Tests features of composite materials under complex mechanical loads

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Abstract. The article presents the results of the analysis of existing standardized and scientifically based methods for studying composite materials under quasistatic, low-velocity impacts and cyclic loadings in conditions of normal, high and low temperatures. Based on a review of existing test methods, research methods have been developed and tested to study the changes in the strength and deformation properties of GFRP composite materials under complex mechanical loads. A new type of interpretation of experimental data in the form of diagrams of fatigue and low-velocity impact sensitivity is proposed. Characteristic sections and points are introduced on the diagrams, which make it possible to further use the data from the diagram for the design of products and structures made of composite materials operated under the conditions of unforeseen external mechanical influences. For all developed methods, the results of experimental studies conducted by the authors of the work are presented. As an example, an experimental study of the influence of additional torsional vibrations on the processes of deformation and fracture of unidirectional fiberglass rod samples under quasistatic tension is considered.

1. Introduction
Existing international standards (GOST, OST, ASTM, ISO, EN, DIN ...) describe methods for determining the main characteristics of materials for individual types of loads, such as uniaxial tension/compression (GOST 25.601-80, GOST 11262-80, ASTM D3039 / 3039M), three-point bending (GOST 25.604-82, GOST 4648-71, ASTM D7264 / D7264M-07, ASTM D790), interlayer shear (OST 92-1472-78, ASTM D2344 / D2344M-00E01), cyclic tension (GOST R 57143-2016, ASTM D3479 / D3479M), etc. Basically, the standards set out the scope, equipment, geometry of the samples, the methodology and processing of test results. The obtained values of tensile strength, elastic modulus, Poisson's ratio, elongation, breaking stress, interlayer shear strength, fatigue limit and fatigue life can be used to set material constants in solving boundary value problems of the mechanics of solids. Scientific evidence-based test methods and standards are rare, which include complex types of loads (GOST 33496-2015, GOST 33495-2015, ASTM D7136, ASTM D7137). In particular, these standards make it possible to obtain indirect material characteristics (maximum impact load, absorbed impact energy, residual strength), which allow a quantitative assessment of damage resistance parameters for composite materials with various components but not included in any defining relations. These standards include GOST 19109-84, GOST 4647-80, ISO 179, ASTM D6110, which determine the value of impact strength and the tendency of the material to brittle/viscous fracture. The above standards and methods do not allow obtaining experimental data (characteristics) describing the
behavior of composite materials under complex mechanical loads. To solve the described problems, experimental techniques for the behavior of samples of polymer composite materials were developed and tested under various combinations of sequential quasistatic, cyclic, and low-velocity impact loads.

2. Research methods for preliminary cyclic effects on the residual strength and stiffness properties of composite materials

Many constructors made of composite materials during operation are subjected to cyclic loads, such as the passage of cars on the bridge, wind gusts, impacts of wheelsets of the train at the joints of the rails. During loading, damage accumulates, followed by fatigue failure. For the design and operation of composite products, data on changes in the strength and deformation properties during cyclic loads are needed. To this end, a methodology has been developed to study the preliminary cyclic impact and subsequent stretching, which is presented in Figure 1.

![Figure 1. Research technique with cyclic and quasistatic effects.](image-url)

The test procedure includes the following steps:
- installation quasistatic tests with a determination of tensile strength $\sigma_B$ and elastic modulus $E$ of the material;
- cyclic tests at various loading parameters $\sigma_{\text{max}} = \delta \cdot \sigma_B$, where $\delta \in [0; 1]$ with determination of the fatigue life $N_{\text{max}}$;
- preliminary exposure with different operating times of cycles $n' = \delta \cdot N_{\text{max}}$, where $\delta \in [0; 1]$;
- sequential quasistatic loading with a determination of the residual mechanical characteristics of the material $\sigma_B', E'$.

The shape and size of the samples must comply with the recommendations of GOST 25.601-80 and ASTM D3039.

