Numerical modeling of mechanical behavior of multilayered composite plates with defects under static loading

V V Korepanov, G S Serovaev
Institute of Continuous Media Mechanics UB RAS, 1, Acad. Korolev St., 614013, Perm, Russia

Abstract. Evaluation of the mechanical state of a structure or its components in the process of operation based on detection of internal damages (damage detection) becomes especially important in such rapidly developing spheres of production as machine building, aerospace industry, etc. One of the most important features of these industries is the application of new types of materials among which polymer based composite materials occupy a significant position. Hence, they must have sufficient operational rigidity and strength. However, defects of various kinds may arise during the manufacture. Delamination is the most common defect in structures made from composite materials and represents a phenomenon that involves the complex fracture of layers and interlayer compounds. Among the reasons of delamination occurrence are: disposition of anti-adhesive lubricants, films; insufficient content of binder, high content of volatile elements; violation of the molding regime; poor quality of anti-adhesive coating on the surface of the tooling. One of the effective methods for analyzing the influence of defects is numerical simulation. With the help of numerical methods, it is possible to track the evolution of various parameters when the defect size and quantity change. In the paper, a multilayered plate of an equally resistant carbon fiber reinforced plastic was considered, with a thickness of each layer equal to 0.2 mm. Various static loading cases are studied: uniaxial tension, three and four-point bending. For each type of loading, a numerical calculation of the stress-strain state was performed for healthy and delaminated plates, with different number and size of the defects. Contact interaction between adjacent surfaces in the zone of delamination was taken into account.

1. Introduction
Evaluation of the mechanical state of a structure or its components in the process of operation based on detection of internal damages (damage detection) becomes especially important in such rapidly developing spheres of production as machine building, aerospace industry, etc. One of the most important features of these industries is the application of new types of materials among which polymer based composite materials occupy a significant position. Hence, they must have sufficient operational rigidity and strength. However, defects of various kinds may arise during the manufacture. To solve such problems, complex theoretical and experimental studies aimed at finding the reasons for their occurrence and investigating the nature of mechanical processes, both in structural elements and in material under possible operational loads are needed.

A layered composite material with different options of microstructure that takes into account the presence of a certain type of defects is considered in this paper. Delamination is the most common among them and represents a phenomenon that involves the complex fracture of layers and interlayer
compounds. The appearance of a delamination leads to the fact that in the region of separation the object is divided into several parts, which begin to absorb the loads independently of each other. In this case, the stiffness of each of the parts is much lower than the stiffness of the object working as a single unit [1]. Among the reasons of delamination occurrence are: disposition of anti-adhesive lubricants, films; insufficient content of binder, high content of volatile elements; violation of the molding regime (high temperature, high cooling rate, unregulated thermal or mechanical impact); poor quality of anti-adhesive coating on the surface of the tooling.

The appearance of delamination can lead to a loss of the bearing capacity of the structure, its breakdown and decommissioning, which makes the task of detecting this defect at an early stage of development highly relevant.

In order to simulate delamination processes, layered material in [2] is modeled as a laminate stacking sequence of homogeneous layers and interlayer interfaces. This simulation is used for predicting the start of delamination and its growth in the case of static loads without buckling. Development of experimental methods for determining the sustainability to delamination and crack resistance of reinforcing fibers and polymer matrix of composites is an active area of research. [3] provides an overview on the standardization of test methods. The latest researches leading to new standardized test methods, complementing and updating earlier reviews are presented. The causes of delamination and its effect on the structural characteristics, as well as, analytical and experimental methods for delamination detection are discussed in [4]. Delamination in layered composite plates under compression loads is analyzed in [5]. The method includes an analytical approach based on fracture mechanics and numerical analysis, assuming that the adhesive layers may be modeled using elastic springs with a finite tensile strength. Analytical and numerical results are compared and discussed. In [6], uniaxial loading tests of laminates with large number of layers which are prone to delamination were performed. The onset of delamination is based on acoustic emission.

Since the use of visual inspection methods is difficult due to the fact that delamination is an internal defect, diagnostic methods aimed at obtaining information about the appearance of delamination type defect and its propagation are of great importance [7-10]. A number of issues need to be answered before the organization of the monitoring of the mechanical behavior of the structure. And first of all what are the mechanical characteristics of the controlled object that can be measured and are most influenced by the appearance of a defect. An effective method for solving this problem is mathematical modeling. The analysis of stress-strain state change of the simulated object under static loading and the appearance and development of delamination type defect in composite materials is studied in this paper.

2. Modeling of defects in composite multilayered plates

Generally, a numerical study of the response of static parameters to the presence of a defect of different sizes can be considered for three models of delamination in a multilayered composite structure.

Free mode model in which the adjacent volumes, simulating the delamination, are not connected (and thus allowing their interpenetration). The free model allows interpenetration of the surfaces, therefore surface $S_1$ and $S_2$ are free from strains.

