Effect of external operational damage on the mechanical behavior of GFRP under quasi-static and fatigue loading

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INTRODUCTION

Polymer composite materials (PCM) are widely used in various industries and are used in the manufacture of critical parts. Thanks to the use of composite materials (CM), it is possible to reduce the weight of the structure and increase its strength. Since composite structures are subjected to various impacts during service that can induce defects, it is necessary to study the influence of these defects on the mechanical properties of materials.

Various defects, acting as stress concentrators, may arise both during the manufacturing of composite materials and during their service life [1]. The presence of defects lowers the load at which composite structures fail, resulting in a reduction of their overall strength.

Currently, there is a problem of the lack of a unified classification and terminology of defects for reinforced PCM. Problems also include translation inaccuracies, as a result of which different defects can be understood under the same term, and the presence of its own internal classification of defects in each area related to composite materials [2].

In [3], a classification of defects in multilayer adhesive structures made of PCM is presented according to their degree of severity. Defects that may occur during operation include cracks, dents, scratches, and chips [4,5]. The reasons for their formation may be shock or mechanical effects during operation [6]. In aviation technology, such damage can occur as a result of bird strikes during flight or from the impact of foreign objects, such as stones. They can also be caused by fragments of ice or concrete that affect the structure during takeoff and landing, hail strikes, or during ground maintenance.

Defects of the stratification type may occur during operation in areas of stress concentration [7], such as holes, stringer protrusions, and similar features. In addition, they can be caused by temperature variations and local loads, for example, impacts on the surface of the structure.

Movement of the composite structure relative to a rough surface or protrusion can cause scratches or "potholes" (breakdowns) that affect the load-bearing layers [8]. Such damage is more likely to occur when the aircraft is parked between flights, during icing, cargo handling, refueling, or interaction with other ground vehicles.

The influence of scratch geometry on the delamination of a laminated composite under tensile loading is investigated in [8, 9]. An indenter was used to create scratches on the carbon fiber sample. It was found that, in a composite laminate containing a deep scratch that penetrates several load-bearing layers, the dominant failure mechanisms are bending and twisting deformations. It was found that the location of the scratch tip within the layer sequence and the scratch depth were identified as the primary factors affecting tensile strength, whereas the overall size and shape of the scratch have a lesser influence.

In cellular structures, defects that occur during operation include one - and two-sided holes, cracks, delamination of the skin due to impacts, separation (the skin from the frame, cellular aggregate from the skin or frame).) [1, 3, 4, 10, 11].

Carbon fiber sandwich panels are significantly more susceptible to impact damage than fiberglass panels, and the predominant damage mechanisms differ: in carbon fiber sandwich panels, fiber fracture is dominant, whereas in fiberglass panels, core failure prevails [12].

During aircraft operation, impacts and operational loads cause damage. Such damages can reduce the residual strength and durability of the structure, potentially leading to failure and endangering the safety of aircraft operation [13, 14].

Polymer composites are vulnerable to impacts even at low speeds, and low-energy impacts can cause complex matrix cracks and delaminations within the composite. The mechanisms of matrix cracking and delamination typically render composite structures unserviceable during operation, necessitating their replacement. The danger of such damage is that, in most cases, it is not visible on the surface and cannot be detected by visual inspection of the structure. This is called barely visible impact damage. With a stronger impact, a chip can be observed on the reverse side of the CM, while no visible traces remain on the front side [12, 13].

Delamination caused by barely noticeable impact damage may not significantly affect the tensile strength, but it can significantly reduce the compressive strength. Delaminating layers exhibit significantly lower compressive resistance than the same layers when firmly bonded together. For this reason, considerable attention is devoted to testing the compressive strength after impact of composite structures [12, 15, 16].

The compression test was performed for undamaged and damaged aircraft panels with stiffeners made of PCM. The decrease in residual strength due to the cutout under the stiffener and due to the impact applied at a low speed was studied. It was found that the decrease in the residual strength during testing is about 30 kN [15].

During axial compression, the composite fails due to buckling. This can be avoided by choosing the length of the part depending on its bending stiffness so that no buckling occurs under the specified boundary conditions and operating load levels [12].

