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MULTISCALE PROCEDURE OF NUMERICAL EVALUATION OF DAMAGE AND TECHNICAL STATE OF STRUCTURES FROM FIBER COMPOSITE MATERIALS

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ABSTRACT

A multiscale procedure of forecasting of stress-strain, damaged and boundary states of structures from typical fiber composite materials was developed. The procedure is based on the combination of macroscale models of describing the state of structurally inhomogeneous brittle materials and mesoscale approaches of continuing modeling of development of damage under the effect of external load. On the example of large-sized cylindrical pressure vessels from glass and carbon fiber composites, features of external load on the damage to the material and boundary state of the structure were investigated.

KEY WORDS: composite materials, damage, boundary state, mathematical modeling, multiscale procedure

INTRODUCTION

The use of composite materials during manufacture of structures for the needs of the aerospace industry, automotive production and building is an effective method for creating structural elements with unique combinations of operational properties. In particular, fiber composites based on glass and carbon fibers became widespread, which allow achieving a high strength of thin-walled structures at their relatively small weight [1–3]. However, spatial heterogeneity of the structure of such materials leads to objective difficulties in designing, expertise of a technical state and analysis of the serviceability of real structural elements, in particular, large-sized ones. The use of generally accepted approaches, consisting in evaluating the effective properties of a material for its further consideration as a homogeneous significantly limit the scope of solvable practically important problems. In particular, it is known that the process of initiation and propagation of material defects is microscopic as to its scale. Therefore, for the correct evaluation of the degree of damage and account of subcritical damages in the evaluation of the boundary state of the structure under the influence of the design load, it is necessary to take into account the features of the material structure and its resistance to a certain mechanism of fracture [4].

The possibilities of numerical description of composite structures in a heterogeneous statement are limited by the resource capacity of the relevant problems. Therefore, the development of analytical approaches that, on a one hand, allow taking into account the features of the microstructural state of the material in modeling, and on the other, considering specific structural elements without a significant simplification, are relevant. Here, it is advisable to separate the methods of multiscale modeling based on modern algorithms for finite element modeling of complex multiscale processes [5, 6]. The aim of this work is to develop methodologies and numerical means of multiscale forecasting of stress-strained, damaged and boundary states of structures from typical fiber composite materials.

The main idea of the developed methodology is a progressive finite element realization of monitoring the state of the structure in general in a homogeneous anisotropic approximation (macroscale) and separately of each regular mesoscale region in a heterogeneous approximation (mesoscale). This allows avoiding excessive requirements to resources of computing means by increasing the speed of a separate calculation. In this case, the independence of calculations of certain mesoscale regions provides extensive opportunities for the use of algorithms for parallel calculation of the corresponding boundary problems with the aim of a significant shortening in the time for carrying out numerical experiments [7]. The connection between the levels is realized by transmitting a certain volume of calculated data, namely, a strained state and a subcritical damage (Figure 1).

For computer realization of the mentioned approach, the methods of finite element modeling based on eight-node elements were used, and each finite element of macroproblem was considered as a regular mesoregion, within which the corresponding mesoproblem was stated.

Thus, macroscale approximation requires the use of averaged physicomechanical properties of the material, depending on the composition of a two-component composite (bulk content of the material of the matrix V_m and a fiber filler V_f) and the properties of its separate components. Here the most common are those approaches based on the rule of mixtures. In particular, for the case in a macroscale, the composite material is considered as an elastic orthotropic one, and the value of the Young modulus along and across the fibers is calculated according to the rule of mixtures [8]:

$$\begin{cases} E_T = \dfrac{E_f E_m}{E_m V_f + E_f \left(1 - V_f\right)}; \\ E_L = E_f V_f + E_m \left(1 - V_f\right), \end{cases} \quad (1)$$

where E_m, E_f is the Young modulus of the material matrix and fibers, respectively; E_T, E_L is the Young modulus of conventionally homogeneous anisotropic composite along and across the fibers, respectively.

In order to determine the Poisson's ratio, the dependence of Whitney and Riley in the next formulation was used [9]:

$$\begin{cases} \nu_{LT} = \dfrac{\nu_m - \left[2\left(\nu_m - \nu_f\right)\left(1 - \nu_m^2\right) E_f V_f\right]}{E_m\left(1 - V_f\right)\left(1 - \nu_f - 2\nu_f^2\right) + E_f\left[V_f\left(1 - \nu_m - 2\nu_m^2\right) + \left(1 + \nu_m\right)\right]}, \\ \nu_{TL} = \nu_m V_m + \nu_f V_f, \end{cases} \quad (2)$$

where v_{LT}, v_{TL} is the Poisson's ratio for directions along and across the fiber, respectively; v_m, v_f is the Poisson's ratio of the matrix and fibers material, respectively.

