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Comparative experimental and numerical analysis of mechanical properties of sandwich plates and honeycombs with different cells configurations manufactured by material extrusion additive technology

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Abstract

Comparative studies of mechanical properties of four types of honeycombs (hexagonal, auxetic, triangular and quadratic), which are produced by additive technology, and sandwich plates with these honeycombs are performed. Experimental approach, which consists of tensions and shears tests of four types of honeycombs and three-points bending of sandwich plates with different honeycombs, is suggested. All experimental studies are accompanied by finite elements numerical calculations. Nonlinear dependences of the tensile forces on displacements are analyzed at tension tests. Character of samples fractures is studied. Linear dependences of applied forces on shears strains and displacements are obtained at shear tests of honeycombs and three-points bending of sandwich plates. Fractures of honeycombs and sandwich plates are analyzed. Comparative study of four types of honeycombs and sandwich plates with these honeycombs are made with respect to their mechanical properties.

Keywords: honeycomb, sandwich plate, additive manufacture, tension and shear tests, three-points bending test, finite elements numerical simulations

1. Introduction

The honeycombs structures produced by additive manufacturing have advantages over structures, which are produced by others technologies [1-5]. Honeycombs productions are simplified by using additive technologies [6, 7]. These technologies are used to produce small weight structures, which are important for aerospace engineering and aviation [8, 9].

Mechanical characteristics of honeycombs, which are produced by additive manufacture, are analyzed numerically and experimentally. As follows from experimental and numerical comparative study, octagonal honeycomb buckling load is higher than the one of hexagonal honeycomb structure [10]. The honeycombs from shape memory material are produced by selective laser melting additive technology [11]. In-plane deformation response of this honeycomb structure is analyzed numerically. The material extrusion additive technology is used to manufacture honeycomb lattice [12]. The in-plane compression of this lattice is studied. The energy absorption of auxetic arc angle gradient honeycomb is analyzed in [13]. The dynamic response of hexagonal honeycomb produced by stereolithography additive technology under the action of low-velocity impact is analyzed experimentally and numerical by using finite elements technique in [14]. As follows from the article [15], capacity of energy absorption is increased by using gradient auxetic honeycomb. Stiffness of the honeycomb sandwich thin-walled structure produced by stereolithography is analyzed in [16]. The effect of strain rate on honeycombs mechanical characteristics is analyzed using the Johnson–Cook theory with account of inertia effect in [17]. The mechanical properties of the honeycomb lattice auxetic structure manufactured by additive technology are analyzed in [18]. Finite element analysis and experimental studies are carried out to analyze the dynamic response of honeycomb lattice in [19]. Dynamic compression experiments are carried out to analyze the mechanical properties of metal honeycomb manufactured by laser powder bed fusion additive technology [20]. Finite element model is obtained to study the compression of honeycomb lattice from PLA material produced by material extrusion additive technology [21]. The buckling of the hexagonal honeycomb is studied experimentally in [22]. The dynamic fracture of honeycomb is tested by Li with co-authors [23]. The mechanical response of the honeycomb lattice produced by selective laser melting additive technology is analyzed by Zhang and co-authors [24]. The impact response of the honeycomb lattice manufactured by stereolithography additive technology is discussed in [25]. The experimental study of the auxetic honeycomb sandwich shell produced by selective laser melting under the action of blast force is carried out by Wei with co-authors [26].

2. Problem Formulation

As follows from literature review, the studies, where honeycombs for sandwich thin-walled structures are manufactured by additive technologies, are developed. Different cells configurations of honeycombs are studied numerically and experimentally. In the present article, the comparative analysis of the mechanical properties of the honeycombs structures with four kinds of cells configurations is carried out. All these honeycombs are manufactured by material extrusion additive technology from polylactic acid (PLA) material, which are orthotropic. The following kinds of honeycomb cells are considered: hexagonal, auxetic, triangular and quadratic. Experimental analysis of honeycombs and these experiments numerical modeling are carried out to perform comparative study. The experiments on honeycombs consist of their tensions and shears. These experiments are simulated using finite element software ANSYS. The experimental results on tensions of dog bone samples, which are manufactured by the material extrusion additive technology from PLA material, are used in mathematical modeling of the experiments. The results of these experiments are published in the papers [4, 27, 28].

Experimental studies of sandwich plates are carried out by three-point bending tests. The sandwich plates with four kinds of honeycombs are studied experimentally in this comparative analysis. Facing layers of these plates are manufactured from carbon fiber composite.

3. Manufacture of honeycombs and sandwich plates

Four kinds of honeycombs (hexagonal, auxetic, triangular and quadratic) are analyzed in this article. These samples are manufactured by material extrusion additive technology from thermoplastic PLA. Nozzles with diameters 0.4 mm are used to print honeycombs. In order to carry out comparative study, dimensions of all honeycombs cells are taken such that the cells are inscribed into the circle with the diameter 13.21 mm. The thicknesses of all cells walls are the same and they are equal to 0.5 mm. The honeycombs are manufactured in the form of rectangular plates of dimension 200×60 mm. Photos of the manufactured honeycombs are shown on Fig.1.

Manufactures of sandwich plates are described. Carbon fiber composite layers are manufactured using carbon fabric T33K200P, which is impregnated by glue Alpha Epoxy 3.1 TC U 20.5-35744044-003:2022. Fig.2 shows the fragment of bonding. Carbon fiber composite layers with thickness 0.5 mm are glued to both sides of honeycombs using glue LOCTITE® EA 9497.

The detailed technology of sandwich plates manufacture is the following. Firstly, three symmetrical samples 200×60×10 mm for every kind of cells are cut out from the honeycomb plates 200×200×10 mm. Fig.1 shows the obtained honeycomb samples. Secondly, two plies of prepregs with thicknesses 0.25 mm are laid out 0/90. The prepared billet is laid into chamber under pressure 6±0.5 atmospheres. The pressure chamber is installed into furnace. The polymerization mode with high pressure is applied.

The technology of carbon fibers composite layers gluing to honeycombs is the following. The carbon fibers composite layers sides are polished. Uniform thin layers (0.3-0.4 mm) of glue

LOCTITE® EA 9497 is coated on prepared surfaces. The samples are kept under pressure during 24 hours. Then, the samples are kept up to complete polymerization during 14 days.

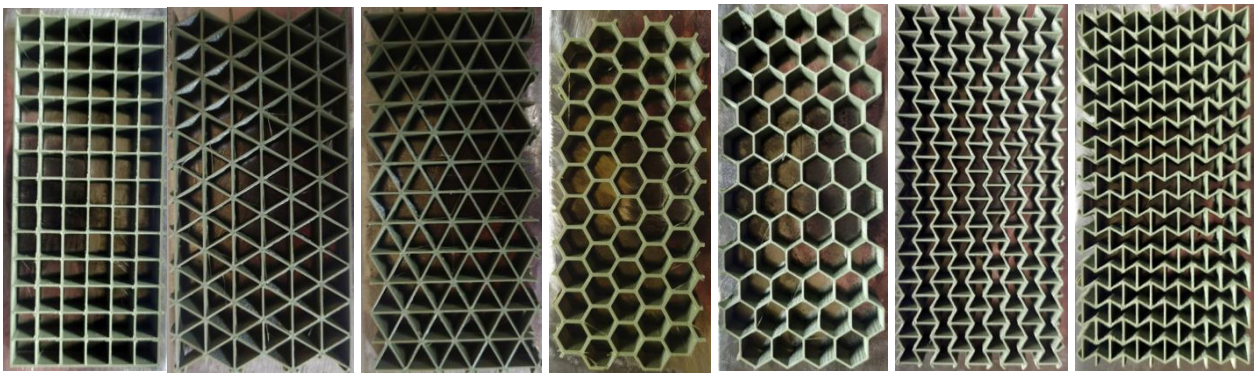


Fig. 1. Honeycomb samples

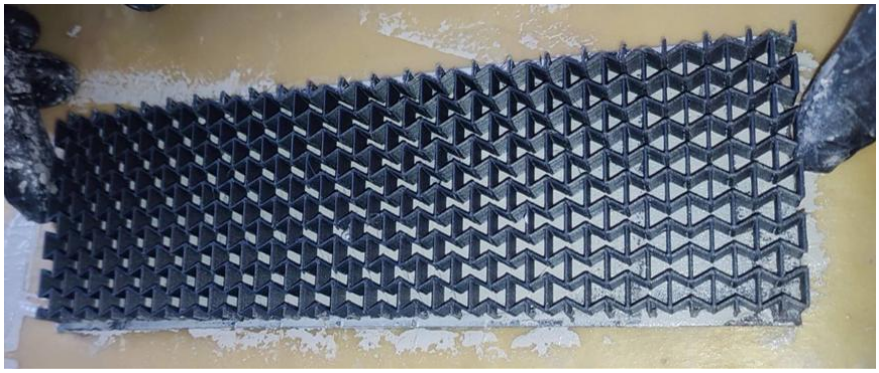


Fig.2. Laying of honeycomb on carbon fibers composite layer with glue

4. Methodology of experimental studies

Experimental analysis of honeycombs and sandwich plates consists of three parts: three-points bending tests of sandwich plates; tensions tests of honeycombs and shear tests of honeycombs. Four kinds of the honeycombs with hexagonal, auxetic, triangular and quadratic cells are tested to obtain their mechanical properties. The mechanical properties of sandwich plates are obtained from three-points bending tests. As a result of the study, the comparative analysis of obtained mechanical characteristics of the honeycombs and the sandwich plates are performed.

Testing on three point bending is performed on the machine Tira Test-2300 for sandwich plates analysis. Fig.3 shows photo of plant with sample during test. Methodology of these tests and basic diagram of three-point bending are presented in the papers [29, 30]. This approach is used in this article. The distance between trunnions is equal to 150 mm. Loading is set by motions of the clamp with velocity 5±1 mm/min. The samples are loaded up to fracture. The fractures of sandwich plates are analyzed.

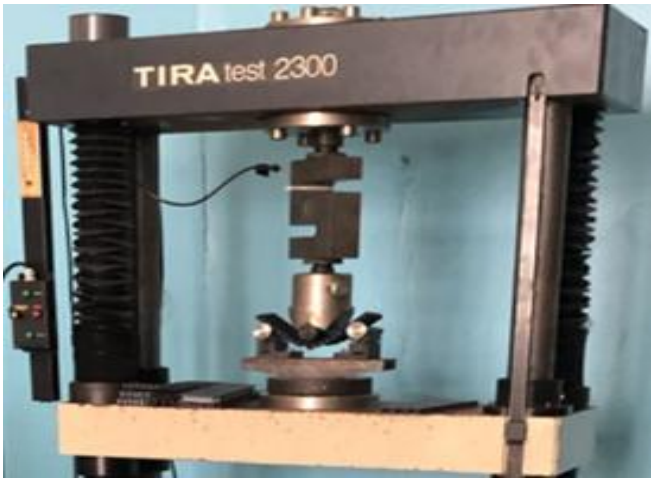


Fig. 3. Photo of Tira Test-2300 with setup on three-points bending

Tests on honeycombs tensions are carried out. Four kinds of the honeycombs with hexagonal, auxetic, triangular and quadratic cells are tested to analyze their mechanical properties. Fig.1 shows all consider kinds of honeycombs. Rectangular honeycombs plates of dimensions 100×60 mm are used for tension tests.

