DOI: https://doi.org/10.15407/pmach2024.03.025

UDC 539.3

MANUFACTURING TECHNOLOGY, EXPERIMENTAL AND NUMERICAL ANALYSIS OF STATIC BENDING OF THREE-LAYER COMPOSITE PLATE WITH HONEYCOMB STRUCTURE

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The use of thin-walled constructions with honeycomb structure manufactured using additive technologies has several advantages compared to the constructions manufactured using traditional technologies. First of all, this is explained by the fact that additive technologies greatly simplify the production of honeycomb structures. A technology for manufacturing a three-layer composite plate with a honeycomb structure obtained using additive technologies is proposed in the paper. PLA plastic was chosen as the material for the honeycomb structure production. Printing was carried out using a "Delta" printer with parallel kinematic chains using FDM technologies. The printing temperature was 215 °C, table temperature – 60 °C. A fundamentally new scheme of an experimental plant for studying the bending of a three-layer plate is proposed. The aim of the research is to conduct tests of samples of a three-layer honeycomb panel for static bending when one edge of the sample is rigidly pinched. For the tests, a certified TiraTest 2300 universal testing machine (UTM), which allows to perform tensile and compression tests at a given traverse speed and measure the load with a relative error of 1%, was used. The UTM allows to load the sample and measure the load and displacement of the traverse. A sixteen-channel strain gauge station is used to measure the surface deformations of the housings. Transverse displacements of a three-layer plate were obtained as experimental data. The bending of the three-layer plate is modeled in the commercial package ANSYS. The results of experimental and numerical analysis coincide well.

***Keywords**: three-layer composite plate, additive technologies, honeycomb structure, finite element model.*

Introduction

The use of thin-walled constructions with honeycomb structure manufactured using additive technologies has several advantages compared to the constructions manufactured using traditional technologies [1–5]. This is due to the fact that additive technologies significantly simplify the production of honeycomb structures and sandwich shells [6, 7]. Honeycomb structures have great strength and rigidity, as well as low weight. These properties are very important for aerospace applications. Moreover, additive technologies can be used for the design and production of satellites and other aircrafts [8, 9].

Some effort has been devoted to the experimental and numerical analysis of honeycomb structures manufactured using additive technologies. Finite element modeling and experiments on the analysis of loss of stability of additively manufactured honeycomb structure with defects are considered in [10]. Resistance to loss of stability of octagonal honeycomb structure is better than that of traditional hexagonal honeycomb structure [11].

A technology for manufacturing a three-layer construction with a honeycomb structure made using additive technologies is proposed in this paper. Thanks to the use of the specified technology, three-layer plates with honeycomb structures were produced. A method of studying the static deformation of three-layer plates with a honeycomb structure printed using additive technologies is proposed. The results of experimental studies are compared with the results of numerical simulation in the ANSYS program.

Technology of manufacturing three-layer plate samples for static tests

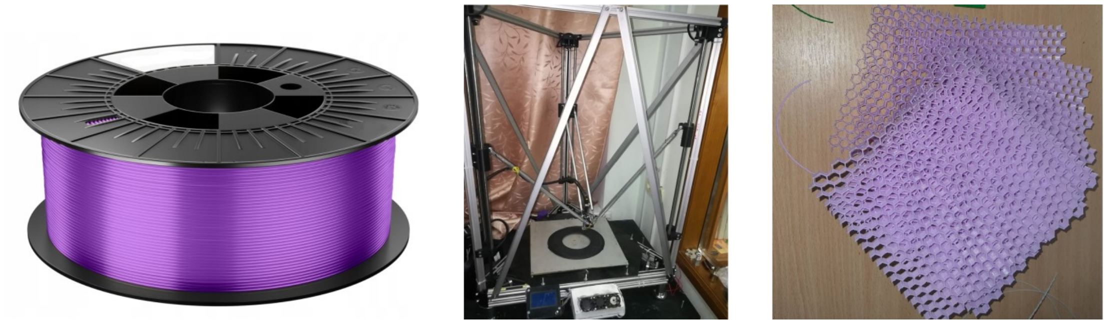
The manufacturing technology of the three-layer plate sample for static testing consists of four blocks of operations, such as:

– production of honeycomb structure from thermoplastic using FDM additive technology;
– production of housing from carbon plastic;
– gluing of honeycomb structure with a three-layer panel;
– mechanical processing of a three-layer panel.