The obtained experimental data are presented in the form of diagrams of the dependence of residual properties (values) on the level of preliminary mechanical loading (values). In general, the dependency diagram is shown in Figure 2.

![Figure 2. Diagram of dependency.](image-url)
Figure 2. Diagram of the dependence of the residual value $A$ on the level of preliminary mechanical stress $B$.

In the case of preliminary cyclic and subsequent quasistatic effects, a diagram of fatigue sensitivity is constructed in the relative coordinates $K_{Bn}'$; $n'$ (Figure 3).

![Figure 3. Diagram of fatigue sensitivity.](image)

$K_{Bn}' = \frac{\sigma_{Bn}}{\sigma_B}$ - the coefficient of static strength under cyclic loading, where $\sigma_{Bn}$ - tensile strength after cyclic loading, $\sigma_B$ - tensile strength without cyclic loading.

$n' = \frac{n}{N}$ - the relative number of cycles of the preliminary cyclic loading, where $n$ - the number of cycles of the preliminary cyclic impact, $N$ - the limiting number of cycles to failure, for given parameters.

There are three sections on the diagram:

I - stage of initial fatigue sensitivity, characterized by a fall in the value of the residual tensile strength by more than 20% of the nominal value of the tensile strength of the composite material;

II - stage of stabilization of fatigue sensitivity, where the change (decrease) in the residual tensile strength does not exceed 5%. The boundaries of the stabilization section are points $S_1$ and $S_2$. To select the position of points $S_1$ and $S_2$, a value of $\delta$ is entered; this is the value of the tangent angle $\alpha$ at the points on the fatigue sensitivity curve $\delta = t g \alpha = -\frac{N \cdot d\sigma_{Bn}}{\sigma_B \cdot d n'}$. The value of $\delta$ can be selected separately for each material;

III - stage of exacerbation of fatigue sensitivity, which is characterized by a sharp decrease in the value of the residual tensile strength.

$n_{0,02}'$ - threshold value relative to the number of cycles at which the change in strength will not exceed the conditionally selected value of 2%.

The developed technique allows us to study the change in the residual strength and stiffness properties of materials in the process of fatigue damage accumulation with various exposure parameters and temperature conditions. According to the developed method, in (Wildemann, V. E., Staroverov, O. A., Lobanov D. S., 2018), (Staroverov, O. A., Wildemann, V. E., Tretyakov, M. P., Yankin, A. S., 2019), (Lobanov, D. S., Staroverov, O. A., 2019) a study was made of the fatigue accumulation of damage to samples of composite materials with various layouts and parameters of preliminary cyclic loads.

3. Methodology for studying the behavior of composite materials under conditions of preliminary shock impact and subsequent quasistatic or cyclic tension

Failure of one of the elements of the loaded structure can lead to an overload of the remaining elements and the destruction of the entire structure. The study of the effects of dynamic overloads is a priority in terms of safety and survivability. In the works of N.G. Chausov and co-authors considered the processes of the reorganization of the structure of plastic metal materials as a result of a sharp
change in the strain rate of the sample, which led to an increase in the ductility of the material (Chausov, N. G., Zasimchuk, E. E., Pilipenko, A. P., Porokhniuk, E. M., 2010), (Chausov, N. G., Maruschak, P. O., Pylpenko, A. P., Markashova, L. I., 2017) (Zasimchuk, E. E., Markashova, L. I., Turchak, T. V., Chausov, N. G., Pylpenko, A. P., Paratsa, V. N., 2009). Based on this, it seems interesting to study the effect of a preliminary impact on the behavior of composite materials. The study of the behavior of composite materials under conditions of preliminary shock and subsequent quasistatic tension can be implemented according to the scheme shown in Figure 4.

**Figure 4.** Tests for preliminary impact and quasistatic tension.

Testing procedure:
- quasistatic tension of composite samples with a determination of nominal values of elastic modulus \( E \) and strength \( \sigma_B \) of the composite;
- impact tensile with a determination of fracture energy \( E_{max} \);
- preliminary tension with various parameters of potential impact energy without fracture of the samples \( e' = \delta \cdot E_{max} \), where \( \delta \epsilon [0; 1] \);
- tensile tests with a determination of residual strength \( \sigma_{B}' \) and stiffness \( E' \) properties of the material.

