MULTISCALE MODELLING THE DEFORMATION AND FAILURE OF COMPOSITE STRUCTURES

Andrey Burov[1], *Olga Burova*[2]

[1]Institute of Computational Technologies, Siberian Branch Russian Academy of Science, SDTB "Nauka", Krasnoyarsk, Russia

[2]Siberian Federal University, School of Architecture and Design, Krasnoyarsk, Russia

INTRODUCTION

Deformation and failure of composite structures is a multi-stage process involving various scale levels, and it is hardly possible to accurately consider it within the framework of a single-dimension model. The mechanical degradation and fracture of composite laminates is essentially a macroscopic reflection of the initiation and accumulation of damage at the microscopic level. Therefore, it is necessary to take into account processes occurring on scales comparable with the characteristic size of the constituents, i.e. fiber diameter. However, despite the development of modern computational technologies, their performance and capabilities are insufficient to carry out calculations based on models, which would adequately couple the material microstructure and scale of engineering composite structures. The fiber diameter does not normally exceed 10 microns, while dimensions of composite structures can be in the order of meters. It is clear that modeling the behavior of such structures leads to a large computational cost even when using parallel computation. This problem requires the use of a hierarchical or so-called multiscale approach linking the evolution of damage at the microscopic level with the macroscopic behavior of the layered composite and the structures. Examples of this approach used for analysis of deformation and fracture of some type of composite elements and structures are demonstrated in [1-7].

A promising implementation of the multiscale approach is a methodology when the progressive damage of a representative volume of the material under applied macroscopic stress is first analyzed. The results of the analysis are then used to establish the relationship between microdamage processes with changes in the deformation properties and loss of the load-bearing capacity of the multilayer composite at the macro level [6-7]. Parameters characterizing the level of material damage are determined directly from the solution at the microlevel, and the effective mechanical characteristics of the corresponding volume at the macrolevel are determined based on the principle of averaging the stress (strain) tensor components (Fig. 1). The use of the same numerical tool (finite element method) makes it possible to solve these two interrelated problems in a single computing space. It should be noted that the finite element should correspond to the composite representative volume, which causes specific requirements to the parameters of finite element discretization [8]. Moreover, the reliability of microstructural analysis will be ensured only if the model reflects all the mechanisms governed the process of initiation and accumulation of "elementary" structural damages of the composite material – fiber debonding, fiber and matrix failure, as well as taking into account the stochastic nature of the mechanical properties of the components (first of all, the strength of the fibers). The assumption of the dominant role of fibers in stiffness and bearing capacity, although it has a physical justification, should not lead to consideration of the composite failure only as a kinetic process of accumulation of fiber breaks without taking into account the progressive damage of the matrix and interface.

