Experimental study of nonlinearity of the mechanical properties of layered woven CFRP

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Abstract. The article presents the results of an experimental study of the nonlinearity of the mechanical properties of layered composite materials made by vacuum infusion based on carbon fabrics and an epoxy resin. The analysis of existing approaches to the modeling of composite materials considering their physical nonlinearity is carried out. A method is proposed for taking into account the degradation of the properties of a composite material, based on the fact that the damage parameters are replaced by the functional dependence of elastic constants on deformations, based on experimental data. The results of the application of this method are given for the test data analysis of two types of layered woven carbon-fiber-reinforced-plastics with a cross-hatching structure.

1. Introduction

Most structural materials currently used in technics are characterized by such a phenomenon as softening under load. This effect manifests itself in a sharp decrease of material’s stiffness when internal forces reach a certain critical value. In metals, softening is described by the models of elastic-plastic behavior [1], which are constructed in accordance with a stress-strain diagram for a given type of material. Accordingly, if plastic phenomena in the material considers in the mathematical model of a metal structure, then it is spoken of as a model with physical nonlinearity.

Due to the active application of composite materials in advanced load-carrying structures, the challenge for increasing the accuracy of predicting their bearing capacity in the inelastic zone at the early stages of design becomes urgent. The phenomenon of softening of a composite material is the subject of damage mechanics and is described by models of the so-called “progressive fracture” [2-4]. These models are determined by the choice of a certain strength criterion and the law according to which the stiffness characteristics of the material decrease as the internal forces exceed certain critical values.

The concept of progressive fracture has found wide application in the field of calculating the fatigue strength of composite structures. The most common approach to taking into account the degradation of the elastic properties of the composite can be simplified as

\[ E = E_0 (1 - d) + E_{\text{fail}} d, \]

where \( E \) – current value of elastic modulus, \( E_0 \) – elastic modulus of undamaged material, \( E_{\text{fail}} \) – modulus of elasticity of a completely damaged material, \( d \) – damage parameter.

This method was applied, in particular, in papers [5,6] in the context of modeling fatigue fracture. A similar idea using the damage factor was used in [7], where the problem of assessing the static strength...
of a T-shaped joint is solved. The analysis of the residual strength of the composite panel of the aircraft wing based on the models of progressive fracture was described in [8]. The common thing of the mentioned works is that the equation (1) in one or another form lies in the basis for modeling the nonlinear behavior of a composite under load. However, in all these works the damage parameter \( d \) is a constant and is selected on the basis of full-scale tests of the full-size constructions. Therefore, in this work an attempt is made to replace the damage parameter with functional dependences of elastic constants on deformations, obtained experimentally from tensile tests of standard specimens, for their subsequent use in modelling of the nonlinear behavior of composite constructions.

2. Research methodology
In the article a new method for taking into account the degradation of the properties of layered composite materials is proposed. It is premised on the fact that the parameters of damage are replaced by the functional dependences of elastic constants on strains, based on experimental data.

The use of modern design approaches suggests that the analysis of the stress-strain state of aircraft constructions is usually carried out by the allowable stresses. This approach allows for lightweight and economical structures. Existing software solutions (CAE-programs) for the strength analysis of composite structures are mainly focused on the calculation of allowable stresses. According to this principle, the structure does not satisfy the strength condition when the maximum fracture index from all elements according to some strength theory in at least one case of loading is greater than 1. However, he engineering practice shows that composite structures do not collapse under load instantly. Thus, when designing a composite spoiler [9] of an aircraft, a structural analysis was carried out, which showed that the fracture index – strength criterion – exceeds 1 in several elements (figure 1).

Figure 1. Results of the strength analysis of the composite spoiler.

However, in practice, this does not mean that the entire structure has exhausted its bearing capacity. During static tests (figure 2), the spoiler structure withstood the design load, and with further loading, the process of gradual degradation of the properties of the structure material was accompanied by the accumulation of internal damage (figure 3).

Figure 2. Testing of composite spoiler.  
Figure 3. Composite spoiler loading diagram.
This real example from the field of aircraft engineering clearly shows that the development of modern high-loaded composite structures without taking into account the nonlinearity of their mechanical characteristics is ineffective.

At the moment, the damage mechanics models are widely used to account the structural degradation under load (damage mechanics) [4]. This approach is implemented, in particular, in the ANSYS software package. The essence of this approach is that upon reaching the limiting state in a certain structural element, its elastic moduli are scaled (reduced) by user-specified constant coefficients. In this case, the element compliance matrix is scaled by the coefficients $1/(1-d)$ when the fracture index reaches 1 according to the selected strength theory:

$$[D]_d = \begin{bmatrix}
\frac{C_{11}}{(1-d)} & C_{12} & 0 \\
C_{21} & \frac{C_{22}}{(1-d)} & 0 \\
0 & 0 & \frac{C_{66}}{(1-d)}
\end{bmatrix},$$

where $C_{ij}$ are compliance matrix components, $d_1, d_2, d_s$ – damage parameters ($f$ – filler, $m$ – matrix, $s$ – shear).

However, the experimental study of composite specimens with a hole (figures 4-6) showed that the models of damage mechanics have an extremely approximate representation of the strain curve. The study was carried out on the bases of [10]. Moreover, the results of finite-element-modelling significantly depend on the dimension of the finite element mesh and the choice of damage parameters.

