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APPLICATION OF MATHEMATICAL MODELING FOR DESCRIBING THE BEHAVIOR OF LAYERED PANELS WITH A TETRAHEDRAL CORE

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Abstract. In the paper, mathematical modeling methods for describing the behavior of sandwich panels with a tetrahedral core under various loads have been used, and a series of numerical calculations carrying out by the ANSYS software. In so doing the previously obtained effective elastic characteristics were taken, which made it possible to replace the direct modeling of the tetrahedral core structure with elements of a simple form using orthotropic material with equivalent characteristics. The problem of the plate's three-point bending was solved, and a deformed state and deflection character of the panel were analyzed. The necessity of applying the heteromodular elasticity theory when modeling such objects and of taking into account the effective elastic characteristics obtained by tension and compression of the periodicity cell was established. Recommendations were given for the use of periodicity cells when computing the iterative changes in material properties and effective characteristics obtained during tension and compression.

Keywords: tetrahedral core, layered panel, effective elastic characteristics, finite element method

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ПРИМЕНЕНИЕ МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ ДЛЯ ОПИСАНИЯ ПОВЕДЕНИЯ СЛОИСТЫХ ПАНЕЛЕЙ С ТЕТРАЭДРАЛЬНЫМ ЗАПОЛНИТЕЛЕМ

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Аннотация. В работе выполнено математическое моделирование с целью описания поведения слоистых панелей с тетраэдральным заполнителем под действием различных нагрузок. При этом была реализована серия численных расчетов в программном комплексе конечно-элементного анализа ANSYS. При моделировании использованы полученные ранее эффективные упругие характеристики, что позволило заменить прямое моделирование структуры тетраэдрального заполнителя элементами простой формы с применением ортотропного материала, имеющего эквивалентные характеристики. Решена задача о трехточечном изгибе пластины, проанализировано деформированное состояние панели и характер ее прогиба. Установлена необходимость применения принципов разномодульной теории упругости при моделировании таких объектов и учета эффективных упругих характеристик, полученных при растяжении и сжатии ячейки периодичности. Даны рекомендации по использованию в расчетах итерационного изменения свойств материала и эффективных характеристик, полученных при растяжении и сжатии ячейки периодичности.

Ключевые слова: тетраэдральный заполнитель, слоистая панель, эффективные упругие характеристики, метод конечных элементов

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Introduction

Due to growing demand for composite panels with various types of cores in diverse industries, it is important to carry out analysis and computational validation of such structural elements using mathematical modeling methods with high-performance computing equipment and modern software [1, 2]. Close attention throughout design, preparation, testing and, consequently, simulation of such panels and products made from them [3–5] should be paid to the structure and shape of the core [6, 7]. Honeycomb core is currently most widely used in aviation, automotive industry and building structures [8–11]. We should note that honeycombs have a closed cell structure and are well suited for thermal insulation; in addition, they provide strength, reliability and load-bearing capacity under significant loads [12].

On the other hand, structures with truss cores have less effective load resistance [13], but they allow for ventilation. That is why such cores have proved to be a solution for extending the service life of building facades by protecting them from adverse climatic events [14–16]. One of the possible core configurations is tetrahedral, i.e., combining truncated tetrahedra [17, 18].

A composite panel with a honeycomb or truss core can be described in simulation as a composite material with a complex microstructure. The core can be considered a homogeneous material in computational continuum mechanics, and its effective properties can be both anisotropic and orthotropic [19, 20]. Panels with tetrahedral cores are regarded in numerical simulation as structurally orthotropic composite material [21, 22].

To correctly implement this approach, a unit cell is selected at the first stage and its effective elastic characteristics are set. The latter are often determined using the direct homogenization method [23], allowing to calculate the effective values of orthotropic physico-mechanical parameters of a composite material with a complex microstructure; the method is also applicable to doubly periodic structures.

The main goal of this study is to propose a calculation procedure substantiating the application of multimodular elasticity theory to simulation of composite panels with core.

The following objectives were posed and achieved for this purpose:

calculate the stiffness parameters of a panel with tetrahedral core under tension and compression;

determine the stress-strain state of the panel in the three-point bending problem.

