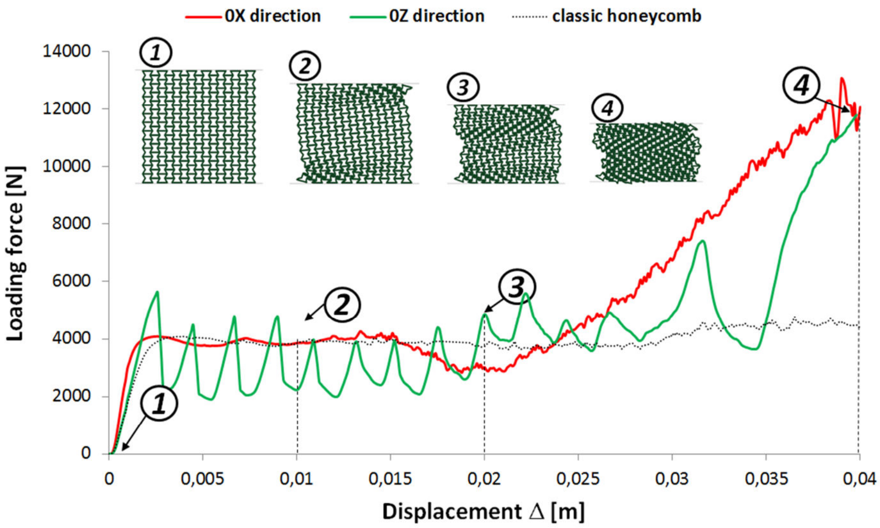

Fig. 17 - The compression curves obtained for variant 4 topology

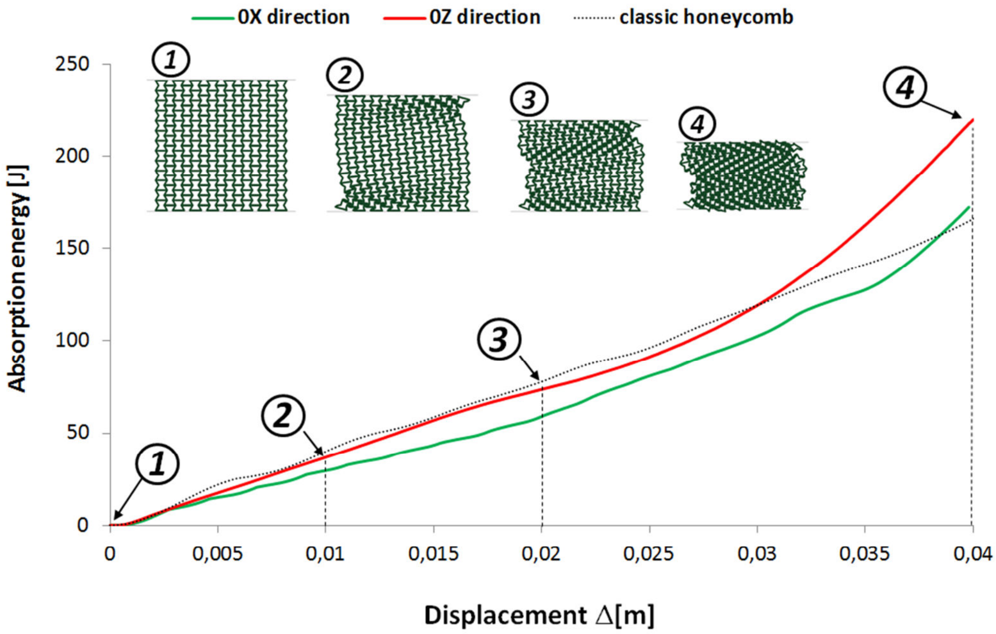

Fig. 18 - The energy absorption curves obtained for variant 4 topology

The last topology presented in this paper was adopted on the auxetic structure (Figs. 11÷12). The modifications applied in cell geometry were associated with an increase in the stiffness behaviour (Fig.2 - variant 6). The number of spring links were limited to fulfil this assumption. Based on the obtained numerical results, it was possible to notice that the structure indicates a higher value of energy absorption in comparison to the preliminary developed auxetic structure. The results of computer simulations are presented in Figs.19÷20. The character of structure deformation is similar to the original solution. The proposed topology redesign allowed increasing the structure crashworthiness.

