Study of Stress-Strain Behavior of the Laminated Plate Damaged by Delamination

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Abstract. The process of manufacturing of the structures of polymeric composite materials is accompanied by various technological defects. Delamination defects have the greatest impact on the bearing capacity of the composite structures. The method for assessment of the stress-strain behavior of a panel structure made of polymeric composite materials, which is damaged by delamination, has been developed. This method allows determining the degree of stress concentration in the area of step change in thickness and identifying the most dangerous point where the structural failure may start. In contrast to the classical theory of laminated plates, the proposed model gives an opportunity to simplify three-dimensional problem by setting the displacement field on the interfaces of layers and their linear interpolation over the plate thickness, taking into account the transverse shear deformation. Stress-strain behavior of the plate with delamination was determined according to the computational model of the plate with a cut for the case when the layers in the defect area cannot take up the applied load. According to the results obtained, distribution of stresses over the plate thickness changes significantly in the area of step transition to the delamination and near it. At the distance, it approaches the stress distribution in a plate of the uniform thickness. It allowed confirming the previous conclusions that maximum rise in stresses may occur in the weakened layer near the delamination, initiating the failure of the structure. Reliability of the developed mathematical model is confirmed by comparison with the results of experimental studies. The resulting maximum error does not exceed 7% and demonstrates good convergence of results. With the use of the developed method, it is possible to solve the important practical tasks of studying the loss of performance of the panel structures made of polymeric composite materials with delaminations and determining the optimal methods for repair of such defects.

1. Introduction
High physical and mechanical characteristics, as well as a number of special properties inherent in polymeric composite materials, are the main reasons for their wider application in all branches of technology [1, 2].

Transition to composites leads to combining the technological processes for creation of the material and finished product, independent of each other for the traditional materials, into one process operation [3]. This specific property of the composite materials explains the fact that properties of the materials and structures made of the same components under the same conditions may differ significantly [4].

In the course of manufacturing of components of the polymeric composite materials, there are complex physico-chemical and thermo-physical processes running in the half-finished products [3]. These processes are accompanied by the mechanical phenomena, which are the causes of occurrence of the various initial technological defects in the unloaded condition [5]. Defects such as delaminations have the greatest impact on the bearing capacity of composite structures [6, 7]. These defects are caused by the layered structure of the polymeric composite material itself; This structure represents an alternation of layers of the reinforcing material with high strength and stiffness.
characteristics with matrix interlayers featuring significantly lower strength and stiffness [3]. Low values of the transverse tensile strength of the composite material and resistance to interlayer shear also lead to frequent occurrence of initial delamination defects [8]. This process is promoted by the difference in the thermo-physical properties of the composite material’s components and low adhesive strength of the binder materials [9]. Most of these defects appear at the stage of the technological process [6]. At the structure operation stage, defect formation process may continue under the impact of heating, local loads, shocks and vibrations [10, 11].

Therefore, strength of the structures made of composite materials in the process of operation significantly depends on the presence of delamination defects in the product.

2. Literature Review

At present time, studies of the effect of delaminations on the performance of composite structures are carried out in several main directions [5–7]:

– assessment of the influence of size, configuration and location of local delaminations over the thickness and area of typical structural elements made of polymeric composite materials on the stress-strain behavior and critical load;

– assessment of the influence of the above factors on the dynamic characteristics of the structure;

– investigation of the conditions corresponding to transition of the defect boundaries into unstable state and initiation of the delamination development.

