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Influence of aging on fatigue strength of carbon fiber reinforced plastics

A.R. Arutyunyan ✉

St. Petersburg State University, St. Petersburg, Russia

✉ a.arutyunyan@spbu.ru

ABSTRACT
Various composite materials are implemented in aircraft, rocket and automobile construction, shipbuilding, railway transport, tidal power and others due to their high strength to weight ratio, superior fatigue strength, and design flexibility. These materials are used in critical areas of engineering practice, so this makes their long-term aging and fatigue characteristics of paramount importance. At the same time, the characteristics of these materials essentially changed after long-term operation. Thus, investigations of aging of these materials are much needed. Experimental studies on alternation of cyclic loading, climatic and thermal aging were conducted to study the characteristics of unidirectional carbon fiber reinforced plastic of the T107/ON190/R132436 mark. Experimental results shown a significant hardening during cyclic experiments, which considerably depends on the aging program.

KEYWORDS
composite materials • carbon fiber reinforced plastics • degradation • climatic aging • deformation aging • fatigue strength

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Introduction

Polymers and polymer-based composite materials are being intensively implemented in almost all areas of industry and construction: in aircraft, rocket and automotive construction, shipbuilding, railway transport, agricultural machinery production, tidal power, as well as in the production of sports equipment. These materials have a high strength-to-weight ratio, superior fatigue strength and design flexibility. Considered applications frequently have a very high performance demand, making the long-term characteristics of polymer and composite materials of paramount importance. At the same time, they were subjected to degradation due to environmental factors, including light, temperature, stress, and others. During the aging, the degradation of polymer and composite materials leads to significant changes of their physical and mechanical properties [1–5].

Polymer and polymer-based composite materials are usually tested for a long time in a liquid medium at certain temperature conditions. This method of evaluation of polymer and composite materials service conditions is termed as hygrothermal aging. Hygrothermal aging at high temperature accelerates the aging process. The natural seawater, distilled water, tap water, demineralized water, alkaline and acid environment, saline solution and any other chemical based applications can be used as aging agents. The effect of aging on the mechanical properties of the fiber reinforced plastics under various environmental factors and loading conditions was investigated in [6–18].

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In the study [6], the flexure, tensile and compressive behavior of the hygrothermal aged carbon fiber reinforced epoxy composite was studied as a function of the absorbed moisture content. Composite specimens were aged by immersing them in the natural seawater at 60°C for different time intervals. The flexure, tensile and compressive strength of the material showed an inverse correlation with the absorbed moisture content, whereas the elastic modulus showed negligible correlation. Similarly, the tensile and flexure failure strain showed an inverse relationship with the absorbed moisture content.

The paper [7] was focused on the effect of hygrothermal aging on the mechanical properties of mixed short fibre/woven composite materials in different environments, i.e. moisture and temperature, for different durations. The seawater is the most aggressive medium that makes materials less resistant than distilled water and makes them brittle. The obtained results, follows that the presence of water in the composite material causes a deterioration of the mechanical properties. The penetration of water or moisture is through the outer surface of the composite within the structure. The fibers do not absorb the solvent, while the matrix is capable of absorbing them through the free volume and the micro-cavities. The water interacts with the matrix, with the reinforcement and the interfacial zones, which can in particular degrade the bonds and thus causes an irreversible degradation of the properties of the composite. In addition, the material undergoes the effect of plasticization, i.e. a modification of the structure, which can result in the simultaneous decrease of the plasticity threshold or damage. The temperature has a negative influence on the resistance of materials. A sharp drop in mechanical properties as follows: 67 % of the elastic stress, 59 % the ultimate stress and 18 % of the elastic modulus is observed during a long duration of temperature (one year). In some cases (1 month), the temperature serves to improve the properties of the material deformations due to the hardening of the material. Indeed, the increase in temperature induces, in general, a softening of the materials and a decrease of the yield point.

To characterize the durability of carbon fiber reinforced plastics (CFRP) and glassy fiber reinforced plastics (GFRP) composites to hygrothermal environment a comprehensive experimental work was carried out in [8]. Composites were directly placed in water at 80°C for accelerated hygrothermal treatment. Moisture absorbed during hygrothermal ageing improved the impact properties of CFRP composites. After absorbing 3.149 wt. % of moisture, the peak contact force of CFRP laminates during impact test increased by 20.60 %. After hygrothermal treatment (in 80 °C water for 912 h), the strength of GFRP composites decreased by 28.53 %. For GFRP laminates, the peak contact force during impact test decreased by 33.44 %. After removing the moisture absorbed, the tensile strength of CFRP composites was recovered to 95.75 % of its original value. The strength retention rate of GFRP composites was only 74.65 %. The modulus of glass fibers and GFRP composites remained nearly unchanged. In contrast, their tensile strength decreased significantly. Growth of surface flaws is considered as the main mechanism for the decrease in strength of glass fibers in the current investigation.