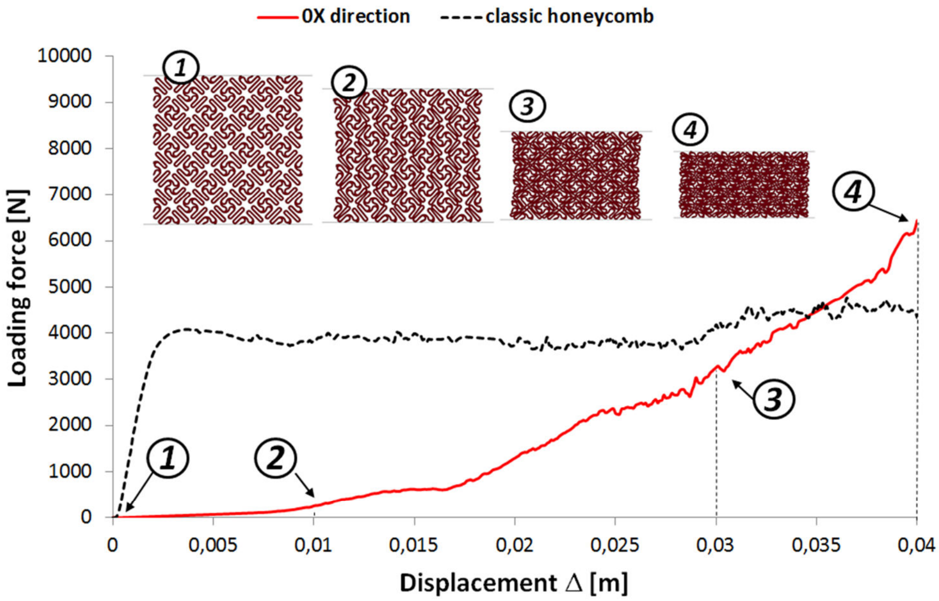

Fig. 19 - The compression curves obtained for variant 6 topology

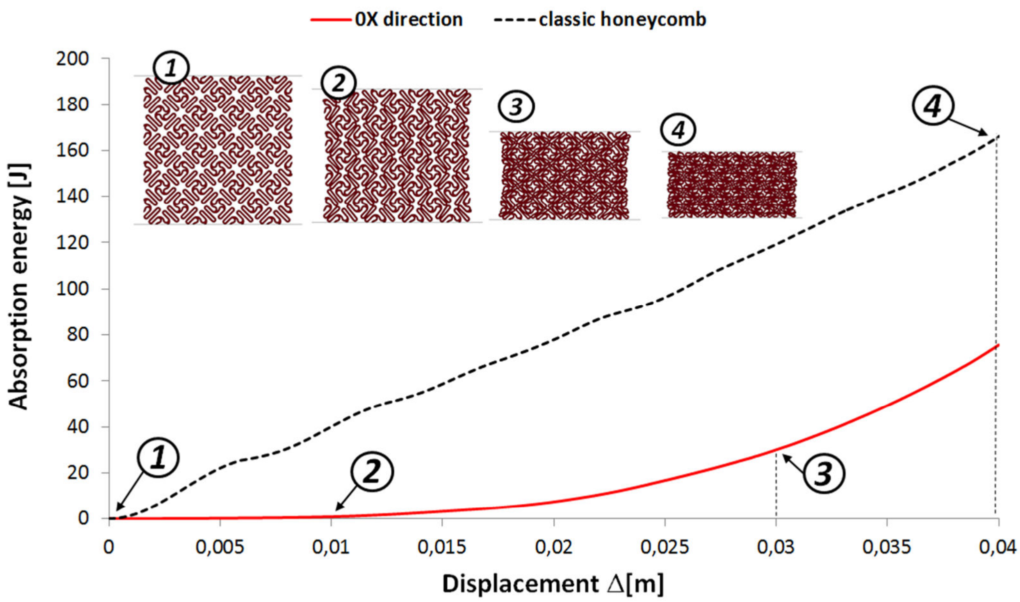

Fig. 20 - The energy absorption curves obtained for variant 6 topology

CONCLUSIONS

Numerical investigations of the regular cellular structure deformation process allowed the authors to predict the mechanical response of the material structure during compression tests under quasi-static loading. Various types of structure topologies, including auxetics, were used in these studies. The honeycomb topology was a starting structure and the additional topologies were proposed based on it. The assumption undertaken during design studies allowed easy and fast manufacturing the specimens of structures. The applied additive manufacturing technique facilitated the process of their production. The structure specimens were used to carry out additional experimental tests. The obtained data allowed performing validation of the proposed numerical approach. High convergence between the results indicates the correctness of the adopted numerical model, applied material and contact definitions. However, it is possible to increase the accuracy of the numerical approach based on implementation of a more sophisticated elements formulation (e.g. meshless models) as well as additional failure material criteria.

