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Simulation Modeling of the 4DL Reinforced Imperfect Composite Elastic Behavior

A E Dvoretskiy, I V Magnitsky, F R Odinabekov, E S Sergeeva, S V Tashchilov

Non-Metal Materials Complex, JSC "Kompozit", 4 Pionerskaya Street, Korolyov, Moscow Region, 141070, Russia
Email: info@kompozit-mv.ru

Abstract. Two models simulating the 4DL-reinforced imperfect material elastic behavior are analyzed. The model that involves direct introduction of an imperfect fiber-matrix contact is found to predict higher values for the compressive modulus of elasticity, rather than for the tensile one. This model also gives non-linear stress-strain diagram along some directions. Both models demonstrate a significant rigidity scale effect. Given the effects observed in actual practice with the materials of this class, conclusion was made about second model's usefulness in engineering practice.

1. Introduction

Currently, two basic simulation modeling concepts exist for simulating the behavior of composite material structures, namely, the effective modulus method and various approaches considering the material microstructure. The effective modulus method involves composite material replacement with a uniform, generally isotropic, medium, its properties being determined experimentally using representative samples of the material. As this method does not involve solving of any special mechanics problems, it is not resource-intensive and has been widely implemented. However, it fails to account for a number of effects observed in actual practice such as various scaling effects. Due consideration for the material microstructure provides closer reproduction of the actual material behavior, while requiring development of special simulation models and means.

In terms of the microstructure approach, different concepts of material irregularity representation have been considered. The best understood and most widely used in engineering practice are methods based on analytic macro-/microstress-strain dependencies [1-4]. Such dependencies, while being relatively simple and easy-to-implement as a software program, provide limited accuracy due to the necessity of multiple arbitrary assumptions. Among numerical methods, those based on asymptotic approximation can be distinguished, as they provide more accurate solutions, while requiring an assumption about a small scale of irregularities (as related to the actual size of the structure in question) and their periodic arrangement [5, 6]. However, the method based on direct simulation of the material irregularity, followed by solving the problem using the finite element method or its equivalent, should be regarded as the most generic approach in terms of both the material nature and the simulated structure behavior. At the same time, its implementation consumes considerable computing resources.

This paper addresses the 4DL-reinforced composite material elastic behavior with due account for the defect that is most frequently encountered in practice, while being ignored generally in the simulation models in use, namely, separation of the reinforcing elements (fibers) both from the matrix and from each other. The computations were based on direct simulation of irregular volumes of the material using the finite element method in the ANSYS software environment.

2. Task definition

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For the ease of material simulation, a single structural cell of the material was taken (see Figure 1). The computational volume of the material was treated as composed of those structural cells. The volume length in the a direction – as l_a. The component elastic properties used in the computations are in accordance with the state-of-the-are composite material (see Table 1).

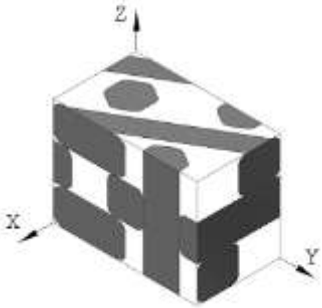

Figure 1. The single structural cell of the material and chosen coordinate system.

Table 1. The components elastic properties.

Characteristic	Value
Longitudinal elastic modulus of the fiber	165 GPa
Transverse elastic modulus of the fiber	3.59 GPa
Longitudinal shear modulus of the fiber	3.84 GPa
Longitudinal and transverse Poisson's ratios of the fiber	0.25
Elastic modulus of the matrix	2.60 GPa
Poisson's ratio of the matrix	0.25

The composite material was deemed as composed of two components, a matrix and a reinforcing element – a core. The components were considered to be solid and uniform, the matrix – isotropic, and the fibers – transversally isotropic.

The boundary conditions set for the material volume simulated the uniaxial loading of a test sample during experimental investigation of the material properties. Thus, under tension along the x axis, they were defined in accordance with [7]

$$\begin{aligned} &x=0 \Rightarrow \begin{cases} u_x = 0, \\ \sigma_{xy} = \sigma_{xz} = 0; \end{cases} \\ &x=l_x \Rightarrow \begin{cases} u_x = s > 0, \\ \sigma_{xy} = \sigma_{xz} = 0; \end{cases} \\ &y \in \{0, l_y\} \Rightarrow \sigma_{yy} = \sigma_{xy} = \sigma_{yz} = 0; \\ &z \in \{0, l_z\} \Rightarrow \sigma_{zz} = \sigma_{xz} = \sigma_{yz} = 0. \end{aligned} \tag{1}$$

Here σ_{ij} – stress tensor components, u_i – displacement vectors. The s value was chosen so as to provide deformation equal to 0.001, unless otherwise stated. For other load patterns, the boundary conditions were defined in similar fashion.