During the manufacturing of composite parts, various defects may occur, negatively affecting the operational and strength characteristics of the final product. In [17, 18], static tests of CFRP samples with embedded technological defects (folds, dry spots) for tension and compression were considered using such systems as acoustic emission and digital image correlation, which were used to determine the location of defects and their influence on the mechanical characteristics of CFRP [19].

According to [20], which reviewed the types of defects in composite materials, the following types of cracks that occur during operation are distinguished: trans-layer (rare), interlayer (most common during service), and trans-fiber (fiber break). In addition to the above-mentioned types of operational defects, they also include fatigue damage, fibers fracture or damage, erosion, matrix cracking, moisture ingress, temperature effects, and damage caused by ultraviolet radiation, chemical exposure, and lightning strikes [20].

In [21], carbon fiber samples were subjected to simulated lightning strike damage at various current levels, after which the samples were tested for residual strength and modulus of elasticity under tension and compression. The results show that the residual tensile strength increases after impact, while the residual compressive strength decreases.

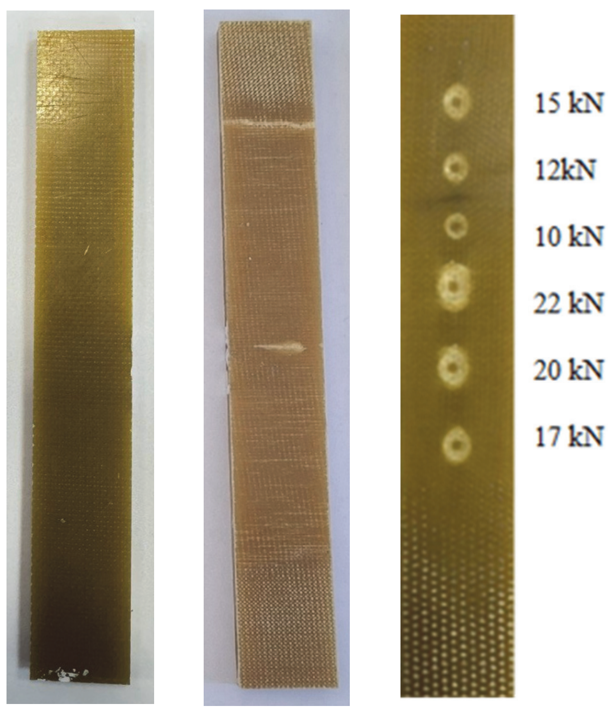
Papers [12, 22] are devoted to the study of the mechanical behavior of layered composites under fatigue loading, specifically under cyclic tensile conditions. The failure mechanisms are described, and the following stages of damage progression are identified: matrix cracking, crack coalescence and interfacial delamination, delamination, fiber fracture, and ultimate composite failure.

Thus, the damage modes that can occur in polymer composites are considered. PCMs are particularly susceptible to operational defects caused by low-speed impacts, static, and cyclic loads. The presence of such operational defects significantly reduces the service life and structural integrity of the components. The relevance of the work is due to the increasing use of composite materials in critical structures and the need to assess the impact of external operational defects on their residual mechanical properties. This work aims to evaluate the impact of operational defects on the fatigue characteristics and failure processes of CFRP.

MATERIAL AND METHODS

This work was carried out in Perm National Research Polytechnic University using Unique Scientific Equipment "A complex of testing and diagnostic equipment to study the properties of structural and functional materials under complex thermomechanical loading conditions http://ckp-rf.ru/usu/501309.

An experimental program of the influence of external operational defects on the fatigue life of polymer-laminated fiberglass was developed and implemented. The study was carried out on samples in the form of strips cut along the weft, with dimensions of 150x20x6 mm (Fig. 1). Before testing, the samples were damaged to simulate the following operational defects: scratch and dent.