The test results are presented in the form of diagrams of the dependence of the residual tensile strength \( \sigma_{B}' \) and elastic modulus (Young's) \( E' \) on the impact energy \( e' \) (Figure 5) similarly to the diagrams described earlier.

**Figure 5.** Diagram of the dependence of the value of the residual tensile strength on the energy of impact tension.

The point ST is entered in the diagram - the point of the shock threshold. This point is characteristic of materials for which up to a certain value of the parameters of the preliminary loads, in this case, impact energy, there is no change in the residual properties (values of the residual tensile strength). On the curve describing the dependence of the residual properties on the preliminary action, in this case, it
is distinguished into two stages: I - the stage of the absence of shock sensitivity, II - the stage of exacerbation of shock sensitivity.

The technique allows us to experimentally investigate the effect of preliminary shock tension with different intensities on the residual mechanical characteristics of composites.

Similarly, this technique can be used to study the effect of impact on the fatigue life of PCM samples. The test design is shown in Figure 6.

![Figure 6. The methodology for studying the effect of preliminary shock extension on the fatigue life of composites.](image)

The technique includes the following steps:

- quasistatic tensile tests to determine the parameters of fatigue tests $\sigma_B$, fatigue tests with a determination of the fatigue life $N_{max}$;
- impact tensile with a determination of fracture energy $E_{max}$;
- preliminary shock tension with various parameters without fracture of the samples $e' = \delta \cdot E_{max}$, where $\delta \in [0; 1]$;
- successive fatigue tests assessing the impact of $N'_{max}$ pre-shock.

The shape and size of test specimens, which are used to study the effect of preliminary impact tension on the residual quasistatic and fatigue characteristics of composites, were selected in accordance with the recommendations of GOST 34250-2017, ISO 8256.

The test results are presented in the form of diagrams of the dependence of the change in fatigue life $N'_{max}$ on impact energy $e'$ similar to the diagrams described previously.

Methodology for assessing the viability of composite materials under conditions of preliminary transverse impact and subsequent quasistatic or cyclic loading

For layered composite materials, one of the most dangerous types of impacts is a shock directed across the laying of the reinforcing elements of the composite. Such impacts lead to delamination in the structure of the material and a significant decrease in strength characteristics. Impacts are especially dangerous, after which, during a visual inspection of the product, failure to assess damage, the so-called “BVID”, such as large hail, stones and debris on the runway, lifted by the wind, or a falling tool used during the installation of the casing. In such cases, it is necessary to conduct a series of experiments with the joint use of non-destructive methods of flaw detection.

The paper considers a variant of impact over the entire width of the sample. This type of testing is necessary for research aimed at studying the processes of deformation and fracture under conditions of a preliminary three-point impact bending and subsequent quasistatic tension. The test design is shown in Figure 7.
Figure 7. Pre-shock bending and quasistatic tensile tests.

Testing stages:
- quasistatic tension of composite samples with a determination of nominal values of stiffness (E) and strength (σ_B) characteristics;
- shock bending with a determination of the fracture energy E_max;
- preliminary impact with various parameters without sample destruction e' = δ · E_max, where δ ∈ [0; 1];
- tensile tests with a determination of residual strength σ_B' and stiffness E' properties.

Similarly, this technique can be used to study the effect of preliminary impact on the fatigue life of polymer composites. Schematically, the technique is shown in Figure 8.

Figure 8. Pre-shock bending and cyclic tensile tests.

Test sequence:
- quasistatic tension of composite samples with determination of nominal values of stiffness (E) and strength (σ_B) characteristics, fatigue tests with determination of the fatigue life value N_max;
- shock bending with determination of the fracture energy E_max;
- preliminary impact with various parameters without sample destruction e' = δ · E_max, where δ ∈ [0; 1];
- consecutive fatigue tests with an assessment of the effect of pre-shock N_max.