The experiments on tensions are carried out on the machine Tira Test 2300, which performs tests on tension/compression with prescribed velocity of a clamp. The samples are fastened in clamps to perform the tensions tests (Fig.4).


Fig.4. Photo of samples in clumps

The tests are carried out by increase the loading up to fractures. This loading is performed by uniform motions of the clamp with the constant velocity 5 mm/min. The dependence of loading on displacements is measured during these tests. The dimensions of the honeycombs are measured during these tests too.

Shear tests of honeycomb samples are carried out. The special samples, which are shown on Fig.5, are manufactured to study shears of the honeycombs. The sample consists of double honeycombs plates, which are glued with three steel plates. Such samples secure in alignment loading without warp. Double honeycombs plates 1 are shown on Fig.5. These honeycombs are glued with steel plates 2. The honeycombs shears are observed if the samples are stretched. Four kinds of honeycombs with hexagonal, auxetic, triangular and quadratic cells are tested to perform comparative analysis. Rectangular plates are manufactured from steel G10200 with thickness 5 mm. The parts of the samples are shown on Fig.6.

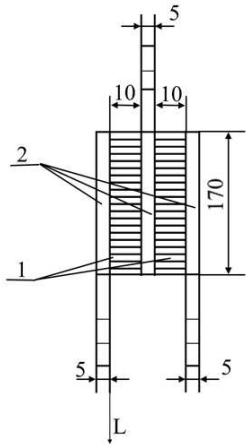


Fig.5. Sketch of samples for honeycomb shear study



Fig.6. Steel plates and honeycombs for samples manufacturing

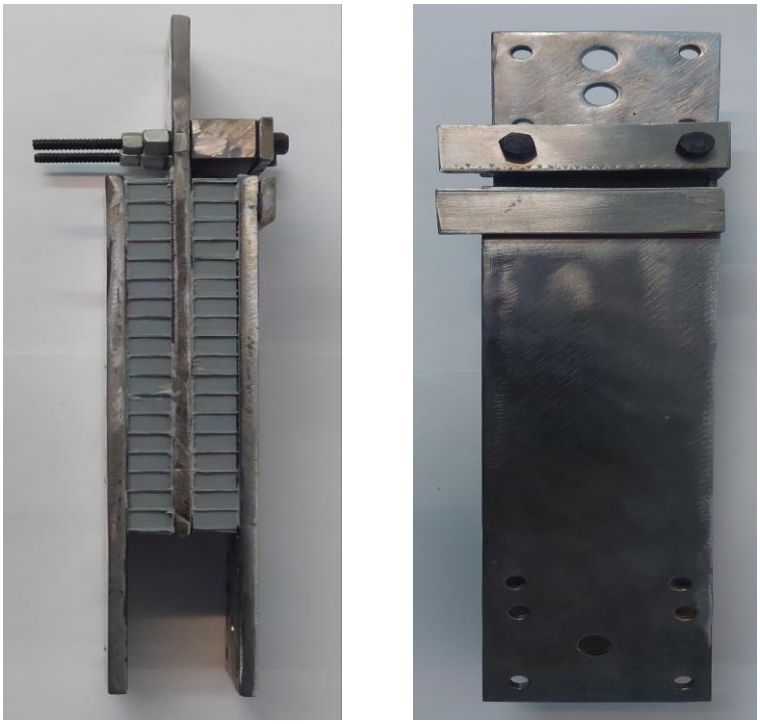


Fig.7. Photos of shear sample

The samples are manufactured in the following way. Two-components glue LOCTITE® EA 9497 is coated by uniform layers on the steel plates. The parts of the sample (Fig.6) are glued. The obtained samples are vacuumized providing uniform pressing of honeycombs to steel plates during 12 hours. Fig.7 shows the samples for the honeycomb shear analysis.

The prepared for testing samples are installed into the clamps of the tensile machine Tira Test 2300. The loadings directions and samples longitudinal axes are the same. Tension tests are performed with pre-set velocity of the clamp motions. The loading is measured using electronic sensor. The tests are performed with increase of the loadings up to samples fractures.

The dependences of loadings on displacements are measured during tests. The suggested approach allows measuring the values of the displacements without deformations of the hinged connections.

5. Modeling of honeycombs tensions

All kinds of experiments, which are considered in the previous Section, are simulated in the finite elements software ANSYS. The approaches for all these calculations are considered below. The simulations of the samples tensions are treated firstly.

Mechanical properties of the PLA material, which are used in calculations, are obtained experimentally. These experiments are described in articles [4, 27, 28]. The mechanical properties of the PLA plastic are the following:

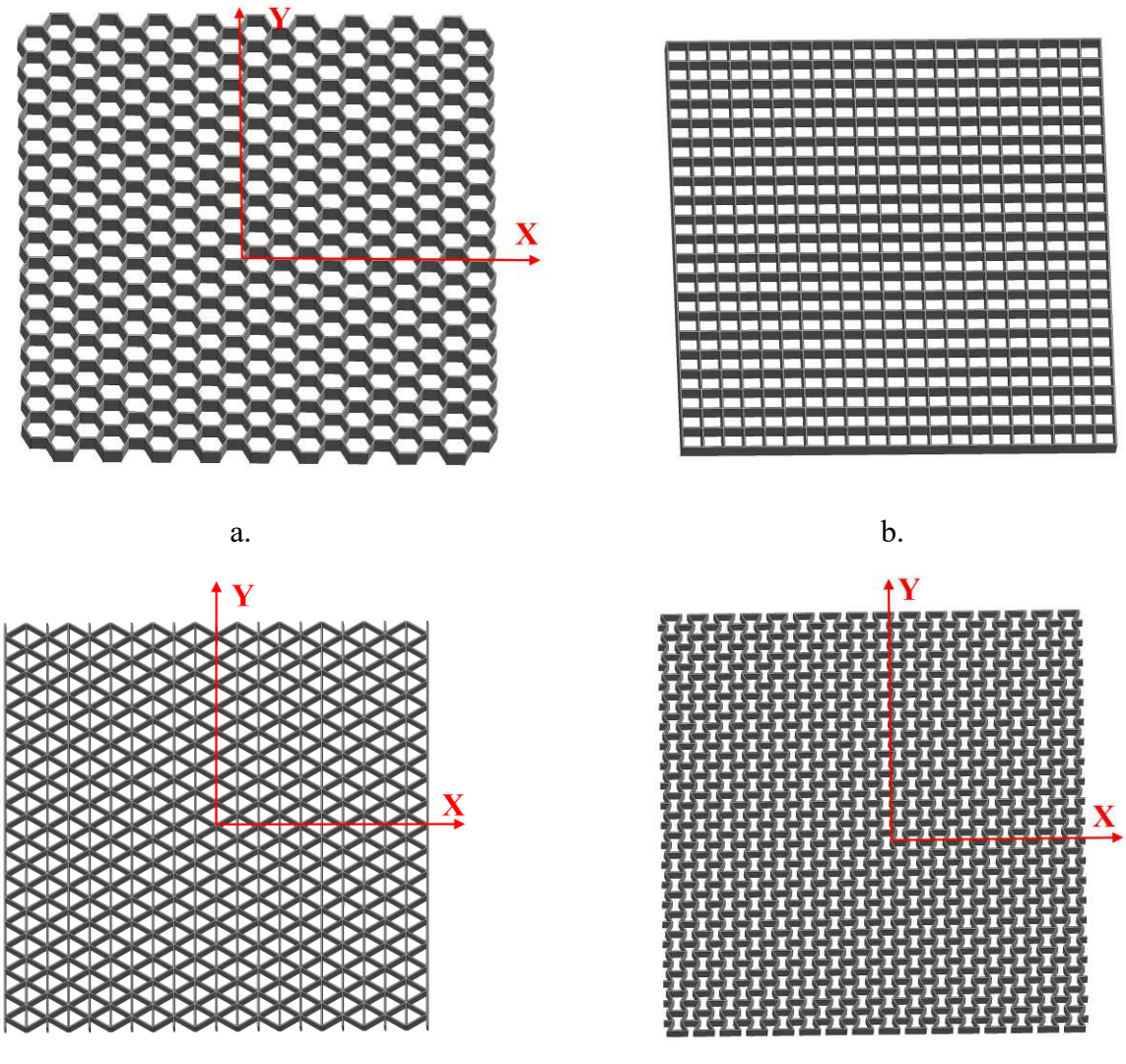
$$E_\zeta = 6 \text{ GPa};\ E_\eta = 2.72\ GPa;\ E_\theta = 0.68\ GPa;\ \upsilon_{\zeta\eta} = 0.343;\ \upsilon_{\eta\theta} = 0.39;\ \upsilon_{\zeta\theta} = 0.343;$$

$$G_{\zeta\eta} = 1.09\ GPa; G_{\eta\theta} = 0.98\ GPa; G_{\zeta\theta} = 1\ GPa, \quad (1)$$

where ζ axis lies along printing direction; η axis lies perpendicularly to the printing direction; θ axis is directed perpendicularly to printing plane. Young modulus, shear modulus and Poisson ratio are denoted by E, G, υ, respectively.

As follows from the papers [4, 28, 29], the plastic behavior of the PLA material is observed. The plastic strains are observed only along ζ axis, which are accounted in the calculations. Bilinear isotropic hardening model with the yield strength σ_y =100 MPa, tangent modulus E_t =1 GPa are used to calculate plastic response at tension and bending.

Modeling of the tension tests of the honeycombs are performed by finite elements method using commercial software ANSYS Mechanical. Geometrical models of the honeycomb plates with hexagonal, auxetic, triangular and quadratic cells are generated. These honeycombs are shown on Fig.8. The directions of the samples X and Y, which are used in the calculations, are depicted on Fig.8.



a. b.

c. d.