The boundary state in a particular finite element of the macroproblem is achieved at an unfavourable combination of longitudinal (relative direction of the fibers) σ_{xx}, transverse σ_{yy} and tangent stresses σ_{xy}, which is mathematically determined, in particular, on the basis of the Hofman formula [10]:

$$\left(\frac{\sigma_{xx}}{X_1}\right)^2 - \frac{\sigma_{xx}\sigma_{yy}}{X_1 X_2} + \left(\frac{\sigma_{yy}}{X_2}\right)^2 + \left(\frac{\sigma_{xy}}{S}\right)^2 > 1, \quad (3)$$

where X_1, X_2, S are the constants of material.

In the case that the axis of the orthotropic composite does not coincide with the direction of the power load, the constants in (3) can be calculated as follows:

$$X_1 = X_s \sin^2\alpha + X_m \cos^2\alpha; \quad X_2 = X_m \sin^2\alpha + X_s \cos^2\alpha, \quad (4)$$

where α is the angle between the vector of force application and the direction of the location of fibers, X_m, X_s are the constants of the material, characterizing the boundary state of the material during loading across and along the fibers, respectively.

The result of the finite element solution of the boundary problem of the stress-strained state (SSS) of a particular structure of a composite material of a certain class is a deformation field used in the analysis of meso-state of each element as boundary states. Calculating mesoproblem, a subcritical damage of the material is evaluated, that affects macroscopic SSS, which is formally taken into account by the transfer of the value of a bulk concentration of damage to the macroproblem.

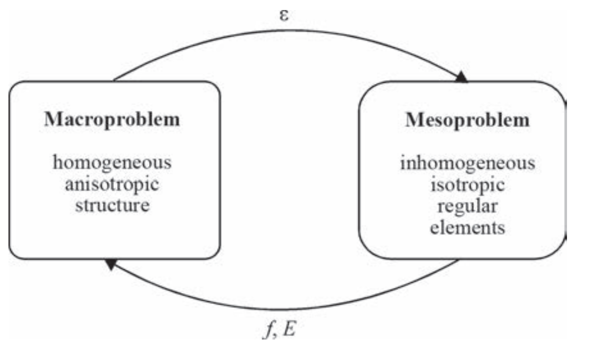

Figure 1. Conditional scheme of statement of multiscale problem of describing stress-strained and damaged state of structures from composite materials for solving typical problems of expertise of technical state

It is known that the peculiarity of the fracture of composite materials is a significant dispersion of the load limit, which is predetermined by a local heterogeneity of properties, natural deviation of the structure from the ideal, acquired by the damage during manufacture, etc. Therefore, to describe the development of subcritical damage in the matrix of the composite, a statistical approach based on the system of Weibull distribution was used:

$$df = \begin{cases} A f_0 \varepsilon_{\max}^{\eta-1} \exp\left[-\left(\dfrac{\varepsilon_{\max}}{\varepsilon_0}\right)^{\eta}\right] d\varepsilon_{\max}, \ \varepsilon_{\max} \geq 0; \\ 0, \ \varepsilon_{\max} < 0, \end{cases} \quad (5)$$

where df is an increase in volumetric concentration of damage to the matrix of the composite; e_{max} is the maximum local deformation; $A = \dfrac{\eta}{\varepsilon_0^{\eta}}$, η, ε_0, f_0 are the constants.

In the case if for a particular finite element, the volumetric concentration of damage f exceeds a certain critical value f_{cr}, it was supposed that this element loses its bearing capacity.

Thus, from the mesoscale problem in the macroscale one, the value of the total damage to F is transmitted:

$$F = \frac{\sum_N f + n_{st}}{N}, \quad (6)$$

where n_{st} is the total number of elements that lost the bearing capacity; N is the number of elements of splitting mesoregion; $\sum_N$ is the operator of the sum on all finite elements of splitting mesoregion.

