PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGNAL

INVESTIGAÇÃO DE DEFORMAÇÔES PERMANENTES EM COMPOSITOS NANOMODIFICADOS APÓS A MOLDAGEM EM TEMPERATURAS ELEVADAS

INVESTIGATION OF PERMANENT STRAINS IN NANOMODIFIED COMPOSITES AFTER MOLDING AT ELEVATED TEMPERATURES

ИССЛЕДОВАНИЕ ОСТАТОЧНЫХ ДЕФОРМАЦИЙ В НАНОМОДИФИЦИРОВАННЫХ КОМПОЗИТАХ ПОСЛЕ ФОРМОВАНИЯ

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RESUMO

Este trabalho investiga o efeito da nanomodificação do carbono no estado de tensão-deformação residual (ETD) após a moldagem. Uma das maneiras de reduzir tensões residuais e deformidades é a nanomodificação. O objetivo principal foi determinar o grau de influência dos parâmetros de nanomodificação no ETD residual. No âmbito deste estudo, foram feitas 4 placas. Duas placas foram feitas com um aglutinante convencional com assentamento [010/9010] e [010/4510] e duas placas com um material de ligação modificado com a mesma estrutura de camada. Para as placas fabricadas, as deformações foram medidas em cada um dos quatro lados, durante o qual foram obtidas deformações residuais nos painéis de fibra de carbono nano modificada para as camadas consideradas com e sem material de ligação modificado. Para analisar o estado de tensão-deformação residual, foi realizado um cálculo numérico e analítico. O cálculo numérico foi realizado pelo método dos elementos finitos para o caso em que a palca é fixada no ponto do centro geométrico, sem carga de energia, e a carga de temperatura é uma diferença de 100 °C. Um cálculo analítico foi realizado para o caso em que a placa está livre de fixação e carga de energia externa, e a carga de temperatura é uma diferença de 100 °C. Durante o estudo, variantes das propriedades físico-mecânicas da monocamada foram obtidas usando o *software* Digimat e o método de média de Mori-Tanaka. Os resultados obtidos pelos métodos analíticos e numéricos têm boa correlação entre si e, no decorrer da comparação com o experimento, foi determinado um método para calcular as características da monocamada mais próxima do resultado experimental. Com base nos resultados obtidos, foram tiradas conclusões sobre a possibilidade de reduzir ETD residual e a deformação em estruturas com esquemas de reforço assimétrico, utilizando uma matriz contendo nanopartículas de carbono.

Palavras-chave: *materiais compósitos, partículas de tamanho nano, nano modificação, deformações, deformidades residuais, tensões residuais, ETD.*

ABSTRACT

This work investigates the effect of carbon nanomodification on the residual stress-strain state (SSS) after molding. One of the ways to reduce residual stresses and deformities is nanomodification. The main objective was to determine the degree of influence of the nanomodification parameters on the residual SSS. Within the framework of this study, 4 slabs were made. Two slabs are made of a conventional binder with laying [0_{10}/90_{10}] and [0_{10}/45_{10}] and two slabs of a modified binding material with the same layer structure. For the fabricated plates,

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deflections were measured on each of the four sides, during which residual strains were obtained in the panels of nanomodified carbon fiber for the considered layings with and without modified binding material. To analyze the residual stress-strain state, a numerical and analytical calculation was performed. The numerical calculation was carried out by means of the finite element method for the case when the slab is fixed at the point of the geometric center, with no power load, and the temperature load is a difference of 100 °C. An analytical calculation was carried out for the case when the slab is free from fastening and external power load, and the temperature load is a difference of 100°C. During the study, variants of the physicomechanical properties of the monolayer were obtained using the Digimat software and the Mori-Tanaka averaging method. The results obtained by analytical and numerical methods have a good correlation between each other, and in the course of comparison with the experiment, a method for calculating the characteristics of the monolayer that was closest to the experimental result was determined. On the basis of the obtained results, conclusions were made on the possibility of reducing residual SSS and deformation in structures with asymmetric reinforcement schemes using a matrix containing carbon nanoparticles.

Keywords: *composite materials, nanosized particles, nanomodification, deformations, residual deformations, residual stresses, SSS*.

АННОТАЦИЯ

В работе исследуется влияние наномодификации углепластика на остаточное напряженно-деформированное состояние (НДС) после формования. Одним из способов снижения остаточных напряжений и деформаций является наномодификация. Основной задачей является определение степени влияния параметров наномодификации на остаточное НДС. В рамках данного исследования изготавливались 4 плиты. Две плиты выполнены из обычного связующего с укладкой [$0_{10}/90_{10}$] и [$0_{10}/45_{10}$] и две плиты из модифицированного связующего, с такой же структурой слоев. Для изготовленных пластин измерялись прогибы по каждой из четырех сторон, в ходе которого были получены остаточные деформации в панелях из наномодифицированного углепластика для рассматриваемых укладок с модифицированным связующим и без. Для анализа остаточного напряженного деформированного состояния проводился численный и аналитический расчет. Численный расчет проводился методом конечных элементов для случая, когда пластина закреплена в точке геометрического центра, силовая нагрузка отсутствует, температурная нагрузка – перепад 100°C. Аналитический расчет проводился для случая, когда пластина свободна от закрепления и внешней силовой нагрузки, температурная нагрузка – перепад на 100°C. В процессе исследования были получены варианты физико-механических свойств монослоя с использованием программы Digimat и метода осреднения Мори-Танака. Результаты, полученные аналитическим и численным методами, имеют хорошую корреляцию между собой, а в ходе сопоставления с экспериментом был определен метод расчета характеристик монослоя наиболее приближенный к экспериментальному результату. На основе полученных результатов было были сделаны выводы о возможности снижения остаточного НДС и поводок в структурах с несимметричными схемами армирования при использовании матрицы содержащей углеродные наночастицы.

