

REVIEW OF EXPERIMENTAL STUDIES OF DEFORMATION PROCESSES IN POLYMER COMPOSITE MATERIALS

Sabir Khalmuradovich Yakubov¹,

¹ Professor Dr. Institute of Military Aviation, University of Military Security and Defense of the Republic of Uzbekistan, Doctor of Technical Sciences, Professor, Karshi, Uzbekistan.

sabir_yakubov@mail.ru; <https://orcid.org/0000-0002-3607-4568>

Rustam Alijonovich Ruzmatov²

² Senior Lecturer Institute of Military Aviation, University of Military Security and Defense of the Republic of Uzbekistan, Karshi, Uzbekistan. <https://orcid.org/0009-0003-0925-9692>

ABSTRACT	KEYWORDS
<p>The article analyzes scientific works of both domestic and foreign authors devoted to the study of deformation and destruction of composite materials, and presents a review of scientific and technical literature devoted to the study of the processes of deformation and destruction of composite materials. Considerable attention is also paid to the wide range of test methods used to determine the strength properties and mechanical characteristics of composite materials.</p>	<p>Polymer Composite Materials, Static and Variable Loads, Mechanical Engineering, Strength, Stiffness, Fatigue Strength, Experimental Equipment, Testing</p>

Introduction

Composite materials are widely used in industry worldwide, where they contribute to increased strength and reduced weight in high-tech structures. Many industrial engineering challenges currently involve the introduction of polymeric and inorganic materials. The development of fiber-reinforced polymer composite materials (PCMs) is determined by their intended use and operating conditions. As a result, their structure, composition, and types of binders vary. Most often, these fiber-reinforced materials are used in the form of unidirectional tapes or fabrics, which are interwoven.

Modern composite materials made from polymers (phenolic, epoxy, cyanoester, and binders), as well as high-quality fillers (glass, carbon, polymer, and metal), and in the form of strips or textile structures, pave the way for enhanced performance in a wide range of products. [The text appears to be incomplete and likely a mistranslation.] Fibers of beryllium, glass, graphite, steel, silicon carbide, boron, or other filiform crystals of oxide, boron carbide, graphite, iron, and other materials are used as reinforcing fillers (the composite base). Matrices are made of synthetic resins (epoxy, polyester, organosilicon) or metal alloys (aluminum, titanium, and others). The bonding of the fibers or filiform crystals to the matrix is achieved by hot pressing, casting, plasma spraying, and other methods.

High-tech structures made of carbon-filled polymercomposites provide exceptional strength and rigidity with minimal thermal expansion. This ensures their operational stability. Furthermore, these composites are significantly lighter than aluminum structures while maintaining or exceeding rigidity. Polymer composites reinforced with carbon fiber or glass are used in mechanical engineering due to their unique properties: non-uniform and anisotropic structure. This results in significantly different behavior under mechanical loads than metallic and other isotropic materials. Failure of polymer composites is caused by a combination of cumulative processes (delamination, fracture of reinforcing threads or matrix), unlike metals, where failure often begins with a single crack and its subsequent growth. The goal of studying the strength of PCM structures is to develop new approaches to assessing the mechanical properties of composites and to substantiate criteria that would allow predicting structural failure under any loading conditions with a limited number of tests, using uniaxial or biaxial stress. Existing experimental methods do not always yield accurate results when the tensile angle does not correspond to the lay angle of the material. This is particularly noticeable when studying the elastic properties of PCMs laid at an angle of 45° to the specimen axis: different methods yield inconsistent results.

2. Methods

Modern scientific research focuses on the failure processes of composite materials, the development of methods for predicting their service life, modeling damage accumulation, and determining the impact of operating conditions on the strength and durability of the structures under study.

Significant progress has been made in the study of failure processes in polymer composites (carbon fiber reinforced plastics and fiberglass), confirmed by research by international and domestic scientists. Despite the development of various models for assessing the strength properties of polymer composites, most are not universally applicable and are applicable only under specific loading conditions and for specific types of materials.