With this test procedure, you can use flat rectangular samples made in accordance with the recommendations of the standards GOST 25.601-80, GOST 4648-71 or ASTM D3039, ASTM D790.

The data obtained by the developed methods can be used to assess the effect of preliminary bending on the residual strength and fatigue characteristics of the composite. Studies conducted by the (Wildemann, V. E., Staroverov, O. A., Tretyakov, M. P., 2020).

A local impact out-of-plane impact followed by quasistatic compression of composite plate samples is shown in Figure 9.
Figure 9. Impact and compression tests after impact.

The test procedure also consists of 4 stages:
- quasistatic compression of samples to assess the bearing capacity of samples $P_{\text{max}}$;
- damage with a local shock transverse to the plane of the sample, exposure with a determination of the energy of penetration of the sample through $E_{\text{max}}$;
- shock effects of various intensities $e' = \delta \cdot E_{\text{max}}$, where $\delta \in [0; 1]$;
- quasistatic compression of damaged samples with an estimate of a decrease in the residual strength $P'$. 

For testing, you can use rectangular plate samples, regulated by the standards GOST 33496-2015, GOST 33495-2015, ASTM D7136, ASTM D7137.

The results of these tests can be used to assess the residual bearing capacity of composite samples, which during their operation are subjected to low-speed impact impacts, such as a tool falling during installation or repair, a stone impact on the sound-absorbing fuselage circuit during take-off of the aircraft (Staroverov, O. A., Babushkin, A. V., Gorbunov, S. M., 2019).

Methodology for studying the influence of additional vibrational effects on the processes of deformation and fracture of composites

During the operation of the product (structure) made of composite materials, in addition to unforeseen cyclic, low-velocity shock longitudinal and transverse loads, they are exposed to vibrational influences. It is known that additional vibrational torsional effects have a stabilizing effect of the process of postcritical deformation under conditions of tension of continuous cylindrical specimens of structural steels (Wildemann, V. E., Lomakin, E. V., Tretyakov, M. P., 2016). Based on this, it can be assumed that additional vibrational effects, in addition to changing the residual strength, can also affect the processes of damage accumulation and destruction of composites. The experimental technique for the deformation and fracture of layered-fibrous rod and tubular composite samples under additional torsional cyclic stresses at various stages of quasistatic tension is shown schematically in Figure 10.

Figure 10. Tensile tests with additional torsional vibration.

The methodology includes the following tests:
- conducting uniaxial tensile tests with determining the maximum tensile forces at fracture $P$;
  Tensile tests with additional torsional vibration effects with small amplitude and high frequency.
The developed technique allows us to study the change in the nature of the deformation and fracture of composite materials and structures under conditions close to operational. In (Staroverov, O. A., Strungar, E. M., Tretyakov, M. P., Tretyakova, T. V., 2017), an experimental study of tubular samples of composite materials under complex stress conditions was carried out. The methodological features of the tests are considered, special attention is paid to comparing the methods for preparing the gripping parts and fixing the samples in the grips of the testing machine.

For example, the influence of additional vibrational influences on deformation and fracture during quasistatic tension of fiberglass unidirectional core samples with a diameter of 8 mm (GOST 31938-12) in accordance with the developed methods is considered.

By vibrational influences is meant cyclic loading with a small amplitude of the twist angle φ and a large frequency v.

To implement such complex loading, it is necessary to take into account the rigidity of the loading test system. Instron 8802 universal two-axis test system has the highest rigidity and allows you to implement complex loading conditions. The main advantage of biaxial testing systems is related to their design feature, which allows simultaneous application of axial load and torque to the sample. The methodological features associated with fixing the samples in the test system were solved by manufacturing special copper half-sleeves (Figure 11), the compression ratio of the sleeves with the sample was 150 bar.

In the specialized WaveMatrix software, test parameters were set such as: the traverse speed of 0.19 mm/min, the frequency of additional torsional vibrations v = 20 Hz, and the amplitude of the twist angle φ = 1°.