Ключевые слова: композитные материалы, наноразмерные частицы, наномодификация, поводки, остаточные деформации, остаточные напряжения, НДС.

1. INTRODUCTION

The paper investigates the effect of carbon-fiber-reinforced plastic nanomodification on the permanent stress-strain state (SSS) after molding. The creation of polymer composites based on nanomodified binders has long been one of the research priorities in the field of CM manufacturing technologies, and significant progress has been achieved in this area (Hsu and Herakovich, 1977; Zweben, 1977; Ditcher *et al.*, 1981; Manders and Bader, 1981; Christensen, 1982; Hucho *et al.*, 1994; Bakis *et al.*, 2002; Yerramalli and Waas, 2003; Gojny *et al.*, 2005; Fatykhov *et al.*, 2006; Stavichenko, 2007; Zhang *et al.*, 2007; Ma *et al.*, 2008; Zhang *et al.*, 2009; Jean *et al.*, 2011; Dong and Davies, 2012; Gururaja and Hari Rao, 2012; Raghavalu Thirumalai *et al.*, 2013; Afanasiev *et al.*, 2014; Sathishkumar *et al.*, 2014; Harik, 2014; Swolfs *et al.*, 2014; Jagannatha and Harish, 2015; O Brien and Zaghi, 2018; Üstündağ *et al.*, 2019; Kurchatov *et al.*, 2019; Bulychev, 2019a; Bulychev, 2019b; Solyaev *et al.*, 2019; Babaytsev and Zotov, 2019). The development of CMs that improve their operational limits is based on reinforcing two or more fibers into a single polymer matrix, which leads to an improved material system called hybrid composites with a wide variety of material properties (Christensen, 1982). The study of the mechanical characteristics of hybrid composites with glass fibers of ± 45° and stainless steel 0°/90° is no less important when using similar structures (Gururaja and Hari Rao, 2012). In this study, hybrid and non-hybrid composites of various obstacles, fiber content, and weave types were fabricated and subjected to hysteretic tensile loads. The current state of hybrid composite materials, their technology, in terms of material properties, has an obvious advantage with an emphasis on various applications (Ditcher *et al.*, 1981).

As a rule, composites are molded at elevated temperatures, after which they are cooled to operating temperature. Due to the high anisotropy of the physicomechanical properties during cooling, the composite layers shrink unevenly in thickness and direction (Stavichenko, 2007). This leads to the appearance of residual deflections and internal stresses in composite parts (Hsu and Herakovich, 1977; Ditcher *et al.*, 1981; Fatykhov *et al.*, 2006; Stavichenko, 2007; Üstündağ *et al.*, 2019). One of the ways to reduce residual stresses and strains is nanomodification (Raghavalu Thirumalai *et al.*, 2013; Sathishkumar *et al.*, 2014; Kurchatov *et al.*, 2019; Bulychev, 2019a; Bulychev, 2019b; Solyaev *et al.*, 2019; Babaytsev and Zotov, 2019). The introduction of nanosized particles into the composition of the composite or its components (fiber or binder) allows not only to increase its physical and mechanical properties, but also to improve the picture of the residual stress-strain state.

The main task is to determine the degree of influence of the nanomodification parameters on the residual VAT.

2. MATERIALS AND METHODS

To study the effect of carbon nanomodification, 4 plates were made, characterized by layering and a binder. Two plates are made of a conventional binder with laying $[0_{10}/90_{10}]$ and $[0_{10}/45_{10}]$, and two plates are of a modified binder with the same layer structure. For the manufactured plates, deflections were measured on each of the four sides, during which residual strains were obtained in the panels of nanomodified carbon fiber.

To analyze the residual stress-strain state, a numerical and analytical calculation was performed. Based on the simulation result, the result obtained was compared with each other and with the experiment for the corresponding version of the stacking under consideration.

The studies used fullerene black produced by “Nanopolimer” (Russia). This fullerene black without other additives contains 10% of C60 and C70 fullerenes and 100% carbon. The black density is 0.3 g/cm^3. The carbon-fiber-reinforced plastic sample was made using EDT-10. Epoxy binder (Russia) and carbon fibers NTA-40 (Toho Tenax Co. Ltd.). Typical matrix properties are as follows: Young’s modulus is 2–3 hPa, Poisson’s constant is 0.35, and the ultimate stress is 20–25 MPa. In order to obtain nanomodified samples, a binder heated to 90 °C without hardeners was added to fullerene black (0.2 wt.%). In the manufacture of samples, the matrix was mixed with a paddle mixer for 30 minutes, followed by ultrasonic dispersion for 5 minutes to reduce agglomeration.

For the experimental study, four plates were made: two plates with $[0_{10}/90_{10}]$ and $[0_{10}/45_{10}]$ with a modified binder and two plates with $[0_{10}/90_{10}]$ and $[0_{10}/45_{10}]$ with a conventional binder. Due to the high anisotropy during cooling after molding, internal stresses arose in the plates and, as a result, leashes. The resulting deflections of the plates were measured on each of the four sides, Figure 1. To measure the deflection of the plate, it was fixed on a flat surface at two extreme points, and the deflection was measured in the center of the side with a caliper. Table 1 presents the results of measurements of the deflections of the manufactured plate with the layer structure $[0_{10}/45_{10}]$ and with the layer structure $[0_{10}/90_{10}]$.

