A probabilistic model of fracture of the composite material of a composite overwrapped pressure vessel

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Abstract. A probabilistic numerical model for fracture of unidirectional composite materials is developed. The algorithm for numerical simulation of the model takes into account the random distribution of carbon fibers, the spread of mechanical properties and the fracture of the structural elements of the material. Multivariate numerical experiments of the composite material of a composite overwrapped pressure vessel under tensile loads were carried out. The analysis of the patterns of deformation and fracture of a composite material is carried out. The physical mechanism of deformation and fracture of a composite material corresponds to a numerical model. The stress-strain curves of a numerical model of a composite material at 70% carbon fiber content are presented. The calculated values of Young’s modulus and tensile strength of the composite material at different percentages are obtained. A comparative analysis of experimental and numerical results showed that the results corresponded to 15%. Using a numerical model of deformation and fracture of unidirectional composite materials makes it possible to track the mechanics of the processes of fracture of fibers and matrix, to obtain the most accurate analysis of the stress-strain state, and to develop generalized methods for calculating the strength of composite overwrapped pressure vessels

1. Introduction

Composite materials (CM) in comparison with other materials have several advantages: high strength, increased stiffness and low specific gravity. In this regard, CM most effectively reveal their potential for use in the shipbuilding, aviation and space industries.

Fracture of unidirectional CM is a complex multi-stage random process. This complexity is associated with the emergence of various mechanisms of fracture, which lead to the formation of rupture of fibers, fracture of the matrix, the loss of communication “fiber-matrix”, etc. The randomness of the process is due to the chaotic arrangement of carbon fibers in the matrix, which prevents the redistribution of stresses from the fractured fiber to the intact. Another factor is the variation in mechanical properties. This situation leads to a large variation in the tensile strength of experimental specimens from CM of a composite overwrapped pressure vessel (COPV), which was investigated in [1].

Experimental and theoretical studies of CM [2-5] are devoted to various processes of deformation and fracture of unidirectional CM, with numerical modeling technologies playing an important role. As a rule, unidirectional CM are modeled using application packages base on the use of the finite element method

In the mechanics of CM systems of interacting structural elements are considered [2-9]. Such models make it possible to predict effective characteristics of mechanical properties, calculate inhomogeneous
stress and strain fields, and simulate CM fracture as a multi-stage process. This approach allows us to study the effect of structure parameters on the effective physic and mechanical properties of composites in order to assess the stress-strain state. A multiscale model of fracture of unidirectional CM under tension is presented in [7, 10, 11], which includes the evolution of damage and fracture of structural elements. In [12-14], the fracture of CM is simulated, which takes into account the spread in the strength of fibers located strictly paralleled to each other in the hexagonal matrix. The works [14–17] are devoted to the study of the initial stage of the occurrence and development of damage in the CM using the damage tensor to describe the mechanisms of the formation of voids and cracks, as well as the fracture of the bond between the fiber and the matrix.

One of the main problems in the numerical simulation of fracture is the correct determination of the residual stiffness of the damaged material, taking into account the implementation of the fracture, the interaction of the fractured and non-fractured elements, the chaotic distribution of fibers, the spread of mechanical properties, as well as the numerical implementation [2]. In this regard, for a better understanding of the laws of deformation and fracture of CM, there is a need for the further development of probabilistic fracture models that take into account random features of the CM structure.

The object of the study was CM COPV. The COPV is installed on telecommunication satellites and serves to store fuel during the active life of the spacecraft [1]. In this regard, the study conducted unidirectional CM based on carbon fibers T1000 and epoxy adhesive ED-I. The aim of the research was:

- Development of a numerical micromodel of fracture of the CM based on experimental data.
- Analysis of the patterns of deformation and fracture of the CM by the method of finite element modeling.
- Construction of stress-strain curves and determination of the mechanical properties of CM at different percentages of carbon fibers.
- Comparative analysis of the experimental and numerical results of testing CM specimens.

