NUMERICAL INVESTIGATION OF INFLUENCE OF INITIAL DAMAGES ON STRENGTH PARAMETERS OF CFRP

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Abstract

The work is devoted to development of structural numerical model of CFRP, analysis of the resin stress/strain state and investigation of influence of initial CFRP fracture on its properties. The model allows investigating the growth of cracks in the resin at microlevel, and obtaining connection of the microcracks sizes with CFRP macro parameters, such as elastic modules and residual static strength.

On the basis of the developed structural model of CFRP the parametrical investigation for different fragments of CFRP with the fiber ratio in a range of 20-70 % and orthotropic laminate (0°/90°) are carried out.

1 General Introduction

Composite fiber reinforced polymers (CFRP) are widely used in up-to-date aircraft structures due to its high specific strength and stiffness characteristics. However, as applied to primary composite aircraft structures, there are many problems, such as low efficiency of CFRP in frames of conventional structure layout, absence of reliable durability criteria and difficult fracture pattern. It is caused by presence of multiple strain concentrations at the microlevel, leading to occurrence and growth of microcracks in resin and the subsequent degradation of strength characteristics of CFRP while in service. Unfortunately, existing strength criteria do not allow at designing to provide long-term strength of high-loaded aircraft structures under the influence of real operation factors: environment (temperature, moisture) and impacts.

For designing primary composite aircraft structures with high weight efficiency, meeting requirements of long-term operation, the reliable engineering strength criteria are necessary. The criteria should consider growth of the microcracks, influencing on CFRP strength characteristics, and consider influence of real operation factors. The strength criteria can be developed only based on the extensive numerical and experimental investigation of CFRP strength parameters.

In order to obtain the required strength criterion it is necessary to have accurate mathematical model of behavior and destruction mechanisms of composites at microlevel. On the base of this model it is possible to obtain universal structural strength criterion that does not directly depend on design parameters.

In this paper a simplified model of composite at microlevel is proposed. The following basic assumptions were made:

- fibers in the monolayer are parallel to each other, and their axes lay in one plane,
- fibers and resin are homogeneous within its volume,
- interaction of fibers and resin occurs over entire area of their contact,
- a fiber is a straight cylinder with circular cross-section with rectilinear axis.

2 Strength features of laminated composites

CFRP has heterogeneous structure. It consists of two main components - high-strength fibers, responsible for load-bearing capacity, and resin, that integrates high-strength fibers into a single structure. Modern high-strength composites, as a rule, consist of carbon fibers and epoxy or other resin. In aviation industry, the most common composites are the laminates with carbon fibers (diameter 5-15 μm) laid in monolayers, oriented at different angles. The thickness of monolayer is 0.1-0.2 mm. Volume fraction of fibers in composites is, as a rule, 40-60 %.

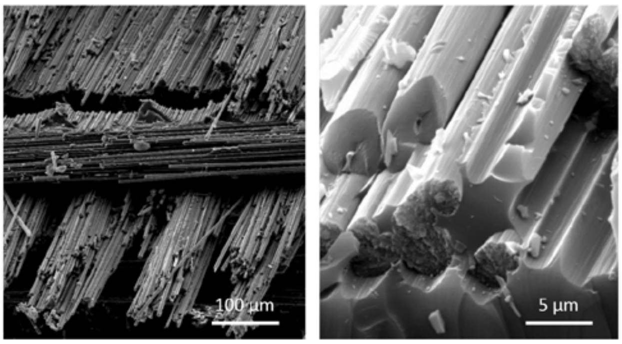

Figure 1 Microstructure of composite in fracture zone

The main problem with the development of composite aircraft is that strong fibers can be integrated into a monolithic structure only by means of resin. Experience and numerous studies show that initial destruction of composite laminate begins in resin. Modern resins have tensile strength $\sigma_{ul.resin}$≈5–7 kgf/mm^2 and allowed strains $\varepsilon_{ul.resin}$≈2.3–2.5 %, whereas tensile strength of modern carbon fibers is $\sigma_{ul.fibers}$≈350–500 kgf/mm^2. Maximum allowed strains of fibers are $\varepsilon_{ul.fibers}$≈1.8–2.1 % [1,2].