The component separation in the material was simulated in two ways. In the first case, a dry friction contact was defined at the components interface. Such problem definition, while providing closer reproduction of the actual material, results in physical nonlinearity, thus adding complexity to the solution and failing to adjust the degree of material imperfection. In the second case, a special isotropic medium featuring small thickness and extremely low rigidness was introduced at the components interface, simulating the air gap. In this case, the problem remained linear, while by adjusting the rigidness of the medium it was possible to simulate partial destruction of the interface.

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However, the operational convenience of this model was achieved at the expense of its adequacy to the actual conditions.

As the value characterizing the material elastic behavior, the elasticity modulus was taken, being determined as follows:

$$E_a = \frac{2Wl_a^2}{s^2 l_x l_y l_z}. \tag{2}$$

Here W – total elastic energy of the volume. The choice of the calculation method was based on the stability of the results that depend only weakly on the special features of the finite element grid and the contact problem settings.

In the computations, a finite element grid composed of mainly SOLID186 second-order 20-node solid elements was used.

As a comparison object, the results obtained using the method described above for the separation-free material were taken.

3. Main results

In the first case (with the separation model), the elasticity module values obtained do not depend on the frictional coefficient between the material components. Moreover, with the frictional coefficient ranging from 0 to 0.5, the elasticity modulus data scattering makes up about 0.5%, meaning that the force transfer between the material components due to the frictional force is negligibly small.

The elasticity moduli along the *x* and *y* axes show presence of the scaling effect. For the *y* axis elastic modulus dependence of the cell number is shown in figure 2. As can be seen in Fig. 2, magnitude of the scaling effect in each certain case being dependent not so much on the absolute volume of the material block under consideration as on the presence or absence of the reinforcing cores passing through the volume from one load-bearing facet to the other. The absolute value of the scaling effect, when loading along the *x* axis, is lower than that along the *y* axis, due to the presence of the cores oriented along the *x* axis.

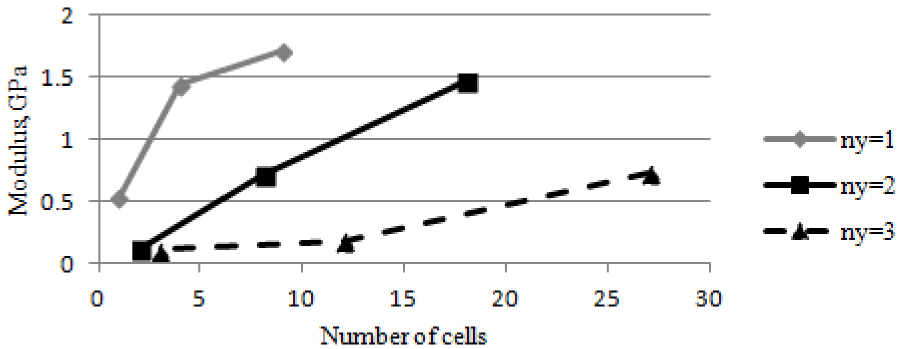

Figure 2. The elastic modulus dependence of the cell number for the *y* axis.

Both effects described above take place both under tension and under compression; however, the elasticity modulus value itself depends on the load direction. That said, it is essential that the elasticity modulus value obtained under tension is smaller than that obtained under compression. This effect is at its greatest when applying loads along the *y* axis, in which case there may be a difference of tens of percent. This can be attributed to the fact that, when compressing a material volume, any separations contained within the material tend to close, therefore, the cores bear the loads almost similar to those in case of a solid material, while when under tension, any cracks tend to open wider, and the presence of the cores transverse to the load direction in the material has almost no effect on the material rigidness. On the other hand, this effect contradicts to the available experimental data, according to which, materials of the type under consideration usually show better rigidness under tension than under compression, thereby demonstrating that the modulus difference revealed in the material can be attributed primarily to the special nature of the material components rather than the presence of component separations within the material volume.

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The compressive stress-strain diagram is of non-linear nature, with the material rigidness growing as the deformation increases. Figure 3 shows an example of the compressive stress-strain diagram along the y axis for a single cell. The tensile stress-strain diagram is approximately linear. Such a difference between material behaviors under tension and compression loads may explain the corresponding elastic moduli values inequality.

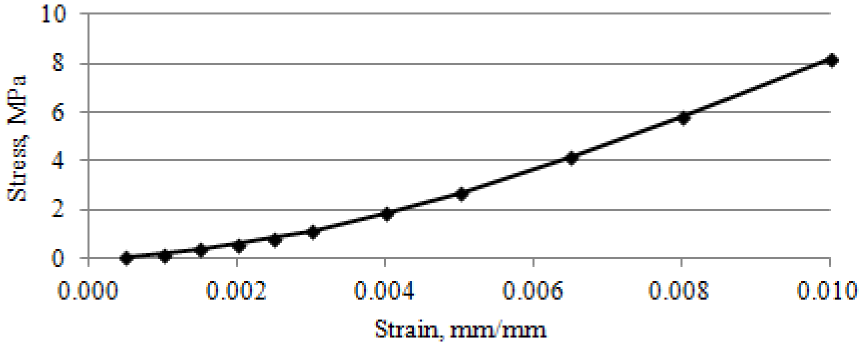

Figure 3. The compressive stress-strain diagram along the y axis for a single cell.