This quantitative value F is used to correct the Young modulus in the macroproblem according to the following ratio:

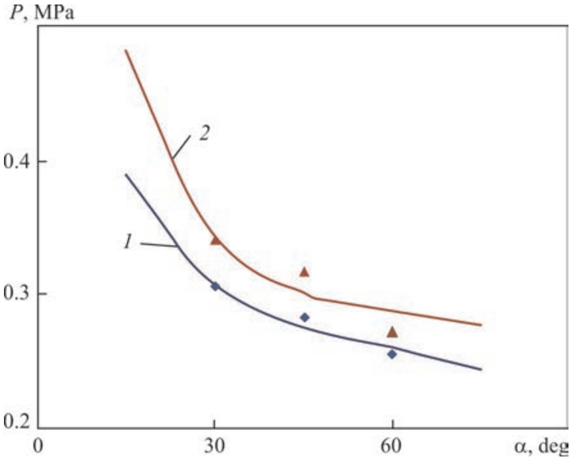

Figure 2. Dependences of fracture stress σ_u of samples of a fiber composite material from an angle of applying force relative to the direction of fibers α as compared to the results of laboratory tests [11]

$$E^f = \frac{E}{1-F}\,. \tag{7}$$

In addition, initiation and propagation of subcritical damage causes an additional component of the deformation tensor, namely:

$$\varepsilon^f = \Delta F/3\,, \tag{8}$$

where ΔF is the increment of F at each step of mechanical load.

Tensors of mechanical stresses σ_{ij} and elastic deformations ε_{ij} are interrelated by the Hooke's law, i.e.:

$$\varepsilon_{xx} = \frac{}{E_x}\sigma_{xx} - \frac{xy}{E_y}\sigma_{yy} + \frac{}{}$$

$$\varepsilon_{yy} = \frac{1}{E_y}\sigma_{yy} - \frac{xy}{E_x}\sigma_{xx} + \frac{}{}\,; \; \varepsilon_{xy} = \frac{1}{G_{xy}}\sigma_{xy}\,. \tag{9}$$

The proposed algorithm includes a number of constants of the material, which should be determined based on the results of the corresponding laboratory tests. For this purpose, in the work, literary data of experimental studies of the boundary load of fiberglass and carbon fiber composites ($V_m = V_f = 0.5$ for both cases, matrix is epoxy resin) were used with different directions of location of reinforcing fibers. Based on processing of these data, the constants of materials were obtained, namely:

- fiberglass composite: $\eta = 3.2$; $\varepsilon_0 = 0.01$; $f_0 = 10^{-5}$; $X_m = 35$ MPa; $X_s = 350$ MPa; $S = 18$ MPa; $f_{cr} = 0.15$; $E_m = 2$ GPa; $E_f = 70$ MPa;
- carbon fiber composite: $\eta = 4.6$; $\varepsilon_0 = 0.007$; $f_0 = 10^{-5}$; $X_m = 50.2$ MPa; $X_s = 1300$ MPa; $S = 20$ MPa; $f_{cr} = 0.20$; $E_m = 2$ MPa; $E_f = 280$ GPa.

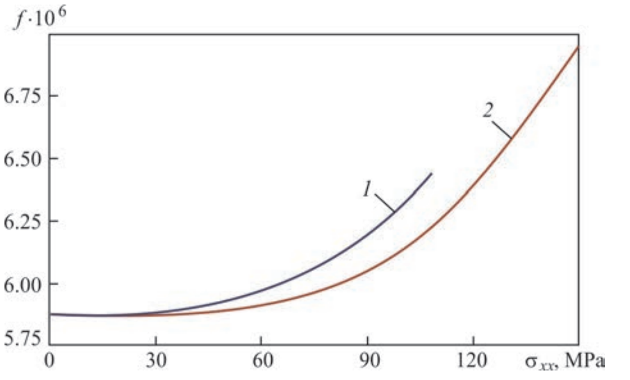

Figure 3. Kinetics of accumulation of bulk concentration f of subcritical damage of composite sample under the action of tensile load σ_{xx} till the boundary state

The calculation was conducted on the basis of a finite element solution of the multiphysical problem in accordance with the abovementioned statement, for macroproblem eight-nodal elements with a linear size of 0.5 mm were used, which sufficiently details a spatially heterogeneous SSS of the material. Detailed software algorithms for solution are given, in particular, in [7].

Figure 2 shows the results of comparing the calculated values of the load limit of samples with experimental results [11]. From these data, it is evident in general the satisfactory accuracy of the results of forecasting the boundary state of the mentioned materials based on the proposed model.

One of the advantages of the developed approach is the possibility of numerical observation of the development of a subcritical damage to individual components of the composite and taking into account the influence of their mesoscale interaction on the boundary state of samples or large-sized structures. Therefore, Figure 3 shows the kinetics of accumulation of a subcritical damage f of the composite samples during loading to the boundary state. Nonlinearity of the development of a bulk concentration of discontinuity in the cross-section as both glass as well as carbon-fiber sample is caused on the one hand, by a gradual weakening of the material and on the other by additional deformation as a result of the appearance and growth of distributed cavities.