Resins do not allow carbon fibers to realize fully their high strength characteristics in quasi-isotropic and other orthogonal laminates.

Experimental and numerical strength analysis of composite structures, carried out in [3,4-8], has shown that in composite laminates even under small external forces there are multiple zones with high level of stresses in the resin. Such concentrators appear because of topology of laminates and the nature of damage growth is caused by low strength characteristics of the resin.

The first step to formation of strength criteria for composites is the study of cracks' appearance and propagation in the resin at the microlevel under the influence of external mechanical loading and also the study of the effect of microcracks on mechanical characteristics of composites.

Existing calculation methods do not allow assessing destructions at microlevel, and, consequently, providing long-term strength of high-loaded aircraft structures under the influence of real exploitation factors: environment and impacts. Therefore, there is a need to model these processes at microlevel.

2.1 Formation of plane model

At first step, a flat model of representative volume element (RVE) of CFRP ($0^0/90^0$) thermosetting resin was created. The resin was modelled as a plastic material with $\varepsilon_{ul.resin}$=2.3 %.

For modeling different volume ratio of fiber and resin were considered: 50/50 %; 60/40 %; 70/30 %.

Stress/strain state analysis of RVE was analyzed under tensile loading with the value of strain about 0.7 % (Figure 2a). The value of strain in resin between fibers was higher than 2.3 %. Figure 2 shows the stress/strain state of RVE.

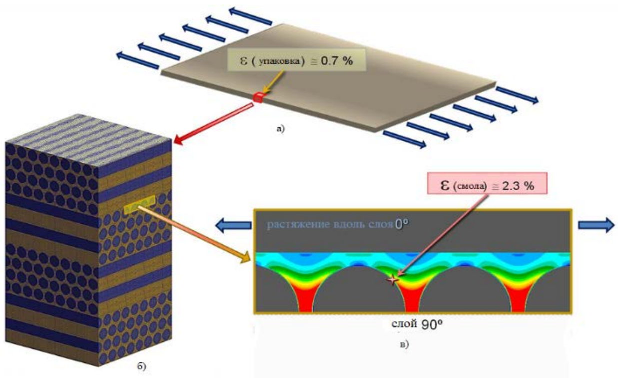

Figure 2 Model of composite

The figure shows the stresses concentrations inside CFRP. This study is carried out to find the relationship between destruction of resin and destruction of the laminate itself.

Computer analysis has shown the critical zones where cracks appear. The destruction modelling method of the laminate under tension was developed to investigate the microcracks growth. According to the method the cracks appear between closely located fibers and propagate along the fiber cross-section (Figure 3).

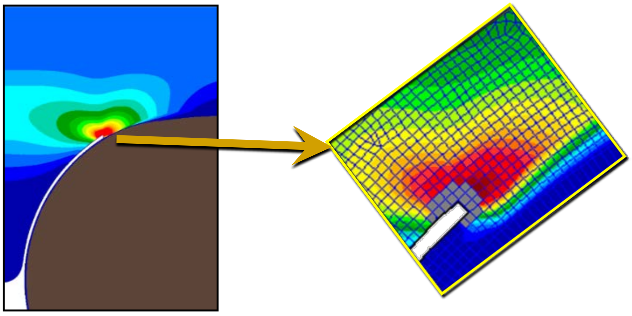

Figure 3 Crack propargation model

A crack can propagate through the interface of two phases and near it if there is high adhesion between fiber and resin. The crack stops (Figure 4) at the place where delamination of CFRP and, consequently, significant strength reduction occurs.

