DOI: https://doi.org/10.15407/pmach2021.04.071

UDC 539. 3

EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE SHEAR PROPERTIES OF HONEYCOMB CORES PRODUCED USING ADDITIVE TECHNOLOGIES

[1, 2] **Ihor I. Derevianko**
dereviankoii2406@gmail.com, ORCID: 0000-0002-1477-3173

[2] **Borys V. Uspenskyi**
Uspensky.kubes@gmail.com, ORCID: 0000-0001-6360-7430

[2, 3] **Kostiantyn V. Avramov**
kvavramov@gmail.com, ORCID: 0000-0002-8740-693X

[4] **Oleksandr F. Salenko**, ORCID: 0000-0002-5685-6225

[2] **Iryna V. Biblik**
miles@ipmach.kharkov.ua, ORCID: 0000-0002-8650-1134

[1] Yuzhnoye State Design Office,
3, Krivorizka str, Dnipro, 49008, Ukraine

[2] A. Pidhornyi Institute of Mechanical Engineering Problems of NASU
2/10, Pozharskyi str., Kharkiv, 61046, Ukraine

[3] Kharkiv National University of Radio Electronics,
14, Nauky ave., Kharkiv, 61166, Ukraine

[4] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute",
37, Peremohy ave., Kyiv, 03056, Ukraine

An approach to the experimental and computational study of the shear properties of honeycomb cores (HC) produced using Fused Deposition Modeling (FDM) technology is proposed. The experimental approach is based on a new sample type for testing HCs for shear. This sample contains two HCs and three steel plates. Shear tests are carried out in the TiraTest 2300 universal tensile testing machine. The HCs are made of ULTEM 9085 and PLA with FDM technology, which is implemented in the 3D Fortus 900 system. The tests resulted in obtaining the shear properties of the HCs by averaging the stress-strain curves of five samples. As follows from the analysis of the experimental results, brittle destruction of an HC is observed. Before its destruction, the value of shear deformation for samples made of PLA was 0.0134, and for samples made of ULTEM, 0.0257. The experimental analysis was accompanied by numerical finite element (FE) modeling of shear experiments, taking into account the deformation of the equipment. With the FE modeling of the experiments, to describe the behavior of the samples, it is necessary to take into account the influence, on the measurements of the shear properties, of the equipment and the deformation of each honeycomb cell. The deformation of three plates was taken into account; the elastic properties of the adhesive joint were not taken into account. A computer model of the deformation of the HCs with equipment was built using ANSYS Design Modeler. With FE modeling, only the elastic behavior of the HCs was considered.

Keywords: *honeycomb, additive technologies, shear, stress-strain curve.*

Introduction

HCs, which are used in multilayer structures, can be manufactured using additive technologies [1]. Using the homogenization theory of [2–3], we replace the HCs in the calculations with a continuous orthotropic layer. Analytical and numerical methods have been developed to calculate the mechanical properties of this orthotropic layer. The analytical methods for calculating the mechanical properties of HCs are discussed in [4–5]. The numerical methods for calculating the mechanical properties of HCs are considered in articles [6–7]. To determine the mechanical properties of HCs, experimental methods are widely used. In [8], studies of the linear mechanical properties of Nomex HCs are presented. The results of experimental studies are compared with the results of FE modeling. An experimental study of the mechanical properties of HCs was carried out in [9]. In this paper, it is shown that beam models describe the mechanical properties of HCs well. Article [10] examines energy damping and damping behavior of a honeycomb structure.

In this paper, we experimentally study the shear properties of PLA-based and ULTEM 9085-based HCs, using FDM. As a result of this analysis, shear stress-strain curves were obtained. The FE modeling of the experiment to determine the shear properties is carried out in the ANSYS package. The modeling takes into account the deformations of the equipment.

Description of the Experiment

The Fortus 900 3D system was used to print samples as HCs (Figure 1). This system uses FDM technology. First, a 3D model of the HC was built. This model was transformed in the Insight ™ software package with the following specified options. The layers were deposited from bottom to top; the liquefier tip was T16 (full filling). The layer height was chosen automatically, based on the developer's recommendations, and the number of layers was 45 with a HC height of 10 mm. All the walls of the HC were two layers-thick, each of the layers being formed by one pass of the extruder. Samples were made of ULTEM 9085 and PLA. To select the remaining parameters of the technological process, the software of the 3D printer itself was used. This program slices the part into layers, and selects the toolpaths. The air gap was assumed to be zero.

