A STRUCTURAL MULTISCALE APPROACH TO THE DESIGN OF SPATIALLY REINFORCED CARBON–CARBON COMPOSITES

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The scientifically founded approach to the selection of the technology and the optimization of the parameters of the manufacturing process, the structure, and the form of the article in the designing of carbon–carbon structures requires a wide use of suitable models of the mechanics of composite materials. The most versatile and consequent solution of the designing of articles and the technologies of carbon constructions can be obtained with the use of multilevel structural models [1], which make it possible to analyze the deformation and the load-carrying capacity of composite 3D-reinforced constructions with account of the statistical nature and the characteristics of the mechanical behavior of the material, and changes in its structure on the corresponding scales and characteristic dimensions.

The dynamic behavior of a composite construction on the macroscopic level is described by a system of equations for the mechanics of the deformed solid

\begin{align}
\sigma_{ij} &= \rho \frac{\partial \mathbf{u}_{ij}}{\partial t}; \\
\sigma_{ij} &= C_{ijkl} \left( I_{klmn} - \psi_{klmn} \right) \varepsilon_{mn}, \\
\varepsilon_{ij} &= \frac{1}{2} \left( \mathbf{u}_{ij} + \mathbf{u}_{ji} + \mathbf{u}_{ik} \mathbf{u}_{kj} \right) / 2,
\end{align}

where \( \sigma \) is the stress tensor; \( \rho \) is the density of the material; \( \mathbf{u} \) is the shifting tensor; \( C \) is the rigidity tensor; \( I \) is the unit tensor; \( \psi \) is the damage tensor; \( \varepsilon \) is the deformation tensor; \( t \) is the time; \( i, j, \ldots, n = 1-3 \). The system of equations (1) is supplemented by the necessary number of limiting and initial conditions.

In order to carry out construction designs with the aim of checking the definition of problem (1) or of its modification with the use of shell hypotheses it is perfectly sufficient when all necessary physicomechanical characteristics are known, i.e., when a complete phenomenological description of the composite material is available. When carrying out design calculations, the density, rigidity, and damage function are design parameters, the values of which are determined by the structure and the properties of the components of the carbon–carbon material. Thus, for the further analysis the processes of deformation and destruction must be considered at a lower, structural level. It must be pointed out that the need in such an analysis can arise also in the usual calculation when a complete or reliable information about the rigidity or strength of the construction material is not available and the need arises for the prediction or an improved precision of the corresponding characteristics.

In the analysis of the mechanical behavior of 3D-reinforced carbon–carbon material at the structural level a representative volume of the composite is investigated. Hereby the system of determining correlations is analogous to the system (1) with the sole difference that the stress and deformation tensors, and the physicomechanical characteristics refer to components of the structure: the reinforcing elements of the skeleton and the carbon binder. If the complete phenomenological description of the properties of the components is available, by using the correlation between the structural and the macroscopic fields of stresses and deformations, averaged with respect to the representative volume

\begin{align}
\sigma_{ij} &= \frac{1}{V} \int_{V} \sigma_{ij} \, dV; \\
\varepsilon_{ij} &= \frac{1}{V} \int_{V} \varepsilon_{ij} \, dV,
\end{align}

all strength and rigidity characteristics can be obtained from the solution of the marginal problem at the structural level. In Eq. (2) the fields of stresses and deformations in the components of a 3D-reinforced fiber composite are denoted by \( \sigma_{ij}^* \) and \( \varepsilon_{ij}^* \).

Due to the fact that the selection of carbon fibers for the formation of the reinforcing skeleton and the methods of its filling with the carbon binder differ strongly, in the projecting of carbon-carbon constructions the properties of the components must also be considered as projection parameters. The reinforcing element of the skeleton is a unidirectional fiber microcomposite, consisting of carbon fibers and the carbon binder; the carbon binder of the 3d-reinforced material contains microscopic pores and inclusions, chaotically distributed in the volume. The boundary problem of the form of (1) must therefore be formulated at the microstructural level; its solution is obtained if a phenomenological description exists of the behavior of the components of the fiber and porous carbon microcomposites, the phenomenological behavior of which will be obtained in turn with the use of the averaged Eq. (2) at the microstructural level.

The traditional problem in the projecting of carbon-carbon constructions is related to the very limited information on the properties of the carbon binder, obtained exclusively within the composite by repeated impregnation and carbonization. The high-temperature treatment of the material in the saturation with carbon leads to a change in the properties of the reinforcing fibers; this requires modeling of a more complicated structure of the components of the carbon-carbon composite. At an even lower (nanostructural) level the carbonaceous material represents polycrystalline graphite. The broad interval of the rigidity and strength characteristics of the different carbon matrices and carbon fibers is mainly due to the mutual orientation of the crystallites, which possess a very strong anisotropy of the properties. Consequently, in the phenomenological description of the polycrystalline carbonaceous material and optimization of its properties the need arises for the definition and solution of the boundary problem of type (1) at the nanostructural level with the use of the averaged expression (2) of the nanostructural fields of stresses and deformations.

Thus, the analysis of the mechanical behavior of a carbon-carbon construction involves the consideration of a sequence of boundary problems of the mechanics of the deformed solid, presented by the schematic diagram in Fig. 1. Since we deal here with inhomogeneous media with anisotropic phases, such problems can be realized only numerically with the use of direct finite-difference methods, in particular, with the finite element method (FEM); the subproblems, separated in the diagram make it possible to form an enlarged block structure of the system for the projecting of carbon-carbon constructions.

We shall start the analysis of the deformation and strength properties of carbon-carbon composite materials (CCCM) by examining the nanostructural level. Investigations of polycrystalline graphite by electron microscopy [2-4], performed for different carbonaceous materials, carbon fibers, and CCCM matrices, permit us to identify three basic structural types and to provide the corresponding finite-element models for their description. Figure 2 shows models of the structures of polycrystalline carbonaceous materials: a statistically isotropic structure with random orientation of the basic crystallite faces (Fig. 2a); a statistically anisotropic structure with predominant orientation of the basic faces in any direction (in Fig. 2b it is the horizontal direction at a mean-square deviation of 15°); an orthogonal structure of the polycrystal, in which the arrangement of the