The effect of seawater immersion on the durability of glass- and carbon-fiber reinforced polymer composites was experimentally investigated in [9]. The materials studied were glass/polyester, carbon/polyester, glass/vinyl ester and carbon/vinyl ester composites used in marine structures. When immersed in seawater at a temperature of 30°C for over two years, the composites experienced significant moisture absorption and suffered chemical degradation of the resin matrix and fiber/matrix interphase region. This degraded the flexural modulus and strength of the composites, although the mode I interlaminar fracture toughness was only marginally affected by immersion.

In the study [10] the aging of an epoxy resin and its CFRP composites in water, acidic, and alkaline solutions at different temperatures was explored. The tensile tests revealed that degradation adversely affected the tensile strength, although the tensile modulus values did not significantly decrease throughout the aging study. According to the thermal and mechanical analysis, degradation occurred in a higher rate as the exposure temperature is higher. In general, from the thermal and mechanical analysis it was observed the rate of degradation is accelerated at elevated temperature and is obvious in acidic conditions. The degradation of the composite materials can be attributed to the deterioration of the resin matrix and debonding at the fiber-resin interface. This damage was visible in the morphological analysis. By correlating the experimental data and prediction results, it can be concluded that the CFRP composite materials may need to be developed further to withstand acidic media and ensure a longer service life.

The effect of specimen thickness on the water absorption and flexural strength of wet lay-up CFRP laminates immersed in distilled water or alkaline solution was investigated in the study [11]. The water uptakes and flexural strength retentions of wet lay-up CFRP laminates were greatly affected by the adopted specimen thicknesses. For CFRP laminates conditioned in distilled water or alkaline solution up to a duration of 180 days, the water uptake decreased in the early stage of immersion and increased in the later stage of immersion with the increase of specimen thickness. Meanwhile, the flexural strength retention generally increased as the specimen thickness increased.

Two different quasi-static crushing tests have been performed in [12] to investigate the effects of humid ageing on the crashworthiness behaviors of the CFRP polymer laminates. Four different types of specimens made from T700/M21 and Cytec woven CFRP materials were placed in a humidity-controlled chamber at 90 % relative humidity (RH) and 80 °C until they reach saturation before performing the crushing tests. From the result obtained, the behavior of the force-displacement curves, crushing morphologies and damage mechanisms between humid ageing specimens and the same specimens are very similar. Nevertheless, in terms of ply mean crushing stress analysis it is quantitatively proven that there are drops nearly to 10 % on the CFRP laminates have been exposed to the humidity environment.

The results of studying the climatic aging of aviation polymer composite materials (PCMs) performed over the last 5-8 years was analyzed in [13]. These results expand the understanding of the mechanisms of the physicochemical transformations under the influence of aggressive environmental factors. The new information is useful in assessing the expected effects of changing the most common deformation-strength parameters of PCMs with allowance for the type of material, the measured mechanical index, the exposure time, and climatic conditions. If the results of selective measurements of the strength or the elastic moduli of a particular material fall out of a general trend, this is the basis for taking into account possible methodological errors in measurements. The traditional control of changing one or several mechanical properties at room temperature is insufficient to characterize the climatic resistance of PCMs. To plan climatic tests of new promising PCMs, one can take into account in advance that the ultimate bending strength changes most strongly and the bending elastic modulus is the most stable property.

Investigation of the water uptake and interlaminar shear strength behavior of CFRP laminates after ageing was performed in [14]. Distilled water, 1.0 % saline solution and pH ≈ 4.0 ± 0.2 acidic solution were prepared to treat the samples for 12 weeks. Short beam shear tests were performed to evaluate the interlaminar shear strength (ILSS). The experimental results show that saline and acidic solution can reduce the water uptake capacity of CFRP laminate compared with distilled water. Delamination in layer and between layers and fiber-matrix interface debonding were the main environmental damages. After 12 weeks of ageing, the ILSS reduction of specimens aged in acidic solution had the largest reduction (21.52 %), followed by saline solution (15.65 %), and distilled water had the smallest reduction (10.59 %). However, there was an increase in ILSS at the early acidic and saline ageing, while a stable in distilled water ageing, which may be a new way to strengthen the CFRP in future. It was also found, that the ILSS degraded nonlinearly with the increasing of water uptake of matrix. The results would guide the application of CFRP in engineering filed.