As should be expected, the general level of the material rigidness is lower than that in case of a perfect material, which is well illustrated by the data given in Table 2.

Table 2. Elastic modulus of the perfect and imperfect composite under the tensile stress.

Volume structure	Elastic modulus of the perfect material, GPa			Elastic modulus of the imperfect material, GPa		
	x axis	y axis	z axis	x axis	y axis	z axis
1×1×1	29.8	7.1	37.3	26.45	0.53	33.20
2×2×2	29.9	10.9	37.4	26.87	0.72	34.84
3×3×3	30.0	14.3	37.4	26.86	0.73	34.85

Since no complete core/matrix separation has been observed in reality, to substantiate the aforesaid effects, computation was performed for a material volume composed of 3×3×3 cells, where the separations were localized in the central cell. The results of the calculations show that the delamination effect on the average elasticity modulus does not exceed 3%. Also average value of elasticity moduli in tension and compression coincide with high accuracy. Thus, there is influence of local delamination on the average stiffness is virtually nonexistent in the real material.

Computation results obtained using the second model showed that in this case, the material behave as a linear one both under tension and under compression. Moreover, no material modulus difference is shown by the results. Comparing to first model results, obtained y axis modulus is significantly lower because of there is no direct contact between cores and matrix in the second model. In respect that the level of imperfect material y axis modulus is extremely low and the local delamination influence at large volume elastic moduli is rather negligible, we may disregard such a difference. It should be noted, however, that within the framework of such a problem definition it is incorrect to perform computations for large deformations, since starting from a certain deformation point, the separation-simulating gaps close, thus necessitating relevant changes in the finite element grid.

Also it was shown that the elastic moduli values depend significantly on the material structural cell choice. As can be seen in Table 3, the elasticity modulus values obtained with different cell assignment differ highly. This effect should be investigated in more detail further.

Table 3. Elastic modulus of the imperfect composite under the tensile stress.

Volume structure	Elastic modulus of the general cell, GPa			Elastic modulus of the modified cell, GPa		
	x axis	*y* axis	*z* axis	*x* axis	*y* axis	*z* axis
1×1×1	26.78	0.53	34.82	26.45	2.59	33.20
2×2×2	26.87	0.72	34.84	28.53	8.45	34.49
3×3×3	26.86	0.73	34.85	28.49	13.22	35.18

4. Conclusion

Analysis of the computation results shows that all the effects observed agree qualitatively with the existing understanding of the peculiarities of the imperfect material behaviour. The results obtained using different models show sufficient agreement.

The first model allows for observing the difference in the material stress-strain state that develops under tensile and compressive loads. With this model, it is also possible to predict successfully the material behavior, including non-linear one, at large deformations; however, the effects predicted therewith do not manifest themselves to a large extent in real materials. This fact makes it possible to conclude that the material defect such as component separation has a very small impact on the observed values of the actual 4DL reinforced material elasticity modulus.

That being said, given the negligibility of these effects in the actual practice, the second model seems to be more useful due to its simplicity, smaller computational resource requirement and the ability of simulating, to some extent, partial destructions in the material, reducing the whole of the local separations to a single value very similar to the degree of destruction in some kinetic criteria of strength. At the same time, when it is necessary to simulate exactly the local state of the material in the fiber/matrix separation area, the first model seems to be quite applicable as well.

The results obtained attest to long-term benefits of this line of research aimed at the development of structural simulation models for 4DL reinforced materials. As an interesting subject for further study, the local stress state of material components, either with or without components separation, can be investigated.

List of Reference

[1] Malmeister A.K., Tamuj V.P., Teters G.A. Resistance of Polymer and Composite Materials. — Riga, Zinatne, 1980. — 572 pp.

[2] Voigt W. Lehrbuch der Kristallphysik. Berlin—Leipzig, Teubner-Verlag, 1910. 964 c.

[3] Hill R. Theory of mechanical properties of fibre-strengthened materials. III. Selfconsistent model. — J. Mech. Phys. Sol., 1965, vol. 13, N 4, p. 189 — 198.

[4] Z. Hashin, B.W. Rozen. Elasticity Models of Fiber Reinforced Materials. Transl. from English. — Applied Mechanics. Series E. 1964, No. 2, pp. 223 — 232.

[5] I.M. Lifshits, L.N. Rosenzweig. On the Theory of Elastic Properties of Polycrystals. — JETF, 1946, 16, 11.

[6] I.M. Lifshits, L.N. Rosenzweig. On the Construction of Green's Tensor for the Fundamental Equation of the Theory of Elasticity in the Case of an Unbounded Anisotropic Elastic Medium. — JETF, 1947, 17, Release 9.

[7] B.S. Sarbayev, I.V. Magnitsky. Method for Estimating the Effective Elasticity Characteristics of 3D Reinforced Composite Materials // Composite Material Structures, 2014, No. 2. pp. 3 — 9.