Exact mathematical problem setting with regard to analysis of discontinuity defects such as delaminations in the composite elements is rather complex and has no correct solution within the existing analytical models [12]. Usage of the multiscale model in order to take into account the impact of delamination of the layers on the strength of composite structures is proposed in the paper [13]. The paper [14] deals with obtaining of the analytical dependences, which allows assessing the quality of technological processes for the formation of half-finished products and goods of polymeric composite materials by the level of defects of the considered class, in contrast to other models. However, disadvantage of this work is that the analytical dependences obtained give an opportunity to assess only the level of decrease in the composite physical and mechanical properties in the presence of local discontinuities in it. When modeling the delamination in [15, 16], it is assumed that interlaminar stresses in the laminated composite are similar to stresses in the adhesive joint. Nevertheless, there are no reliable mathematical models of discontinuity defects of the composite material constructed in this way. The paper [17] shows the essential role of stability calculations for delamination defects. The method of stability calculation for thin-walled structural elements with the delamination defects under compression is proposed in [18]. The papers [6, 19], using the example of a compressed multilayer plate with through delamination between layers, give the solutions of the problems of stability loss and the process of damage. The studies have shown that for the adequate solving of the class of problems under consideration it is reasonable to use the numerical models based on the finite-element method. The paper [20] proposes the finite-element mathematical model, which allows to analyze the delamination behavior from the moment of buckling to the loss of bearing capacity. Another direction for the analysis of composite elements’ discontinuity defects in the form of delamination is proposed in [21]. In this paper, well-known mathematical models of the multilayer medium are reduced to the system of differential equations with variable coefficients, with the use of various numerical and analytical methods. The result is the geometrically nonlinear system of equations, but the lack of the true solution of this system is a disadvantage of this work. In all papers cited above, the development of so-called “admissible” delamination is studied. Such delamination is understood as a defect the shape and dimensions of which allow the product to be operated under the compressive force for a certain time. During this time, the defect develops, increasing its size up to the failure. The paper [7] assumes the beginning of local delamination under the regulated compressive load as the exhaustion of the bearing capacity of a composite structural element. Under these conditions, tolerances for the input parameters are established. This paper deals with the numerical example for the composite element with the specified structure and shape of the delamination. Comparison with the results of finite-
element modeling showed the satisfactory agreement of results. Expediency of using the numerical implementation of the problem is confirmed by the comparison with the results of experimental strain-gage measurements [19]. However, the main disadvantage of this approach is that the computational model is created for the strictly defined structure and cannot be arbitrarily extended to similar elements [2, 7]. Presence of the local and edge effects caused by delamination imposes certain conditions for the solvability of boundary problems and determines the instability of calculations in the process of numerical implementation of the problem. In recent times, the mathematical apparatus of spline functions is widely used for solving such problems [22]. The advantage of this approach lies in high stability of spline approximations with regard to various kinds of local perturbances, fast convergence, simplicity and ease of implementation of the algorithms. The most adequate assessment of the bearing capacity of composite structures with the considered technological defects is possible with the use of experimental studies [23, 24]. It should be recognized that in order to assess the strength and stiffness of structural elements made of polymeric composite materials it is necessary to subject them to direct mechanical tests [25, 26]. Among the experimental methods for the deformation measurement, the method of tensometry is widely spread [25]. However, the scope of its application is limited to areas of the structure with the regular stress-strain behavior, since the strain gage measures the average value of deformation within the base only. With rare exceptions, the methods of nondestructive testing of structural elements made of polymeric composite materials do not allow reliably predicting the moment of failure [27]. In this case, only the weakest point of the structure can be identified [26].

In view of this, the urgent task today is to develop a methodology for assessment of the stress-strain behavior of panel structure of polymeric composite materials, which is damaged by delamination.

3. Materials and Methods
The problem of determining the stress-strain behavior of the damaged panel structure is solved in the linear setting with the use of methods of the elasticity theory and the basic dependencies of the mechanics of composites. The layerwise theory is chosen for the calculation of stress-strain behavior. Stress-strain behavior of the plate with delamination is determined according to the computational model of the plate with a cut for the case when the layers in the defect area cannot take up the applied load. Reliability of the developed mathematical model is confirmed by comparison with the results of experimental studies. Results of experimental studies presented in the paper were obtained in the laboratory conditions using standard equipment, instruments and work tools. In the process of experimental studies, the method of double exposure holographic interferometry with the registration of holograms in counter-propagating beams was used.

4. Results
Let’s consider a flat rectangular plate with the specified delamination consisting of \( k \) orthotropic layers. For each layer, physical and mechanical characteristics of the material and the fiber orientation angle relative to the axes of the common coordinate system \((x, y, z)\) are known. We assume that the coordinate plane \((x, y)\) coincides with the bottom surface of the plate, and \(z\)-axis is directed upwards. The planes of elastic symmetry of the materials of each layer are mutually perpendicular, and one of the planes of elastic symmetry at each point of each layer is parallel to the outer parallel planes of the plate. Position of the coordinate system and geometric parameters of the plate are shown in Figure 1.
The delamination, which in practice has an arbitrary shape, will be approximated by the rectangle with an area equal to the area of the real delamination and considered flat in the unloaded condition. The lines $x_1, x_2, y_1, y_2$ in Figure 1 correspond to the boundary where the plate thickness changes stepwise by the value of the delamination depth $\delta$.