In the paper [15], the tension-tension (T-T) and tension-compression (T-C) fatigue properties and static strength of hygrothermal aged laminates were investigated. A tensile and compressive strength reduction of laminates is observed. Based on run-out specimen data, an average 18 % reduction in fatigue strength was shown. The damage initiation and fatigue life reduction of aged specimens were higher in T-C loading as compared to T-T loading.

Experiments on accelerated aging of carbon/epoxy and glass/epoxy laminates in an artificial seawater environment with 3.5 % salinity were carried out at 60 °C for 45 days [16]. Mechanical experiments including tensile and 3-point bending tests were conducted on the reference/dry and aged standard specimens at room temperature and at 60 °C. The loss in the mechanical properties including tensile and flexural strength of carbon/epoxy and glass/epoxy laminates at 60°C and ambient temperature is observed.

The work [17] is devoted to investigation of the static and fatigue three-point bending behavior of the carbon fiber reinforced polymer laminates. Two types of layup (unconstrained and constrained) under the dry and hygrothermal aged conditions were considered. Fatigue behavior was investigated at two stress ratios of 0.1 and 0.5. The effective flexure strength, modulus and failure strain of both constrained and unconstrained laminates degraded due to hygrothermal aging. The degradation degree depends on the aging duration. Aging significantly reduces the fatigue life of the unconstrained laminate at both stress ratios. The reduction in the fatigue limit due to aging is considerably at the high stress ratio than at the low stress ratio. The greater degradation of the aged unconstrained and constrained laminates at high stress ratio is responsible for diminishing the stress ratio effect.

The aim of the paper [18] was to investigate the combined effects of seawater ageing and fatigue loading on the bearing performance and failure mechanism of CFRP/CFRP single-lap bolted joints. The bolted joints with an interference fit size of 1.15 % were prepared and then immersed in artificial seawater (50°C-3.5% NaCl solution) for 7 months. After that, fatigue loads were further applied to the unaged and aged joints. Finally, single-lap bearing tests were carried out to evaluate the bearing performance of seawater aged and fatigue load treated joints. The experimental results showed that the ultimate bearing load of joints suffered the single effect of seawater ageing decreased exponentially with the increase of ageing time, while the joints suffered the combined effect of seawater ageing and fatigue loading decreased linearly. Moreover, compared with the single effect joints, the bearing capacity of combined effect joints showed a significant improvement. Furthermore, the failure mechanism of single effect joints was mainly the shearing fracture in bearing zones and the failure mechanism of combined effect joints was changed to be delamination in bearing zones. Those findings can provide an effective support during the use of CFRP/CFRP bolted joints for marine applications. Treated the joints with fatigue loads is an alternative method to improve the bearing performance of CFRP/CFRP bolted joints. However, it is very necessary to further explore the effect of fatigue loading parameters (load peak, load ratio and fatigue cycles) on the bearing performance of CFRP/CFRP bolted joints, which will make us have a deeper understanding of the fatigue loads.

In this work, experimental studies on the alternation of cyclic loading and climatic and thermal aging were conducted to study the fatigue strength change of carbon fiber reinforced plastics.

Materials and Methods

Specimens of unidirectional carbon fiber reinforced plastic (CFRP) of the T107/ON190/R132436 mark with a length of 250 mm, a working length of 140 mm, a width of 15 mm and a thickness of 0.8-1 mm we used in tension and fatigue experiments. The geometry and dimensions of specimens and tabs are shown on Fig. 1.

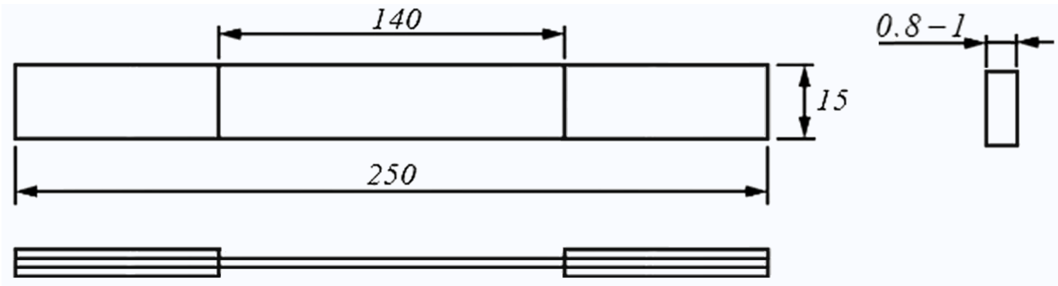

Fig. 1. Geometry and dimensions of specimens and tabs (mm)

The experiments on tension were performed on a tearing test machine TINIUS OLSEN H10K-T. Fatigue experiments were carried out on a desktop fatigue servo hydraulic test machine Si-Plan SH-B. Aging at evaluated and low temperatures were conducted correspondingly in a muffle furnace Nabertherm N40E and in a standard freezer.