Fig.8. Geometrical models of honeycomb plates with different cells: a.-hexagonal; b.-quadratic; c.-triangular; d.-auxetic

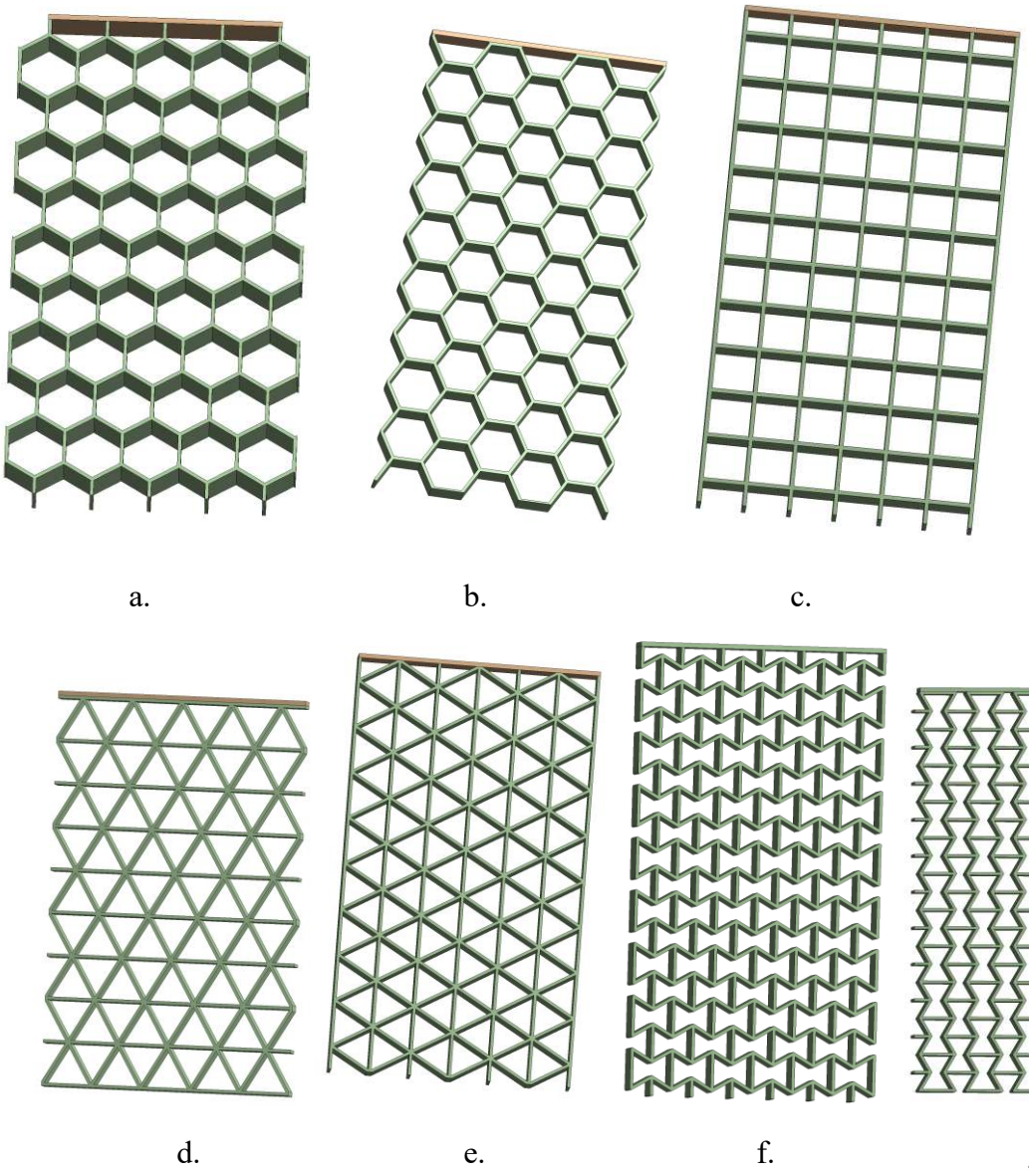


Fig.9. Geometrical models for simulations of tensions tests: a, b: hexagonal honeycombs in X, Y directions; c: honeycomb with quadratic cells; d, e: honeycomb with triangular cells in X, Y directions; f, g: auxetic honeycomb in X, Y directions

The geometrical models of the honeycombs tensions tests are generated. These models consist of the honeycomb samples (Fig.9) and stiff plates on the one end of the samples, which describe clamp of the tensile machine Tira Test 2300. These stiff plates distribute loadings uniformly.

Finite element model is generated in ANSYS Workbench. Orthotropic properties of PLA material is accounted by using Element Orientation Tool. Table 1 contains main parameters of finite element models. Types of honeycombs cells in longitudinal directions (Fig.8) are presented in the first column of the Table. Numbers of finite elements and nodes are shown in the second and third columns of the Table. Predominant type of finite elements is presented in fourth column. 10 nodes tetrahedral element TEt10 and 20 nodes elements Hex20 in the form of parallelepiped are predominant elements.

Table 1. Parameters of finite element models for samples tensions. The cell directions are shown on Fig.8

Types of honeycombs cells and cells directions	Numbers of elements	Numbers of nodes	Predominant type of finite elements	Average quality of elements
Hexagonal, X	83329	170428	Tet10	0.71932
Hexagonal, Y	82461	183090	Tet10	0.70708
Quadratic	80801	455213	Hex20	0.90909
Triangular, X	51204	343923	Hex20	0.92393
Triangular, Y	135708	274021	Tet10	0.69175
Auxetic, X	96721	556714	Hex20	0.83387
Auxetic, Y	166747	351050	Tet10	0.70409

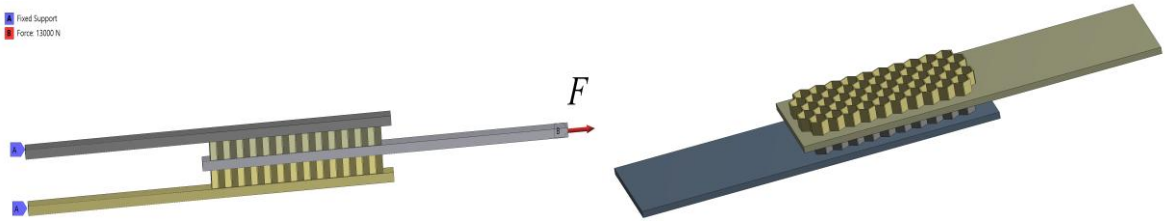
The boundary conditions are considered to simulate the samples tensions. One end of the sample is clamped. The boundary condition «Force» $\boldsymbol{F}$ is used for the second end of the sample. The values of this force are taken from the experimental tests.

As follows from the experimental studies, the displacements of the honeycomb ends are commensurable with thickness of honeycomb plate. Therefore, the geometrical nonlinear deformations of the cells walls are accounted [4].

6. Simulations of honeycombs shears

Numerical simulations of honeycombs shears tests are carried out in finite element software ANSYS. Geometrical models of the samples are generated to study shears of four kinds of honeycombs with the following cells: hexagonal, auxetic, quadratic and triangular. The samples

consist of two similar plates of honeycombs, which are clutched rigidly between the steel plates (Fig.10). The mechanical properties of the honeycomb materials are presented in (1).



a. b.

Fig.10. Geometrical models of honeycombs shears tests

Table 2. Parameters of finite element models of the samples shears studies

Configurations of honeycombs cells and cells directions	Numbers of elements	Numbers of nodes	Predominant types of finite elements	Average quality of elements
Hexagonal, X	150979	311415	Hex20, Tet10	0.63856
Hexagonal, Y	144197	297341	Hex20, Tet 10	0.63983
Quadratic	97511	215417	Hex20, Tet 10	0.62409
Triangular, X	93824	213437	Hex20, Tet 10	0.60125
Triangular, Y	99450	226459	Hex20, Tet 10	0.59975
Auxetic, X	142829	311728	Hex20, Tet 10	0.6053
Auxetic, Y	146721	322125	Hex20, Tet 10	0,60841

The finite elements models of the samples (Fig.7) are generated using ANSYS Workbench. Table 2 contains main parameters of finite elements models of the samples. The first column of the Table shows the types of the honeycombs with configuration of longitudinal directions (Fig.8). Predominant finite elements are shown in the fourth column of the Table. Finite elements Tet10 are used to simulate the steel plates.

The boundaries conditions for shears tests modeling are the following. The clumped boundary conditions are used at the ends of the outward steel plates. The boundary conditions «Force» are used at the end of the middle steel plate. These boundary conditions are shown on Fig.10a.

7. Simulation of three-points bending tests for sandwich plates

Manufacture of the sandwich plates is discussed in the previous section of this paper. The sketch of the sandwich plate is shown on Fig.11. The methodology of three-points bending tests is treated in [29, 30].

The mechanical properties of carbon fiber composite outer layers are determined experimentally. They take the following values:

$$E_x = E_y = 45\ GPa; E_z = 5\ GPa; \upsilon_{xy} = \upsilon_{xz} = \upsilon_{yz} = 0.3; G_{xy} = 2.8GPa; G_{xz} = G_{yz} = 0.6GPa, \quad (2)$$

where x and y axes are located in the plane of outer layer; z axis is perpendicular to the outer layer plane. The mechanical properties of the honeycomb material take the values (1).

Finite element software ANSYS Mechanical is used together with preprocessor and postprocessor ACP to simulate three-points bending tests. The model of three-points bending of the sandwich plate is shown on Fig.11. The bearing rollers are described by the cylinders A and B. The loading shaft is modeled by cylinder C. Contact interactions between cylinders A, B, C and sandwich plates are accounted. Four types of honeycombs sandwich plates with hexagonal, auxetic, quadratic and triangular cells are considered in this analysis.

The outer layers of plate are simulated using preprocessor ACP (Pre) for composite materials. Finite elements models are generated using shell elements. Finite elements models of honeycombs, bearing rollers and loading shafts are generated in the software ANSYS. Fig.11 shows one finite element model of the structure. The sandwich plates have four different types of honeycombs cells: hexagonal, auxetic, quadratic and triangular.

Table 3 contains main parameters of the finite elements models of the three-points bending experiments with the sandwich plates. First column of Table 3 presents types of the honeycombs and their longitudinal directions. Types of predominant finite elements are shown in the fourth column of the Table. As follows from this Table, 20 nodes parallelepiped element Hex20 and 15 nodes prismatic element Wed15 are predominant finite elements.

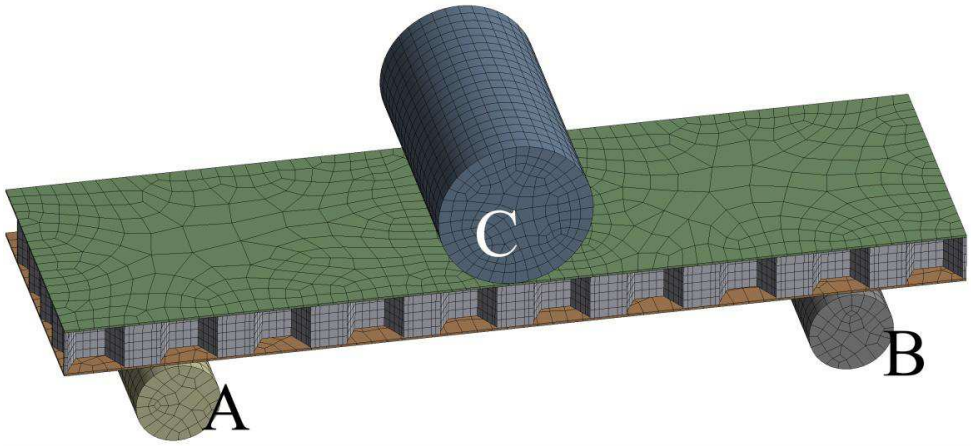


Fig.11. Sketch of three-points bending test of sandwich plate with finite element mesh

Table 3. Finite elements models parameters of three-point bending of sandwich plates

Configurations of honeycombs cells and longitudinal directions of samples	Numbers of elements	Numbers of nodes	Predominant finite elements	Average quality of elements
Hexagonal, X	13733	79652	Hex20	0.63607
Hexagonala, Y	13888	69929	Hex20	0.64103
Quadratic	6134	29415	Hex20	0.39733
Triangular, X	12448	75282	Hex20	0.60388
Triangular, Y	13611	80223	Hex20	0.60546
Auxetic, X	17607	98305	Hex20/Wed15	0.59982
Auxetic, Y	19264	104360	Hex20/Wed15	0.58468

Both outer layers and honeycombs are manufactured from orthotropic material. ANSYS preprocessor is used to set these orthotropic properties. Five contact surfaces are accounted in the model of three-point bending. The honeycombs are connected with outyer layers by Bonded contacts, which are rigid connections between parts. Contacts with frictions are used to model interactions between rollers and outer leyers. The Columb's friction model [31] is used with the coefficient of sliding friction f_N =0.1.