For analytical calculation, we considered a plate free from fastening and external power load, and the temperature load is a difference of 100 °C.

Numerical calculation is carried out using the finite element method. The plate under consideration was fixed at the point of the geometric center, there was no power load, and the temperature load was a difference of 1000°C.

3. RESULTS AND DISCUSSION:

3.1. Numerical and analytical modeling of residual strains in panels with asymmetric styling

We will carry out numerical and analytical modeling of residual strains in panels with asymmetric styling. A multilayer panel of a polymer composite with anisotropy due to the non-symmetry of the properties of the structure of the package in thickness is considered. For the panel, we introduce the x, y, z coordinate system so that the x, y axes are centered around the reinforcement plane, and the z-axis is directed along with the panel thickness. Generally, six internal force factors arise in the panel: N_x, N_y, N_{xy}, M_x, M_y, M_{xy}. Physical relations, in this case, will be the following (Equation 1).

Where $N_x{}^T, N_y{}^T, N_{xy}{}^T, N_x{}^н, N_y{}^н, N_{xy}{}^н$ – linear forces caused by thermal deformation (index *T*) and initial layers tension (index *н*); $M_x{}^T, M_y{}^T, M_{xy}{}^T, M_x{}^н, M_y{}^н, M_{xy}{}^н$ – linear moments caused by thermal deformation (index *T*) and initial layers tension (index *н*); B_{mn}, C_{mn}, D_{mn} – panel generalized rigidities (*m, n* = 1,2,3); $\varepsilon_x, \varepsilon_y \varepsilon_{xy}$ – panel linear strains in the reference plane; $\kappa_x, \kappa_y \kappa_{xy}$ – panel curvature in the reference plane.

The relation between the panel strains in the reference plane with displacements u_0, v_0 (Equation 2). Relationship between panel curvature and standard rotation angles θ_x, θ_y (Equation 3). The relationship between standard rotation angles with deflection w has the following form (Equation 4). Where ψ_x, ψ_y – lateral shears.

Panel generalized rigidities are defined as follows (Equations 5-8). Where e – reference plane coordinate (for an asymmetric panel is chosen arbitrarily); m, n = 1,2,3, r = 0,1,2. Formulae for the force and moment caused by temperature fields (Equations 9-10). Where (Equations 11-12): Z_k – coordinate of *k* layer, counted from the reference plane; *N* – number of layers; $b_{ij}^{(k)}$ – linear stiffness of *k* layer, referenced to the panel axes (*x*, *y*); (*i, j* = 1, 2, 3); ΔT – temperature drop due to cooling; $\overline{\alpha_1}^{(k)}, \overline{\alpha_2}^{(k)}, \overline{\alpha_3}^{(k)}$ – coefficients of linear thermal expansion of *k* layer in the panel axes.

Similarly, we record the force and moment from the initial tension (Equations 13-14). Where (Equations 15-16): $\overline{\varepsilon_{н1}}^{(k)}, \overline{\varepsilon_{н2}}^{(k)}, \overline{\varepsilon_{н3}}^{(k)}$ – initial layers' strains in the panel axes.

The linear stiffness for *k* layer in the case of an asymmetric panel are as follows (Equations 17-18). The coefficients of linear thermal expansion for *k* layer, as well as layer strains caused by the initial tension, in the panel axes, are determined by appropriate transformation (Equations 19-20). In the above formulae, $m^{(k)}$ and $n^{(k)}$ are the trigonometric functions of $\varphi^{(k)}$ layers' orientation angle relative to the *x* panel (Equation 21).

We will consider a flat panel without initial curvature with free of load and fixing edges, subject to the temperature field evenly distributed over the thickness (Yerramalli and Waas, 2003; Raghavalu Thirumalai *et al.*, 2013; Sathishkumar *et al.*, 2014; Harik, 2014; Swolfs *et al.*, 2014). The reference surface coincides with the median surface. The orthotropic composite structure $B_{13} = B_{31} = 0$ and $C_{13}, C_{31}, C_{23}, C_{32}, D_{13}, D_{31}$ coefficients are small and can be neglected. Taking this into consideration, the physical relations for the orthotropic composite structure in the expanded form will look like (Equations 22-23).

Thus, in the case of the orthotropic composite structure, the determination of the deformed state splits into 2 independent problems of finding the deflections (curvature component κ_x, κ_y) and twist (κ_{xy}).

3.2. Determination of stress in layers using Hooke's law

Stresses in the layers are determined by Hooke's law using the curvature and deformation components obtained from (Equation 1), i.e. (Equations 24) (Harik, 2014; Sathishkumar *et al.*, 2014; Swolfs *et al.*, 2014; Babaytsev and Zotov, 2019; Bulychev, 2019b). In this case, z_k is the coordinate of the layer's median surface, i.e., $z_k = (Z_k - e) - h_k/2$. To move to the σ_1, σ_2, τ_{12} stresses in the layer axes, it is necessary to use the transformation formulae when turning the coordinate axes (Equation 25).

As it is evident from the physical relations (1) in multilayer panels with asymmetric lay-up, layers subject to tension-compression will cause the panel bending. Such complex behavior of panels in highly loaded structures can lead to a decrease in their efficiency. In addition, the molding of such panels will be accompanied by the permanent temperature flexural strains (buckling) (Hsu and Herakovich, 1977; Ditcher *et al.*, 1981; Fatykhov *et al.*, 2006; Stavichenko, 2007; Üstündağ *et al.*, 2019).

Panels with a symmetrical layers' arrangement, i.e., when the same layer (*N-k*) corresponds to the layer (*k*), where N is the total number of layers in the panel. Taking this into account, we write the formulae for generalized stiffness in the following simplified form (Equation 26).