We consider the pressure with the intensity $p$ uniformly distributed over the surface as an effective load.

The layerwise theory, which allows simplifying three-dimensional problem by setting the displacement field on the interfaces of layers and their linear interpolation over the plate thickness [28, 29], is chosen for the calculation of stress-strain behavior.

The following assumptions were made:
- the normal displacement $\omega_i$ in each layer of the plate does not depend on $z$ coordinate, therefore: $\varepsilon_z=0$ and $\omega_i=\omega(x, y)$;
- normal stresses $\sigma_z$, acting in sections parallel to the median plane are negligible compared to the main stresses and they are not taken into account in the calculations;
- deformations $\varepsilon_x, \varepsilon_y, \gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ are approximated by linear functions within the layer;
- all layers of the plate are orthotropic in the axes $(x, y)$.

In the process of calculation of the plate, conditions for its edges’ fixing correspond to the boundary conditions of free bearing and suppose the absence of deflection and displacement along the edge and free movement across the edge. The fixing conditions as a set of static and geometric boundary conditions are written as follows:

at $x=\pm a$: $\omega=0, v=0, \theta_y=0, N_x=0, M_x=0$;

at $x=\pm b$: $\omega=0, u=0, \theta_x=0, N_y=0, M_y=0$.

The advantage of such boundary conditions consists in fairly accurate modeling of the common panel fixation patterns in real structures of various applications [3, 30].

Similar to the method proposed in [28, 29], we define the displacements $u_i, v_i, \omega_i$ of the certain point on the $i$-th surface of the plate in the directions $x, y, z$ as a function of variables $x, y$. In this case, owing to acceptance of the hypothesis of inextensible normals the displacement $\omega_i$ is the same for all layers of the plate. The displacements of points of the $i$-th surface are specified so as to satisfy the adopted boundary conditions at the edges of the plate. The $i$-th surface of the plate is understood as the interface of the “$i-1$”-th and “$i$”-th layers.

In the event if the plate contains the layers with the same geometric dimensions and properties of the material, calculations can be reduced by grouping the same layers into one “mathematical” layer. As a result, the number of “mathematical” layers can be significantly less than the number of actual layers of the material.

Within the $i$-th layer the displacements $u_i', u_i''$ are approximated by linear functions. The displacement $u_i'$ remains constant for all layers of the plate and equals $\omega$. 

**Figure 1.** Geometric parameters of the plate and delamination.
The displacement \( u_i \) is defined as follows:
\[
 u_i = u_i + \left( u_{i+1} - u_i \right) \left( z - z_i \right) / \delta_i .
\] (1)

We define the displacements \( u_i \) in a similar way:
\[
 u_i = v_i + \left( v_{i+1} - v_i \right) \left( z - z_i \right) / \delta_i .
\] (2)

The stress-strain behavior is determined in the framework of the linear theory. We assume that arising deformations are small and they are associated with displacements by the linear geometric relationships. Then, the deformations in the \( i \)-th layer are determined by the geometric dependencies:
\[
e_i^x = \frac{\partial u_i^x}{\partial x} ;
\]
\[
e_i^y = \frac{\partial u_i^y}{\partial y} ;
\]
\[
\gamma_{xy} = \frac{\partial u_i^x}{\partial y} + \frac{\partial u_i^y}{\partial x} ;
\]
\[
\gamma_{xz} = \frac{\partial u_i^x}{\partial z} ;
\]
\[
\gamma_{yz} = \frac{\partial u_i^y}{\partial z} .
\] (3)

Since each layer is orthotropic one in the \((x, y)\) axes and, therefore, has three planes of elastic symmetry, the solution to equations of the generalized Hooke’s law with regard to stresses \( \sigma_i^x, \sigma_i^y, \tau_{xy}, \tau_{xz}, \tau_{yz} \) appears as follows:
\[
\sigma_i^x = b_{11} \cdot e_i^x + b_{12} \cdot e_i^y ;
\]
\[
\sigma_i^y = b_{21} \cdot e_i^x + b_{22} \cdot e_i^y ;
\]
\[
\tau_{xy} = b_{44} \cdot \gamma_{xy} = b_{44} \cdot \gamma_{xz} ;
\]
\[
\tau_{xz} = b_{55} \cdot \gamma_{xz} .
\] (4)

Stiffness matrix coefficients included in the equations (4) are calculated by the known formulas [30].

