Deformation and failure of polymer composite materials under preliminary cyclic and low-velocity impacts

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Abstract. The paper presents the results of an experimental study of the behavior of samples of polymer composite materials under complex mechanical loads. A technique has been developed for the experimental assessment of changes in the residual strength and stiffness properties of layered composites for various parameters of preliminary cyclic and low-velocity impacts. Corresponding experimental data were obtained for fiberglass samples with various layouts. In accordance with the considered method for analysis of the obtained data, a fatigue sensitivity diagram has been introduced, which contains the characteristic sections of the change in the residual static strength and its threshold values, and is used to study the processes of damage accumulation and fracture of composites at various loading parameters. The results of a study of the effect of preliminary shock tension on the processes of deformation and fracture of fiberglass samples are presented. As a result of the analysis of the influence of a preliminary three-point impact bending on the mechanical characteristics of fiberglass specimens during tension, a threshold value of impact sensitivity was noted, until which a decrease in the residual strength of fiberglass was not observed. A change in the mechanisms of destruction of the samples under static tension with an increase in the energy of preliminary impact is noted.

1. Introduction

The development of composite materials production technologies allows introducing composites in safety-critical parts and structural nodes of the space, aeronautical, petrochemical industry. In operation, the structures are under various combinations of cyclic exposure, shock impact and quasi-static effects. One of the most common types of effects is cyclic loading. In the process of such impacts, damage accumulation occurs, leading to subsequent fatigue fracture [1-3]. Moreover, for composite materials, a decrease in mechanical properties is already observed at the initial stage of cyclic operating [4-5]. In the literature, the stage behaviour in residual properties is noted, which is associated with the fracture mechanism such as matrix cracking, local fibre breaking and lamination [6-8]. For composite laminate, one of the most dangerous types of impact is a blow in the transverse direction relative to the laying of the armour layers of the composite. Such shock impact leads to the appearance of lamination in the...
structure of the material, consequently, reflecting in a decrease in some strength properties of the composites. The particular danger of shock impact, after which visual inspection of products fails to assess the damage, in such cases, it is necessary to conduct set of studies with co-utilization of the non-destructive testing [9-10]. Therefore, to assess and describe the processes of damage accumulation and fracture of composites, as well as for designing and operation of composite products, experimental data on the change in strength and deformation properties under different loading conditions, including in the process of cyclic and low-speed shock effects are required. Thus, the purpose of this paper was to obtain and analyze new experimental data reflecting the processes of damage accumulation and fracture of composite materials under complex mechanical influences.

2. Test procedure and materials
In order to study the changes in strength and deformation properties in the process of cyclic and low-speed shock effects, a method of experimental study of the effect of preliminary cyclic exposure on the mechanical characteristics of composite laminates under subsequent tension was developed (figure 1), which consists of four stages: 1 - quasi-static stretching ($\sigma_B$, $E$); 2 - fatigue tests ($N_{max}$); 3 - preliminary impact with different cycling without fracture of samples ($n'$); 4 - subsequent quasi-static stretching ($\sigma'_B$, $E'$). The developed technique allows studying the change of residual strength and stiffness properties of materials in the process of fatigue damage accumulation with different parameters of impact and temperature conditions.

![Figure 1](image1.png)

**Figure 1.** The research methodology under cyclic and quasistatic effects

The behaviour study of composite materials under conditions of preliminary shock and subsequent quasi-static stretching is implemented according to the scheme presented in figure 2.

![Figure 2](image2.png)

**Figure 2.** The test for preliminary shock tension and tension or fatigue loads

Testing procedure: 1 - quasi-static stretching of composite samples with determination of rated values of stiffness ($E$) and strength ($\sigma_B$) properties; 2 - shock stretching with determination of energy to fracture ($E_{max}$); 3 - preliminary shock stretching with various parameters without fracture of samples ($e'$); 4 - stretching tests with determination of residual strength ($\sigma'_B$) and stiffness ($E'$) properties. To study the precursory attack, the paper considers an option of shock impact across the entire width of the sample according to the scheme of three-point bending (Fig. 3).
The tests for preliminary shock bending and quasistatic tension

The given technique consists of the following stages: 1 – quasi-static stretching (σ₀, Е); 2 – shock bending with determination of fracture energy (Еₘₐₓ); 3 – preliminary impact with different parameters without destruction of samples (е'); 4 – sequential quasi-static stretching (σ'B, Е').

The given research techniques allow obtaining new experimental data on the regularities of the behaviour of composite materials samples under complex mechanical influences, including quasi-static, cyclic, low-speed shock under normal, high and low temperatures.

The samples were made on the basis of prepreg VPS-48 and binder VSE 1212 with reinforcement scheme [0/90]ₙ.

3. Test results

On the basis of the developed methods, experimental dependence of the residual strength of laminated fiberglass under tension after preliminary cyclic exposure with different parameters is obtained (figure 4, a). The values of the stress amplitude in the cycle at a constant value of the asymmetry coefficient R=0.1 are given on the ordinate axis, the number of cycles of preliminary exposure (logarithmic scale) is given on the abscissa axis. According to the dependency graph, the growth of preliminary exposure cycles leads to decrease in residual strength, and the increase of the cycle maximum stresses value leads to decrease in fatigue endurance (the maximum number of cycles to fracture).