The Z_k coordinate is then counted from the *e=h/2* medial plane, and the sum is calculated only by half the panel. The physical relations (Equation 1) for an orthotropic panel with load-free edges will then take such a form (Equations 27-28). From (Equation 28), it is easy to see that the molding of flat panels with a symmetrical panel structure will not lead to their buckling.

As a result of the study, we can distinguish the algorithm in the analytical analysis of the residual stress-strain state, conditionally divided into the main stages:

1. The calculation of the stiffness characteristics of the package according to Equations 5, 17-21;

2. Determination of internal force factors caused by the initial tension and temperature difference according to Equations 23-26;

3. Determination of the components of deformations and curvature from physical relations (Equation 1);

4. Calculation of stresses in composite layers using Hooke's law (Equations 24, 25).

As the calculated characteristics of the monolayer used in the simulation, the values obtained from the assumption that the reinforcing particles of fullerene soot are absolutely solid and not destroyed, and at the same time have the shape of a sphere, are used. Therefore, a spherical inclusion model was used to model the properties of the filled matrix using the Digimat-MF program using the Mori-Tanaka averaging method (Zweben, 1977; Ditcher *et al.*, 1981; Christensen, 1982; Hucho *et al.*, 1994; Gojny *et al.*, 2005; Stavichenko, 2007; Jean *et al.*, 2011; Gururaja and Hari Rao, 2012; Jagannatha and Harish, 2015). The calculation was carried out with the effective volume content (volume content of the filler + volume content of the interfacial layer, under the assumption that their properties are equal). The effective volumetric content was selected, taking into account the results obtained at the test entrance: 1) in terms of tensile strength; 2) in modulus. In the course of this, the value of the average Young's modulus of the packet was obtained, but it differs from the test. It is known that when using test data for unidirectional material in the calculation of the properties of a layered package, errors can occur. Therefore, it is usually necessary to use the stiffness data of several package options with different layer stackings (Bulychev, 2019b). In this work, for the properties of a monolayer, we will use an overestimated value of the transverse modulus equal to 28 GPa, which is more than the experimental data obtained on unidirectional samples (6.5 GPa). In this case, it is possible to reliably describe the obtained experimental data on the Young's modulus of the composite samples with symmetric stacking [0^o, 90^o] (Manders and Bader, 1981; Ditcher *et al.*, 1981; Christensen, 1982; Bakis *et al.*, 2002; Ma *et al.*, 2008; Gururaja and Hari Rao, 2012; Afanasiev *et al.*, 2014; O Brien and Zaghi, 2018).

For numerical and analytical calculations, the calculation was carried out for four variants of the physicomechanical characteristics of the monolayer taking into account two stacking options using the properties of a monolayer of pure carbon fiber and nanomodified carbon fiber, Table 2. A total of 8 calculations were performed for the stacking option [$0_{10}/45_{10}$], the calculation results of deflections are presented in Table 3 and 8 of the calculations for [$0_{10}/90_{10}$], the calculation results of the deflections are presented in Table 4.

The results of the distribution of normal stresses between the layers for laying [$0_{10}/45_{10}$] and [$0_{10}/90_{10}$] are given in Figure 2. The results obtained by analytical and numerical methods are the same. However, the greatest similarity with experimental data is provided by 4 methods for determining the effective properties of a monolayer. The residual deformations and stresses for laying [$0_{10}/90_{10}$] are 25-46% higher than in laying [$0_{10}/45_{10}$]. At the same time, nanomodified composites, to a greater extent, reduce residual strains and stresses for laying [$0_{10}/45_{10}$], about 26%.

4. CONCLUSIONS:

Investigation of the residual stress-strain state of structural elements made of carbon fiber reinforced plastic using the values of thermoelastic characteristics of composite monolayers identified on the basis of the developed methods revealed the possibility of reducing the residual SSS and leash in structures with asymmetric reinforcement schemes using a matrix containing carbon nanoparticles.

The results obtained by analytical and numerical methods are identical. The most similar to experimental data is the fourth method for determining the effective properties of a monolayer. This method is a model of spherical inclusions for modeling the properties of a filled matrix using the Digimat-MF program and the Mori-Tanaka averaging method taking into account the results of physical and mechanical tests.

Using the proposed model of thermoelasticity of the layered composite, it was also found that the addition of nanoparticles within the range recommended by the standard range of 10% only leads to a slight increase in the longitudinal elastic modulus and the shear modulus of the monolayer.

The obtained result showed the possibility of improving the mechanical properties of carbon fiber samples with a nanomodified binder, as well as the possibility of taking into account the effect of carbon nanomodification on the residual stress-strain state (SSS) after molding. The process of further reducing residual deformations and stresses by adding nanosized particles to the composition of the composite or its components (fiber or binder) takes place. However, this process is non-linear and requires further investigation, taking into account the models used to calculate the results obtained.