Constrained model in which the matching nodes in the delamination zone are bound by the same component of displacement. For the constrained model the matching nodes, belonging to surfaces $S_1$ and $S_2$, have the same displacement in the $z$ direction, but in the other directions the displacements are independent.

A model, taking into account contact interaction in delamination zone. The following states of contact are considered in simulation:

1) the state of open contact (Figure 1) when the surfaces are separated;

2) the state of closed contact (Figure 2). In this case, the surfaces contact with each other and their relative behavior is determined by the contact stiffness, which is equal to the elastic modulus of the material multiplied by the size of the contact element adjacent to the surface.
3. Numerical calculation of the composite multilayered plate with defects under static loading

As the object of the study a 15-layer plate of equal strength CFRP UWC-39, with the thickness $h_{1c}=0.2$ mm of each layer was considered. Each layer of the plate was simulated within a three-dimensional model of elasticity theory with orthotropic effective characteristics for each layer. The effective characteristics for each layer were made equal and are shown in Table 1.

The following variants of the arrangement of defects at the boundary of the layers are considered: one central defect (Figure 3, Figure 5); two symmetrically (with respect to the $Y$ axis) located defects (Figure 4, Figure 6). The number of delaminations between the layers along the thickness of the plate was set from one to six, as schematically shown in Figure 5 and Figure 6, the linear size of the defects $L_d$ varied from 10 to 40 mm.

Table 1. Orthotropic effective characteristics of composite

| Material  | $E_{xx}$, GPa | $E_{yy}$, GPa | $E_{zz}$, GPa | $G_{xy}$, GPa | $G_{xz}$, GPa | $G_{yz}$, GPa | $v_{xy}$ | $v_{xz}$ | $v_{yz}$ |
|-----------|---------------|---------------|---------------|---------------|---------------|---------------|---------|---------|---------|
| UWC-39    | 58.0          | 58.0          | 10.0          | 4.5           | 3.0           | 3.0           | 0.05    | 0.3     | 0.18    |

Elements with quadratic displacement approximation were used to create a finite element model of the plate. The construction of the finite element model was performed in ANSYS.

The virtual work principle is used for mathematical formulation of the problem

$$ \int_V \sigma_{ij} \delta e_{ij} dV = \int_S F_i \delta u_i dS \quad (1) $$

$u_i$ - components of the displacement vector, $e_{ij} = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right)$ - components of strain tensor, $\sigma_{ij} = C_{ijkl} e_{kl}$ - components of stress tensor, $C_{ijkl}$ - stiffness tensor, $F_i$ - components of the body forces vector.
The following load cases are considered:
- uniaxial tension;
- 3 point bending (Figure 7);
- 4 point bending (Figure 8).

For each of the considered loading schemes, the change in the parameters of the stress-strain state as a function of the number of defects and their dimensions in a multilayer plate was analyzed. The corresponding components of stress and strain tensors can be chosen as such parameters. For the problem of uniaxial tension of a plate, these parameters are longitudinal strain and stress, for 3 and 4 point bending problems, tensile strain and stress are examined. The sensitivity of the selected parameters will be estimated by comparing the results on a homogeneous plate and a plate with defects.

The results of the calculations showed that the stress-strain state remains practically unchanged for uniaxial tension and four-point bending (the difference in the respective strain and stress components in the defect zones is no more than 2%). The three-point bending is of the greatest interest from the strain response point of view (Figure 7).

The dependences of the tensile strain $\varepsilon_{xx}$ on the surface along the $Y=0$ line for a homogeneous plate and a plate with defects for one and 6 delaminations along the thickness of the plate with one and two defects in the layer (Figure 3 and Figure 4) and for different defect sizes are shown in Figures 9-11. Six delaminations along the thickness of the plate were set as shown in Figure 5 and Figure 6, and one delamination over the plate thickness was set in the section $Z = h/2$, where $h$ is the thickness of the plate.
Dependences of the tensile strain $\varepsilon_{xx}$ on the surface of the plate at the point $(X=0, Y=0)$, depending on the size of the delamination $Ld$ for the case of one and six delaminations with one and two defects in the layer are represented in Figure 12.

![Figure 9. Tensile strain distribution along the Y=0 line, Ld=20 mm.](image)

![Figure 10. Tensile strain distribution along the Y=0 line, Ld=30 mm.](image)

![Figure 11. Distribution of tensile strain along the Y=0 line, Ld=40 mm.](image)

![Figure 12. Dependences of the tensile strain on the size of the delamination Ld.](image)

The analysis of the obtained numerical results showed that when measuring the strain fields with the purpose of recording the development of delaminations in composite materials, it is necessary to locate sensors in the zone of 3 or 4 sizes of the expected defect. Therefore, in this case, two options are possible:

- In the first variant it is necessary to provide a dense sensor arrangement in the volume of the monitored defect;
- In the second variant, the sensors are located in the zones of stress concentration, where defects are expected to appear.

Zones of stress concentration can be determined for a specific construction using methods of mathematical modeling.

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