Experiments on tension of CFRP specimens

Experiments on tension of CFRP specimens with a rate of 1 mm/min were conducted. The obtained tension stress-strain diagram is shown on Fig. 2.

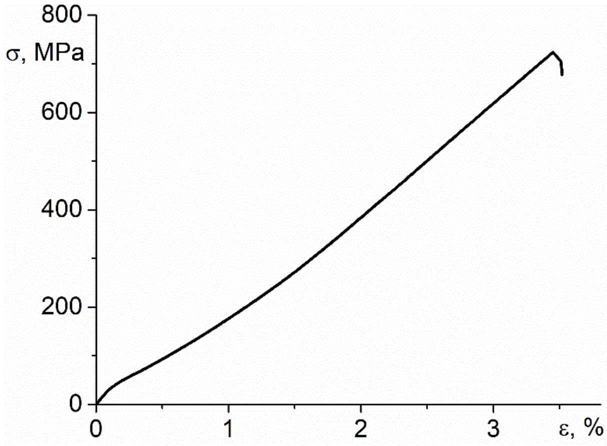

Fig. 2. Tension stress-strain diagram of CFRP specimens of the T107/ON190/R132436 mark

From Fig. 2 it can be seen that the tension stress-strain diagram has a shape close to a straight line, which is observed in experiments for various polymer composite materials [6,15,19-20].

Influence of climatic and deformation aging on fatigue strength of CFRP specimens

Cyclic experiments of CFRP specimens with constant amplitude were conducted with a sinusoidal variation in stress б = 337 MPa (0.45 of the ultimate tensile strength), stress ratio R = 0 and a loading frequency of 20 Hz. Thus, the average number of cycles N to fracture was determined to be 696 119 cycles.

To study the effect of climatic and deformation aging on fatigue strength, the following experimental programs were used.

Program 1. Specimens were tested up to 0.4 N cycles at noted loading parameters; placed in a muffle furnace at 120°C for 2 hours; aged in laboratory conditions for 3 months, and then tested to fracture.

Program 2. Specimens were tested up to 0.4 N cycles at noted loading parameters; placed in distilled water at room temperature, then frozen at temperature −16°C and kept in ice for 2 days; then unfrozen and kept in distilled water for 3 weeks; aged in laboratory conditions for 3 months and then tested to fracture.

Program 3. Specimens were placed in distilled water at room temperature, then frozen at temperature −16°C and kept in ice for 2 days; then unfrozen and kept in distilled water for 3 weeks; aged in laboratory conditions for 3 months and then tested to fracture.

The results of the influence of climatic and deformation aging on the cyclic strength of CFRP specimens according to programs 1-3 are presented in Table 1.

According to the obtained results, a significant hardening during cyclic experiments is observed, which considerably depends on the aging program. Therefore, for the case of cyclic loading and aging of specimens at elevated temperatures, the number of cycles to fracture increased by more than two times, compared to specimens without aging. For the case of cyclic loading and aging of specimens at low temperatures, it is increased by more than 5 times. For specimens not subjected to initial cyclic loading, but aged at negative temperatures, it is increased by more than 9 times, compared to specimens without aging.

Table 1. Effect of climatic and deformation aging on the cyclic strength of CFRP specimens at σ = 337 MPa, stress ratio R = 0 and loading frequency of 20 Hz according to various programs

	Without aging	Aging		
		Program 1	Program 2	Program 3
Average number of cycles to fracture N	696 119	1 789 977	3 791 257	6 295 671
$N/N_{without\ aging}$	1	> 2	> 5	> 9

Conclusions

To study the changes in deformation and strength characteristics of unidirectional carbon fiber reinforced plastic of the T107/ON190/R132436 mark, experiments on alternation of cyclic loading and climatic and thermal aging were conducted. The specimens were aged according to several programs, including the alternation of cyclic loading, thermal and natural aging. According to the experimental results, a significant hardening during cyclic experiments is observed, which considerably depends on the aging program. For the case of cyclic loading and aging of specimens at elevated and low temperatures, the number of cycles to fracture increased by a factor of more than 2 and 5, respectively, compared to specimens without aging. For specimens not subjected to initial cyclic loading, but aged at negative temperatures it is increased by more than 9 times, compared to unaged specimens.

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About Author

Alexander R. Arutyunyan Sc
Candidate of Physical and Mathematical Sciences
Senior Researcher (St. Petersburg State University, St. Petersburg, Russia)