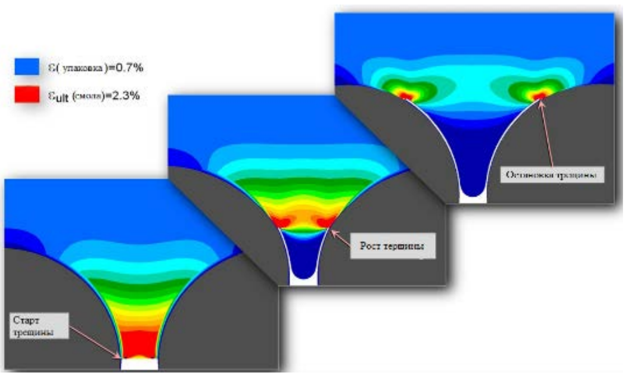

Figure 4 Crack propagation in CFRP modeling

2.2 Formation of solid model

For more detailed analysis, the structural parametrical model of CFRP based on FEM was developed. The model consists of solid finite elements (tetrahedrons, prisms and hexahedrons) modeling resin, interphase layer and reinforcing fibers. The model allows determining stress/strain state of resin between fibers in automatic mode. For calculations the "idealized" RVE of 0°/90° CFRP was considered. The choice of 0°/90° CFRP is caused by the fact that destruction occurs in 90° layers (in respect to vector of tension). As a simplification, it was assumed that a monolayer was formed by a single row of fibers. The model allows to specify properties of the resin, fibers, and take into account the influence of interphase layer. In this paper, properties of the interphase layer were assumed equal to those of the resin.

MSC.Patran was used to automatic forming the model of "idealized" RVE. The initial data for forming the model are elasticity modules, Poisson's ratios and strength limits of fibers, resin and interphase layer, as well as the fibers volume ratio and the size of FEs.

Fibers and the boundary layer are divided into equal amount of finite elements. FE model of the resin is formed separately (Figure 5). The interphase layer is modeled by Hex 8 finite elements. It allows predicting the propagation of microcracks quite accurately. To save calculation time, the fibers are modeled by a single layer of finite elements. FE properties are assumed isotropic.

Modeling of microcrack propagation was carried out by exclusion of those FEs of the resin, where the value of strains reached the ultimate value.

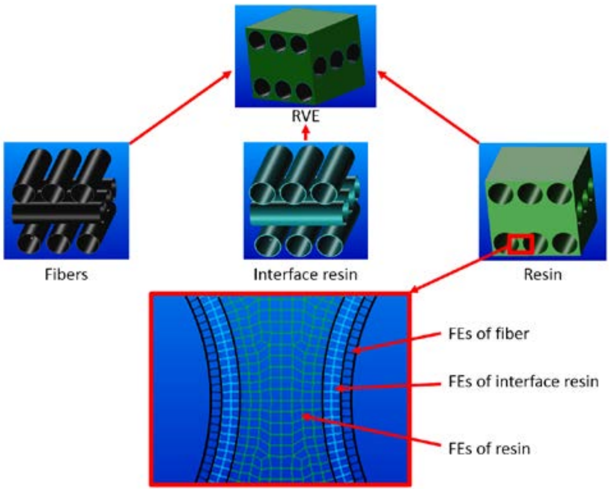

Figure 5 Formation of FE model

The solid model was fixed by one of the RVE sides, the tensile load was applied to the opposite RVE side. Figure 6 shows the zones with the maximum level of strains in a layer orthogonal to the vector of tension. The initial damages of CFRP occurs at that zones.