As a result of experimental studies, in addition to reducing the maximum load, characteristic dependencies of the influence of additional vibrational influences on the behavior of the samples and the implementation of the supercritical stage of deformation were revealed (Figure 12).
Figure 12. Loading diagrams of rod samples (1 - without additional vibration, 2 - with additional vibrational influences) dashed lines indicate zones of dynamic fracture.

The diagram shows that due to additional vibrational torsional vibrations, the maximum load $P_{\text{max}}$ decreases and the stage of supercritical deformation begins earlier (Figure 12). Disruptions at the stage of supercritical deformation (transition to the dynamic stage of fracture) occurred later. The nature of the destruction of the rod samples was stepped. It is worth noting that, when testing samples fixed with copper half sleeves, partial slipping of the sample occurred. Subsequently, unidirectional fiberglass rod samples were glued into brass sleeves (Figure 13).

Figure 13. Fiberglass composite reinforcement sample glued into brass sleeves.

This type of sample preparation made it possible to prevent the rods from slipping out of the grips of the test system.

In addition, a study was conducted on the influence of vibrational influences with various parameters on the processes of deformation and fracture of fiberglass rods. The results are presented in the form of loading diagrams (Figure 14). For clarity, the curves are offset relative to each other along the abscissa axis ($u, \text{mm}$).

Figure 14. Typical loading diagrams of unidirectional composite rods.

As a result, we can conclude that the parameters of additional torsional vibrations can affect the behavior of the material during fracture and the implementation of the supercritical stage of deformation of unidirectional composites. Figure 14 shows how changes in the parameters of torsional vibrations affect the slope of the falling curve at the softening stage. It should be noted that an increase in the amplitude of the oscillations led to a decrease in the number of breakdowns in the loading curve of the sample.

4. Conclusions
The presented set of research methods can be used to obtain new experimental data and patterns on the behavior of samples of composite materials under complex mechanical conditions, including quasistatic, cyclic, low-speed shock, impacts under conditions of normal, elevated, and lowered temperatures. The developed methods are based on existing scientifically based standards for testing composite materials. An experimental study was made of the influence of additional vibrational torsion forces on the processes of deformation and fracture of unidirectional fiberglass rod samples. The methodological features of fixing composite rod samples in the gripping parts of the test system are considered. It was revealed that for the studied samples, additional vibrations contributed to the appearance of sections of equilibrium loading. The transition to dynamic fracture in the loading curves occurred later, relative to the curves describing the loading process of nominal samples.

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References

[1] Chausov N G, Maruschak P O, Pylypenko A P, Markashova L I 2017 International Scientific and Technical Journal "Mechanics of Machines, Mechanisms and Materials" 96
[2] Chausov N G, Zasimchuk E E, Pilipenko A P, Porokhniuk E M 2010 Tambov University Reports 892
[3] Lobanov D S, Staroverov O A 2019 Procedia Structural Integrity 651
[4] Staroverov O A, Babushkin A V, Gorbunov S M 2019 PNRPU Mechanics Bulletin 161
[5] Staroverov O A, Strungar E M, Tretyakov M P, Tretyakova T V 2017 Bulletin of the perm national research polytechnic university Aerospace engineering 104
[6] Staroverov O A, Wildemann V E, Tretyakov M P, Yankin A S 2019 Procedia Structural Integrity 757
[7] Wildemann V E, Lomakin E V, Tretyakov M P 2016 Doklady Physics 147
[8] Wildemann V E, Staroverov O A, Lobanov D S 2018 Mechanics of Composite Materials 313
[9] Wildemann V E, Staroverov O A, Tretyakov M P 2020 IOP Conf. Series: Materials Science and Engineering doi:10.1088/1757-899X/747/1/012034
[10] Zasimchuk E E, Markashova L I, Turchak T V, Chausov N G, Pylypenko A P, Paratsa V N 2009 Physical mesomechanics 77