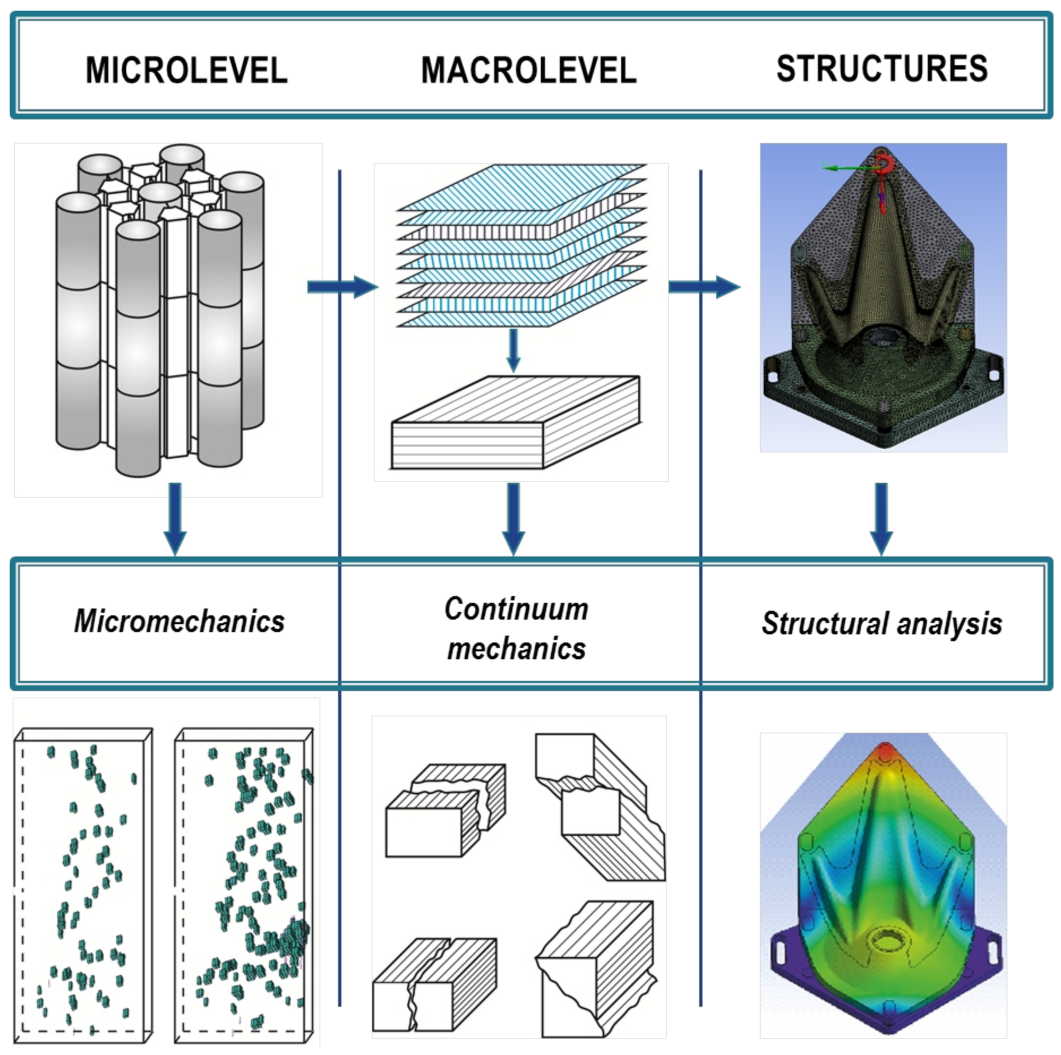

Fig. 1 - Implementation of the multiscale approach

RESEARCH METHODS

Polymer composites based on carbon fibers have a pronounced structural-mechanical heterogeneity. This requires analyzing either a significant number of representative volumes or a representative volume of a very large size in order to consider the variability of constituent properties. Thus, there is still the need to reduce the dimensionality of modeling task without sacrificing accuracy. To solve this problem, in our work we couple FEM, the structural-imitation approach, and the statistical modeling method [9-10]. The main idea is to discretize the continuum of the composite with a set of interconnected finite elements, which represent the microstructural constituents. If it is required, each of them can be characterized by an individual value of ultimate stress (strain) or deformation law.

Consider a composite with a periodic hexagonal fiber arrangement under tension (Fig. 1). The structural components are fiber elements, matrix elements carrying a tensile load, and elements that bear only shear deformations of the matrix. Each "tensile" element of the matrix is connected to three "shear" elements. Dividing the load-bearing capacity of the matrix into two functional components allows simulating the matrix failure and fiber debonding simultaneously. Fibers are represented by a 2-node 3-D truss. The element is uniaxial tension-compression; this simplification is legitimate, given a high modulus of carbon fibers. The same type of element simulates the tensile load-bearing capacity of the matrix. The shear rigidity of the matrix is represented by 4-node in-plane shell elements (Fig. 2).

Structural-imitation modeling the failure of unidirectional composite includes the following main steps.

1. Preparation of the initial data, building the finite element model, applying the initial displacement, assigning the ultimate stress (strain) for the structural elements according to the two-parameter Weibull distribution:

$$F(\sigma_f) = 1 - \exp\left[-\frac{L_e}{L_0}\left(\frac{\sigma_f}{\sigma_0}\right)^m\right] \qquad X_{f,m} = \sigma_0\left[\frac{L_0}{L_e}\ln(1-\eta)\right]^m \tag{1}$$

where F ([0..1]) is the probability of fiber (matrix) failure at stress $\sigma\leq$ the axial stress σ_f (σ_m); ([0..1]) - a random number from 0 to 1; *m* - the shape parameter; σ_0 - the scale parameter; L_0 - the fiber base length; L_e - the length of the structural element in the axial direction; *X* – the ultimate stress. The failure of an element occurs when $|\sigma_f|, |\sigma_m| \geq X_{f,m}$.

2. Determining the stress-strain state of the "sample".

3. Limit state analysis – comparing the stress (strain) acting in elements with the critical values. In case of the element failure its stiffness are reduced to a negligible value.

4. Repeating the step 3 if there are "failed" elements or increasing the displacement for the whole "sample" and following the steps 2 and 3.