It should be noted that the manufacturing technology of honeycomb structure is considered in [4].

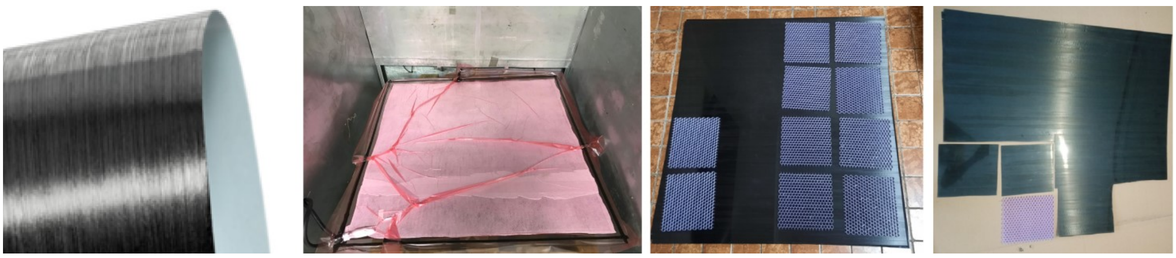
PLA plastic (Fig. 1, a) was chosen as a material for the honeycomb structure production. Printing was carried out on a "Delta" printer with parallel kinematic chains (Fig. 1, b) using FDM technologies. The printing temperature was 215 °C, the table temperature was 60 °C in accordance with the recommendations for printing with this material. Blanks of honeycomb structure (Fig. 1, c) with dimensions of 200 mm×180 mm×10 mm were produced.

Carbon fiber based on SIGRAPREG C U200-0/NF-E310/30% prepreg (Fig. 2, a) was chosen as the housing material. The thickness of the layer is 0.2 mm. Structurally, the upper and lower housings are made symmetrically, each consists of four layers with a laying scheme of 0, 90, 0, 90. The layers are laid layer by layer according to the scheme in a logement, which is placed in a vacuum film, which is installed in an assembly in the oven, and polymerization is carried out according to the mode specified by the manufacturer (Fig. 2, b, c). An important feature is taken into account when laying the prepreg in the logements: fabrics, which allow the outer surface to be smooth, and the inner surface to be rough, are laid on the inner and outer surfaces. Roughness provides increased adhesion during gluing. As a result, a plate for housings with dimensions of 1000 mm×1000 mm×0.8 mm was made. Before the production of three-layer panels, the plate was cut into blanks (Fig. 2, d) with dimensions of 200 mm×200 mm.



a b c

Fig. 1. Honeycomb structure production:
a – coil with filaments of PLA plastic; b – "Delta" printer with parallel kinematic chains;
c – produced blanks of honeycomb structure from thermoplastic



a b c d

Fig. 2. Production of housings from carbon fiber:
a – single layer of prepreg; b – prepreg in the process of polymerization in the oven;
c – produced carbon fiber plate; d – cutting into blanks

The gluing of the honeycomb structure with the housings was carried out with 3M Scotch-Weld DP190B/A (Grey) two-component epoxy glue. Previously, the inner surface of the housings was treated with a peel and wiped with isopropyl alcohol. An even layer of glue was applied to the housings through a plunger using a syringe-applicator with smoothing with a rubber spatula according to the markings made. The resulting blanks were placed in a vacuum bag on a fabric backing with the plates with the adhesive seam facing down, preventing the glue from flowing. To prevent crumpling of the honeycomb structure, a technological plate cut to the dimensions of the structure was placed on the upper part of the blanks. The assembly was vacuumed, ensuring uniform pressing of the structure at a pressure of 0.95 atm for 22 hours until the gain of transportation strength. The lower housing was glued similarly. Before mechanical processing, the parts were aged for 14 days.