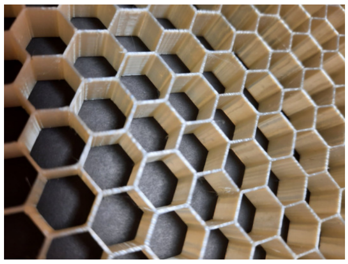

Fig. 1. Picture of a HC

The HCs were printed according to the following algorithm.

1. To print a job, it is first necessary to send the job file to a 3D printer from the application installed on a workstation. Jobs are sent to the printer in a CMB format, and spooled.
2. A new model sheet is installed on the print bed.
3. Containers for model and auxiliary materials are installed, and a filament is loaded into the head.
4. The printer is powered up. It takes approximately four hours for the printer to stabilize.
5. Printing is performed in automatic mode.
6. Once the product has been printed and the material has cooled down, both it and the auxiliary material are removed from the printer.

As a result of the work carried out, a series of honeycomb plates were manufactured in the amount necessary for the planned scope of testing.

For shear tests, a TiraTest 2300 universal tensile testing machine was used, which allows tensile/compression tests. A scheme of the experimental setup and a sketch of the sample are shown in figure 2. The sample (Fig. 2, a) consists of two honeycomb blocks 1. These blocks are glued to three rectangular steel plates 2. The geometric dimensions of the structure are shown in figure 2, a in mm.

The plates are made of a 5 mm thick grade 20 steel sheet, and have holes for the sample to be installed in the testing machine. The plates and HCs were glued with the 3M ™ Scotch-Weld ™ DP190B/A epoxy two-component adhesive.

For the shear testing of the honeycomb panels, groups of samples were made of ULTEM 9085 and PLA. The final view of the samples is shown in figure 3. Below is the sample, whose HCs are made of ULTEM 9085, and above is the sample, whose HCs are made of PLA. The dimensions of the block of one HC are 120×60×10 mm.

The prepared sample was installed in the grips of the test machine (Fig. 2, b), so that the direction of the load action coincide with the longitudinal axis of the sample (*L* direction). The schematic diagram of the experimental setup is shown in figure 2, b. It consists of a sample (1), three joints (2), and a displacement measuring device (3) (micrometer).

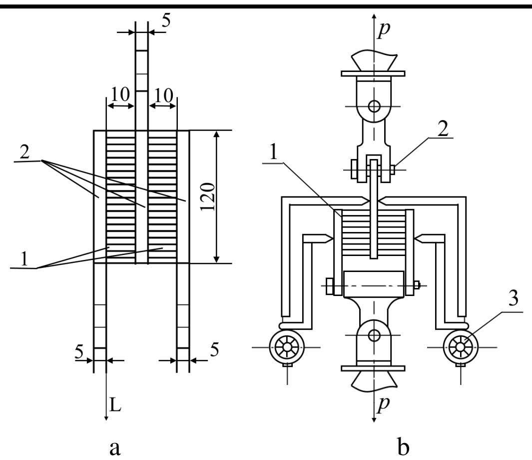

Fig. 2. Schematic diagram of the experimental setup:
a – sketch of the sample; b – installation diagram

Fig. 3. Samples for the shear testing of the PLA-based HC (top) and the ULTEM 9085-based one (bottom)

The tests were carried out by gradually increasing the load until the destruction of the sample at a uniform speed of the machine loading-grip movement, equal to 2 mm/min. During testing, loads, displacements, and time were recorded. The load was recorded using an electronic sensor in the measurement range of up to 10 tons, and displacements, using two dial-type point displacement indicators for each block separately. They make it possible to measure the displacement values without taking into account the deformations of metal hinge joints.

General Approach to Numerical Modeling

A FE modeling of mechanical experiments was carried out to determine the shear properties, in which, to describe the behavior of the samples, it is necessary to take into account the influence, on the shear properties, of the equipment, and the deformation of each honeycomb cell. The deformation of three plates was taken into account (Fig. 2, a); the elastic properties of the adhesive joint were not taken into account. The computer model of the deformation of the HCs with equipment was built in ANSYS Design Modeler. One honeycomb block consists of 12 rows, each having 5 hexagons. The dimensions of the PLA-based HCs were 117.6×60.8×10 mm, and those of the ULTEM 9085-based ones, 104.7×60.8×10 mm. When constructing the FE mesh of a HC with account taken of the deformation of each honeycomb cell, 8-node hexagonal elements (Hex8) were used, i.e., 3D modeling of the deformation state was used. The geometrical model of the structure is shown in figure 4. Due to the small size of the FEs and the need to connect the FE models of the samples and equipment, the steel plates were divided into a large number of tetrahedral elements (Tet10).