To solve the problem, we define the total deformation energy of the elastic system as the difference between the potential energy and the external force energy:
\[
 A = U + V ,
\] (5)

where \( U \) – potential deformation energy; \( V \) – external force potential.

Potential deformation energy of the \( i \)-th layer is defined as follows:
\[
 U_i = \frac{1}{2} \iint_S \left( \sigma_i^x \cdot e_i^x + \sigma_i^y \cdot e_i^y + \tau_{xy} \cdot \gamma_{xy} + \tau_{xz} \cdot \gamma_{xz} + \tau_{yz} \cdot \gamma_{yz} \right) \cdot dx \cdot dy \cdot dz ,
\] (6)

where \( Z_i \), \( Z_{i+1} \) – coordinates of the surfaces bounding the \( i \)-th layer.

Then, potential deformation energy of the plate as a whole is equal to the sum of the potential deformation energies of all layers:
\[
 U = \sum_{i=1}^{k} U_i .
\] (7)

For the final determination of total energy of the elastic system, it is necessary to define the work of external forces applied to the plate. In case if the transverse uniformly distributed load with intensity \( p \) acts on the plate, the potential of external forces is determined by the formula:
\[
 V_p = -\iiint_S p \cdot \omega_k \cdot dx \cdot dy .
\] (8)
For the determination of the plate’s stress-strain behavior under action of the applied load, we use the Ritz-Timoshenko method, which allows obtaining an approximate solution in the displacements based on the Lagrange variational principle.

In accordance with the chosen method, we define the displacements \( u_i, v_i, \omega \) of the \( i \)-th surface of the plate in the form below:

\[
\begin{align*}
    u_i (x, y) &= \left( y^2 - b^2 \right) \left( u_{i,j} + u_{i,j+1} x + u_{i,j+2} y + u_{i,j+3} x^2 + u_{i,j+3} y^2 + \ldots + u_{i,j+5} y^{st} \right); \\
    v_i (x, y) &= \left( x^2 - a^2 \right) \left( v_{i,j} + v_{i,j+1} x + v_{i,j+2} y + v_{i,j+3} x^2 + v_{i,j+3} y^2 + \ldots + v_{i,j+5} y^{st} \right); \\
    \omega (x, y) &= \left( x^2 - a^2 \right) \left( y^2 - b^2 \right) \left( \omega_1 x + \omega_2 y + \omega_3 x^2 + \omega_4 x^2 + \omega_5 y + \ldots + \omega_6 y^{st} \right),
\end{align*}
\]

where \( st \) – degree of the polynomial which determines the plate displacement; \( u_{i,j}, v_{i,j}, \omega_k \) – unknown coefficients to be determined.

We obtain the variational equation by equating to zero the first variation of total energy of the system.

Consequently, the resolving system of equations will be as follows:

\[
\frac{\partial A}{\partial u_{i,j}} = 0, \quad \frac{\partial A}{\partial v_{i,j}} = 0, \quad \frac{\partial A}{\partial \omega_i} = 0 \quad (i = 1...n).
\]

Since the total energy is the quadratic function of displacements, the equations (10) represent a complete system of the linear algebraic equations for the coefficients being determined. After finding of the coefficients \( u_{i,j}, v_{i,j}, \omega \) as a result of this system’s solving, we can determine, with the use of formulas (9), the displacements, and then deformations and stresses, that is, we obtain a complete solution to the problem.

To determine the degree of the polynomial which provides the required error in calculating the stress-strain behavior of the plate, we have made preliminary calculations of the maximum deflection \( \omega \), maximum normal stress \( \sigma \), and maximum shear stress \( \tau \), of the square orthotropic plate. The results demonstrate the good convergence of the values of deflection and stresses. With the holding of the term of series \( st=6 \), the error in determining the deflection is 0.042%, normal stresses 0.28%, and transverse shear stresses 0.1%.