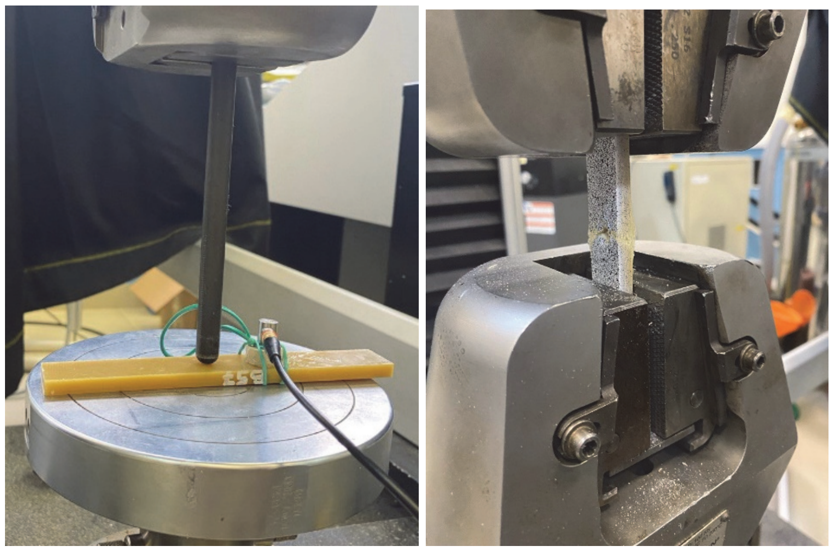
a *b* *c*

Figure 1: Sample appearance: (*a*) original sample appearance, (*b*) sample with scratch defect, (*c*) sample with dent defect.

The scratch defect was applied using a 10 mm wide steel blade inserted into the gripper of the test machine. When applying the defect, the indentation load (1 kN) on the sample and the movement of the active gripper (1 mm) were controlled. The appearance of the sample with the scratch defect is shown in Fig. 1, *b*.

To apply the "dent" defect under controlled loading parameters (force, displacement), a method was developed [23], applying a load to a fiberglass sample in the transverse direction through a steel shaft with a hemispherical tip with a diameter of 10 mm. In preliminary tests, this type of defect was applied with loads of 10 kN, 12 kN, 15 kN, 17 kN, 20 kN, and 22 kN (Fig. 1, *c*). The process of applying the dent defect to the sample is shown in Fig. 2, *a*.

As a result of preliminary tests of a dent defect, ranges of indentation loads were established, which either did not lead to damage to the sample at all or did not affect the load-bearing capacity of the GFRP. We also determined the load ranges that caused visible macroscopic defects (such as through-thickness cracks, surface layer rupture, etc.) during indentation. It was found that a load of 22 kN is critical, leading to the destruction of the sample. Thus, the indentation defect was applied at three load levels (10, 12, and 15 kN) of the indenter into the sample. These loads caused moderate damage to the material. To determine the cyclic loading, a series of quasi-static tensile tests was performed. Samples with dent defects (10 kN, 12 kN, and 15 kN) and a 10 mm wide transverse scratch were tested, as well as samples without defects (initial ones). Three samples were tested in each batch. Tensile tests were performed on an Instron 5882 electromechanical testing machine (Fig. 2, b). The loading rate during tensile tests for all sample groups was 2 mm/min, and the sample was loaded to failure. Deformations were measured using a VIC-3D system based on the digital image correlation method. Shooting was done with cameras at a resolution of 16.0 Mp with a shooting frequency of up to 3 Hz.



a *b*

Figure 2: Application of a dent defect (a) and the specimen mounted in the grips of the Instron 5882 testing machine (b).

Based on the obtained results of static tests, the types of simulated defects and loading parameters for cyclic testing were determined. Tests to assess the effect of external operational defects on the fatigue life of polymer fiberglass were performed for groups of samples without defects, with a dent defect of 10kN, with a dent defect of 15kN, and a scratch defect.
Tensile fatigue tests were performed on the Instron 8802 servo-hydraulic test system (100kN). Parameters of cyclic loading were as follows: frequency of 10 Hz, load ratio R=0.1, and a maximum stress-to-ultimate strength ratio σ/σ_b=0.3-0.7. The shape of the cycle is chosen as a sine. The average values of maximum stresses for each sample series were taken as the ultimate strength. One sample were tested in each batch. The following conditions were used as the failure criterion: reduction of the maximum load from cycle to cycle by 50% or specimen failure into parts.