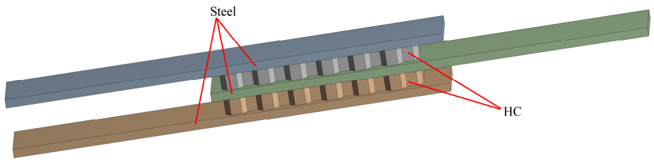

Fig. 4. Sketch of the sample with equipment

When simulating the experiment, the following boundary conditions were used. The two outermost steel plates (Fig. 4) are clamped at their left edges, and the middle plate on the right is under the action of the force *F* directed along the plate orthogonal to its edge. The *F* values were selected from the experiment.

The mechanical properties of the HC material were determined experimentally. They are published in the article [11]. These properties are given in tables 1, 2.

Table 1. Mechanical properties of the sample made of the orthotropic ULTEM 9085 material

E_{11}, Pa	E_{22}, Pa	E_{33}, Pa	G_{12}, Pa	G_{13}, Pa	G_{23}, Pa	ν_{32}	ν_{13}	ν_{12}
2.25×10^9	2.96×10^9	2.41×10^9	6.67×10^8	8.29×10^8	8.89×10^8	0.32	0.33	0.31

Table 2. Mechanical properties of the sample made of the orthotropic PLA material

E_{11}, Pa	E_{22}, Pa	E_{33}, Pa	G_{12}, Pa	G_{13}, Pa	G_{23}, Pa	ν_{23}	ν_{31}	ν_{21}
3.58×10^9	3.00×10^9	3.81×10^9	1.07×10^9	1.40×10^9	1.41×10^9	0.224	0.22	0.25

Results of Experimental Research and Numerical Modeling

Let us consider the results of numerical modeling and experimental analysis of the shear properties of the PLA-based and ULTEM 9085-based HCs. The dimensions of one ULTEM 9085-based honeycomb cell are: h=0.5 mm, l=6.05 mm where h is the wall thickness of one cell; l is the length of the inner side of the cell. The dimensions of one PLA-based honeycomb cell are: h=0.4 mm, l=6.11 mm. The value of the concentrated force *F* varied over a wide range from 750 to 9829.9 N.

The results of the experimental and calculated analysis of the shear properties for the PLA-based and ULTEM 9085-based HCs are shown in figures 5, 6. The ordinate in these figures shows the value of the force *F*, and the abscissa, the shear strain γ_{x1x3}. The solid line in figures 5, 6 shows experimental data. They were obtained by averaging the deformation curves of the five samples. The triangular markers show the results of FE shear modeling based on a computational model that takes into account the deformation of each HC and that of the equipment. As follows from the experimental analysis, brittle fracture of an HC is observed. With FE modeling, only the elastic behavior of the HC was considered.

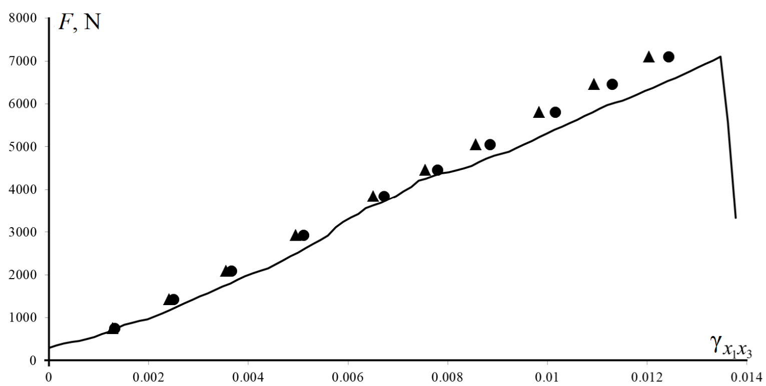

Fig. 5. Comparison of the FE calculation results for the PLA-based HC shear with experimental data

Before the destruction of the PLA-based HC, the values of the force *F* and the shear strain γ_{x1x3} took the following values: F=7101.86 N, γ_{x1x3}=0.0134. Before the destruction of the ULTEM-based HC sample, the following values of the force F and the shear strain γ_{x1x3} were observed: F=9829.90 N, γ_{x1x3}=0.0257.