To assess the preliminary cyclic exposure effect on the residual strength properties of fiberglass samples, the function of relative reduction of the residual ultimate strength was introduced: ω_B = 1 – σ_Bn/σ_B where σ_Bn is the ultimate strength after preliminary cycling, σ_B is the ultimate strength without preliminary cycling shown in figure 4, (b), in which the data are given as a dependence on the relative number of cycles of preliminary exposure n. The constructed diagrams analysis of the relative decrease in the residual ultimate strength allows us to conclude that the cyclic exposure with the parameters σₘₐₓ=0.4·σₐ already in the range of preliminary exposure (0-0.2)·n led to a decrease in the residual ultimate strength by 30 %, while for the samples tested at σₘₐₓ=0.5·σₐ and σₘₐₓ=0.6·σₐ – less than 20%.

The stabilization section is the most informative from the point of view of design, operation and safety of the structure made of composite materials. For example, fatigue fracture does not occur after 3000 exposure cycles on the design but the static ultimate strength is reduced significantly — more than
25%. Thus, in the design of structures, the use of a diagram of relative reduction of the residual ultimate strength is appropriate in reliability prediction.

For the studied fibreglass materials in the process of fatigue damage accumulation, white spots were formed on the surface of the samples with an increase in operating time which is associated with the development of local layer separation zones.

Photos of the development of local layer separation zones on the surface of the working zone of fibreglass samples are shown in figure 5 when exposed to $\sigma_{\text{max}} = 0.5 \cdot \sigma_B$.

![Figure 5. Photo of the surface of the working zone of samples in the process of fatigue damage accumulation](image)

In a similar manner to the method of constructing a diagram of the relative reduction of the residual ultimate strength, Figure 6 shows a diagram of the relative change of the samples elastic coefficient in the coordinates $\omega_E; n'$. The values of the residual static elasticity modulus were determined on the linear section of the deformation diagram.

![Figure 6. Diagram of relative elastic modulus of fiberglass specimens with various loads parameters](image)

When analyzing the diagram of the relative change in the elastic coefficient of fibreglass samples, it is noted that the variations in the parameters of the preliminary cyclic exposure did not affect the form of curves describing the change in the residual hardness in the process of fatigue damage accumulation. For the studied material in the range of cyclic exposure ($0.4 – 0.6$) $\sigma_{\text{max}}$, the nature of the change and the values of the residual elastic coefficient have similar values.

Dynamic loads such as shock tension applied in the longitudinal direction relative to the orientation of the reinforcing fibres can lead to local fracture of the fibres, which in turn leads to a decrease in the ultimate strength of the material and the load-bearing capacity of the structure. A series of experiments with different levels of potential loading energy was carried out in order to study the effect of preliminary impact in the direction of laying the reinforcing layers of fibreglass samples. The experimental data obtained are presented in figure 7.
The analysis of the obtained experimental data allows us to conclude that the preliminary impact
tensile does not affect the residual strength characteristics of the studied fibreglass composite.
In the operation, the composite constructions most take uploads in the longitudinal and transverse
direction relative to the direction of laying the armour layers. Current standards and techniques such as
ASTM D7136, D7137 are aimed at obtaining experimental data for concentrated local impact, the
contact patch of which is much smaller than the test sample. The paper considers the option of loading
in which the shock impact contact occurred locally over the entire width of the sample. Based on the
results of tests for preliminary three-point shock bending and subsequent quasi-static stretching, a
diagram of the residual strength of fibreglass samples is constructed (figure 8).

The diagram shows that the preliminary impact with energies greater than 3 J leads to a decrease in
the residual strength of fibreglass samples under tension. Thus, the value of the impact energy E=3 J is
the threshold value of the shock sensitivity for the studied samples. At impact energies above 3.5 J, the
destruction mechanisms of the samples changed from normal fracture to normal fracture with lamination
in the longitudinal direction. Photographs of samples destroyed under tension after impacts with
different energies are shown in Figure 9.

![Figure 7. Diagram of residual strength of fiberglass samples after low-velocity impact tensile](image)

![Figure 8. Diagram of the residual strength of fiberglass specimens after a preliminary tech-point shock bending with different impact energies](image)
Figure 9. Photos of fractures of samples after quasistatic tension with preliminary impact 
\(a - 3 \text{ J}, b - 3.5 \text{ J}, c - 4 \text{ J}\)

Under the shock impact with energies less than 3 J and subsequent quasi-static stretching, the fracture of the samples occurred near the grips of the test system by the type of normal fracture. As the impact energy increased, areas of lamination appeared on the fractures, fracture occurred in the operating zone of the samples.

4. Summary

As a result of the study, a methodology for the experimental assessment of changes in the residual strength and stiffness properties of laminated composite with various parameters of preliminary cyclic and low-speed impacts is proposed. The obtained experimental data are presented in the form of a diagram of the dependence of the relative decrease in the residual ultimate strength on the operating time, the use of which seems promising in studying the processes of damage accumulation and fracture of composites at various loading parameters. On the basis of the experimental data obtained, a stepwise change in the residual strength and stiffness for fibreglass samples with different loading parameters was noted. The influence of the parameters of the preliminary cyclic loading on the strength properties of fibreglass was revealed, while the change did not affect the nature of the dependence of the stiffness properties. The influence of preliminary shock tension on the mechanical properties of fibreglass samples was studied. It was revealed that for the material under study, in the presented range of impacts, the shock impact tension on the residual strength of the samples affected slightly. As part of the paper, the impact of the preliminary three-point impact on the mechanical characteristics of fibreglass samples was evaluated. As a result, the change in the residual strength properties of fibreglass samples depending on the impact energy was noted. For the studied material, the presence of a threshold value of impact sensitivity was found, before which a decrease in the residual strength of fibreglass was not observed. A change in the fracture mechanisms of samples under static tension with an increase in the precursory attack energy is noted.

Acknowledgements

The work was carried out in the Perm National Research Polytechnic University with support of the Russian Science Foundation (Project 16-19-00069).

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