Advances in science and technology, on the one hand, necessitate the development of new structural materials, and on the other, are largely determined by the results of these developments. Emerging from the natural desire to improve existing structures, new materials, in turn, open up opportunities for the implementation of new design solutions and technological processes. Composite materials (CMs) possess a range of properties and characteristics that differ from traditional structural materials (metal alloys) and, taken together, offer extensive opportunities for both improving existing designs for a wide variety of applications and developing new designs and technological processes. Successful realization of the vast potential inherent in the concept of a composite material and the properties of its components depends largely on the designer's awareness of these capabilities, design principles, and calculation methods. Unfortunately, this level does not fully correspond to scientific advances. The situation is further exacerbated by the fact that the existing (and quite extensive) literature on composites is primarily aimed at researchers rather than engineers involved in the calculation, design, and fabrication of composite structures. The challenge of increasing structural strength lies not only in enhancing strength properties but also in ensuring high resistance to ductile fracture with high strength—in other words, in enhancing the material's reliability.

Based on the above, it should be noted that the development of new approaches to modeling the behavior of polymer-based composite materials under loading, taking into account the significant

anisotropy of the materials, as well as studying the deformation processes of composite structures and assessing their strength, remains a pressing issue. This task requires obtaining experimental data through mechanical testing of specimens of such materials. The primary methods for determining the mechanical properties of composite materials are tensile, compressive, shear, and bending tests.

The objective of this study is to substantiate experimentally validated data that determine the static and cyclic strength of polymer composite materials (PCMs) to predict the service life of multilayer composites.

To achieve this primary objective, the following important and understudied research objectives must be addressed: implementing a new approach to determining the static strength of polymer composites; developing a methodology for determining cyclic strength intended for predicting the service life of PCMs under demanding conditions; proposing methods for identifying the properties and characteristics of the test material; and substantiating its static and dynamic strength indicators; conducting tests using precision testing methods used to determine cyclic and static strength, as well as validating methods for determining the properties of the test material based on experimental data.

3. Results and Discussion

The current state of experimental research on composite materials is reflected in the following works [1, 2], which examine various approaches to tensile, compression, bending, and shear testing, and highlight the advantages and disadvantages of these various methods.

Experimental studies conducted in [1, 7] demonstrate that determining the parameters of the elastic deformation model and the strength criterion for polymer composite materials is possible based on the results of a limited series of tests on specimens with three lay-up angles under tension and compression. The authors note that the elastic parameters of the model must be determined based on the results of testing a batch of specimens and using averaged characteristics; the strength criterion parameters are determined based on the minimum characteristics for the batch.

The study [10] presents the results of both experimental and theoretical studies of the mechanical and strength characteristics of reinforced plastics under various types of loading: tension, compression, and shear. The authors address the problem of predicting the mechanical and strength characteristics of such materials with different reinforcements. The book [4] presents methods for calculating structures made of layered composite materials, addresses statics and stability problems for shells and plates made of such materials, and also contains the results of experimental studies and presents the mechanical properties of some polymer composite materials.

The results of the experimental studies presented in [5] indicate that unnoticeable defects and distortions in the structure of a fiber composite material can have a significant impact on the determined elastic and strength properties, in some cases reducing them by 15%.

The authors of [11] present a methodology for determining the mechanical properties of composite materials based on epoxy resin reinforced with carbon fabric. The methodology is based on standardized tensile and fatigue tests using a digital image correlation method, which allows for real-time acquisition of information on the stress-strain state of the test specimen. It is noted that the advantage of using digital image correlation is the ability to study the reinforcement structure and predict material failure.

Research on the deformation of mesh composite structures, based on discrete and continuous approaches, is presented in [6, 9]. A comparison of experimental results on unidirectional carbon fiber reinforced plastic rods and calculated ratios is discussed in [3]. Many Russian and foreign authors have studied the stress-strain state of plates and shells with defects in the form of cutouts and holes [8, 13]. The scientific community has long identified fatigue strength as a critically important area of research. In subsequent years, numerous experimental studies were conducted on the fatigue behavior of structural materials, both metallic and composite. As technologies developed, new test rigs and measuring instruments were invented; complex fatigue experiments became increasingly easier to conduct. Thus, to date, virtually all failure modes of composite materials have been defined, and numerous theoretical models for fatigue life prediction have been developed.

The mechanical behavior of composite materials depends on many parameters, and homogeneity and manufacturing quality are of great importance for the structural integrity of the material. Internal defects, such as fiber displacement or voids in the matrix, that arise during the manufacturing process can act as initiation points and progress to failure by mechanisms such as matrix cracking, fiber rupture, delamination, and so on. These failure mechanisms can originate and proceed independently of each other, or they can interact, leading to accelerated material failure. As stated in [23], the damageability of polymer matrix composite materials can be assessed by the reduction in strength or stiffness of the material.