So, the calculation results shown in figures 5, 6 indicate that the data obtained from direct FE calculation, taking into account the deformation of each honeycomb cell, are close to those obtained experimentally.

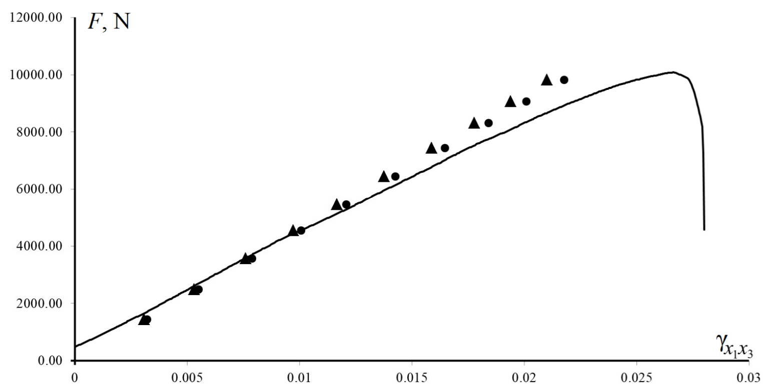

Fig. 6. Comparison of the FE calculation results for the ULTEM 9085-based HC shear with experimental data

Based on the calculation results, the shear modulus G_{x1x3} was determined for the PLA-based HC and ULTEM 9085-based HC. For the PLA-based HC, the shear modulus obtained experimentally is 36.790 MPa; G_{x1x3} obtained from the FE calculation of the model (Fig. 5), with account taken of the deformation of each honeycomb cell and that of the equipment, is equal to 40.390 MPa; the relative difference between the results obtained is 0.097. For the ULTEM 9085-based HC, the experimentally obtained shear modulus is 34.383 MPa; G_{x1x3}, obtained from the FE calculation of the model (Fig. 6), with account taken of the deformation of each honeycomb cell and that of the equipment, is equal to 36.772 MPa; the relative difference between the results obtained is 0.069, i.e. the calculated and experimental results are close.

The destruction of the HCs during their testing for shear took place in the honeycomb cells. The adhesive joint of the metal and the honeycomb cells remained intact. In this paper, static processes in structures are considered. Dynamic processes are considered in other works of the authors of this article [12–13].

Conclusion

An approach is proposed for the experimental determination of the mechanical properties of HCs made by additive technologies. For this, an experimental setup is used, which simultaneously determines the shear mechanical properties of two HC plates. As a result of the experimental analysis, both the shear stress-strain curve and shear moduli are found.

An FEM-based mathematical model has been built to describe the shear experiment. The model is based on the direct FE modeling of all honeycomb cells, with account taken of the deformation model of the equipment. The latter takes into account the deformations of the plates, and does not take into account the elasticity of the adhesive joint.

Financing

The study was funded by the National Research Foundation of Ukraine (grant 128/02/2020).

References

1. Chen, Y., Li, T., Jia, Z., Scarpa, F., Yao, C.-W., & Wang, L. (2018). 3D printed hierarchical honeycombs with shape integrity under large compressive deformations. *Materials and Design*, vol. 137, pp. 226–234. https://doi.org/10.1016/j.matdes.2017.10.028.
2. Hohe, J. & Becker, W. (2002). Effective stress-strain relations for two-dimensional cellular sandwich cores: Homogenization, material models, and properties. *Applied Mechanics Reviews*, vol. 55, iss. 1, pp. 61–87. https://doi.org/10.1115/1.1425394.
3. Vougiouka, G., Rodrigues, H., & Guedes, J. M. (1998). Prediction of elastic properties of sandwich panels using a homogenization computational model. In: Vautrin, A. (eds.) Mechanics of Sandwich Structures. Springer, Dordrecht, pp. 147–154. https://doi.org/10.1007/978-94-015-9091-4_17.
4. Gibson, L. J., Ashby, M. F., Schajer, G. S., & Robertson, C. I. (1982). The mechanics of two-dimensional cellular materials. *Proceedings of the Royal Society London A*, vol. 382, pp. 25–42. https://doi.org/10.1098/rspa.1982.0087.
5. Masters, I. G. & Evans, K. E. (1996). Models for the elastic deformation of honeycombs. *Composite Structures*, vol. 35, iss. 4, pp. 403–422. https://doi.org/10.1016/S0263-8223(96)00054-2.