Mechanical processing was carried out using a TT180-BM cutting machine (Fig. 3, a) with a pump for aspiration of harmful coal dust and a JET JSG-64 grinding machine (Fig. 3, b) for the samples ends fitting. Masking tape was previously glued to the cutting site to prevent peeling of threads and harnesses at the ends of the carbon-plastic housings. After cutting, the tape was removed. For the same purpose, grinding was performed exclusively in the longitudinal direction. Ready three-layer samples are shown in Fig. 3, c.

a b c

Fig. 3. Mechanical processing of a three-layer panel:
a – cutting machine TT180-BM in the process of cutting; b – grinding machine JET JSG-64;
c – completed three-layer samples for static and cyclic bending tests

Experimental analysis of static deformation of a three-layer plate

The aim of the research is to conduct tests of samples of a three-layer honeycomb panel for static bending when one edge of the sample is rigidly pinched. For this purpose, a certified TiraTest 2300 universal testing machine (UTM) (Fig. 4), which allows to perform tensile and compression tests with a given traverse speed and measure loads with a relative error of 1%, was used. The UTM allows to load the sample and measure the load and displacement of the traverse. A sixteen-channel strain gauge station is used to measure the deformations of the housings surface, which allows measuring deformations with an accuracy of 0.001%.

A modified three-point bend (Fig. 5, a) was used to fasten the sample. Direct fastening of the sample is carried out in pressure-type clamps, taking into account the provision of a horizontal level. The influencing roller is a cylinder with a diameter of 30 mm. The point of contact of the roller is 15 mm away from the edge of the sample. In addition, to confirm the reliability of displacement measurement, a time-type displacement indicator was used, and strain gauges of the BF200-10AA-A(11)-BX30 type were used to register deformations. 12 strain gauges were installed on each sample according to the scheme (Fig. 5, b).

Before placing the sample in the clamps, strain gauges are glued to it using a cyanoacrylate-based glue. A microcircuit with resistors is installed for each strain gauge, which is a bridge measuring circuit. For their installation, cardboard overlays are glued to the sample. Those overlays do not affect the stiffness of the sample, but at the same time allow for the installation of microcircuits (Fig. 6, a), which excludes sagging and breakage of the antennae of the strain gauges.

During the tests, the sample was loaded smoothly at an average speed of 2 mm/min. As a result of the tests, two types of possible destruction of the samples were observed: a fracture in the fastening zone or fragmentary separation of the housings from the honeycomb structure in the area of maximum bending (Fig. 6, b).