Object of research

The general view of the panel and tetrahedral core with its geometric characteristics, considered in this case, are shown in Fig. 1. Panels of this type are predominantly used in the construction industry, specifically in ventilated facades and enclosures.

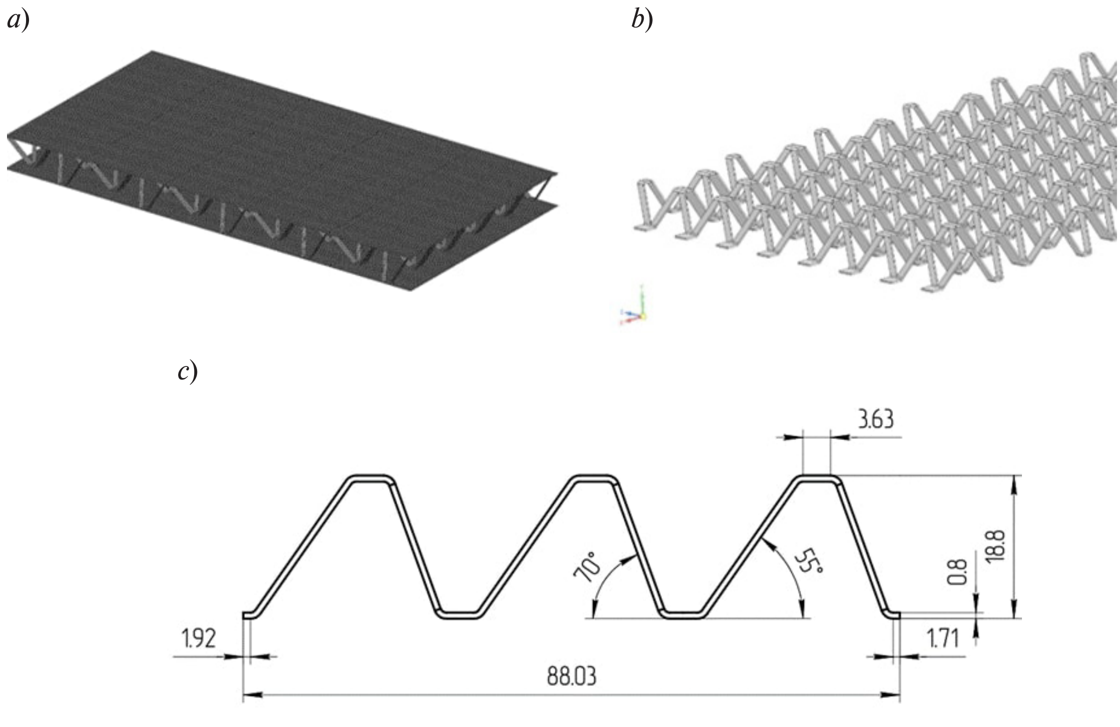

Fig. 1. General view of panel with tetrahedral core (*a*), its core (*b*) and its geometric characteristics (*c*)

The AMG2 material used has the following physico-mechanical parameters:

Density, kg/m^3 ....2,680;
Elastic modulus, GPa 71.0;
Ultimate tensile strength, MPa 190;
Yield strength, MPa 80;
Poisson's ratio ....0.33.

It is assumed that the same material is used to manufacture the face sheets of the panel and the core.

The unit cell considered, measuring 28×58×19 mm, is shown in Fig. 2.

a) *b*)

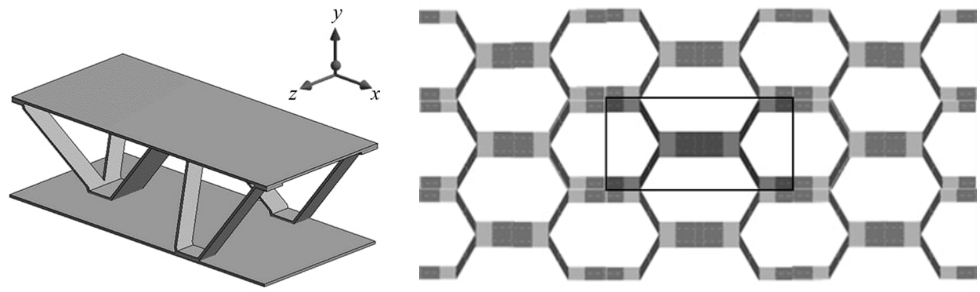

Fig. 2. Schematics of unit cell (*a*) and tetrahedral filler (top view) (*b*);
the cell is marked by a rectangle