**Figure 4.** Specimen with a hole after testing.  **Figure 5.** Results of modeling the process of destruction of a specimen with a hole.
To improve the accuracy of modeling composite structures, it is proposed to use a method based on replacing the damage parameters with functional dependences of elastic constants on strains. Such a model can be obtained by approximation of the experimental dependences of stresses on material strains using an n-order polynomial. This will significantly improve the accuracy of stress-strain-state analysis of composite structures. At the same time, standard tests of composite specimens for tension/compression and shear are sufficient to form a mathematical model of the material considering nonlinear effects.

The problem of polynomial approximation of experimental data using the least squares method can be formulated as follows. A series of measurements of the experimental value:

$$y_1, y_2, \ldots, y_n$$

by unknown function $$y = f(x)$$ for some preselected values of the independent variable

$$x_1, x_2, \ldots, x_n$$

can be well represented by a polynomial of degree $$m$$

$$y = a_0 + a_1 x + \ldots + a_m x^m$$

The degree $$m$$ of the polynomial is known, and the coefficients $$a_0, a_1, \ldots, a_m$$ must be determined based on measurements. It is assumed that the number of dimensions is greater than $$m$$, since otherwise the problem would not have an unambiguous solution [11].

The unknown coefficients $$a_i$$ of the polynomial (4) are determined using the following principle. For each observation point, the value of losses

$$a_0 + a_1 x + \ldots + a_m x^m - y_i$$

and determine the sum of the squares of all losses

$$Q = \sum (a_0 + a_1 x + \ldots + a_m x^m - y_i)^2$$

The value of $$Q$$ is non-negative by its nature, and a zero value is possible only if each loss value individually equals zero, that is, the measurements are all consistent and exactly correspond to the polynomial degree of $$m$$. This is impossible for experimental data. However, it is possible to define such $$a_0$$ at which the sum of $$Q$$ becomes minimal. The problem of finding the minimum has a unique solution and is obtained as a result of solving a certain system of linear equations. Ensuring the minimum condition requires that the partial derivatives of $$Q$$ for each $$a_i$$ be equal to zero, which leads to a system of linear equations:
As a result of solving this system of equations, the values \( a_0, a_1, \ldots, a_n \) are determined. Substituting them into equations (4), we obtain the function \( y' = f(x) \).

3. Results and discussion

The analysis of the nonlinearity of the mechanical characteristics of composites is considered by the processing of the experimental data for layered woven carbon-fiber-reinforced-plastics with a cross-hatching structure of tensile reinforcement. The specimens were made using two types of the reinforcing material - biaxial carbon fabric GG200T and GG200P of twill (figure 7) and plain (figure 8) weaving and epoxy resin SR8100/SD8824. Vacuum infusion parameters were chosen to ensure the volume fraction of the reinforcing material in the range of 0.5-0.6 of the laminate blanks (figure 9). The cured blanks they were processed on a CNC-milling machine (figure 10).

Tensile tests were carried out at normal temperature using an MTS universal testing machine in accordance with test standard ASTM 3039 [12]. The series of specimens for each type of material was 10 units. During the tests, the specimens were loaded at a speed of 5 mm/min. The strains of the working area of the specimen were measured using a contact biaxial extensometer. Loading graphs for specimens are shown in figures 11 and 12.
Figure 11. Loading graphs for specimens made of twill carbon fabric.

Figure 12. Loading graphs for specimens made of plain carbon fabric.

The carried-out tests give out the diagrams of the stress-strain state, which can be “embedded” into the mathematical model of the composite by approximating the dependences of stresses and strains in a suitable way (figures 13 and 14).

Figure 13. Dependences of the modulus of elasticity on deformation for specimens made of twill carbon fabric.

Figure 14. Dependences of the modulus of elasticity on deformation for specimens made of plain carbon fabric.

Table 1 shows the data of the elastic modulus approximation function for the given experimental data.
Table 1. Data of function of approximation of the elastic modulus.

| n  | T45     | P45     |
|----|---------|---------|
| a1 | -73.692 | -295.8  |
| a2 | 1030.8  | 3486.7  |
| a3 | -5961.7 | -16104  |
| a4 | 18058   | 36991   |
| a5 | -28572  | -43484  |
| a6 | 19396   | 22379   |

Figures 13-14 shows the dependences of the elastic constants on deformations which are, in fact, the dependence of the derivatives of the corresponding stresses (normal - for the elastic modulus, and shear – for the shear modulus) on deformations. Let us consider, for example, Hooke's law for normal stresses: $\Delta \sigma = E(\epsilon) \Delta \epsilon$. The graph on figure 13 s nothing more than a function $E = E(\epsilon)$. The physical interpretation of the obtained dependences naturally agrees with the "stress-strain-state" diagram: a monotonic decrease in elastic moduli corresponds to a gradual softening of the material under load, and reaching a "plateau" – to complete destruction of fibers and the transition of the binder in the entire volume of the working zone of the sample to the plastic state.

Thus, a model of a composite material with physical nonlinearity is formed, based on experimental data. This makes it possible to reduce the inaccuracy in assessing the stress values of the structure under development due to the appointment of traditional degradation coefficients due to the absence of the latter as such, and to increase the accuracy of predicting the supercritical behavior of the composite.

4. Conclusion

A method is proposed for taking into account the physical nonlinearity of composite materials based on experimental data. According to the results of processing and analytical approximation of tensile test data for types of composite materials with a cross-reinforced structure, stress-strain state diagrams were obtained. In addition, the material damage coefficients were calculated, which can also be used to describe the physical nonlinearity of the material. The results presented in this article can be used to create a model of a layered composite material with physical nonlinearity in the ANSYS CAE-program.

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