5. The calculation is stopped when there is a spontaneous grown of the failed elements at a constant strain.

The load in composite is redistributed after a single element failure and a new FEM task should be solved but then the computation time is significantly increased. On the other hand, a large number of elements failed at one loading step often causes the instability of solution. To find optimal conditions, test calculations have been performed, which gives an acceptable number of "failed" elements in the range of 5-10 for one step of the solution.

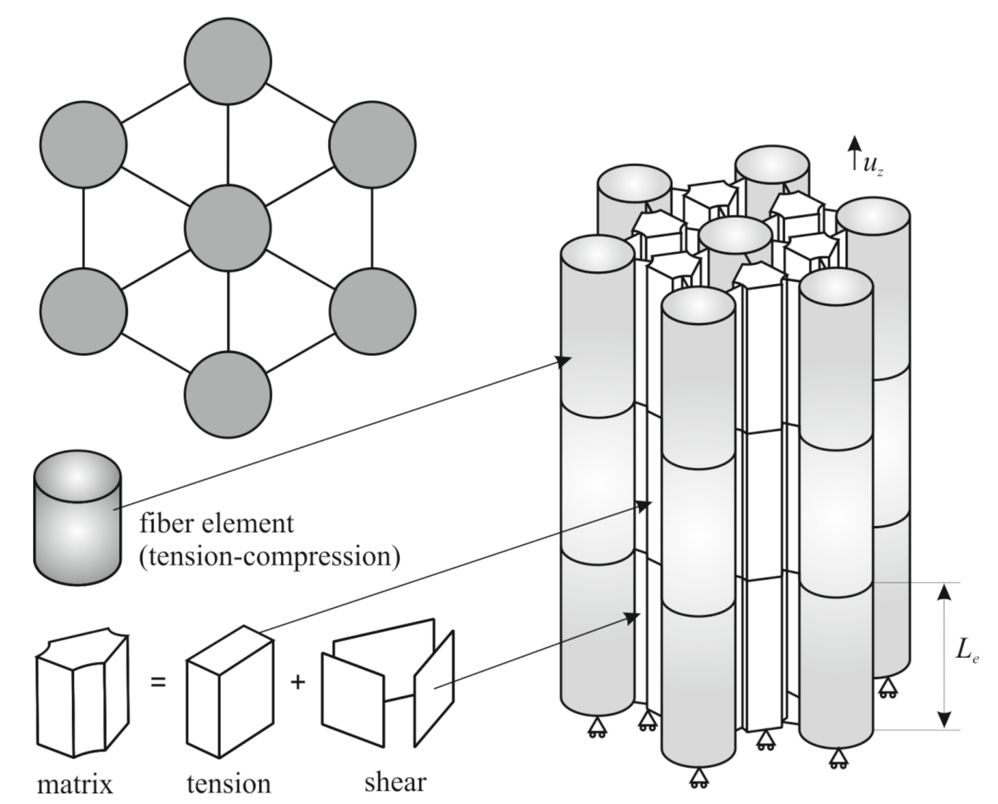

Fig. 2 - Microstructural elements and calculation scheme of imitation modelling the failure of composite at the microscopic level

RESULTS AND CONCLUSIONS

The failure modeling of a polymer matrix carbon fiber composite has been carried out employing the structural-imitation model described above. The sample model has contained 900 fibers. The following material properties have been used: volume fraction = 66%, fiber elastic modulus E_f = 300 GPa, Poisson's ratio ν_f = 0.16, E_m = 3 Gpa, ν_m = 0.33, σ_{0f} = 390 Mpa, m_m = 6.2, σ_{0m} = 90 MPa, m_f = 8.2.

The results of the calculation are shown on Fig. 3, where the stages of damage accumulation in the composite structure depending on applied strain level are demonstrated. For the sake of clarity, only the failed elements of fiber and matrix in tension are presented. The obtained data on the damage evolution are used to determine the mechanical properties of the material at the macroscopic level as a function of the stress-strain-damaged state (SSDS). In addition to the values of stress and strain, one of the variables of SSDS can be the fraction of failed elements of fibers [6] or matrix [7]. Assuming that the mechanical behavior of a composite with broken fibers and debondings is equivalent to the behavior of a similar material with the exclusion of these elements, the relative value of these failed volumes serves as a damage parameter *d*:

$$d = \frac{V_d}{V} \tag{2}$$

where V_d – number of excluded volumes.