According to the obtained results, it was noticed that the honeycomb topology indicates high crashworthiness properties. Nevertheless, based on topology modification it is possible to minimize the detrimental effects of a cracking mechanism which decreases the crashworthiness capacity. The authors suggest implementation of additional corner fillets in order to reduce the stress concentration during deformation process.

Taking into consideration the mechanical response of auxetic structures under compression boundary conditions their susceptibility to densification was observed. This phenomena causes an exponential increase in the loading force. The destructive effects of the cracking mechanism appeared at the final stage of the deformation process.

Both a numerical approach and the obtained results presented in the paper have an preliminary character. The further investigations concerning the crashworthiness behaviours of regular cellular structures will be extended. The advanced additive manufacturing LENS technique will be used in order to build the structure samples. The experimental studies will be realized with consideration to the strain rate effects under dynamic loading conditions. The other elements formulations or meshless methods and additional failure criteria will be tested in a further numerical approach. The numerical simulations will be carried out in order to determine the strain rate effect on the structural response. Application of additional optimisation procedures will enable improving the geometrical features of the proposed topologies.

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REFERENCES

[1]-Evans, A. G., Hutchinson, J. W., Fleck, N. A., Ashby, M. F., & Wadley, H. N. G. (2001). The topological design of multifunctional cellular metals. Progress in Materials Science, 46(3-4), 309-327

[2]-Goodship, V., Middleton, B., Cherrington, R., & Wood, B. M. (2016). Chapter 5 Multifunctionality in Additive Manufacturing. Design and Manufacture of Plastic Components for Multifunctionality.

[3]-Ferreira, A. D. B. L., Nóvoa, P. R. O., & Marques, A. T. (2016). Multifunctional Material Systems: A state-of-the-art review. Composite Structures, 151, 3-35.

[4]-Gibson, R. F. (2010). A review of recent research on mechanics of multifunctional composite materials and structures. Composite Structures, 92(12), 2793-2810.

[5]-Gibson, L., & Ashby, M. (1988). Cellular Materials: Structure and Properties.

[6]-Ma, Q., Cheng, H., Jang, K. I., Luan, H., Hwang, K. C., Rogers, J. A., Zhang, Y. (2016) A nonlinear mechanics model of bio-inspired hierarchical lattice materials consisting of horseshoe microstructures. Journal of the Mechanics and Physics of Solids, 90, 179-202.

[7]-Rafsanjani, A., & Pasini, D. (2016). Bistable auxetic mechanical metamaterials inspired by ancient geometric motifs. Extreme Mechanics Letters, 9, 291-296.

[8]-Eidini, M. (2016). Zigzag-base folded sheet cellular mechanical metamaterials. Extreme Mechanics Letters, 6, 96-102.

[9]-Yan, C., Hao, L., Hussein, A., & Raymont, D. (2012). Evaluations of cellular lattice structures manufactured using selective laser melting. International Journal of Machine Tools and Manufacture, 62, 32-38.

[10]-Zhou, S., Cadman, J., Chen, Y., Li, W., Xie, Y. M., Huang, X., Li, Q. (2012). Design and fabrication of biphasic cellular materials with transport properties - A modified bidirectional evolutionary structural optimization procedure and MATLAB program. International Journal of Heat and Mass Transfer, 55(25-26), 8149-8162.

[11]-Campanelli, S. L., Contuzzi, N., Ludovico, A. D., Caiazzo, F., Cardaropoli, F., & Sergi, V. (2014). Manufacturing and characterization of Ti6Al4V lattice components manufactured by selective laser melting. Materials, 7(6), 4803-4822.

[12]-Tantikom, K., & Aizawa, T. (2005). Compressive Deformation Simulation of Regularly Cell-Structured Materials with Various Column Connectivity. Materials Transactions, 46(6), 1154-1160.

[13]-Babaee, S., Jahromi, B. H., Ajdari, A., Nayeb-Hashemi, H., & Vaziri, A. (2012). Mechanical properties of open-cell rhombic dodecahedron cellular structures. Acta Materialia, 60(6-7), 2873-2885.

[14]-D. Prall, R.S. Lakes, (1997). Properites of a chiral honeycombe with a Poisson's ratio of - 1, Int. J. Mech. Sci., Vol.39, No 3, 305-314, 1997

[15]-Nemat-Nasser, S., Kang, W. J., McGee, J. D., Guo, W. G., & Isaacs, J. B. (2007). Experimental investigation of energy-absorption characteristics of components of sandwich structures. International Journal of Impact Engineering, 34(6), 1119-1146.