An important factor in analyzing the technical state of composite structures is the evaluation of the influence of acquired or long-term operation of damaged material. Within the proposed methodology, the initial damaged state of the material is characterized by a constant f_0 from (5). Figure 4 shows the effect of a particular value f_0 on the value of the boundary load of the sample from the composite material. It is quasilinear, which is predetermined by a relatively small impact of damage to the deformed state at the beginning of the load and elastic deformation. Therefore, the component is additive.

Note. Here and in Figures 3–5: *1* — fiberglass composite; *2* — carbon fiber composite.

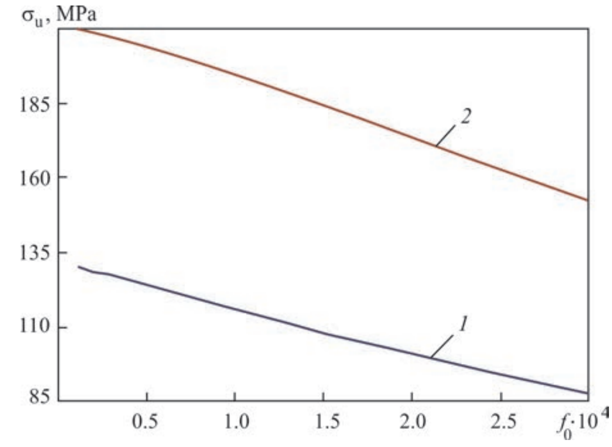

Figure 4. Dependence of ultimate strength σ_u of the fiber composite sample ($V_f = V_m = 0.5$, $\alpha = 45°$) on the initial bulk concentration of subcritical damage to the material f_0

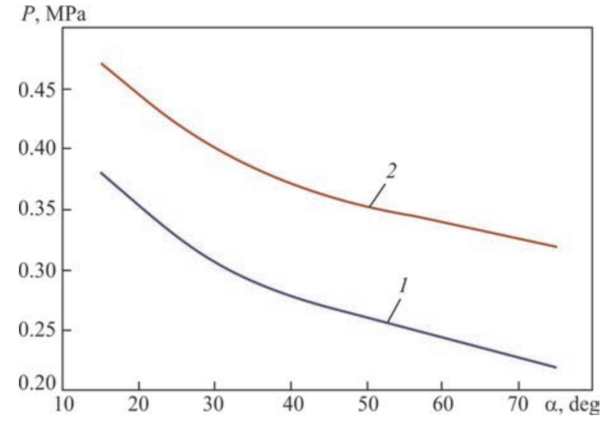

Figure 5. Dependence of ultimate pressure P in a cylindrical vessel (diameter D = 1200 mm, wall thickness t = 3 mm) from composite material on the angle of fibers α relative to the structure axis

Regarding modeling of the state of large-sized structures, a cylindrical pressure vessel with a diameter D = 1200 mm, wall with a thickness t = 3 mm under the influence of inner pressure was considered. Here, a characteristic feature is a pronounced biaxility of the stressed state of the structure in the circumferential and axial directions. This does not significantly change the qualitative view of the dependence of the boundary pressure in the structure on the angle of the location of the fibers relative to the pressure vessel axis (Figure 5) as compared to the results of the studies of sample fracture at a one-axial tension (see Figure 2), but changes the corresponding quantitative indices.

CONCLUSIONS

1. A methodology for multiscale forecasting of stress-strained, damaged and boundary states of structures from typical fiber composite materials was developed and software implemented. The proposed approach is based on the finite element realization of monitoring of the state of the structure in general in a homogeneous anisotropic approximation (macroscale) and separately of every regular mesoscale region in a heterogeneous approximation (mesoscale). Comparison of the results of forecasting the boundary state of samples from glass and carbon fiber composites with existing literary data showed a satisfactory accuracy of the developed approach.

2. The peculiarities of the subcritical fracture of the fiber material were investigated at a single load of standard samples. The characteristic nonlinearity of the development of a bulk concentration of discontinuity in the cross-section of a composite sample is shown, which is predetermined by a gradual weakening and additional deformation of the material as a result of arising and growth of distributed cavities. The influence of the initial damaged state of the material on its bearing capacity as an example of applying the developed approach to evaluate the technical state of structures and components from fiber composites was demonstrated.

3. The example of a cylindrical pressure vessel shows the peculiarities of the biaxiality of the stressed state to the boundary load of the structure, in particular, when changing the orientation of the fibers relative to its axis, as compared to similar dependencies obtained for standard test samples.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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