The values of the elastic characteristics are calculated on the basis of the damage parameters:

$$E_{di} = E_{di}(1 - \varphi_i d) \tag{3}$$

where φ_i is a coefficient depending on the fiber volume fraction, the size of the representative volume and other structural features of a particular composite.

The degradation of the elastic moduli according to (3) as a function of the level of the load at the macroscopic level is shown in Fig. 4. Here, the stress values along the fiber direction are calculated by the rule of mixture.

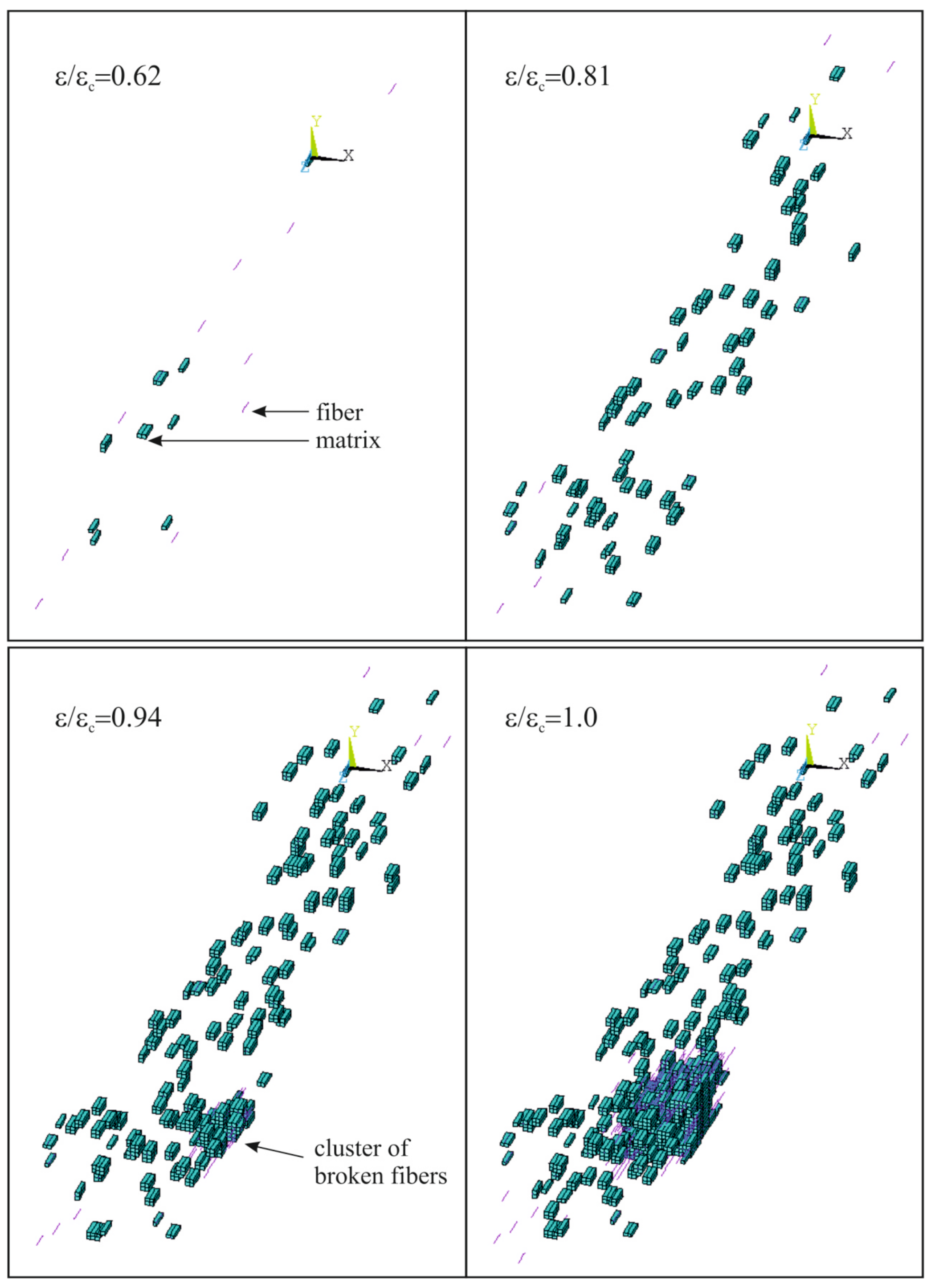

Fig. 3 - Progressive damage at the microscopic level

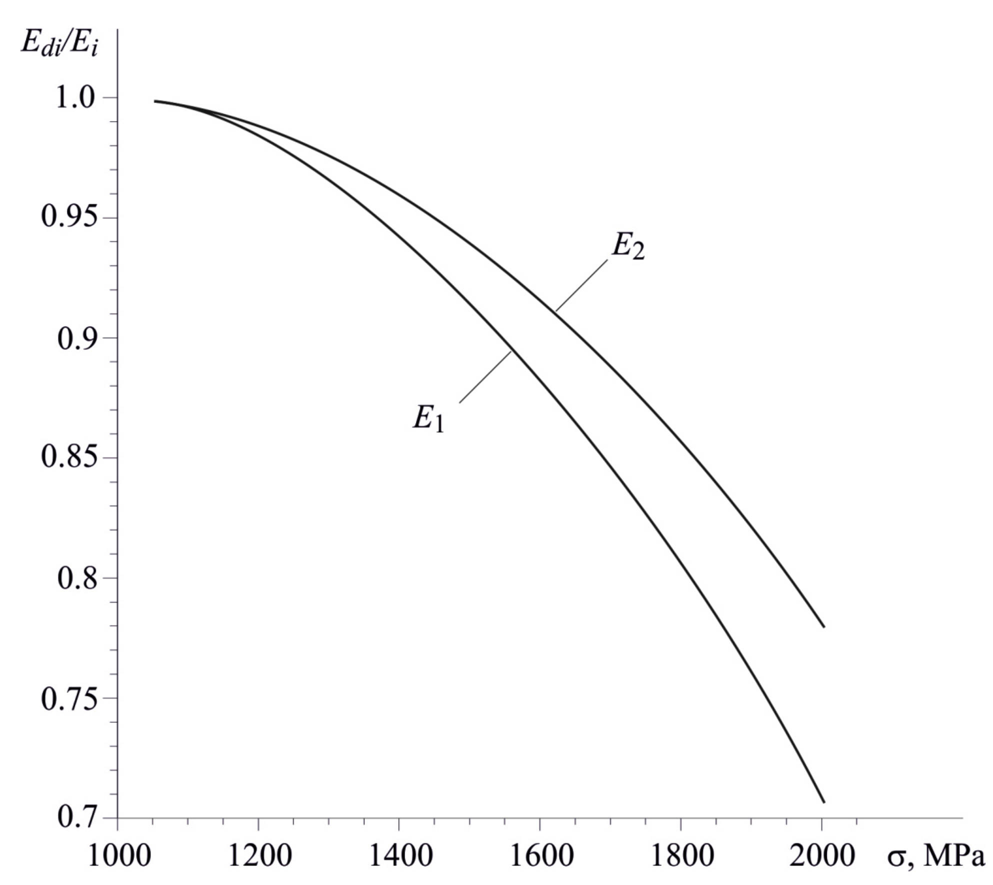

Fig. 4 - Degradation of the composite elastic moduli at the macroscopic level

ACKNOWLEDGMENTS

This work was done within a complex project and financially supported by the Russian Federation Government (Ministry of Education and Science of the Russian Federation), contract No. 02.G25.31.0147.