This theory, based on property degradation, has several major drawbacks:

- Residual life cannot be estimated using non-destructive testing methods, since the initial data in this theory is the failure of the material;
- Strength degradation is not a sensitive criterion for damage accumulation, since it changes very slowly until the point of failure, after which instantaneous failure occurs.

This behavior of composite materials under cyclic loading was discussed in the book [30], whose authors even coined the term “sudden failure phenomenon”:

- To create a database on the degradation of strength and stiffness of composite materials, extensive experimental studies are necessary for each type of material.

Stiffness degradation can be measured using non-destructive testing methods and tools; however, changes in stiffness are usually greater than changes in residual strength during fatigue loading. Research into the stiffness, strength, and fatigue characteristics of composite materials is of great importance in the design and strength calculations of products made from such materials. As noted previously, the mechanical and elastic properties are determined through experimental studies of tension, compression, and shear. As noted in [21], the purpose of experimental studies is directly related to their results, and the studies themselves can be conducted on both material samples and structural elements, as well as on complete products. Typically, experimental studies of the behavior and fatigue characteristics of composite materials are conducted on standardized material samples. Thus, in [16, 24, 29], the authors attempted to describe the behavior of a composite material and explain the reduction in strength or stiffness based on observations of fracture surfaces. The authors of [14, 25, 27] used fractographic analysis to describe the interlaminar fracture toughness of multidirectional [14] and carbon composites [27], as well as unidirectional fiberglass [25].

In [17, 28], the authors created their own databases for developing fatigue failure criteria, and in [20], the authors created their own database for evaluating existing fatigue failure theories. Experimental

studies aimed at creating their own fatigue databases are often conducted within the context of industrial applications, for example, in the production of turbine blades or in the aerospace industry [18, 19]. Furthermore, experimental research is often aimed at developing analytical models and predicting the fatigue life of products and structural elements. This category includes studies devoted to adhesive-bonded and bolted joints used as structural components [22, 26, 31].

Experimental studies of material samples, structural components, and full-scale products are also used to verify the developed behavioral models. In [15], verification was conducted by applying a cyclic load with a constant amplitude equal to the working ultimate stress causing maximum deformation of the structure. Verification can be performed using either accelerated fatigue testing of material samples or tests of full-scale products. Full-scale testing eliminates undesirable factors such as the size effect and the free edge effect, making it possible to obtain reliable fatigue life results for the structure. The disadvantages of this type of experimental research are its high cost and labor intensity.

Experimental equipment for testing composite materials is also of great importance. For example, thin laminates, often used in lightweight structures, are prone to instability; if improperly designed, the adhesive-bonded joint can collapse under compressive loads.

A number of anti-crushing devices have been developed to protect such structures made of thin composite plates; however, as noted in [12], the results have been inconsistent. Assessing the shear characteristics of composites is also problematic, since it is difficult to apply a force to the test specimen in a manner that creates a pure shear stress field. However, tensile tests with a $\pm 45^\circ$ shear stress distribution can be used to evaluate the shear parameters of laminated composites, and the shear modulus, as noted in [12], is most successfully measured using the V-notch beam method. There are also other parameters that can influence the results of fatigue experiments, the most important of which are: the loading pattern, frequency and mode, the cycle asymmetry coefficient, the waveform, temperature, ambient humidity, etc. [21].

4. Conclusion.

A discussion and review of the research literature resulted in the substantiation of a method for assessing the strength of polymer composite materials. This method combines an analysis of the strain state of the test material with structural approaches, the laws of elastic deformation for orthotropic materials, and the Hashin strength criterion. An approach to assessing the strength of polymer composite materials has been implemented, integrating methods and algorithms for structural analysis of the strain state of the test material, the law of elastic deformation for orthotropic materials, and the Hashin strength criterion. A method for assessing the cyclic strength of polymer composites is also proposed, enabling the prediction of the service life of the material under variable loading conditions based on experimental data and taking into account asymmetry coefficients. The proposed changes to the Hashin static strength criterion contribute to a significant improvement in the accuracy of calculating the fiber rupture moment under tension under shear loading. 5. Tensile and compressive strength testing of both unidirectional specimens and products with symmetrical reinforcement confirmed the validity and validity of the criteria for static and cyclic strength of polymer composite structures. It should be noted that a comparison of experimental data with computer modeling results demonstrates the effectiveness of the method for assessing the strength of structures made from polymer composite materials.

Abbreviations

PCMs - Polymer composite materials

CMs - Composite materials

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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