The values of the elastic parameters were determined by direct homogenization (the corresponding results and a detailed description of the method are given in [24]). The method of direct homogenization used is based on kinematic and static boundary conditions [25], allowing to determine the effective orthotropic physico-mechanical properties of a composite material with a complex microstructure.

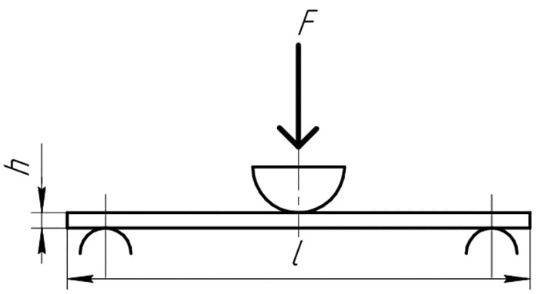

Fig. 3. Loading conditions for problem statement of three-point bending of the panel. Geometric parameters and the direction of the loading force *F* are shown

Problem of three-point bending of composite panel

This problem is of both scientific and practical interest [26–28]. Consider such a problem for a plate with a tetrahedral core, where the core structure is modeled without any simplifications and the structure is represented by a homogeneous medium with effective properties.

The loading conditions for the three-point bending problem of such a panel (its overall dimensions are 292 × 140 × 19 mm) is shown in Fig. 3.

Nonlinear shell finite elements were used for numerical simulation. Conducting convergence analysis, we selected a model consisting of 156,050 elements and 532,325 nodes; the characteristic size of the element was 1 mm.

Based on the calculation performed, let us analyze the stress-strain state of the panel. Fig. 4 shows the vertical displacements of the panel under consideration and the dependence of its deflection in the central section along the length *l*.

a) *b*)

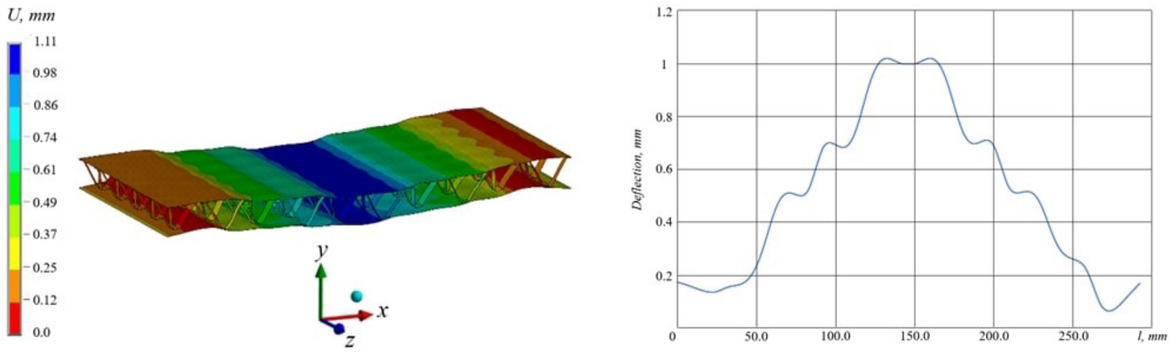

Fig. 4. Stress-strain state of sandwich panel: vertical displacements (*a*), color map, 10 : 1 scale; dependence of deflection of panel in its central section along the length *l* (*b*), see Fig. 3

It can be seen from the presented results that the location of the core affects the magnitude and behavior of the deflection for the plate with tetrahedral core. The deflection is smaller at the points where the core is attached.

The next stage in the simulation procedure is to establish a correspondence between the mean deflection of the panel with core and the deflection under bending in a similar panel but made of homogeneous, multimodular material with orthotropic characteristics. We emphasize that the loading behavior of two objects should be compared for this purpose:

panel with tetrahedral core,

panel made of homogeneous multimodular material with orthotropic characteristics.