2. Development of a probabilistic model of fracture of the CM

To ensure the necessary indicators of strength and resource CM are designed for specific objects. We use finite element models that take into account the micromechanical effects on a “fibers-matrix” scale to predict the deformability and fracture of the material. Such models make it possible to obtain information on permissible damage in the material, as well as to identify the prospects for studying damage and fracture under conditions of cyclic and high temperature loading. In this regard, a 3D numerical model was developed using the ANSYS Mechanical APDL finite element analysis software system. The Model included a number of features:

- Complete parameterization with input data.
- Generation of random arrangement of carbon fibers inside the matrix.
- Accounting for the variation in the characteristics of mechanical properties.
- Fracture of structural elements in case of stress overload.

The flowchart of the task algorithm is presented in figure 1. The effectiveness of applying the iterative method is due to the possibility of obtaining a reliable approximation at each stage of the solution. If the solution for a CM structure without fracture of elements is known, then for the model containing the fracture of structural elements, the results of the calculation at the previous stage are taken into account.

Based on the studies in [2-10, 18], the fibers in the CM are located randomly and even with large distances between them, which makes it necessary to model a variant with a random arrangement of fibers inside matrix. The process of generating a random arrangement of fibers is to create disjoint circles (fibers) in a limited plane. The program calculated the required number of fibers \(n_f\) with diameter \(d_f\) in boundary region \(S_m\) to ensure a giver percentage of carbon fibers \(V_f\). After the calculations, a cycle is started in which circle \#1 (fiber) and circle \#2 are randomly drawn, after which the distance between them is checked if they intersect, then the last drawn circle is deleted, and a new random coordinate for
the circle is generated. The cycle works until the required number of fibers is fixed at a given percentage of fibers in the matrix.

![Flowchart of the task algorithm](image)

**Figure 1.** Flowchart of the task algorithm.

Most CM reinforced with high modulus carbon fibers have a high variation in mechanical properties [1, 19-20]. In accordance with this, the fibers must be modeled as a chain consisting of units with different characteristics of mechanical properties. Rupture of a fiber occurs at a failure stress of the weakest chain link. If we assume that the mechanical properties obey the normal Gaussian distribution, then the probability density function of the distribution will be described by the equation:

$$f(x) = \frac{1}{\sigma \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}},$$

(1)

where $\mu$ - expected value; $\sigma$ - standard deviation.

The fracture of the CM is determined using the failure criteria of finite elements. At each loading step, stress analysis in elements of the CM is performed, after which a database of these elements is formed. If an element goes into a certain limiting state, then the material is considered fractured. Fracture is fixed by reducing the stiffness matrix of the elements (the stiffness of the fractured elements tends to zero) and excluding them from the calculation (figure 2).
Figure 2. The process of fracture (exclusion) of finite elements in a numerical model.

To model fracture in the CM, it is necessary to specify a failure criteria of structural elements [21, 22]. The simplest failure criteria for tensile unidirectional CM are the criteria for maximum tensile stresses for fiber (2) and for matrix (3).

$$\sigma_i \geq \sigma_{TS}',$$  \hspace{1cm} (2)

$$\sigma_{EQV} \geq \sigma_{TS}'_m,$$ \hspace{1cm} (3)

where $\sigma_{TS}'$ – fiber tensile strength; $\sigma_{TS}'_m$ – matrix tensile strength.

The following geometric parameters were used as initial data for a numerical experiment in the tension of a unidirectional CM: carbon fiber percentage $V_f$ ranged from 40 to 70%, fiber diameter $d_f = 130 \, \mu m$, fiber length $l_f = 130 \, \mu m$, initial matrix area $S_m = 130 \, \mu m$. The characteristics of the mechanical properties of the structural elements are presented in table 1.

| Characteristic          | Fiber | Epoxy resin |
|-------------------------|-------|-------------|
| Young’s modulus, GPa    | 290   | 3           |
| Tensile strength, GPa   | 6.6   | 0.1         |
| Poisson’s ratio         | 0.28  | 0.32        |

The analysis of the stress-strain state was carried out under tension along the direction of reinforcement of carbon fibers. Constant displacement was uses as the load. The model included up to 800000 volume finite elements.

3. Results and discussion

In the course of the study, numerical simulation of CM was carried out at different percentages of carbon fibers. Based on the results of multivariate simulation, stress-strain diagrams were constructed for each percentage of carbon fibers in the CM. Figure 3 shows one of the numerical experiments.
Figure 3. Stress-strain curve for CM (70% fiber content).