The boundary conditions for two bearing rollers are treated. They have two upper contacts with sandwich plate and two lower contacts with foundation (Fig.11). The boundary conditions «Remote Displacements» are satisfied on the contact line of the rollers with foundation. In this case, the displacements and rotation angles are equal to zero.

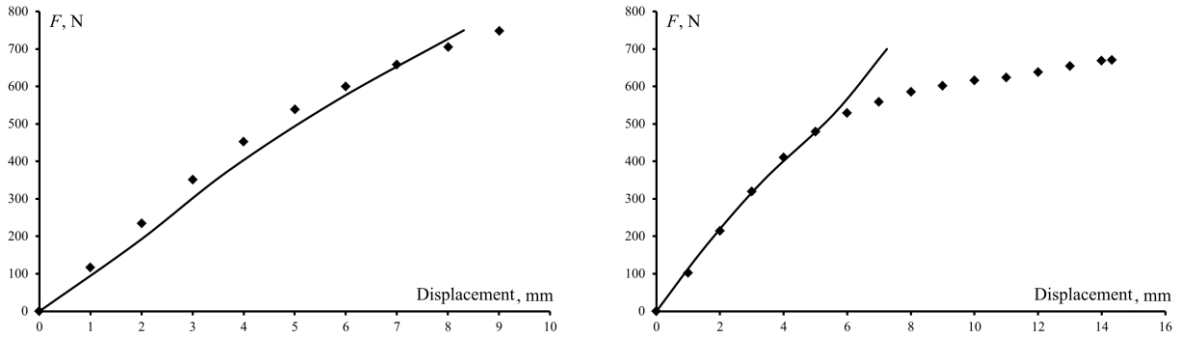
8. Results of modeling and experimental analysis of honeycomb tension

The results of numerical simulations of the honeycomb tension are compared with the data of experimental studies. The conclusions about behavior of four types of honeycombs with hexagonal, auxetic, quadratic and triangular cells are presented in this section.

Simulations of honeycombs permit to analyze their stress-strain state in wide range of loading. Figs.12-15 show both the experimental data and the results of the numerical calculations. The dependences of the tensile forces on the clamp displacements of the machine Tira Test 2300 are

presented on these Figures. The solid curves show the results of the numerical calculations and points present the experimental data.

The responses curves, which are shown on Figs.12a,b; 14a; 15a,b, have nonlinear behavior, which are explained by geometrically nonlinear deformation of honeycomb plates. This conclusion is made from the experiments on unloading of the samples from the nonlinear behavior. The unloading of the samples occurs on the loaded curves. The plastic strains are not observed in the samples after complete unloading. The samples take initial unloaded shape.



a. b.

Fig. 12. Calculation results and experimental data of hexagonal honeycombs tensions: a. – X is sample longitudinal direction; b. – Y is sample longitudinal direction

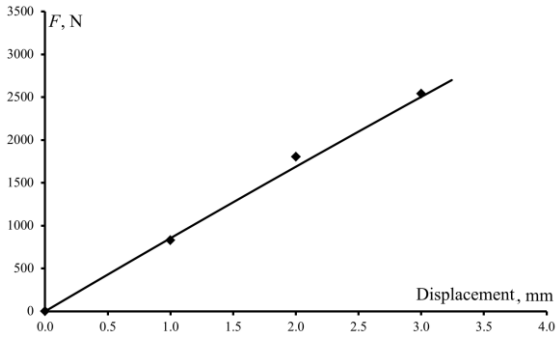
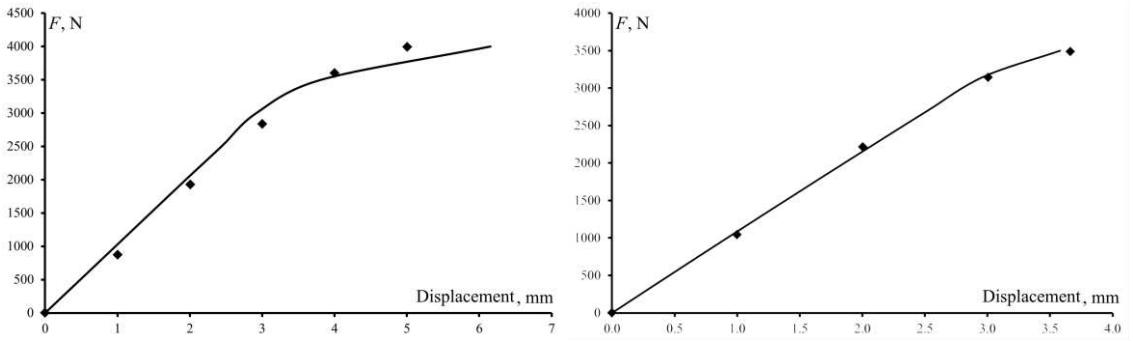
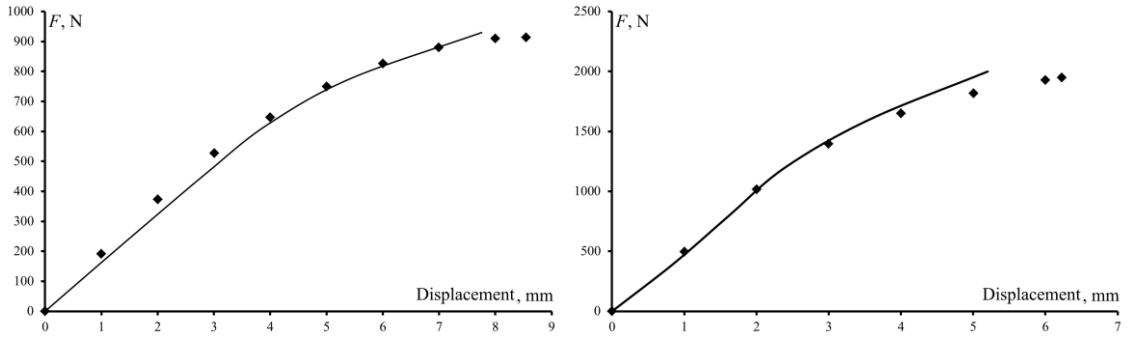


Fig. 13. Calculations results and experimental data on tensions of honeycombs with quadratic cells



a. b.

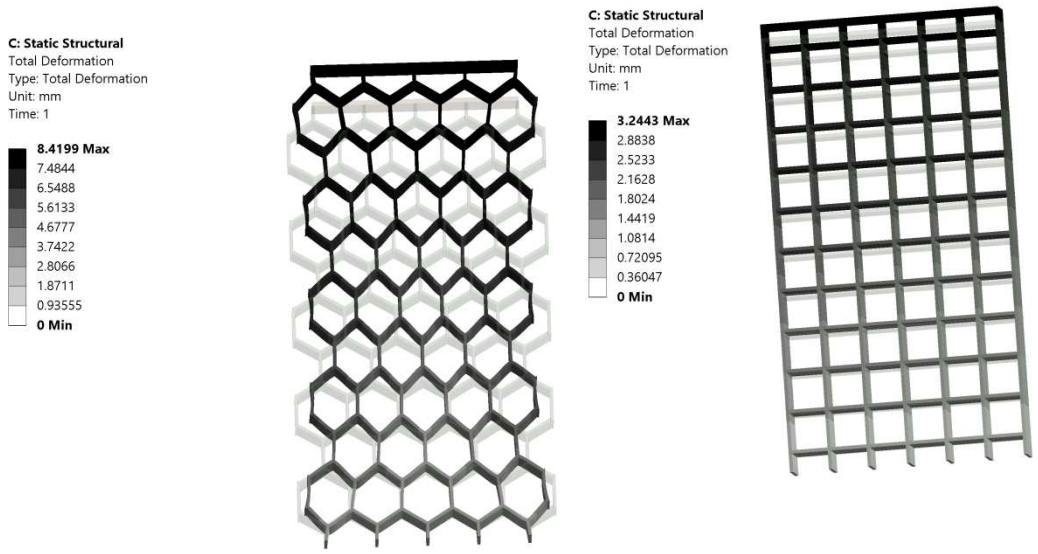
Fig.14. Calculation results and experimental data on tensions of honeycombs with triangular cells: a.- X is longitudinal direction of honeycomb; b. – Y is longitudinal direction of honeycomb



a. b.

Fig.15. Calculation results and experimental data of auxetic honeycombs tensions: a. – X is longitudinal direction; b. – Y is longitudinal direction

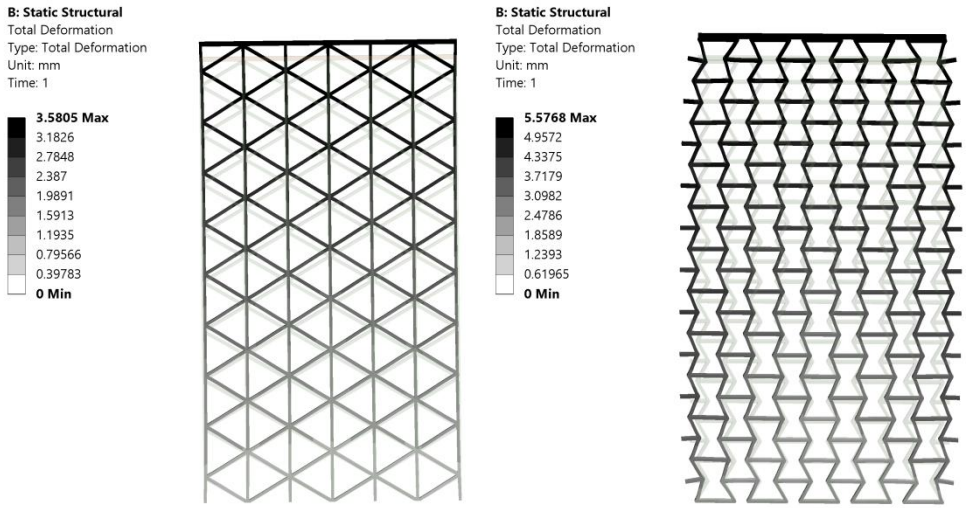
Figs.16, 17 show displacements fields of the honeycombs. Shadows are shown unstrained positions of the honeycombs. The honeycombs with quadratic and triangular cells do not change they width on tensions. The hexagonal honeycombs get narrow essentially on tension. The auxetic honeycombs are widened on tensions.



a. b.