REFERENCES

1. *P. Liu and J. Zheng, Mat. Sci. and Engin. 485, 711-717 (2008).*
2. *B.N. Nguyen and K.L.Simmons, J. Compos. Mat. 47, 2113-2123 (2013).*
3. *P. Xu, J.Y. Zheng and P.F. Liu, Mat. Design. 30, 2295–2301, (2009).*
4. *P.F. Liu and J.Y. Zheng, Mat. Design. 31, 3825–3834 (2010).*
5. *S. Blassiau, A.R. Bunsell and A. Thionnet, Proc. R. Soc. A. 463, 1135–1152 (2007).*
6. *H.Y. Chou, A.R.Bunsell, G. Mair and A. Thionnet, Compos. Struct. 104, 144–153 (2013).*
7. *P.F. Liu, J.K. Chu, S.J. Hou and J.Y. Zheng, Comp. Mat. Sci. 60,137–148 (2012).*
8. *Yu. V. Svetova, Yu. N. Sidorenko and V.A. Skripnyak, Phys. Mesomech. 16, 59-65 (2013).*
9. *A. S. Ovchinsky, Fracture processes of composite materials: imitation of micro- and macromechanisms with computer (Nauka, Moscow, 1988).*
10. *A.E. Burov, I.I Koksharov and V.V. Moskvichev, Modelling the failure and crackresistance of fibrous metalcomposites (Nauka, Novosibirsk, 2003).*