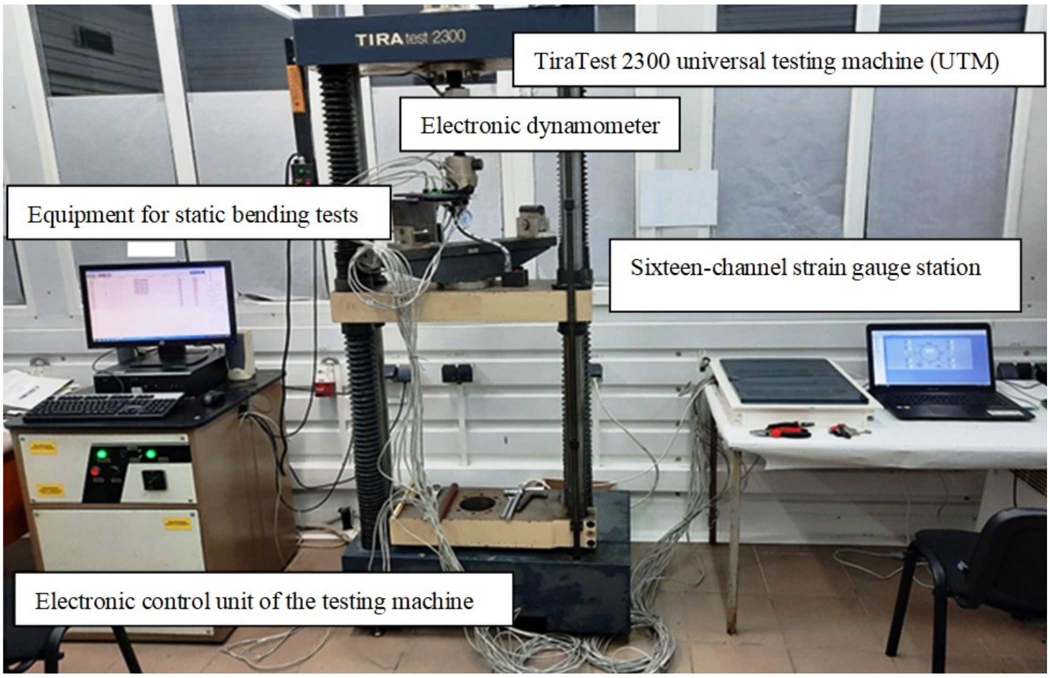
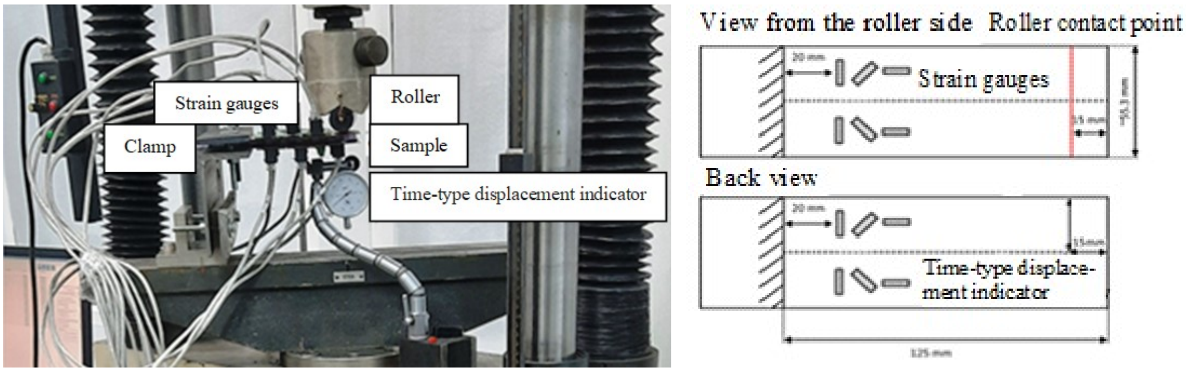
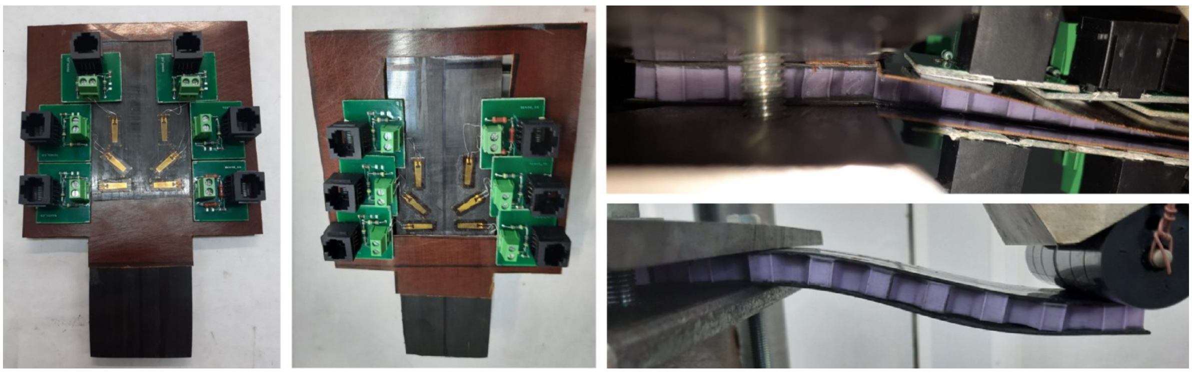


Fig. 4. Picture of the experimental plant for static bending tests



a b

Fig. 5. The sample fastening in the test equipment:
a – picture of fastening; b – sample diagram showing dimensions



a b

Fig. 6. A sample of a three-layer honeycomb panel before and after loading:
a – photo of housings with installed strain gauges and microcircuits; b – typical destruction of the sample

Based on the obtained data, the dependences of load and deformations before failure were constructed (Fig. 7). The values of the deformations of the horizontal and inclined strain gauges record insignificant values commensurate with the measurement error. The strain gauges that were glued in the longitudinal direction are of main interest.