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$$\begin{pmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{pmatrix} = \begin{pmatrix} B_{11} & B_{12} & B_{13} & C_{11} & C_{12} & C_{13} \\ B_{21} & B_{22} & B_{23} & C_{21} & C_{22} & C_{23} \\ B_{31} & B_{32} & B_{33} & C_{31} & C_{32} & C_{33} \\ C_{11} & C_{12} & C_{13} & D_{11} & D_{12} & D_{13} \\ C_{21} & C_{22} & C_{23} & D_{21} & D_{22} & D_{23} \\ C_{31} & C_{32} & C_{33} & D_{31} & D_{32} & D_{33} \end{pmatrix} \times \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{pmatrix} - \begin{pmatrix} N_x{}^T \\ N_y{}^T \\ N_{xy}{}^T \\ M_x{}^T \\ M_y{}^T \\ M_{xy}{}^T \end{pmatrix} - \begin{pmatrix} N_x{}^н \\ N_y{}^н \\ N_{xy}{}^н \\ M_x{}^н \\ M_y{}^н \\ M_{xy}{}^н \end{pmatrix}. \quad \text{(Eq. 1)}$$

$$\varepsilon_x = \frac{\partial u_0}{\partial x}; \varepsilon_y = \frac{\partial v_0}{\partial y}; \varepsilon_{xy} = \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x}. \quad \text{(Eq. 2)}$$

$$\kappa_x = \frac{\partial \theta_x}{\partial x}; \kappa_y = \frac{\partial \theta_y}{\partial y}; \kappa_{xy} = \frac{\partial \theta_x}{\partial y} + \frac{\partial \theta_y}{\partial x}. \quad \text{(Eq. 3)}$$

$$\theta_x = \psi_x - \frac{\partial w}{\partial x}; \theta_y = \psi_y - \frac{\partial w}{\partial y}, \quad \text{(Eq. 4)}$$

$$B_{mn} = I^{(0)}{}_{mn}, \quad \text{(Eq. 5)}$$

$$C_{mn} = I^{(1)}{}_{mn} - eI^{(0)}{}_{mn}, \quad \text{(Eq. 6)}$$

$$D_{mn} = I^{(2)}{}_{mn} - 2eI^{(1)}{}_{mn} + e^2 I^{(0)}{}_{mn}, \quad \text{(Eq. 7)}$$

$$I^{(r)}{}_{mn} = \int_0^h b_{mn} Z^r dt = \frac{1}{r+1} \sum_{k=1}^{N} b_{mn}^{(k)} (Z_k{}^{r+1} - Z_{k-1}{}^{r+1}), \quad \text{(Eq. 8)}$$

$$N_x{}^T = \sum_{j=1}^{3} N_{1j}^T, N_y{}^T = \sum_{j=1}^{3} N_{2j}^T, N_{xy}{}^T = \sum_{j=1}^{3} N_{3j}^T, \quad \text{(Eq. 9)}$$

$$M_x{}^T = \sum_{j=1}^{3} M_{1j}^T, M_y{}^T = \sum_{j=1}^{3} M_{2j}^T, M_{xy}{}^T = \sum_{j=1}^{3} M_{3j}^T, \quad \text{(Eq. 10)}$$

$$N_{ij}^T = \Delta T \sum_{k=1}^{N} [b_{ij}{}^{(k)} \overline{\alpha_j^{(k)}} (Z_k - Z_{k-1})]; \quad \text{(Eq. 11)}$$

$$M_{ij}^T = \Delta T \sum_{k=1}^{N} b_{ij}{}^{(k)} \overline{\alpha_j^{(k)}} \left[\frac{1}{2} (Z_k{}^2 - Z_{k-1}{}^2) - e(Z_k - Z_{k-1}) \right]; \quad \text{(Eq. 12)}$$

$$N_x{}^{н} = \sum_{j=1}^{3} N_{1j}^{н}, N_y{}^{н} = \sum_{j=1}^{3} N_{2j}^{н}, N_{xy}{}^{н} = \sum_{j=1}^{3} N_{3j}^{н}, \quad \text{(Eq. 13)}$$

$$M_x{}^{н} = \sum_{j=1}^{3} M_{1j}^{н}, M_y{}^{н} = \sum_{j=1}^{3} M_{2j}^{н}, M_{xy}{}^{н} = \sum_{j=1}^{3} M_{3j}^{н}, \quad \text{(Eq. 14)}$$

$$N_{ij}^{н} = \sum_{k=1}^{N} [b_{ij}{}^{(k)} \overline{\varepsilon_{нj}^{(k)}} (Z_k - Z_{k-1})]; \quad \text{(Eq. 15)}$$

$$M_{ij}^{н} = \sum_{k=1}^{N} b_{ij}{}^{(k)} \overline{\varepsilon_{нj}^{(k)}} \left[\frac{1}{2} (Z_k{}^2 - Z_{k-1}{}^2) - e(Z_k - Z_{k-1}) \right]; \quad \text{(Eq. 16)}$$

$$\begin{aligned}
b_{11}{}^{(k)} &= [\overline{E_1} m^4 + \overline{E_2} n^4 + 2(\overline{E_1} \nu_{12} + 2G_{12}) m^2 n^2]^{(k)} \\
b_{22}{}^{(k)} &= [\overline{E_1} n^4 + \overline{E_2} m^4 + 2(\overline{E_1} \nu_{12} + 2G_{12}) m^2 n^2]^{(k)} \\
b_{12}{}^{(k)} &= b_{21}{}^{(k)} = \left[\overline{E_1} \nu_{12} + [\overline{E_1} + \overline{E_2} - 2(\overline{E_1} \nu_{12} + 2G_{12})] m^2 n^2 \right]^{(k)} \\
b_{13}{}^{(k)} &= b_{31}{}^{(k)} = \left[mn \left[\overline{E_1} m^2 - \overline{E_2} n^2 - \left(\overline{E_1} \nu_{12} + 2G_{12} \right) \left(m^2 - n^2 \right) \right] \right]^{(k)}, \\
b_{23}{}^{(k)} &= b_{32}{}^{(k)} = \left[mn \left[\overline{E_1} n^2 - \overline{E_2} m^2 + \left(\overline{E_1} \nu_{12} + 2G_{12} \right) \left(m^2 - n^2 \right) \right] \right]^{(k)} \\
b_{33}{}^{(k)} &= [\overline{(E_1} + \overline{E_2} - 2\overline{E_1} \nu_{12}) m^2 n^2 + G_{12} (m^2 - n^2)]^{(k)}
\end{aligned} \quad \text{(Eq. 17)}$$