6. Catapano, A. & Montemurro, M. (2014). A multi-scale approach for the optimum design of sandwich plates with honeycomb core. Part I: Homogenisation of core properties. *Composite Structures*, vol. 118, pp. 664–676. https://doi.org/10.1016/j.compstruct.2014.07.057.
7. Grediac, M. (1993). A finite element study of the transverse shear in honeycomb core. *International Journal of Solids and Structures*, vol. 33, iss.13, pp. 1777–1788. https://doi.org/10.1016/0020-7683(93)90233-W.
8. Foo, C. C., Chai, G. B., & Seah, L. K. (2007). Mechanical properties of Nomex material and Nomex honeycomb structure. *Composite Structures*, vol. 80, iss. 4, pp. 588–594. https://doi.org/10.1016/j.compstruct.2006.07.010.
9. Balawi, S. & Abot, J. L. (2008). The effect of honeycomb relative density on its effective in-plane elastic moduli: An experimental study. *Composite Structures*, vol. 84, iss. 4, pp. 293–299. https://doi.org/10.1016/j.compstruct.2007.08.009.
10. Bates, S. R. G., Farrow, I. R., & Trask, R. S. (2019). Compressive behaviour of 3D printed thermoplastic polyurethane honeycombs with graded densities. *Materials and Design*, vol. 162, pp. 130–142. https://doi.org/10.1016/j.matdes.2018.11.019.
11. Derevianko, I., Avramov, K., Uspenskyi, B., & Salenko, A. (2021). *Eksperymentalnyi analiz mekhanichnykh kharakterystyk detalei raket-nosiiv, vyhotovlenykh za dopomohoiu FDM adytyvnykh tekhnolohii* [Experimental analysis of mechanical characteristics of parts of launch vehicles manufactured using FDM additive technologies]. *Tekhnichna mekhanika – Technical Mechanics*, iss. 1, pp. 92–100 (in Ukrainian). https://doi.org/10.15407/itm2021.01.092.
12. Avramov, K. V. (2018). Nonlinear vibrations characteristics of single-walled carbon nanotubes by nonlocal elastic shell model. *International Journal of Non-Linear Mechanics*, vol. 107, pp. 149–160. https://doi.org/10.1016/j.ijnonlinmec.2018.08.017.
13. Avramov, K. V. & Gendelman, O. V. (2009). Interaction of linear system with snap-through vibrations absorber. *International Journal of Non-Linear Mechanics*, vol. 44, iss. 1, pp. 81–89. https://doi.org/10.1016/j.ijnonlinmec.2008.09.004.

Received 22 October 2021

Експериментальний та чисельний аналіз зсувних характеристик стільникових заповнювачів, отриманих адитивними технологіями

[1,2] І. І. Деревянко, [2] Б. В. Успенський, [2,3] К. В. Аврамов, [4] О. Ф. Саленко, [2] І. В. Біблік

[1] Державне підприємство «Конструкторське бюро «Південне» ім. М. К. Янгеля», 49008, Україна, м. Дніпро, вул. Криворізька, 3

[2] Інститут проблем машинобудування ім. А. М. Підгорного НАН України, 61046, Україна, м. Харків, вул. Пожарського, 2/10

[3] Харківський національний університет радіоелектроніки, 61166, Україна, м. Харків, пр. Науки, 14

[4] Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», 03056, Україна, м. Київ, пр. Перемоги, 37

Запропоновано підхід до експериментально-розрахункового дослідження зсувних характеристик стільникових заповнювачів, виготовлених за допомогою моделювання шляхом пошарового наплавлення (FDM). адитивною технологією FDM. В основі експериментального підходу лежить новий вид зразка для випробування стільникових заповнювачів на зсув. Цей зразок містить два стільникових заповнювача і три сталеві пластинки. Випробування на зсув проводяться в універсальній розривній машині TiraTest 2300. Стільникові заповнювачі виготовляються з матеріалів ULTEM 9085 і PLA за допомогою технології FDM, яка реалізується в 3D-системі Fortus 900. В результаті випробувань отримані характеристики зсуву стільникових заповнювачів через усереднення кривих деформування п'яти зразків. Як випливає з аналізу експериментальних результатів, спостерігається крихке руйнування стільникового заповнювача. Перед його руйнуванням величина деформації зсуву для зразків з матеріалу PLA становила 0,0134, а для зразків з матеріалу ULTEM – 0,0257. Експериментальний аналіз супроводжувався чисельним скінченно-елементним моделюванням експериментів на зсув з урахуванням деформації оснащення. При скінченно-елементному моделюванні експериментів для опису поведінки зразків необхідно враховувати вплив на вимірювання зсувних характеристик оснащення і деформування кожної комірки стільникових заповнювачів. Враховувалося деформування трьох пластин; пружні властивості клейового з'єднання не враховувалися. Комп'ютерна модель деформування стільників з оснащенням була побудована в ANSYS Design Modeler. При скінченно-елементному моделюванні розглядалася тільки пружна поведінка стільникових заповнювачів.