Fig. 16. (a) displacements field of hexagonal honeycomb with X longitudinal direction;

(b) displacements fields of the honeycomb with quadratic cells



a. b.

Fig.17. (a) displacements field of honeycombs with triangular cells and Y longitudinal direction;

(b) displacements fields of auxetic honeycomb with Y longitudinal direction

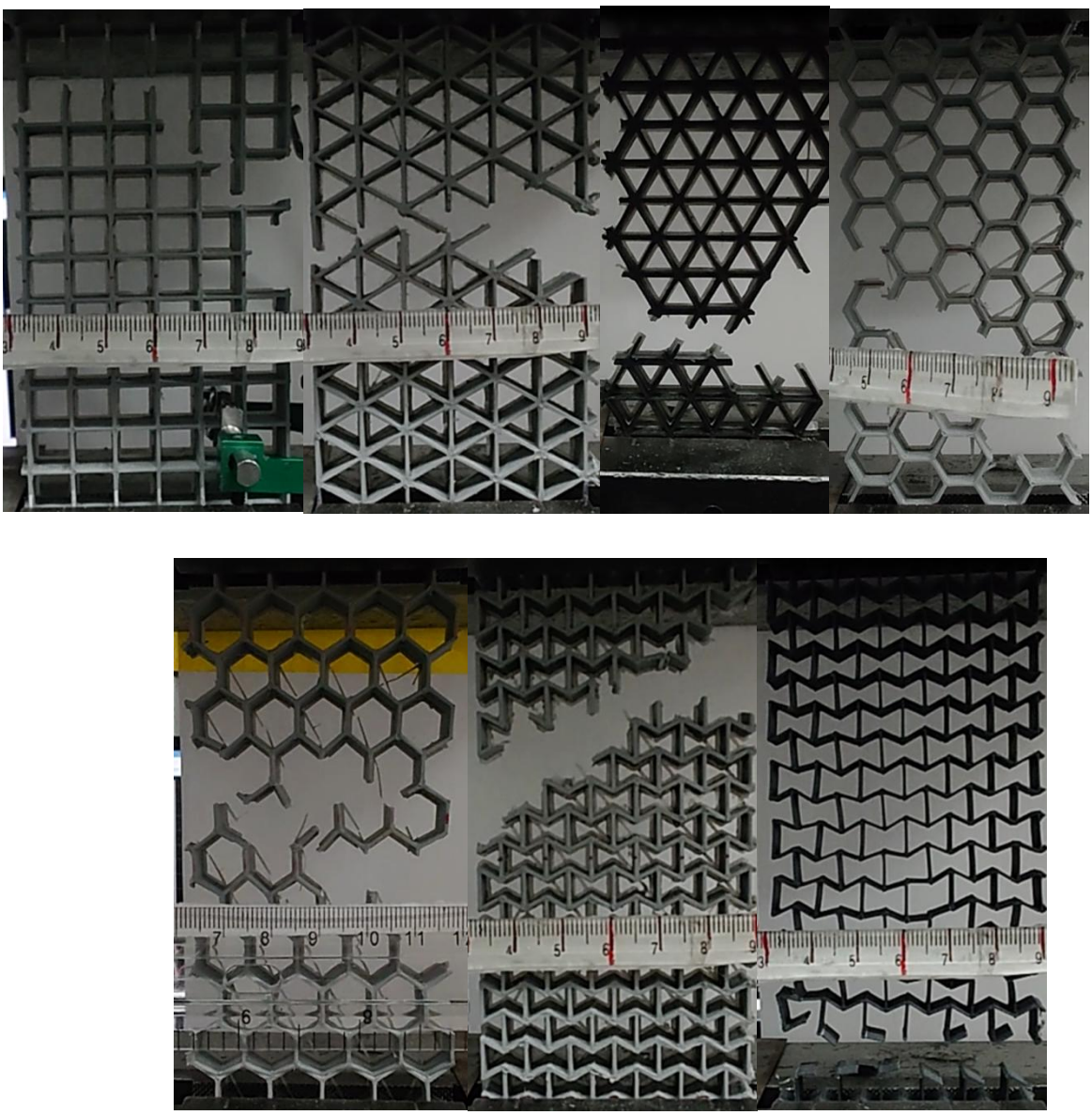


Fig.18. Photos of fractured samples owing to tension

The tensioned samples bring to fracture. Fig.18 shows the examples of the fractured samples as a result of tension.

The configurations of the cells affect essentially on honeycomb samples deformations. The following conclusions are made as a result of the study.

–The honeycombs with quadratic cells under the action of tensions have not transversal displacements; the tensions occur on the cells walls, which coincide with the loading axis;

– honeycombs with triangular cells have deformations properties close to honeycombs with quadratic cells; they differ by presence of small transversal contraction in honeycomb with triangular cells;

– hexagonal honeycombs have the least ultimate stresses and have maximal elongations and significant transversal contractions;

–hexagonal honeycombs have close mechanical properties in two main perpendicular directions;

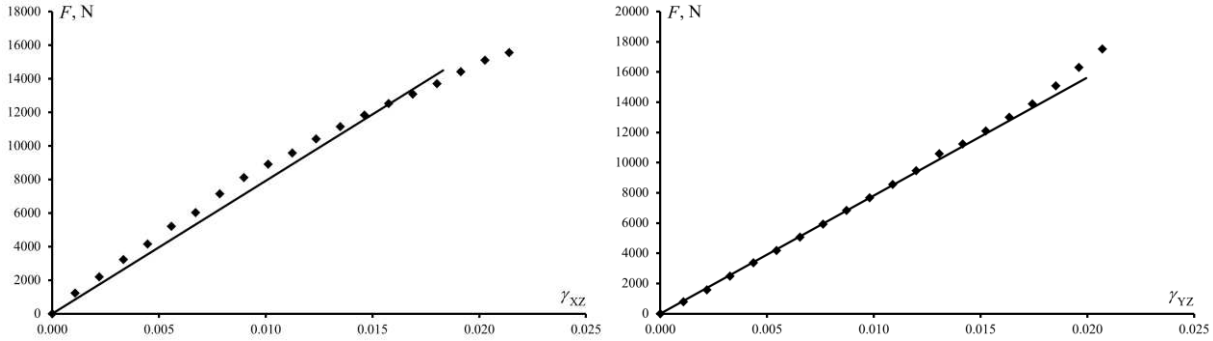
– auxetic honeycombs have middle values of the ultimate stresses in comparison with all types of honeycombs; the mechanical properties of the auxetic honeycombs in main perpendicular directions differ essentially;

– the tensions of the auxetic honeycombs in longitudinal directions accompany by tensions in transversal directions;

– samples with the same configuration have close mechanical properties.

9. Simulation results and experimental data on shear of honeycomb samples

The results of the experimental analysis of honeycomb shear with different cells are compared with numerical data in this section. Figs.19-22 show the calculations results of honeycombs shears and experimental data. The dependences of forces on the shear strains are shown on these Figures. Solid curves show the calculations data and the points present the experimental data.



a. b.

Fig.19. Simulations results and experimental data of hexagonal honeycombs shear:

a. – X axis is longitudinal direction; b. – Y axis is longitudinal direction

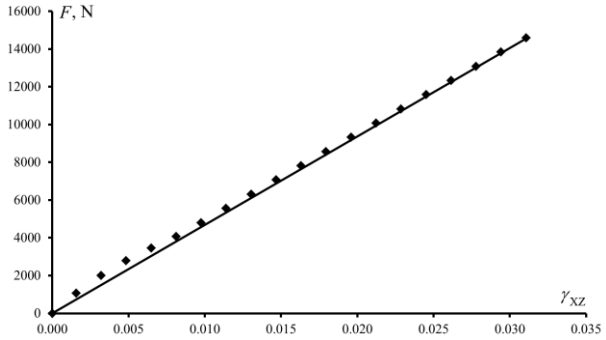
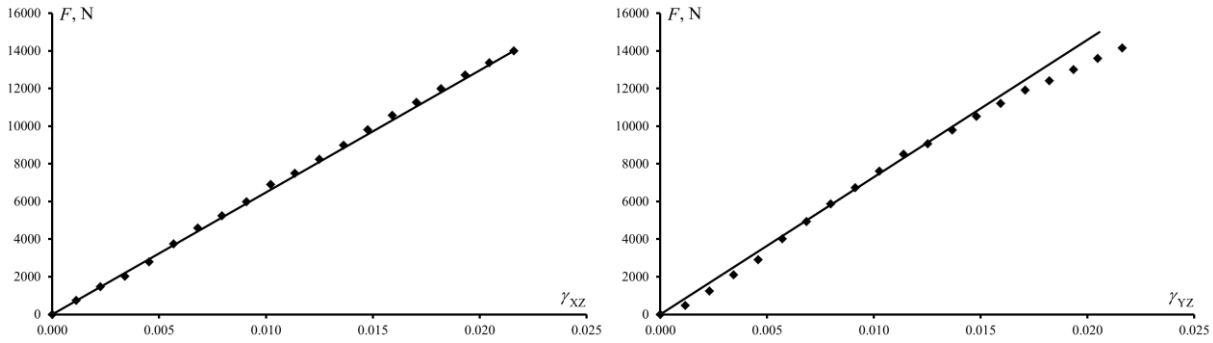


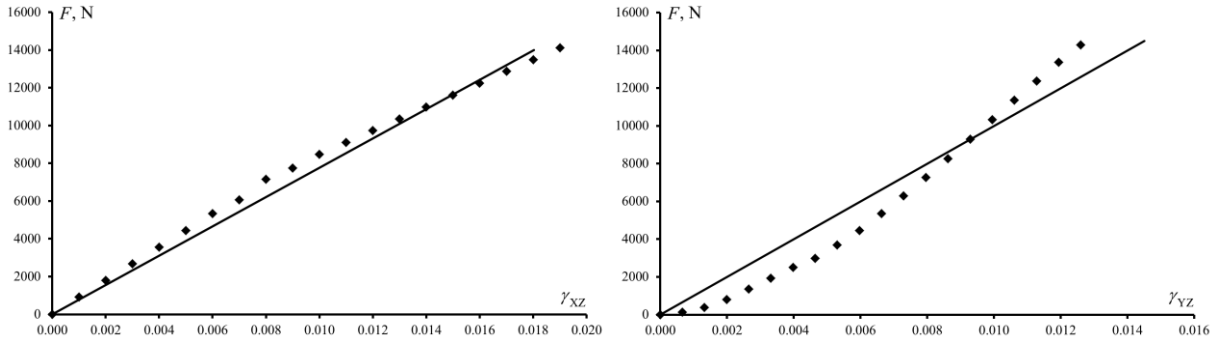
Fig.20. Simulations results and experimental data on shears of honeycombs with quadratic cells



a. b.