$$\begin{aligned}
E_1{}^{(k)} &= \frac{E_1{}^{(k)}}{1 - \nu_{12}{}^{(k)} \nu_{21}{}^{(k)}}, \\
E_2{}^{(k)} &= \frac{E_2{}^{(k)}}{1 - \nu_{12}{}^{(k)} \nu_{21}{}^{(k)}},.
\end{aligned} \quad \text{(Eq. 18)}$$

$$\begin{pmatrix} \overline{\alpha_1} \\ \overline{\alpha_2} \\ \overline{\alpha_3} \end{pmatrix}^{(k)} = \begin{pmatrix} m^2 & n^2 \\ n^2 & m^2 \\ 2mn & -2mn \end{pmatrix}^{(k)} \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix}^{(k)}, \quad \text{(Eq. 19)}$$

$$\begin{pmatrix} \overline{\varepsilon_{н1}} \\ \overline{\varepsilon_{н2}} \\ \overline{\varepsilon_{н3}} \end{pmatrix}^{(k)} = \begin{pmatrix} m^2 \\ n^2 \\ 2mn \end{pmatrix}^{(k)} (\varepsilon_{н})^{(k)}. \quad \text{(Eq. 20)}$$

$$\begin{aligned}
m^{(k)} &= \cos(\varphi^{(k)}), \\
n^{(k)} &= \sin(\varphi^{(k)}).
\end{aligned} \quad \text{(Eq. 21)}$$

$$\begin{cases} 0 = B_{11}\varepsilon_x + B_{12}\varepsilon_y + C_{11}\kappa_x + C_{12}\kappa_y - N_x{}^T - N_x{}^{н} \\ 0 = B_{12}\varepsilon_x + B_{22}\varepsilon_y + C_{21}\kappa_x + C_{22}\kappa_y - N_y{}^T - N_y{}^{н} \\ 0 = C_{11}\varepsilon_x + C_{12}\varepsilon_y + D_{11}\kappa_x + D_{12}\kappa_y - M_x{}^T - M_x{}^{н} \\ 0 = C_{21}\varepsilon_x + C_{22}\varepsilon_y + D_{21}\kappa_x + D_{22}\kappa_y - M_y{}^T - M_y{}^{н} \end{cases}. \quad \text{(Eq. 22)}$$

$$\begin{cases} 0 = B_{33}\varepsilon_{xy} + C_{33}\kappa_{xy} - N_{xy}{}^T - N_{xy}{}^{н} \\ 0 = C_{33}\varepsilon_{xy} + D_{33}\kappa_{xy} - M_{xy}{}^T - M_{xy} \end{cases} \quad \text{(Eq. 23)}$$

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}^{(k)} = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix}^{(k)} \begin{pmatrix} \varepsilon_x + \kappa_x \cdot z_k - \overline{\alpha_1}^{(k)} \cdot \Delta T - \overline{\varepsilon_{н1}}^{(k)} \\ \varepsilon_y + \kappa_y \cdot z_k - \overline{\alpha_2}^{(k)} \cdot \Delta T - \overline{\varepsilon_{н2}}^{(k)} \\ \varepsilon_{xy} + \kappa_{xy} \cdot z_k - \overline{\alpha_3}^{(k)} \cdot \Delta T - \overline{\varepsilon_{н3}}^{(k)} \end{pmatrix}. \quad \text{(Eq. 24)}$$

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix}^{(k)} = \begin{pmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & (m^2 - n^2) \end{pmatrix}^{(k)} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}^{(k)}. \quad \text{(Eq. 25)}$$

$$B_{mn} = 2\sum_{k=1}^{N/2} b_{mn}{}^{(k)}(Z_k - Z_{k-1})$$
$$D_{mn} = \frac{2}{3}\sum_{k=1}^{N/2} b_{mn}{}^{(k)}(Z_k{}^3 - Z_{k-1}{}^3) \quad \text{(Eq. 26)}$$
$$C_{mn} = 0$$

$$\begin{cases} 0 = B_{11}\varepsilon_x + B_{12}\varepsilon_y - N_x{}^t - N_x{}^{н} \\ 0 = B_{12}\varepsilon_x + B_{22}\varepsilon_y - N_y{}^t - N_y{}^{н} \\ 0 = D_{11}\kappa_x + D_{12}\kappa_y \\ 0 = D_{21}\kappa_x + D_{22}\kappa_y \end{cases} \quad \text{(Eq. 27)}$$

$$\begin{cases} 0 = B_{33}\varepsilon_{xy} - N_{xy}{}^t - N_{xy}{}^{н} \\ 0 = D_{33}\kappa_{xy} \end{cases} \quad \text{(Eq. 28)}$$

Table 1. *Comparison of deflections for lay-up [0_{10} / 45_{10}] and lay-up [0_{10} / 90_{10}] with and without nano*

		Lay-up experiment [0_{10}/45_{10}]	**Lay-up experiment [0_{10}/90_{10}]**
Deflection on the long side, mm	With nano	5.85	4.35
	Without nano	5.95	3.2
Deflection on the short side, mm	With nano	4.1	2.1
	Without nano	3.7	2.75