RESULTS AND DISCUSSION

Based on experimental static test data obtained from the Vic-3D video system, deformation diagrams were presented in Fig. 3. The deformation diagrams of the initial samples and samples with defects coincide in the initial linear section, which may indicate that the presence of dent and scratch defects does not significantly affect the material's tensile stiffness. Based on the tensile test results, mechanical characteristics were determined for samples without defects (Tab. 1) and the following characteristics of GFRP samples with defects: load-bearing capacity, maximum fracture stresses, and stiffness (Tab. 2). The stiffness of a sample of a material with a defect is an equivalent characteristic of the elastic modulus. The maximum stresses during failure of samples with defects were determined similarly to the ultimate strength, i.e., as the ratio of the maximum load to the initial cross-sectional area of the sample without a defect. All samples exhibit similar initial behavior, and as the dent application force increases, the maximum stresses at fracture decrease significantly, indicating substantial material degradation. The maximum stresses at fracture for specimens with a dent defect decrease relative to defect-free specimens as follows: by 17% for samples with a dent applied with a force of 10 kN; by 25% for samples with a dent applied with a force of 12 kN; by 30% for samples with a dent applied with a force of 15 kN. Applying a defect scratch does not affect the conditional tensile strength. The presence of operational defects such as dents and scratches does not reduce the stiffness of the defective material sample.

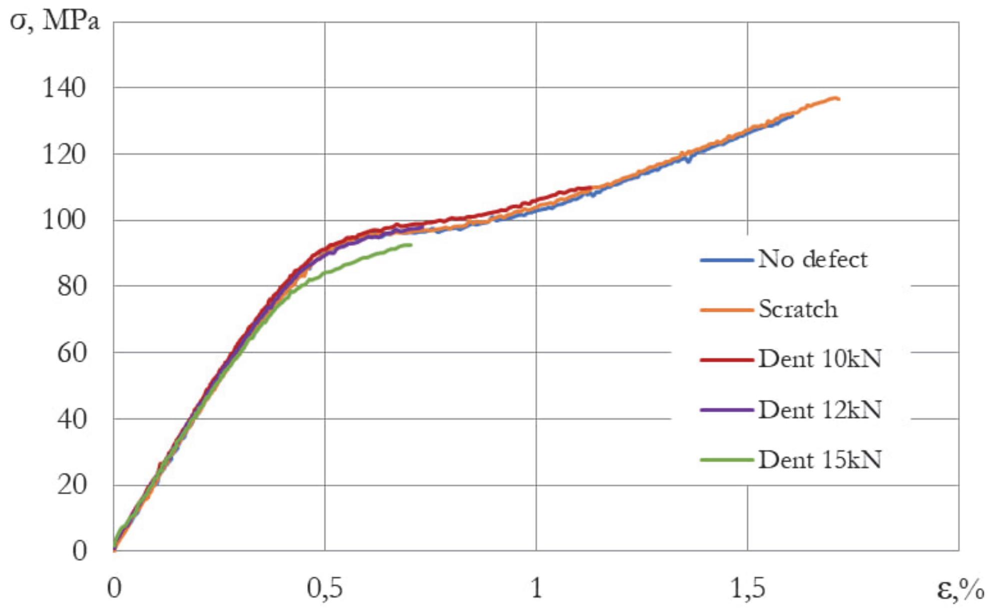


Figure 3: Characteristic deformation diagrams of GFRP samples with simulated operational defects applied.

Maximum load P_{max}, kN	Ultimate strength σ_v, MPa	Modulus of elasticity E, GPa
16.7	137	20.1

Table 1: Mechanical characteristics of defect-free GFRP samples.