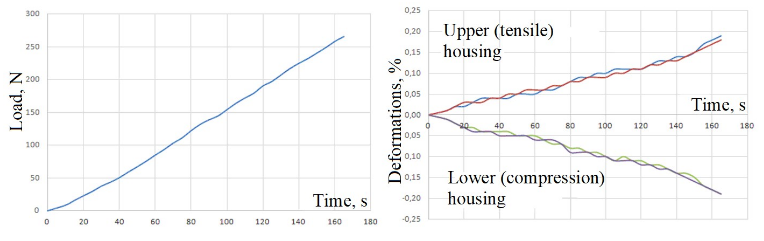


Fig. 7. Graphs of dependences of loads and deformations

As can be seen (Fig. 7), the obtained deformation curves are very close. At the same time, the tensile deformations of the upper housing are close to the compressive deformations of the lower housing. Uniform deformations across the width and between the skins of the honeycomb panel samples indicate that the panel is a high-quality, one-piece and uniformly rigid structure.

Three samples were made for experimental research and were studied. The obtained results are similar.

Mathematical model of the study of static deformation of the plate

The mathematical model, which is used in the study of the stress-strain state of the honeycomb structure in the composition of a three-layer plate, is considered. The finite element analysis platform ANSYS Workbench (ANSYS WB) came in handy for building the mathematical model. Mathematical model consists of the following components: geometric model; physical model of used materials; finite element model; model of boundary conditions; load model.

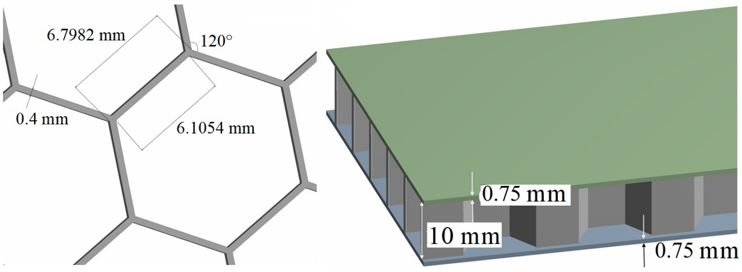
A sandwich plate consisting of carbon fiber housings and honeycomb structure manufactured by the FDM method is considered. The process of making a sandwich plate is described above. When modeling, the thickness of the housings is assumed to be 0.75 mm. The adhesive joint is considered ideal and inelastic; therefore, a three-layer model is chosen to simulate the static deformation of the plate [4, 5]. The geometric parameters of the sandwich plate and the cells of the honeycomb layer are shown in Fig. 8.

DesignModeler software, which is part of ANSYS WB, was used to build a geometric model. The geometric model of the honeycomb structure is constructed in two versions: as complete and as homogenized ones. The complete model includes modeling of honeycomb structure with finite element model construction of each cell, homogenized is a honeycomb structure with a uniform layer with effective mechanical properties.

The geometric model of the honeycomb structure is built by modeling one cell with a wall thickness of 0.2 mm and copying it sequentially. As a result, we will get a collection of solids shown in Fig. 9.

Parallelepipeds with a thickness of 0.75 mm are built to model the housings of the sandwich plate, which are positioned with the help of Translate operations along the structure edges.

To assess the deformations in the places where the strain gauges are attached, points are placed on the housings using the Point tool. The Remote Force point type allows to get data about strain values. Models of housings and structure are combined into a single Part object to reduce the number of contacts in finite element model and to form a correct mesh.



a b

Fig. 8. Geometric dimensions of the object:
a – cell dimensions of the structure; b – dimensions of the plate layers

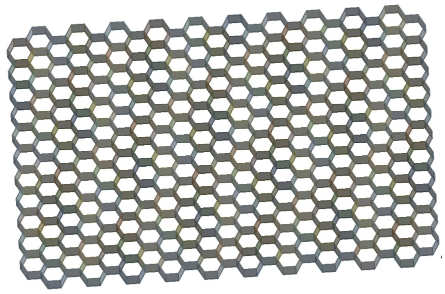


Fig. 9. Honeycomb structure

In the homogenized model, the honeycomb structure is a homogeneous parallelepiped (Fig. 10). Places of attachment of strain gauges and the load plane are set similarly to the full geometric model.