Table 2. *Material stress-strain properties*

No.		**E_{11} [MPa]**	**E_{22} [MPa]**	**G_{12} [MPa]**	**v_{12}**	**$α_{1ь}$ [10^{-6} K^{-1}]**	**$α_2$, $α_3$ [10^{-6} K^{-1}]**	**G_{23} [MPa]**
1	Carbon fiber-reinforced plastic	129960	7056	2658	0.593	0.7	42	2214
	Nanomodified carbon fiber-reinforced plastic	135130	19078	8225	0.567	3.4	44	6085
2	Carbon fiber-reinforced plastic	129510	5211	1917	0.596	0.46	42	1632
	Nanomodified carbon fiber-reinforced plastic	129760	6266	2337	0.594	0.6	42	1965
3	Carbon fiber-reinforced plastic	129500	4730	2050	0.29	0.19	20	1670
	Nanomodified carbon fiber-reinforced plastic	129750	5700	2500	0.29	0.26	20	2010
4	Carbon fiber-reinforced plastic	129500	4730	2050	0.29	-10.4	20	1670
	Nanomodified carbon fiber-reinforced plastic	129750	5700	2500	0.29	-12	20	2010

***Table 3**. Comparison of deflections for options 1-4 and lay-up [0_{10} / 45_{10}] with experiment*

		1	**2**	**3**	**4**	**Experiment**
Deflection on the long side, mm	With nano	10.6	6.6	3.2	5.1	4.35
	Without nano	7	5.3	2.8	4.3	3.2
Deflection on the short side, mm	With nano	5.7	3.5	1.7	2.8	2.1
	Without nano	3.8	2.8	1.5	2.3	2.75

Table 4. *Comparison of deflections for options 1-4 and lay-up [0_{10} / 90_{10}] with experiment*

		1	**2**	**3**	**4**	**Experiment**
Deflection on the long side, mm	With nano	19.9	12.4	5.6	9.2	5.85
	Without nano	13.3	10	5	7.7	5.95
Deflection on the short side, mm	With nano	10.7	6.7	3	4.9	4.1
	Without nano	7.2	5.4	2.7	4.2	3.7