Based on the multivariate numerical simulations, the average Young’s modulus and tensile strength were determined at different percentages of carbon fibers. The characteristics of mechanical properties are shown in Table 2.

| Carbon fiber percentage, % | Young’s modulus, MPa | The coefficient of variation of Young’s modulus | Tensile strength, MPa | Coefficient of variation of tensile strength |
|---------------------------|-----------------------|-----------------------------------------------|----------------------|--------------------------------------------|
| 40                        | 80676                 | 0.052                                         | 1789                 | 0.12                                       |
| 45                        | 93311                 | 0.065                                         | 2041                 | 0.115                                      |
| 50                        | 102404                | 0.058                                         | 2233                 | 0.127                                      |
| 55                        | 111620                | 0.054                                         | 2357                 | 0.124                                      |
| 60                        | 118266                | 0.055                                         | 2533                 | 0.119                                      |
| 65                        | 124179                | 0.049                                         | 2627                 | 0.12                                       |
| 70                        | 129465                | 0.052                                         | 2746                 | 0.118                                      |

Figure 4 shows a phased fractured model. If a limiting state arises in the fiber elements (figure 4 (a)), then with the subsequent solution this fibers is fractured (figure 4 (b)) and the process of fracture of the CM begins (figure 4 (c), (d)). After the fracture of the fibers, the stresses redistributed to the undamaged fibers, while the CM does not lose its bearing capacity and a new stress-strain state arises in the material.
Figure 4. Phase fracture of fibers: (a) three iteration; (b) fourth iteration; (c) fourteenth iteration; (d) twenty-third iteration.

It is important to note that when a fiber breaks, a local stress concentrator arises in the matrix that lead to an increase in the stress level in the entire CM (figure 7).

Figure 5. Local fracture of matrix: (a) fractured fiber; (b) fracture of matrix elements.

Thus, if a high level of damage occurs in the material, which includes breaking of the fibers and fracture of the matrix, then the CM completely loses its bearing capacity.

In [1], tensile tests of flat unidirectional specimens of CM COPV (70% fiber content) were performed. Specimens were made from fragments of the composite tape, which were peeled off from the surface of the composite shell of the COPV. Figure 6 shows examples of the strain diagram of numerical simulations and experiment. Based on the diagram, it can be noted that the process of deformation and fracture of a numerical experiment corresponds to experimental data.
Figure 6. Stress-strain curves of numerical and experimental data for CM (70% fiber content): (a) numerical simulations; (b) experimental data.

A comparative analysis of the calculated and experimental average characteristics of the mechanical properties showed a difference of up to 15%. The values of the calculated and experimental characteristics of the mechanical properties of the CM are presented in Table 3.

Table 3. Characteristics of the mechanical properties of CM COPV.

| Test method            | Young’s modulus, MPa | Tensile strength, MPa |
|------------------------|-----------------------|-----------------------|
| Laboratory testing     | 115702                | 2334                  |
| Numerical simulations  | 129465                | 2746                  |

These differences occur because the reinforcement angle of the experimental specimens is 10 degrees, while in numerical simulations the reinforcement angle of 0 degrees was considered. In addition, in the manufacture of laboratory CM specimens, there was a mechanical effect on the material due to the separation of the tape from the composite shell of the COPV. Thus, the developed parameterized numerical model allows one to carry out numerical experiments with the well-known set of information on the structural elements of CM.

4. Conclusions

A probabilistic parameterized model of CM fracture with a random arrangement of fibers and a spread of mechanical properties is developed. Investigations of the stress-strain state of CM COPV were carried out, in which the calculated values of the Young’s modulus and tensile strength were determined for different percentages of carbon fibers.

Numerical simulation of CM showed good qualitative and quantitative agreement with experimental data. The calculation results allow us to conclude that the use of a numerical model of deformation and fracture of unidirectional CM specimens makes it possible to track the mechanics of the processes of fracture of fibers and matrix, to obtain the most accurate analysis of the stress-strain state, and to develop generalized methods for calculating the strength.

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