Type of defect	Load-bearing capacity P_{max}^*, kN	Maximum failure stresses σ_B^*, MPa	Stiffness E^*, GPa
Scratch	16,6	138	21,0
Dent (10 kN)	13,7	112	20,6
Dent (12 kN)	12,0	99	21,6
Dent (15 kN)	11,4	93	20,9

Table 2: Test results of GFRP samples with defects under quasi-static tension

Fig.4 shows the fields of longitudinal strains on the surface of a sample without defects and on the surface of samples with scratch and dent defects. The load level at point 1 corresponds to 0.2 σ_{max}, at point 2 corresponds to 0.5 $\sigma_{\sigma\ max}$, and at point 3 corresponds to 0.99σ_{max}. Between the fracture (0.99σ_{max}) and the ultimate strains, the maximum concentration of longitudinal strains in the defect region before fracture is estimated.

$$K_\varepsilon = \frac{\varepsilon_c}{\varepsilon_v} \quad (1)$$

where K_ε is the maximum concentration of longitudinal strains, ε_c is the value of the maximum longitudinal strain in the defect area before failure, and ε_v is the maximum value of the longitudinal strain from virtual extensometers installed outside the defect area.

For the scratch defect, the maximum concentration of longitudinal strains is 2.45, and for the dent defects applied with forces of 10, 12, and 15 kN: 3.27, 3.19, and 3.61, respectively. Thus, it can be noted that as the intensity of exposure to the sample increases, the strain concentration in the defect region increases.

The assessment of the risk of operational defects (dent and scratch) on the fatigue life of GFRP was carried out. The test results are shown in Tab. 3. Samples that were not destroyed during the tests are marked with (*).