Fig. 21. Simulations results and experimental data on shears of honeycombs with triangular cells:

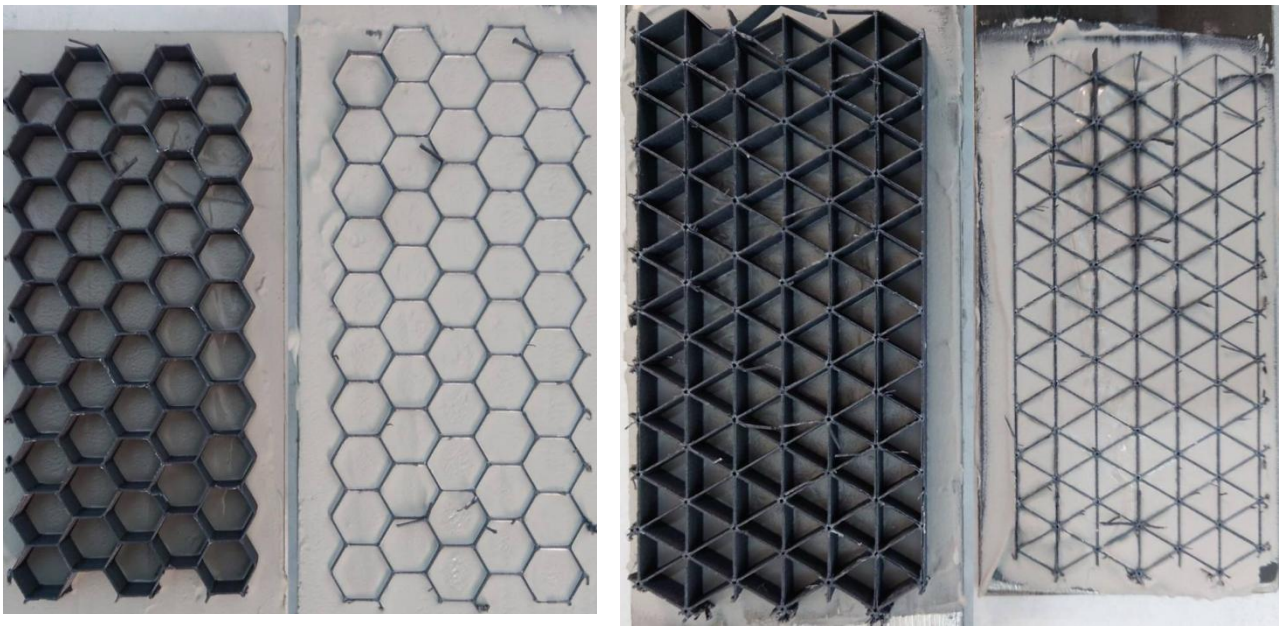
a. X is longitudinal direction; b. Y is longitudinal direction



a. b.

Fig.22. Simulation results and experimental data on auxetic honeycomb shear:

a. X is longitudinal direction; Y is longitudinal direction



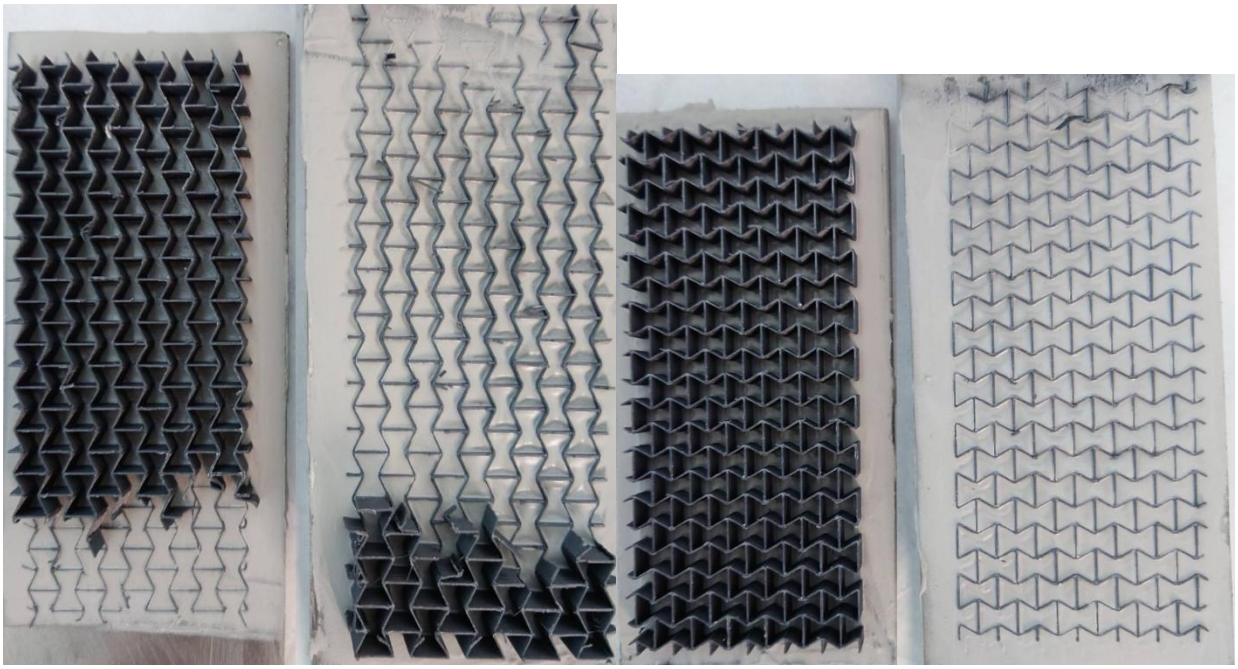


Fig.23. Fractures of samples at shear

As a result of the shear tests, the following conclusions are made. The samples are fractured in glue layer between honeycomb and steel plate. Fig.23 shows the fractured samples. The samples are fractured at loading range 18÷23 kN.

The experimental results on honeycombs shears and their fractures indicate the following:

– dependences of forces on shear strains are close to linear law; plastic strains and geometrical nonlinear behavior of the honeycombs are not observed up to the samples fractures;

– the glue LOCTITE® EA 9497 has the best strength properties in comparison with others epoxy analogs, which allows to glue complex surfaces;

–low dispersions of the experimental results for identical samples are observed, which is explained by technology of glue layer laying.

10. Homogenization of elastic properties of honeycomb

In many numerical studies of sandwich thin-walled structures, honeycombs can be replaced by solid orthotropic layer with equivalent mechanical properties [32, 6, 7, 33]. This is called homogenizations of the honeycombs. Such homogenized models can be used to analyze static and vibrational behavior of sandwich thin- walled structures. In this section, the results of the homogenization are compared with the experimental data.

The comparative analysis of equivalents mechanical properties of the homogenized honeycombs with the hexagonal, auxetic, quadratic and triangular cells is carried out in this section. The finite element homogenization procedure, which is considered in [32], is used for comparative analysis. This approach is based on the reference volume, which is a part of a cell of a honeycomb. The loadings are applied to the reference volumes to obtain flexibility matrix of a honeycomb. Thus,

the elasticity matrix and homogenized mechanical properties of honeycombs are obtained. The obtained numerical results are compared with experimental results, which are treated above.

Fig.24 shows all references volumes of hexagonal, auxetic, quadratic and triangular cells. The references volumes consists of PLA material and «elastic air», which has very small mechanical properties. The «elastic air» is used for continuity of displacements.

Homogenized mechanical properties of the honeycombs are obtained by numerical simulations. These values are shown in Table 4. X and Y directions of the honeycombs are shown on Fig.8. Direction Z is perpendicular to the plane XY. The following notations are used in Table 4: E is Young modulus; G is shear modulus; ν is Poisson ratio; ρ is average density. The mechanical properties of the honeycombs, which are obtained experimentally, are presented in Table 4. The numerical and experimental data are shown in columns A and B, respectively. As follows from this Table, the numerical and experimental results are close.