The materials of the housings (4-layer composite SIGRAPREG C U200) and the structure (PLA) are orthotropic. Their mechanical characteristics, as well as the characteristics of the homogenized structure, are given in the table.

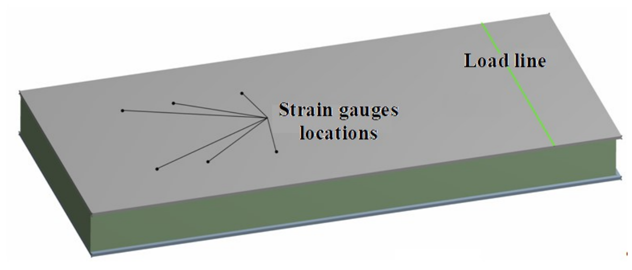


Fig. 10. Homogenized sandwich plate model

For housing materials and homogenized structure, the *XY* plane corresponds to the plane of the housing (structure), the *Z* axis is transverse. For PLA, the *X* axis corresponds to the direction of the thread laying, the Y axis is perpendicular to it in the plane of the print layer, the Z axis is perpendicular to the print layer.

The standard Ansys Mechanical subroutine is used to build finite element model. As a result, a finite element grid was built, including 6,106,989 nodes and 1,999,604 elements. The average value of the Element Quality metric was 0.84126. The plate housings are divided into tetrahedral elements. Finite element model of honeycomb structure consists mainly of 20-node hexagonal elements.

Table. Mechanical properties of sandwich plate materials

Characteristic	Housing	PLA	Homogenized aggregate
Elasticity modulus during tensile (*X* / *Y* / *Z*), MPa	35000 / 35000 / 8000	3580 / 3000 / 3810	2.16 / 2.16 /272.67
Elasticity modulus during shear (*XZ* / *YZ* / *XY*), MPa	30000 / 30000 / 6000	1400 / 1410 / 1070	52.29 / 52.29 / 0.84
Poisson's ratio (*XZ* / *YZ* / *XY*)	0.09 / 0.09 / 0.01	0.21 / 0.22 / 0.30	0.0018 / 0.0017 / 0.98
Density, kg/m^3	1477	1240	88.741

To take into account the anisotropy of the material, the orientation of the bound coordinate system of the finite elements is determined. The Element Orientation utility is used for this. Finite element model elements of the housings are directed along the axes of the global coordinate system. For the task of orientation of the connected coordinate system elements of the structure, they are directed along the Y axis perpendicular to the side surfaces of the cells, and along the *Z* axis – parallel to the transverse direction.

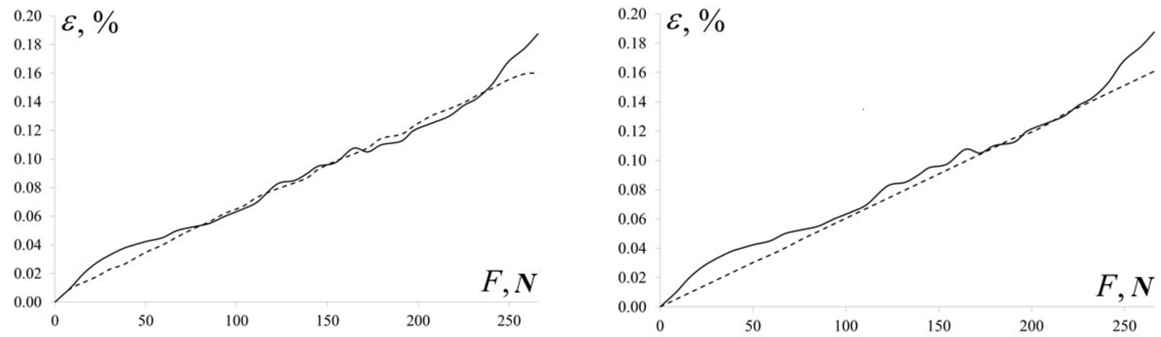
When conducting static tests, the plate is fixed in clamps. Fixed Support boundary conditions are used to model these clamps.