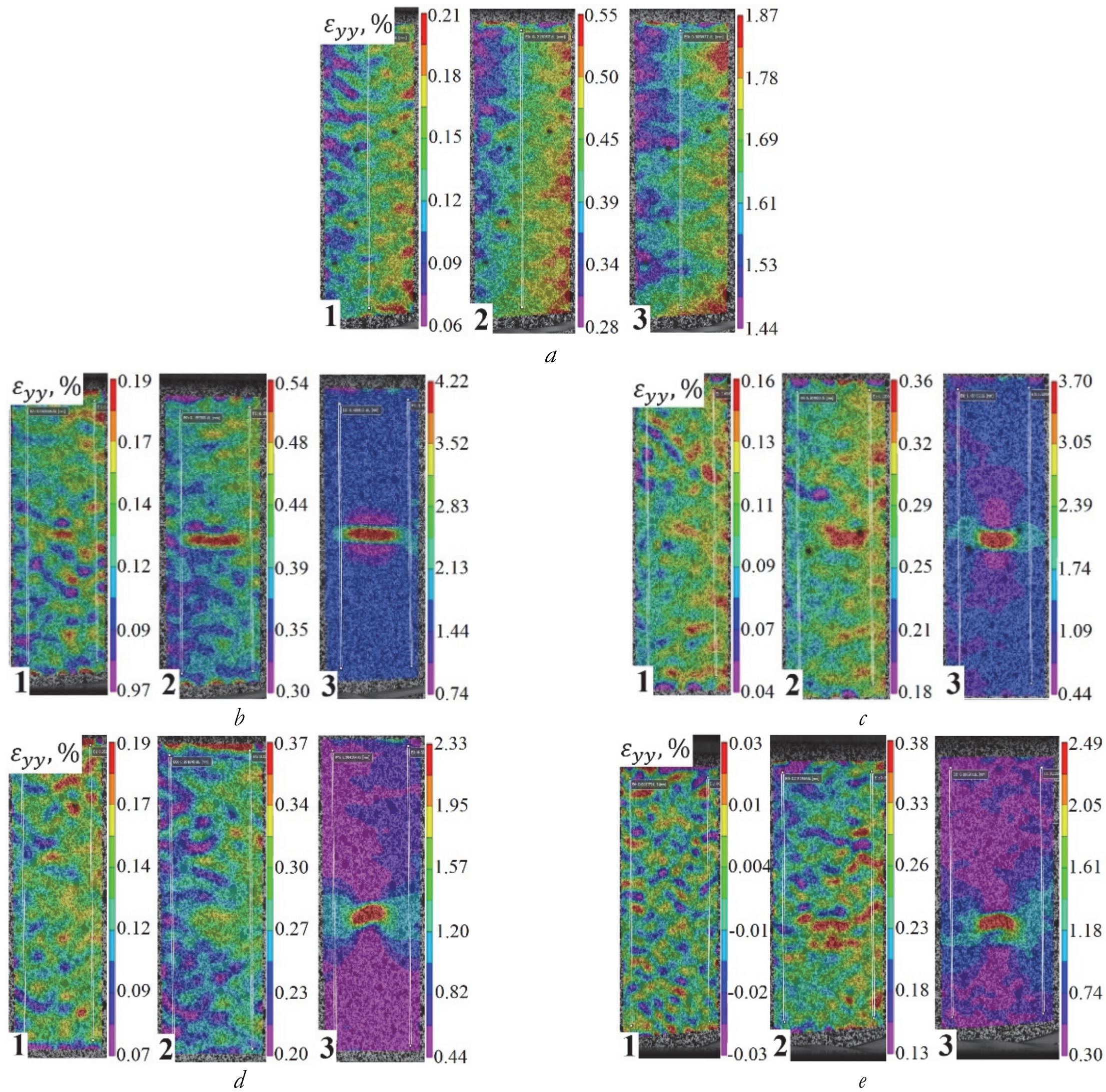


Figure 4: Fields of longitudinal strains on the surface of samples cut in the weft direction: *a*) without defects; *b*) with a scratch; *c*) with a dent (10 kN); *d*) with a dent (12 kN); *e*) with a dent (15 kN)

Load levels σ/σ_b	Number of cycles, *N*			
	No defect	Scratch	Dent 10kN	Dent 15kN
0,30	3206056*	9825050*	20000000*	12976652*
0,35	-	-	10791406*	1088153
0,40	1043508	1099022	395689	78923
0,45	166894	100553	24302	31423
0,50	21576	19216	18817	5441
0,60	5046	2804	3277	368
0,70	900	-	-	-

Table 3: Results of cyclic tensile testing of fiberglass samples with various operational defects

Based on the results of fatigue tests, the tensile fatigue curves of fiberglass for various types of external damage are plotted in logarithmic coordinates (Fig. 5). The most dangerous type of external damage is determined: a dent of 15 kN. For this series of samples, a decrease in the fatigue life of GFRP is observed with an increase in the level of loading relative to samples without a defect. For example, at a loading level of 0.6, the fatigue life of samples with a dent of 15 kN relative to samples without defects decreases by 93 %.

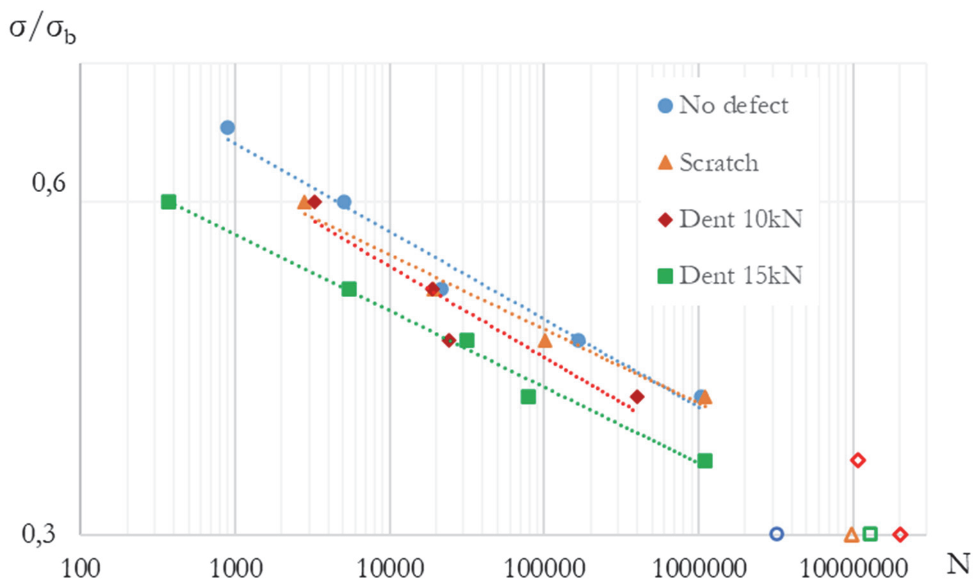


Figure 5: Fatigue curves with different types of external damage: ● – no damage, ▲ – scratch, ♦ – 10kN dent, ■ – 15kN dent, blank markers correspond to undamaged samples.