When passing from the computational model of the whole plate to the pattern of the plate with delamination, we use the approach proposed in [29], and introduce the auxiliary function \( F \), which ensures the defect modeling:

\[
F = 1 - H(x - x_1) \cdot H(x - x_2) \cdot H(y - y_1) \cdot H(y - y_2),
\]

where \( x_1, x_2, y_1, y_2 \) – coordinates of the left and right boundaries along \( x \) and \( y \) axes of the step change in the plate thickness in the \( i \)-th layer (Figure 1); \( H \) – the Heaviside function.

Using the function \( F \), we define the stiffness matrix coefficients of layers containing the defect, \( \overline{b_{ij}} \) as:

\[
\overline{b_{ij}} = H \cdot b_{ij},
\]

where \( b_{ij} \) – stiffness matrix coefficients for the defect-free layer.

This setting of stiffness properties of the package allows modeling a delamination with any geometric and physico-mechanical parameters.

For the study of stress-strain behavior of the multilayer plate with delamination, we choose the square orthotropic plate with geometric dimensions of 100x100x2.8 mm. The plate is made of AeroGlass–163 glass cloth and “Epicur” hot cured epoxy binder. The reinforcement structure is [0°,90°]. Side of delamination is \( a = 20 \) mm in size, with the depth \( \delta \) of 0.7 mm. Physical and
mechanical characteristics of the glass cloth material are as follows: $E_1 = E_2 = 60$ GPa; $G_{12} = 6$ GPa; $G_{13} = G_{23} = 4$ GPa; $\nu_{12} = 0.28$; $\delta = 0.35$ mm [29].

For clarity, Figure 2 shows the plate section in the area of delamination, which characterizes its position.

![Figure 2. Location of delamination in the plate.](image)

First of all, let’s consider the pattern of change of stress distribution over the plate thickness during transition from the defect-free structure to the defective one with a delamination. Graphs of distribution of normal stresses $\sigma_x$ and transverse shear stresses $\tau_{xz}$ in the plate section at $y=0$ are shown in Figure 3. Stress distribution in the defect-free plate is shown by dashed line, while solid line is used for its indication in the delaminated plate. As shown by Figure 3, distribution of stresses over the plate thickness, changing significantly in the delamination area and near it, at the distance approaches the stress distribution in the defect-free plate.

![Figure 3. Distribution of normal stresses and transverse shear stresses over the plate thickness.](image)

For assessment of the degree of change in the maximum normal stresses, we compare them for the defect-free plate with stresses in the damaged plate with the delamination of the relative area $S_{delam}$ 5 and 15%. Distribution patterns are shown in Figure 4.

![Figure 4. Distribution of dimensionless normal stresses in the defect-free plate ($S_{delam}=0$) and the plate damaged by delamination: a – on the upper surface of the plate; b – on the lower surface of the plate.](image)
For the damaged plate with delamination, it is necessary to take into account the increase in shear stresses and transverse shear stresses because of their effect on strength of the structure. Their distribution patterns are shown in Figure 5.

**Figure 5.** Distribution of shear stresses in defect-free plate ($S_{delam}=0$) and plate damaged by delamination: a – $\tau_{xy}$ on the upper surface of the plate; b – $\tau_{xz}$ in the layer with delamination.

Figures 5 and 6, as before, show the stress distribution in the plate by the dashed line. Vertical dashed lines in the figure indicate the boundary of the change in thickness of the delamination. The patterns of changes in stress distributions are presented in Figures 4 and 5 in the form of graphical dependencies of distribution of the dimensionless normal and shear stresses in the plate under study, determined as follows:

$$
\frac{\sigma}{\sigma_{0}^{\text{max}}} \quad \text{and} \quad \frac{\tau}{\tau_{0}^{\text{max}}},
$$

where $\sigma$, $\tau$ – stresses acting in the plate; $\sigma_{0}^{\text{max}}$, $\tau_{0}^{\text{max}}$ – maximum stresses in the defect-free plate.

Experimental studies were carried out to verify the results of theoretical calculations using the proposed mathematical model. Since the stress field in the damaged plates with delamination is not the uniform one, it is impossible to use the tensometry research method. At the same time, a number of optical methods allow obtaining the displacement field in the structure under study and compare it with the analytical results [19, 25].