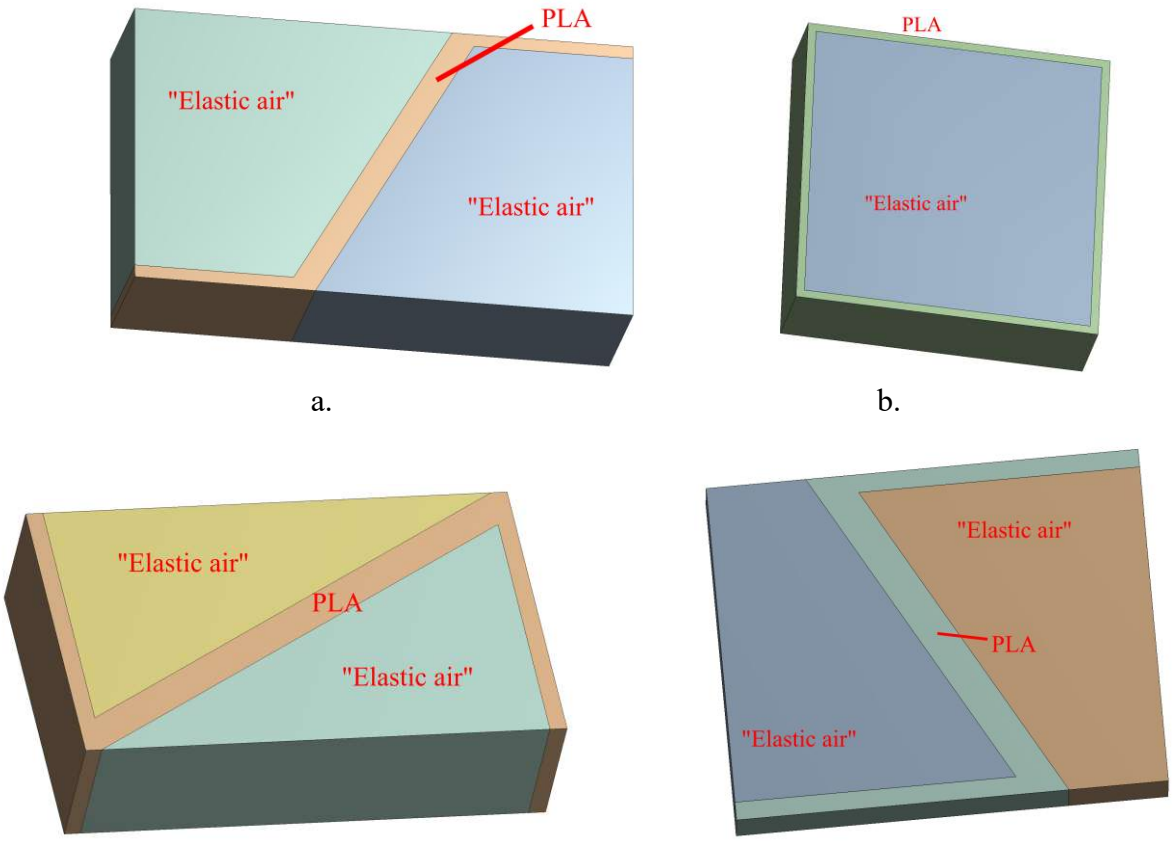


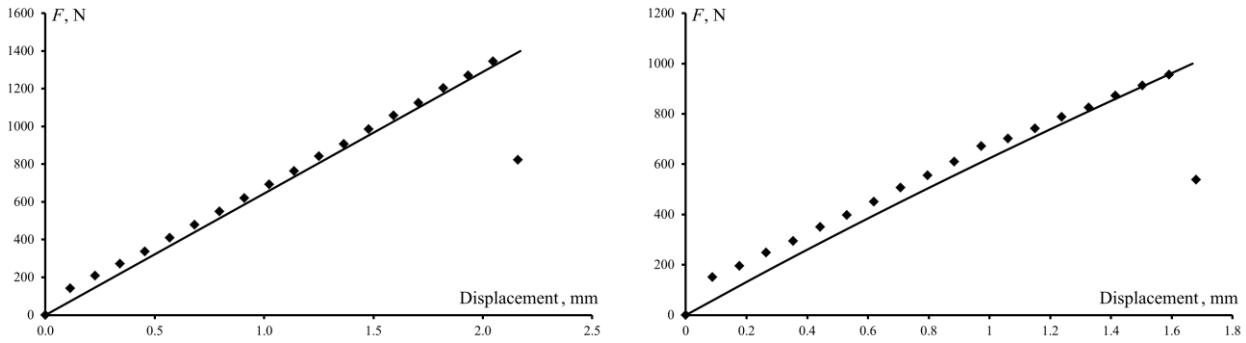
Fig.24. References volumes for finite element homogenizations of honeycombs: a. hexagonal cell; b. quadratic cell; c. triangular cell; d. auxetic cell

Table 4. Homogenized mechanical properties of honeycombs. Columns A and B shows the numerical and experimental data, respectively.

	Hexagonal		Quadratic		Triangular		Auxetic	
	A	B	A	B	A	B	A	B
E_x, MPa	12.3	13.0	142.2	151.0	162.4	161.5	29.6	29.3
E_y, MPa	12.5	13.2	142.0	151.0	173.1	171.2	59.2	63.3
E_z, MPa	77.2		327.8		387.3		342.4	
ν_{xy}	0.96	0.94	0.037	0	0.272	0.22	-0.657	-0.64
ν_{xz}	0.008		0.197		0.130		0.009	
ν_{yz}	0.005		0.197		0.139		0.018	
G_{yz}, MPa	60.9	58.0	34.2	32.8	52.1	50.1	81.3	79.6
G_{xz}, MPa	61.0	58.7	34.3	32.8	67.9	65.7	78.7	76.4
G_{xy}, MPa	4.85		0.9		57.3		7.0	
ρ, kg/m^3	141		203		240		283	

11. Results of experimental analysis and numerical simulations of three-points bending tests

The experimental studies and numerical simulations of three-points bending tests are performed according to the approaches considered above. Simulations results of three-point bending of sandwich plates with hexagonal, auxetic, quadratic and triangular honeycombs cells are shown by solid lines on Figs.25-28. The clamp displacements of the machine Tira Test 2300 in mm are shown in abscissa axes. The forces, which act on the cylinder C (Fig.11), are shown on ordinate axes. The experimental results are shown by points on Figs.25-28. As follows from experimental and numerical results, bending of plates satisfy the linear law. The fractures of the sandwich plates are brittle.



a. b.

Fig.25. Simulations and experimental results of hexogonal honeycombs sanwich plate bending:

a. X is longitudinal directions of honeycombs; b. Y is longitudinal directions of honeycombs

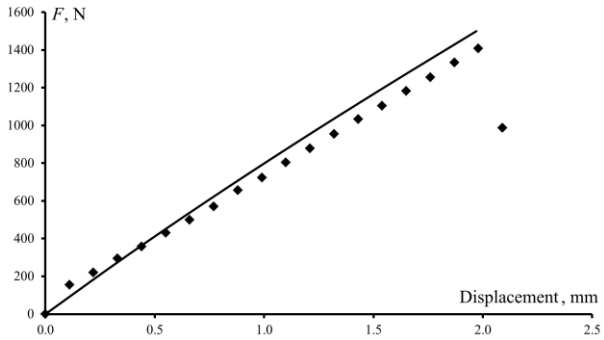
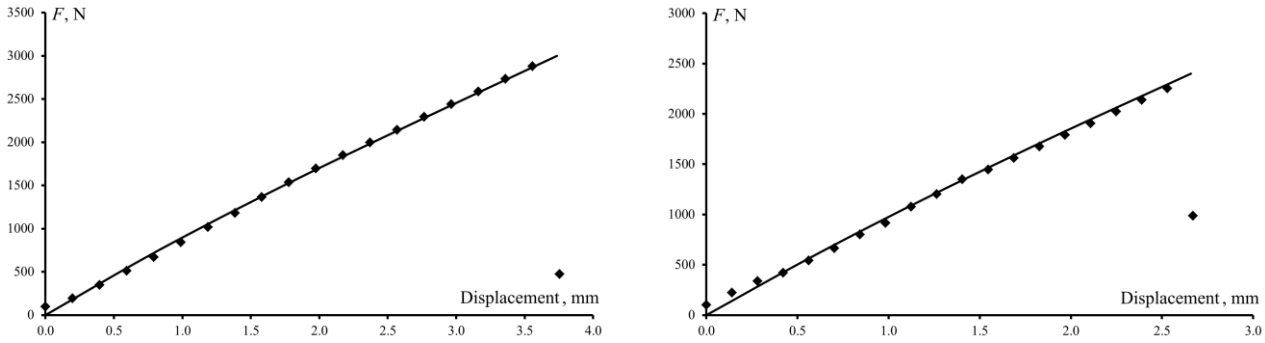


Fig.26. Simulations and experimental results of sandwich plate bending with quadratic cells honeycombs



a. b.

Fig.27. Simulations and experimental results of sandwich plates bending with triangular cells honeycombs: a. X is longitudinal directions of honeycombs; b. Y is longitudinal directions of honeycombs

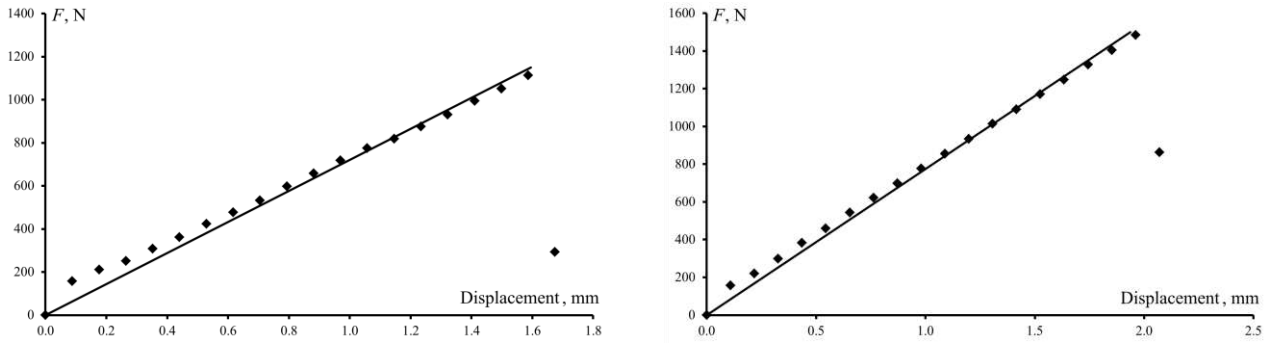


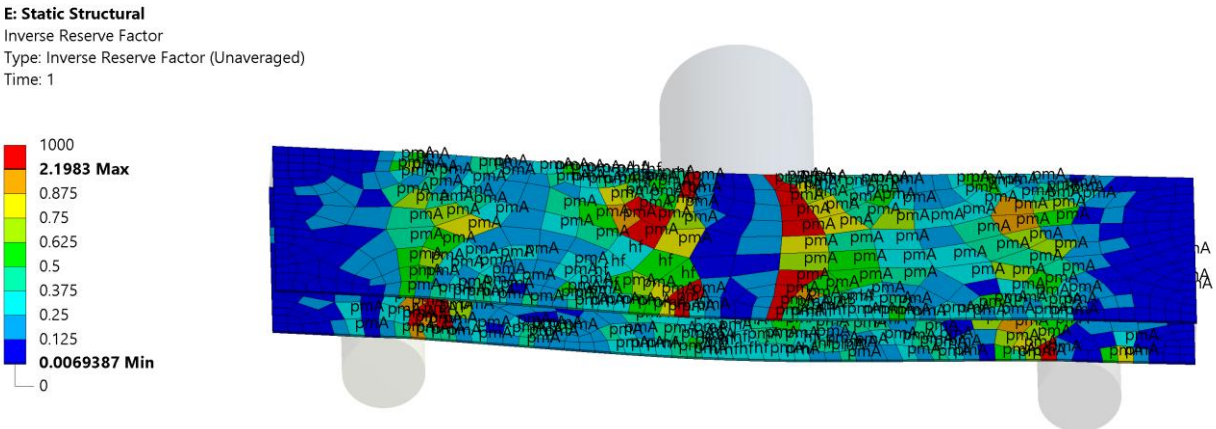
Fig.28. Simulations and experimental results of auxetic honeycombs sandwich plates bendings:

a. X is longitudinal direction of honeycombs; b. Y is longitudinal direction of honeycombs

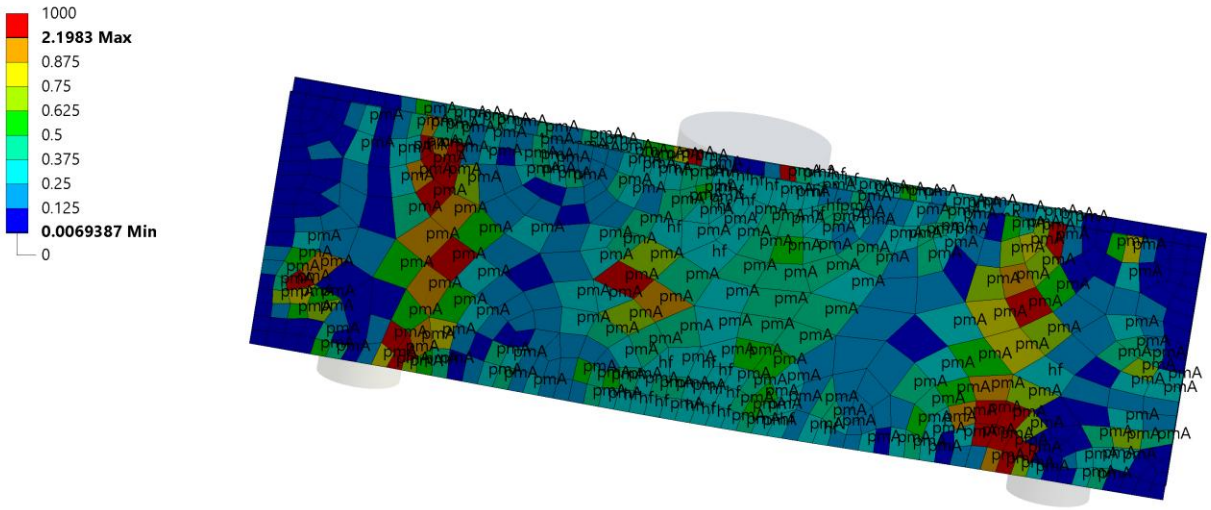
Numerical simulations include strength analysis of three-point bending tests of the sandwich plates. Inverse reverse factor (IRF) [34-39], which is calculated in software ACP Post, is used for fracture analysis. IRF is a parameter, which is used to identify the composite failure. A composite structure is failed, if IRF>1. If IRF<1, a composite structure is safe. In order to perform numerical studies, the load 2250 N is applied on the cylinder C (Fig.11). The mechanical properties of outer layers material are taken in the form (2) and the mechanical properties of honeycombs are taken in the form (1).