For this comparison, we first consider two auxiliary problems:

evaluating the behavior of the unit cell under tension and compression,

analyzing the application of the principles of multimodular elasticity theory.

We should note that the formulation of these problems is of independent scientific interest.

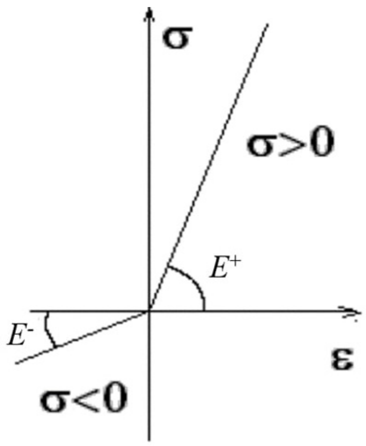

Fig. 5. Initial section of characteristic stress-strain curve (stress σ–strain ε) in accordance with multimodular elasticity theory: material has elastic modulus E^+ for uniaxial tension and E^- for uniaxial compression

Application of principles of multimodular elasticity theory

In case of analysis at the macroscale, the geometric characteristics of the selected unit cell and its behavior under loading should be correctly described. Tetrahedral core with complex structure in layered composites behaves differently under tension and compression [25, 29–30], so approaches underlying the multimodular elasticity theory [31–33] can be reasonably applied.

The mechanical characteristics of homogeneous isotropic material in classical elasticity theory are described by two elastic constants: Young's modulus E and Poisson's ratio ν.

On the other hand, according to multimodular elasticity theory, the material has different Young's moduli for cases of uniaxial tension and uniaxial compression: E^+ and E^-, respectively, as well as different Poisson's ratios characterizing transverse contraction under tension and transverse expansion under compression: ν^+ and ν^-, respectively.

According to multimodular elasticity theory, the stress-strain curve can be represented as two straight lines in the first approximation (Fig. 5).

To verify the applicability of this approach and validate it, in other words, to confirm the applicability of multimodular elasticity theory to design of sandwich panels withtetrahedral core, we carried out a series of numerical experiments on tension of the unit cell (see Fig. 2,*b*) in the directions of the *x*, *y* and *z* axes.

a) *b*)

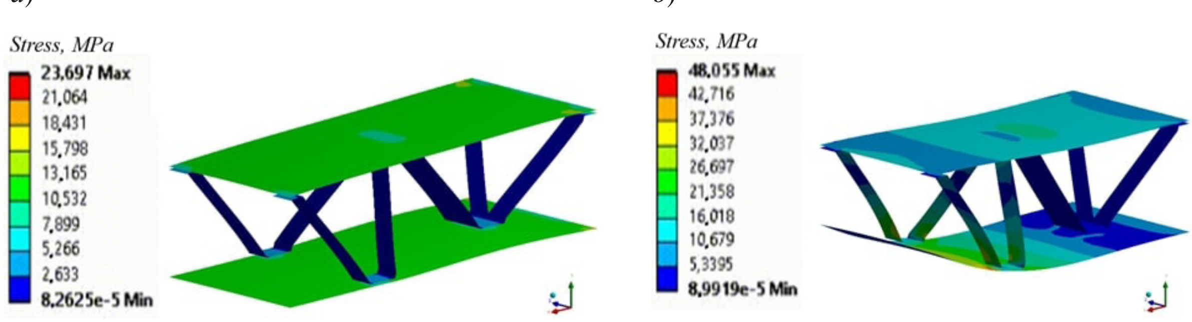

Fig. 6. Intensity of von Mises stresses (see color scale) for unit cell under tension (*a*) and compression (*b*) along the *x* axis

These simulations were performed using the ANSYS Mechanical software package. Nonlinear shell finite elements were used in numerical simulation. After conducting convergence analysis, we selected a model consisting of 4,148 elements and 13,177 nodes; the characteristic size of the element was 1 mm. The same finite element model was previously used in [24].