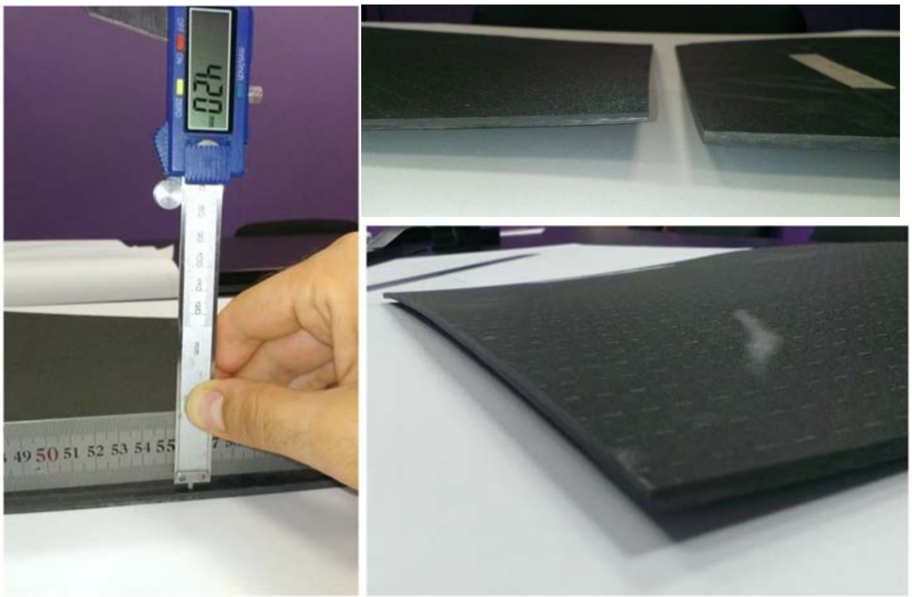

Figure 1. *Measurement of the panel deflection using caliper rule*

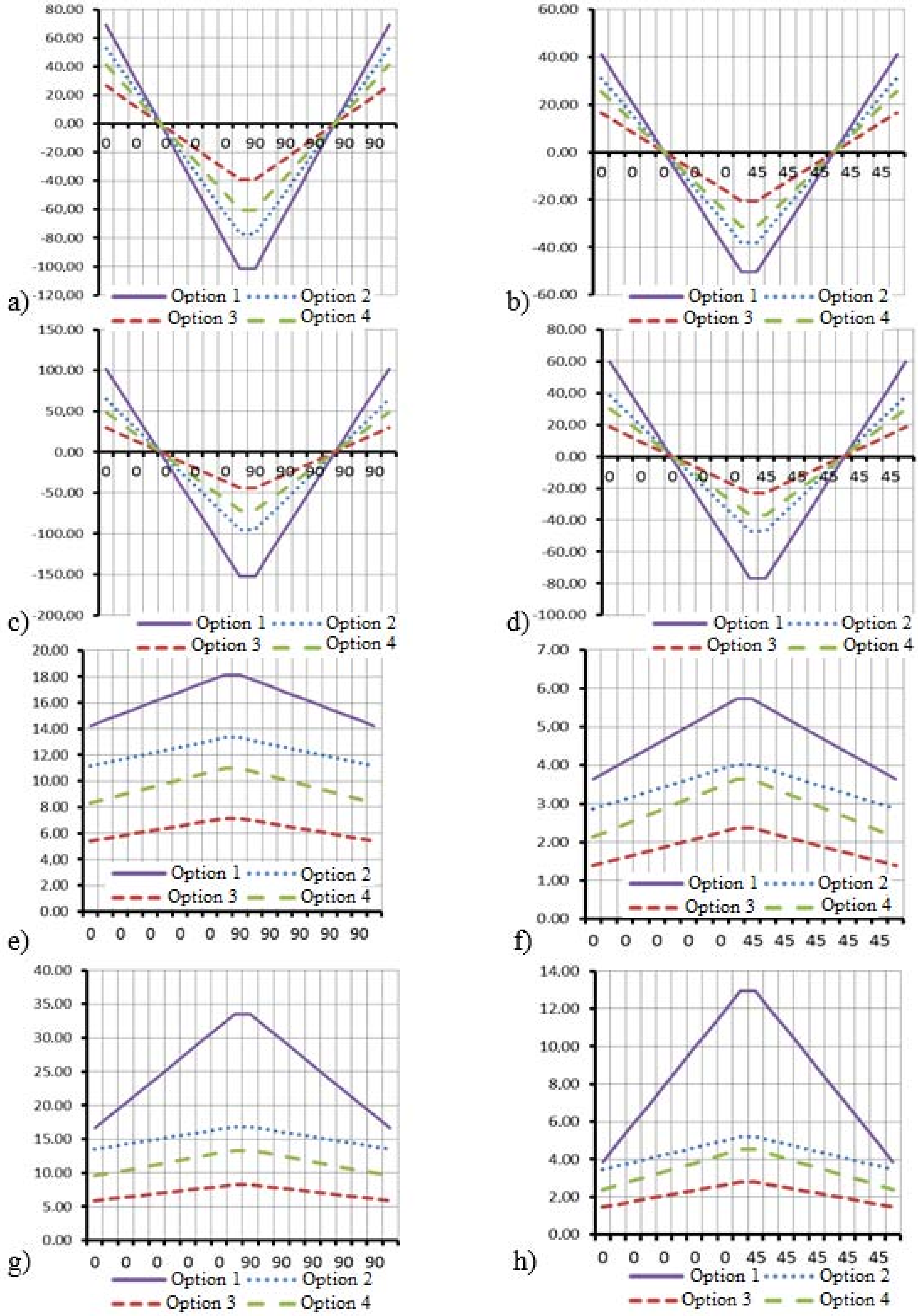

Figure 2. *The results of the distribution of normal stresses between the layers for laying [0_{10}/90_{10}]: a, e – without nanoparticles; c, g – with nanoparticles and [0_{10}/45_{10}]: b, e – without nanoparticles, d, h – with nanoparticles (a, b, c, d – Distribution of normal stresses in the layers σ_1, MPa; e, f, g, h – Distribution of normal stresses in the layers σ_2, MPa)*

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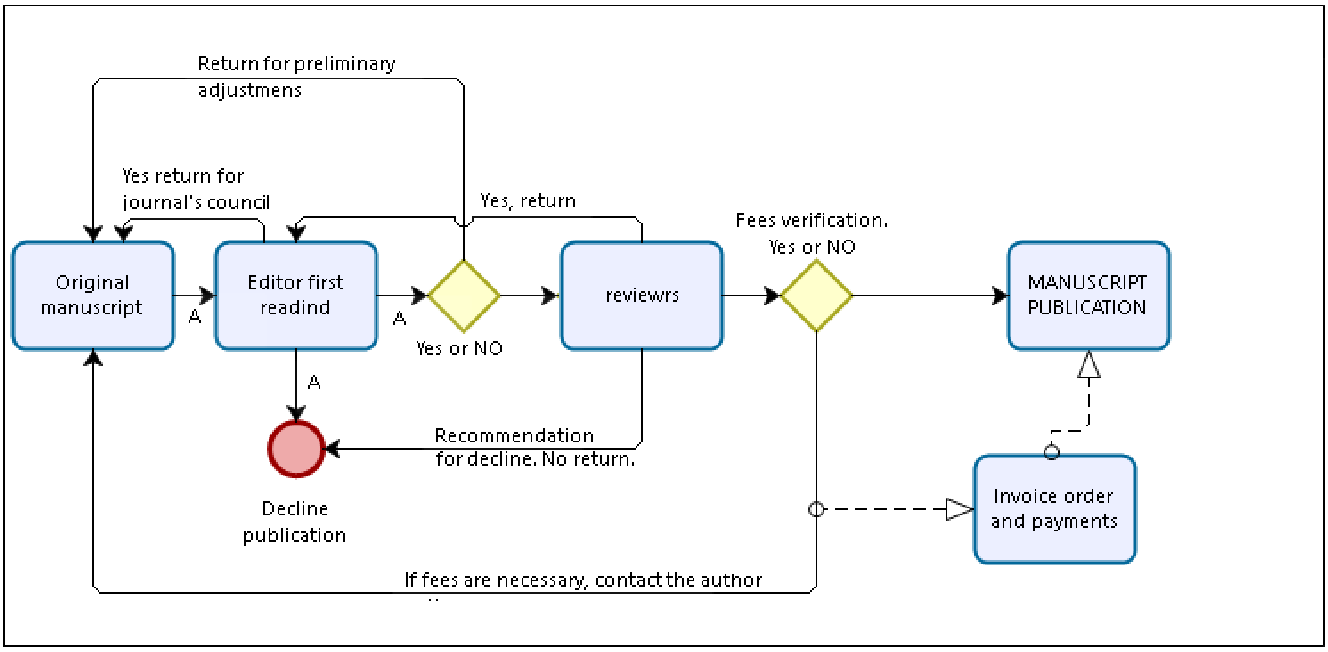

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