Plate loading is modeled using the Force tool, where forces are applied to the load line. The applied force corresponds to the value measured during the experiment. It is directed in the direction opposite to the *Z* axis of the global coordinate system.

A finite element analysis of the static deformation of a three-layer sandwich plate under the influence of a transverse load was carried out. The ANSYS WB platform, the Static Structural system of the Ansys Mechanical package was used for numerical analysis. The force value varied from 0 to 265.89 N. The same force values were used in the experiment.

Two plate models were chosen for calculations. In the full model, direct modeling of honeycombs was used, and in the homogenized model, the honeycomb structure was replaced by a homogeneous orthotropic layer. The deformations of the outer surface of the plate at the points of installation of strain gauges were compared. For this, the Normal strain/Shear strain tools of the Ansys Mechanical package were used at the strain gauge installation points. Since the values of the deformations at the points on the left, right, top and bottom of the plate are the same in magnitude, the average readings of the strain gauges at four points were used as reference data.

A comparison of the longitudinal deformations of the sample obtained by the results of the finite element analysis (dotted line) and the experiment (solid line) is shown in Fig. 11. The value of the force applied to the roller (in the experimental analysis) or to the load line (in the finite element analysis) is plotted along the abscissa axis, and the values of the longitudinal deformations of the upper housing at the place of the strain gauge attachment are plotted along the ordinate axis.



a b

Fig. 11. Comparison of the results of the finite element analysis with the results of the experiment:
a – complete finite element model; b – homogenized finite element model

Conclusions

The results of the finite element simulation are close to the experimental data for both the complete and the homogenized sandwich plate deformation model. Significant differences in the results start being observed at force values exceeding 249 N. At this moment, the adhesive layer connecting the honeycomb structure and the housing was destroyed.

Thus, the proposed finite element model was used to analyze the static deformation of a sandwich plate under the influence of a transverse load. Both finite element models (complete and homogenized) allow to estimate plate deformations with sufficient accuracy. The developed finite element model sandwich plates have been successfully verified and can be used to analyze the strength of the FDM-made sandwich plate structure.

Financing

The above results were obtained under the project 2023.04/0001, funded by the National Research Foundation of Ukraine.

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Received 21 August 2024

Технологія виготовлення, експериментальний та чисельний аналіз статичного вигину тришарової композитної пластини із стільниковим заповнювачем

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Використання тонкостінних конструкцій із стільниковим заповнювачем, виготовленим за допомогою адитивних технологій, має декілька переваг у порівнянні із конструкціями, виготовленими завдяки використанню традиційних технологій. Передусім це пояснюється тим, що адитивні технології значно спрощують виготовлення стільникових заповнювачів. У статті запропоновано технологію виготовлення тришарової композитної пластини із стільниковим заповнювачем, отриманим за допомогою адитивних технологій. Як матеріал для виготовлення стільникового заповнювача було обрано пластик PLA. Друк здійснювався з використанням принтера «Дельта» з паралельними кінематичними ланцюгами із застосуванням FDM технологій. Температура друку становила 215 °C, температура стола – 60 °C. Запропоновано принципово нову схему експериментального стенду для вивчення вигину тришарової пластини. Метою досліджень є проведення випробувань зразків тришарової стільникової панелі на статичний вигин при жорсткому защемленні одного краю зразка. Для випробувань використовувалася атестована розривна машина TiraTest 2300, що дозволяє проводити випробування на розтягнення і стиснення із заданою швидкістю руху траверси й вимірювати навантаження з відносною похибкою, що складає 1%. Розривна машина дає змогу провести навантаження зразка й провести замір навантаження і переміщення траверси. Для вимірювання деформацій поверхні обшивок використовується шістнадцятиканальна тензометрична станція. Як експериментальні дані отримані поперечні переміщення тришарової пластини. Вигин тришарової пластини моделюється в комерційному пакеті ANSYS. Результати експериментального і чисельного аналізу добре збігаються.

Ключові слова *тришарова композитна пластина, адитивні технології, стільниковий заповнювач, скінченноелементна модель.*

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