[16]-Restrepo, D., Mankame, N. D., & Zavattieri, P. D. (2015). Phase transforming cellular materials. Extreme Mechanics Letters, 4, 52-60.

[17]-Dubinsky, A., & Elperin, T. (2006). Mechanics of Materials and Structures. Materials and Structures, 1(September).

[18]-Stephani, G., Andersen, O., Quadbeck, P., & Kieback, B. (2010). Cellular metals for functional applications - An overview. Proceedings of the World Powder Metallurgy Congress and Exhibition,

[19]-Scarpa, F., Blain, S., Lew, T., Perrott, D., Ruzzene, M., & Yates, J. R. (2007). Elastic buckling of hexagonal chiral cell honeycombs. Composites Part A: Applied Science and Manufacturing, 38(2), 280-289.

[20]-Roberts, A. P., & Garboczi, E. J. (2002). Elastic properties of model random three-dimensional open- cell solid, 50(March 2016), 33-55.

[21]-Yan, C., Hao, L., Hussein, A., Young, P., & Raymont, D. (2014). Advanced lightweight 316L stainless steel cellular lattice structures fabricated via selective laser melting. Materials and Design, 55, 533-541

[22]-Leary, M., Mazur, M., Elambasseril, J., McMillan, M., Chirent, T., Sun, Y., Brandt, M. (2016). Selective laser melting (SLM) of AlSi12Mg lattice structures. Materials and Design, 98, 344-357.

[23]-Goodship, V., Middleton, B., Cherrington, R., & Wood, B. M. (2016). 5 - Multifunctionality in Additive Manufacturing. Design and Manufacture of Plastic Components for Multifunctionality, 171-204.

[24]-Labonnote, N., Rønnquist, A., Manum, B., & Rüther, P. (2016). Additive construction: State-of-the-art, challenges and opportunities. Automation in Construction, 72, 347-366.

[25]-Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Martina, F. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. CIRP Annals - Manufacturing Technology, 65(2), 737-760

[26]-Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. Computer-Aided Design, 69, 65-89.

[27]-Bauer, J., Hengsbach, S., Tesari, I., Schwaiger, R., & Kraft, O. (2014). High-strength cellular ceramic composites with 3D microarchitecture. Proceedings of the National Academy of Sciences of the United States of America, 111(7), 2453-8.

[28]-Chang, K.-H. (2013). Rapid Prototyping. Product Manufacturing and Cost Estimating Using CAD/CAE

[29]-Wang, X., Xu, S., Zhou, S., Xu, W., Leary, M., Choong, P., Xie, Y. M. (2016). Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review. Biomaterials, 83, 127-141.

[30]-Giannitelli, S. M., Mozetic, P., Trombetta, M., & Rainer, A. (2015). Combined additive manufacturing approaches in tissue engineering. Acta Biomaterialia, 24, 1-11.

[31]-Jin, X., Wang, Z., Ning, J., Xiao, G., Liu, E., & Shu, X. (2016). Dynamic response of sandwich structures with graded auxetic honeycomb cores under blast loading. Composites Part B: Engineering, 106, 206-217.

[32]-Wadley, H. N. G. (2006). Multifunctional periodic cellular metals. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 34(1838), 31-68.

[33]-Restrepo, D., Mankame, N. D., & Zavattieri, P. D. (2016). Programmable materials based on periodic cellular solids. Part I: Experiments. International Journal of Solids and Structures, 100-101, 485-504.

[34]-Restrepo, D., Mankame, N. D., & Zavattieri, P. D. (2016). Programmable materials based on periodic cellular solids. Part II: Numerical analysis. International Journal of Solids and Structures, 100-101, 505-522.

[35]-Vairis, A., Petousis, M., Vidakis, N., & Savvakis, K. (2016). On the Strain Rate Sensitivity of Abs and Abs Plus Fused Deposition Modeling Parts. Journal of Materials Engineering and Performance, 25(9), 3558-3565.

[36]-Dawoud, M., Taha, I., & Ebeid, S. J. (2016). Mechanical behaviour of ABS: An experimental study using FDM and injection moulding techniques. Journal of Manufacturing Processes, 21, 39-45.

[37]-J. O Hallquist, LS-DYNA. Keyword User's Manual, V971 R4 Beta, LSTC Co., CA, USA 2009.