In the process of experimental studies, the method of double exposure holographic interferometry with the registration of holograms in counter-propagating beams was used. Comparison of the analytical results with the values obtained by the holographic method was carried out for two types of samples:

– defect-free samples;

– samples with a cut (delamination) (Figure 2).

For each type of samples, holographic interferograms were obtained and graphs of normal displacements along the central section of the plate were constructed. The results are shown in Figure 6.
Figure 6. Deflection of the defect-free plate and plate damaged by delamination under action of the uniformly distributed pressure $p$: $\omega_e$ – experimental distribution; $\omega_a$ – theoretical (analytical) distribution; $\delta_{\text{max}}$ – maximum relative error.

Therefore, the results of experimental studies of the deformed state of the defect-free plate and plate damaged by delamination showed the degree of correspondence of the displacement fields obtained in practice to the predicted theoretical results.

5. Discussion
In contrast to the classical theory of laminated plates [30], the proposed model gives an opportunity to simplify three-dimensional problem by setting the displacement field on the interfaces of layers and their linear interpolation over the plate thickness, taking into account the transverse shear deformations. Consideration of these factors allows proceeding to the consideration of flexible plates widely used in practice [2, 3].

The developed method allows modeling a plate actually with any geometric parameters in the plan and thickness, as well as combined physico-mechanical characteristics of the composite by setting the relevant stiffness matrix coefficients. In contrast to existing works, it gives an opportunity to determine:
- degree of stress concentration in the area of step change in thickness
- the most dangerous point where the structural failure may start.

According to the obtained results, distribution of stresses over the plate thickness changes significantly in the area of step transition to the delamination and near it. At the distance, it approaches the stress distribution in the plate of the uniform thickness. It allowed confirming the conclusions of [6, 7, 19] that the maximum rise in stresses may occur in the weakened layer near the delamination, initiating the failure of the structure. In this case, the pattern of the change in stresses on the lower surface of the plate, without a sharp change in thickness, is smoother than on the upper one. These features are to be taken into account in the designing of composite structures of various applications [2, 8].

The proposed mathematical model is characterized by the certain field of applicability, in which the accuracy of results corresponds to the required one. Based on the comparison of results with the literature data [29, 30], the error of the theoretical determination of the deflection does not exceed 3%,
and that of stresses - 8%. This corresponds to sufficiently high accuracy of the description of a multilayer plate stress-strain behavior. In order to improve the accuracy of calculations, it is enough to increase the number of “mathematical” layers. However, this will lead to the significant increase in the number of variables and the time of calculation. It should also be taken into account that the proposed modeling of a plate with delamination is possible only for the case when the layers in the defect area cannot take up the applied load. This can happen if [5]:
- a delamination occurs because of non-uniform impregnation of the reinforcing material and is characterized by the lack of binder in the defect area, which provides redistribution of the external loads between individual fibers;
- delamination resulting from the violation of the joint work of layers lies in the compressed zone when the plate is bent under action of the transverse load and loses its stability, since the stresses in the defect area exceed the certain critical level.

The experimental method chosen for the study, compared to existing works [19, 23, 24], allowed obtaining the results in the form of a continuous displacement field. It gives an opportunity to better understand the behavior of the structure in the area of irregularity.

The displacement fields obtained experimentally correspond to the predicted theoretical results. The resulting maximum error does not exceed 7% and demonstrates the good convergence of results.

It allows concluding that the proposed method can be applied for the assessment of stress-strain behavior of a panel structure made of polymeric composite materials, which is damaged by delamination.

6. Conclusions
The method for assessment of the stress-strain behavior of a panel structure made of polymeric composite materials, which is damaged by delamination, has been developed. This method allows determining the degree of stress concentration in the area of step change in thickness and identifying the most dangerous point where the structural failure may start. With the use of the developed method, it is possible to solve the important practical tasks of studying the loss of performance of the panel structures made of polymeric composite materials with delaminations and determining the optimal methods for repair of such defects.

The obtained results can be further used for the calculation of delaminations in the sandwich panels. However, in this case the results of calculations using the proposed method are to be assessed separately, in particular, if the filler is the discrete one.

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