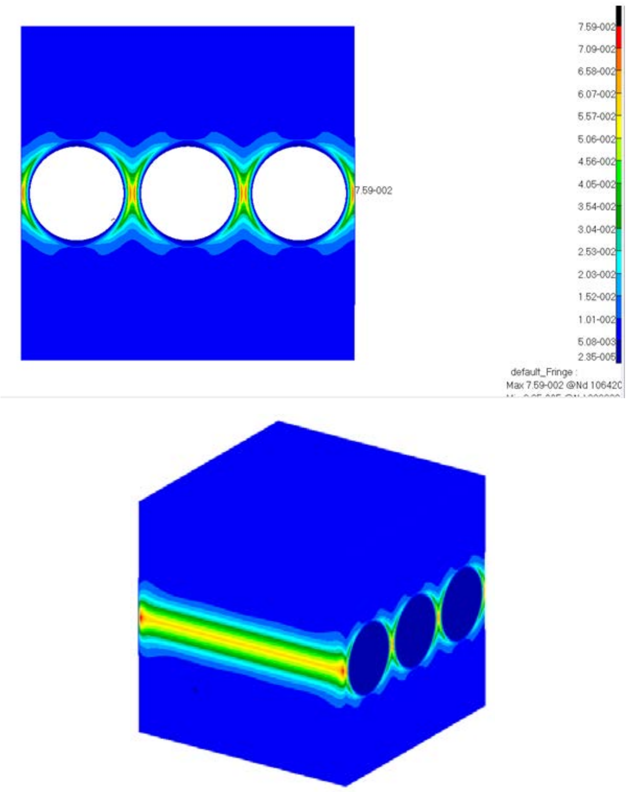

Figure 6 Stress concentration in material T1000SC-12K(ER 450), fiber content 64.5 % (average strains)

3 Results

The developed parametrical FEM model of CFRP RVE allowed performing a number of calculations in automated mode and determining stress/strain state of the resin between the fibers for materials with different fiber volume ration.

Numerical investigations have shown that the highest level of strain concentrations arise in the resin in the layer orthogonal to the direction of tensile force. The highest strains occurs in the zones between the fibers orthogonal to the direction of the tensile load. Table 1 shows the values of main parameters of CFRP and strain concentrations in the resin for one of the CFRP materials considered.

Table 1

Material	T700SC-12K(REM 180)
Lay up	(0°/±45°/90°)
Elastic modulus E_x, MPa	240000
Poisson’s ratio for fiber	0.15
Elastic modulus of interphase layer E_x, MPa	4000
Poisson’s ratio for interphase layer	0.33
Elastic modulus of binder Ex, MPa	4000
Poisson’s ratio for binder	0.33
Computational model for initial destruction analysis 0/90°	tension 1%
Fiber content, %	64
Concentration of deformations under tension, %	6.89
Concentration of deformations (without averaging)	8.04

On the basis of the developed model the parametrical investigations were carried out. The dependencies of averaged strains and elastic modulus of RVE on the size of growing microcrack for different values of fiber volume ratio 30, 40 and 50 % were obtained (Figures 6,7). Strain concentrations increase with the increase of the fiber volume ratio.

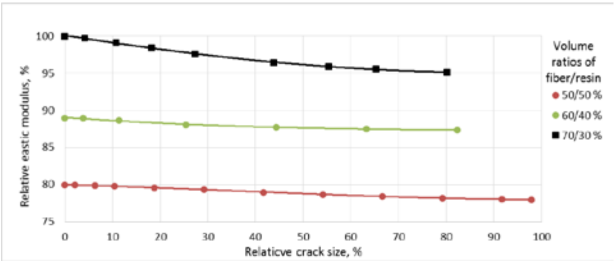

Figure 7 Elastic modulus on crack size dependence

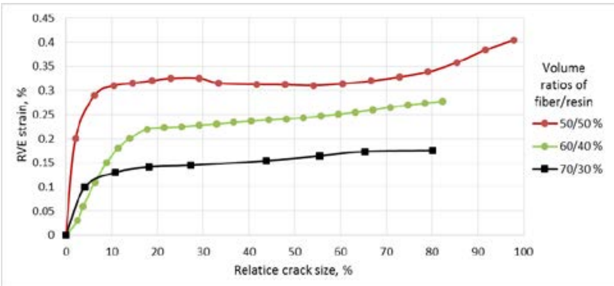

Figure 8 Elongation on crack size dependence

4 Conclusions

In the work, the parametrical structural computational model of composite fiber reinforced polymer based on FEM was developed. The model consists of solid elements (tetrahedrons, prisms and hexahedrons) modeling separately resin, interphase layer and reinforcing fibers in an automated mode.

The model allowed carrying out a number of calculations at microlevel in automated mode to determine stress/strain state of the resin between the fibers for materials with different values of fiber volume ratio.

Accumulation of such numerical results will allow determining the critical sizes of microcracks and obtaining a reliable engineering criterion for strength evaluation of composite structures at designing.

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