Ключові слова: *стільниковий заповнювач, адитивні технології, зсув, крива зусилля–деформації.*

Література

1. Chen Y., Li T., Jia Z., Scarpa F., Yao C.-W., Wang L. 3D printed hierarchical honeycombs with shape integrity under large compressive deformations. *Materials and Design*. 2018. Vol. 137. P. 226–234. https://doi.org/10.1016/j.matdes.2017.10.028.
2. Hohe J., Becker W. Effective stress-strain relations for two-dimensional cellular sandwich cores: Homogenization, material models, and properties. *Appl. Mech. Rev.* 2002. Vol. 55. Iss. 1. P. 61–87. https://doi.org/10.1115/1.1425394.
3. Vougiouka G., Rodrigues H., Guedes J. M. Prediction of elastic properties of sandwich panels using a homogenization computational model: Vautrin A. (eds.) Mechanics of Sandwich Structures. Springer, Dordrecht, 1998. P. 147–154. https://doi.org/10.1007/978-94-015-9091-4_17.
4. Gibson L. J., Ashby M. F., Schajer G. S., Robertson C. I. The mechanics of two-dimensional cellular materials. *Proc. R. Soc. London*. 1982. Vol. 382. P. 25–42. https://doi.org/10.1098/rspa.1982.0087.
5. Masters I. G., Evans K. E. Models for the elastic deformation of honeycombs. *Composite Structures*. 1996. Vol. 35. Iss. 4. P. 403–422. https://doi.org/10.1016/S0263-8223(96)00054-2.
6. Catapano A., Montemurro M. A multi-scale approach for the optimum design of sandwich plates with honeycomb core. Part I: Homogenisation of core properties. *Composite Structure.* 2014. Vol. 118. P. 664–676. https://doi.org/10.1016/j.compstruct.2014.07.057.
7. Grediac M. A finite element study of the transverse shear in honeycomb core. *Intern. J. Solids and Structures*. 1993. Vol. 33. Iss. 13. P. 1777–1788. https://doi.org/10.1016/0020-7683(93)90233-W.
8. Foo C. C., Chai G. B., Seah L. K. Mechanical properties of Nomex material and Nomex honeycomb structure. *Composite Structures*. 2007. Vol. 80. Iss. 4. P. 588–594. https://doi.org/10.1016/j.compstruct.2006.07.010.
9. Balawi S., Abot J. L. The effect of honeycomb relative density on its effective in-plane elastic moduli: An experimental study. *Composite Structures*. 2008. Vol. 84. Iss. 4. P. 293–299. https://doi.org/10.1016/j.compstruct.2007.08.009.
10. Bates S. R. G., Farrow I. R., Trask R. S. Compressive behaviour of 3D printed thermoplastic polyurethane honeycombs with graded densities. *Materials and Design*. 2019. Vol. 162. P. 130–142. https://doi.org/10.1016/j.matdes.2018.11.019.
11. Деревянко І., Аврамов К., Успенський Б., Саленко А. Експериментальний аналіз механічних характеристик деталей ракет-носіїв, виготовлених за допомогою FDM адитивних технологій. *Техн. механіка.* 2021. Вип. 1. С. 92–100. https://doi.org/10.15407/itm2021.01.092.
12. Avramov K. V. Nonlinear vibrations characteristics of single-walled carbon nanotubes by nonlocal elastic shell model. *Int. J. Non-Lin. Mech.* 2018. Vol. 107. P. 149–160. https://doi.org/10.1016/j.ijnonlinmec.2018.08.017.
13. Avramov K. V., Gendelman O. V. Interaction of linear system with snap-through vibrations absorber. *Int. J. Nonl. Mech*. 2009. Vol. 44. Iss. 1. P. 81–89. https://doi.org/10.1016/j.ijnonlinmec.2008.09.004.