The puck failure criterion [34-39], which is accounted fiber degradation, is used to simulate fracture of outer layers. The ultimate strains in the outer layers plane is: $\varepsilon_{1,lim} = 0.014$ and the ultimate strains in the transversal direction $\varepsilon_{2,lim} = 0.005$. The ultimate shear strain is $\gamma_{lim} = 0.01$.

The IRF fields on top and bottom layers of sandwich plate are shown on Fig.29. The outer layers fracture can be observed in the red regions. The regions of contacts between outer layers and cylinders A, B, C (Fig.11) belong to red area. Glue joints between honeycombs and outer layers are not accounted in the considered model of strength. Therefore, the fracture owing to delamination in sandwich plate is not predicted by this model.



a.



b.

Fig.29. IRF distribution in the outer layers of honeycomb with triangular cells ans X orientation:

a. top layer; b. bottom layer

The character of sanwich structures fractures are analyzed experimentally using three-point bending tests.

The fractures of the sandwich plates with quadratic honeycombs cells are observed by breaks of cells walls corners in the cental part of the plates. In these regions debonding of the layers take place too.

The fractures of the sandwich plates with triangular honeycombs cells are observed in the form of top layer debonding. These debondings take place between cylinder C and cylindre A or between cylinder C and cylinder B (Fig.11). These fractures accompany by bearing failure of the honeycombs.

The sandwich plates with hexagonal cells honeycombs are fractured by cracks originations and their growth in the honeycombs between cylinder C and cylinder A or between cylinder C and cylinder B. Fig.30 shows this type of fracture.

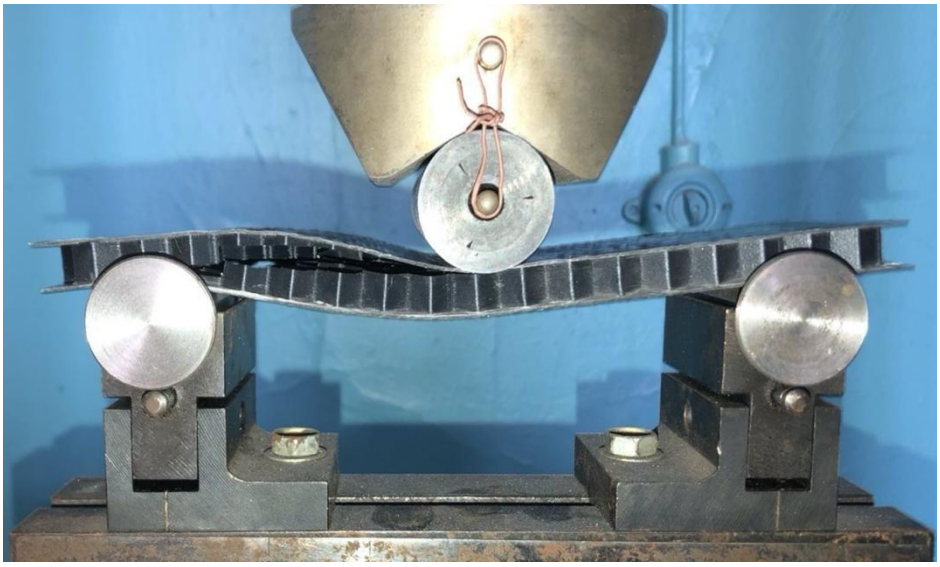


Fig.30. Fracture of sandwich plate with hexagonal honeycomb

Fractures configurations of the sandwich plates with auxetic honeycombs are similar to fractures of sandwich plates with triangular cells honeycombs. Fig.31 shows example of this fracture.

Character of fracture does not depend on X or Y longitudinal direction of honeycombs cells (Fig.8). Fractures natures of every kind of honeycombs are different, which are explained by deformations of honeycombs and strength of gluing.

The sandwich plates with triangular cells honeycombs are the most strength among the considered structures.

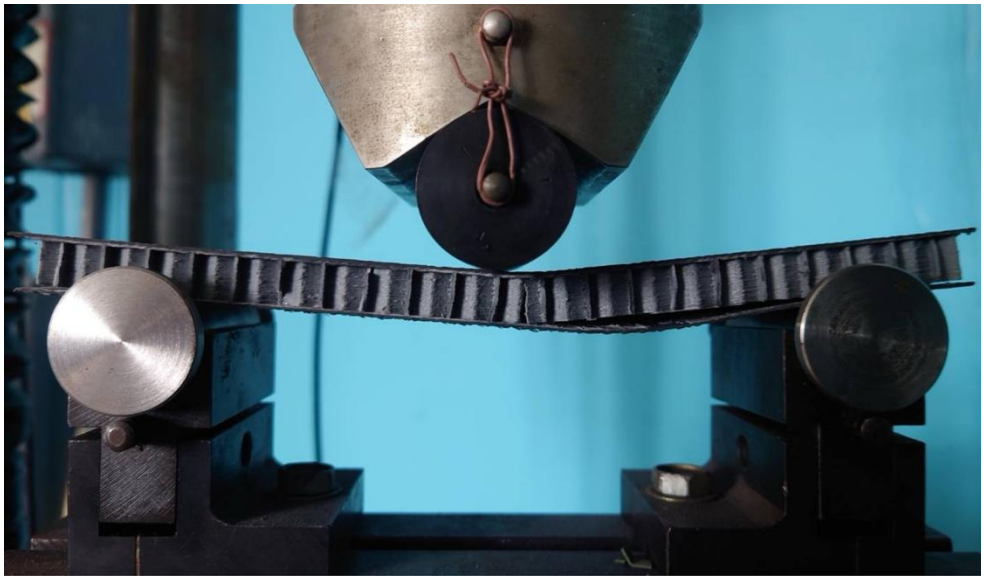


Fig.31. Fracture of sandwich plate with auxetic honeycomb

12. Discussions and conclusions

Study of mechanical properties of the honeycombs permits to make the following conclusions:

– the honeycombs with hexagonal cells are the most light among considered samples. These honeycombs have the greatest ratios of transversal shear module to masses. The ratios of ultimate transversal shears of hexagonal honeycombs to the masses are the greatest among the honeycombs.

– The honeycombs with quadratic cells are the most compliant on transversal shears and the most stiff on the tensions. The widths of such honeycombs are not changed on tensions. The ratios of stiffness on transversal compressions to masses are the greatest.

– The honeycombs with triangular cells have the greatest ratios of the stiffness on transversal compressions to the masses. These honeycombs are the most strength on the tensions. These honeycombs have the most high shear module in plane G_{xy}. The widths of these samples are changed slightly on the tensions.

– The auxetic honeycombs have high transversal mechanical properties E_z, G_{yz}, G_{xz} and low stiffness and strengths on the tensions.

– The cells configurations effect essentially on honeycomb plates strains at tension.

– The honeycombs with quadratic cells have not transversal displacements at uniaxial tensions. The tensions take place on the cells walls, which have the same directions with the loadings axes;

– the properties of triangular cells are closed to the properties of quadratic cells. The triangular cells have short enhancements of the ultimate strengths;

– hexagonal honeycombs have the least ultimate strength among considered honeycombs and have maximal elongations and big transversal contraction;

– hexagonal honeycombs have close mechanical properties in the X and Y directions;

– auxetic honeycombs have middle values of the ultimate strengths and middle values of the ultimate axial strains among all considered honeycombs. The mechanical properties of the auxetic honeycombs differ essentially in different directions.

– If the auxetic honeycomb is tensioned in longitudinal direction, this sample is enlarged in transversal direction. This is the most important properties of the auxetic honeycombs.

– The honeycombs of the same kinds have close mechanical properties.

– If loadings on a honeycomb are not known exactly, the honeycomb with triangular cells must be used.

The experimental and calculations studies of the three-points bending of sandwich plates are performed. The sandwich plates bending takes place according to linear laws. Plate fracture is brittle. The geometries of the cells influence slightly on the bending stiffnesses of the sandwich plates. The sandwich plates with triangular honeycombs are strength by 2 times, than the plates with the hexagonal honeycombs. The auxetic honeycombs supply the greatest bending strength of the sandwich plates.

Fracture natures of the sandwich plates are studied on the basis of experimental study of big number of samples using three-points bending. The following conclusions about sandwiches fractures are made.

– The fractures of the sandwich plates with quadratic cells are observed in central parts of the samples in the form of cells walls destructions and delamination of the layers in these areas.

– The fractures of honeycombs sandwich plates with triangular cells are observed between the loading shafts and bearing rollers by delamination of the upper layers. The fractures are accompanied by honeycombs bearing failures in the contacts areas of the loading shafts and sandwich plates.

– The fractures of honeycombs sandwich plates with hexagonal cells originate by cracks formations on the honeycombs materials and these cracks growth between loading shafts and bearing rollers. The sandwich plates with auxetic honeycombs are fractured similarly to plates with triangular honeycombs.

– Natures of sandwich plates fractures do not depend on the longitudinal orientations of the honeycombs cells (X or Y). Types of fractures of the sandwich plates honeycombs are essentially different and depend on the honeycombs cells configurations, which are explained by deformations of the honeycombs and strengths of the glue joints.

The sandwich plates with triangular cells honeycombs are the most strength among the considered in this article.

Authors Contributions Uspensky and Usserov performed numerical simulations. Derevianko and Salenko carried out all experimental work. Avramov and Myrzaliyev suggested methodology of research and wrote the paper. Maksymenko-Sheiko printed the samples.

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Data Availability The data generated during the current study are available from the corresponding author on reasonable request.

Declarations
Competing Interests The authors declare no competing interests.

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