Fig. 6 shows the von Mises stress intensity distribution under tension and compression of the unit cell along the *x* axis.

Tensile and compressive behavior of the unit cell

The graph for the dependence of the reaction force on the maximum displacement U_{max} in different loading directions is shown in Fig. 7. The dashed line shows the linear dependence of force on displacement in the compressive region with the stiffness equal to the tensile stiffness. The values of reactions upon load reversal are given in Table 1.

Thus, comparing the tensile and compressive behavior of the unit cell, we found a difference in the magnitude of reactions under loading in the *x* and *y* directions.

Notably, we used the values of effective elastic characteristics (Table 2) that we obtained in [24].

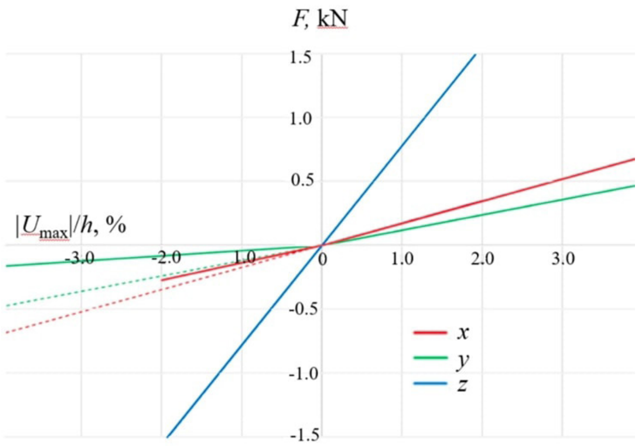

Fig. 7. Dependences of reaction force on normalized maximum displacement in different loading directions (along the axes *x*, *y*, *z*)

Dashed lines show the linear dependence of force on displacement in the compressive region with the stiffness equal to the tensile stiffness

Table 1

Comparison of reactions in unit cell for varying direction and sign of load application

Loading direction	Parameter value		
	$+F_1$, kN	$-F_2$, kN	$\|U_{max}\|/h$, %
Axis *x*	0.347	0.271	2
Axis *y*	5.991	2.032	50
Axis *z*	1.561	1.562	2

Notations: $+F_1$, $-F_2$ are the reaction forces under tension and compression, respectively; $|U_{max}|/h$ is the ratio of the maximum displacement along each axis to the thickness of the sheet.

The data in Fig. 7 and in Table 1 confirm that different values of reactions are observed in the *x* and *y* directions upon load reversal. This is especially pronounced for the *y* (vertical) direction. This result allows us to conclude that multimodular elasticity theory can be reasonably applied to describing the behavior of structures with the selected type of core. For more accurate description of the behavior of the unit cell, it is necessary to find effective characteristics for the case of compression as well.

Table 2

Effective elastic parameters used for simulations

Young's moduli, GPa	Poisson's ratios	Shear moduli, GPa
$E_1^* = 58.60$	$\nu_{12}^* = 0.31$; $\nu_{21}^* = 0.03$	$G_{12}^* = 1.030$
$E_2^* = 0.899$	$\nu_{23}^* = 0.01$; $\nu_{32}^* = 0.10$	$G_{23}^* = 0.113$
$E_3^* = 4.53$	$\nu_{13}^* = 0.29$; $\nu_{31}^* = 0.30$	$G_{13}^* = 0.832$

Note. The parameter values given in Table 2 were presented in our earlier study [24].

Conclusion

The results of numerical simulation indicate that the sandwich panel with the selected type of tetrahedral core has different stiffness characteristics under compression and tension.

We validated the application of the homogenization method combined with the principles of the multimodular elasticity theory to improve the simulation accuracy for the behavior of the plate at the macro level.

The obtained results open up opportunities for further research. The next stage is to confirm that the mean deflection of the panel with core corresponds to the same deflection under bending in a panel made of homogeneous multimodular material. The behavior of the panel with tetrahedral core should also be compared with the behavior of a panel made of homogeneous multimodular material with orthotropic characteristics. It should be noted separately that it is planned to describe the multimodular behavior of the structure by successive refinement of the equilibrium state for the current stress-strain state of the structure.

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