The Basquin function is essential in material fatigue analysis. This well-known approach, with its different variations, continues to be frequently used by researchers in their studies. For instance, see studies [22, 24, 25]. The Basquin function can be expressed as follows:

$$\sigma(N) = a * N^{-b} \quad (2)$$

For numerical comparison of the results, the coefficients of the Basquin equations for GFRP with and without external defects were determined. The obtained coefficients are shown in Tab. 3.

Type of defect	a	b
No defects	1.169	0.0792
Scratch	0.995	0.0670
Dent 10kN	1.117	0.0821
Dent 15kN	0.901	0.0688

Table 3: Basquin equation coefficients for GFRP fatigue curves with and without external defects

To more comprehensively assess the influence of external defects on fatigue life over the entire range of cycles tested, we introduce an analogy with the effective stress concentration factor. This factor is calculated using the fatigue limits of smooth (unnotched) samples and samples containing a stress concentrator. In our analysis, the coefficient *Kf* is defined as the ratio of the stress amplitude of an undamaged sample to the stress amplitude of a sample with an external defect, for the same fatigue life (number of cycles to failure). The *Kf* (N) relationship was obtained based on the fitted Basquin equations. Fig. 6 presents the dependence of the calculated effective stress concentration coefficient *Kf* on the fatigue life N for all types of external defects.

For samples with a scratch, the maximum effect of about 5% is observed closer to the region of low-cycle fatigue. In the region of high-cycle fatigue, the effect is almost negligible. For samples with a dent of 10 kN, the maximum effect, on the contrary, occurs in the high-cycle fatigue region and reaches 9%whereas in the low-cycle region it is about 6%. For a 15 kN dent, the maximum effect was found in the low-cycle fatigue region and reaches around 20%, decreasing to about 13% in the high-cycle region. The different behavior at dents of 10 and 15 kN shows that at 10 kN the fibers do not experience significant damage compared to the matrix. And with a dent of 15 kN, the fibers at the dent site receive significant damage, which leads to a decrease in fatigue life in the low-cycle region.

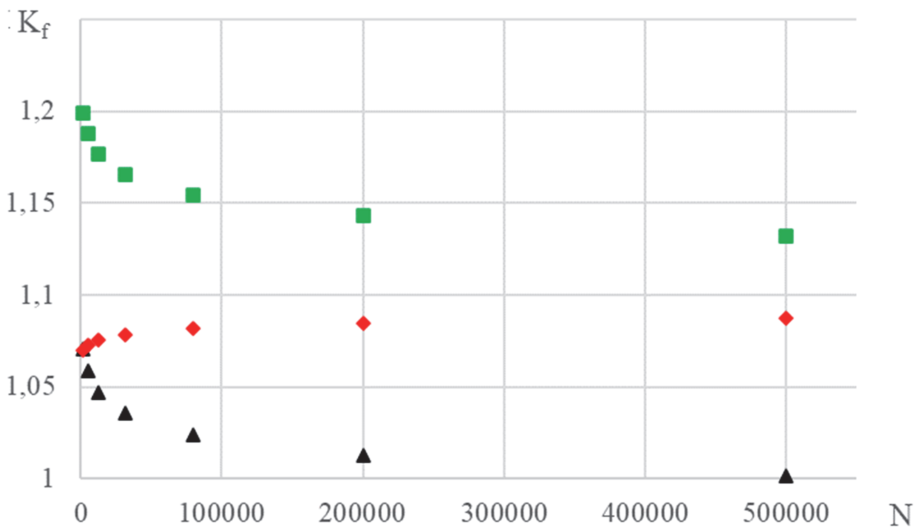
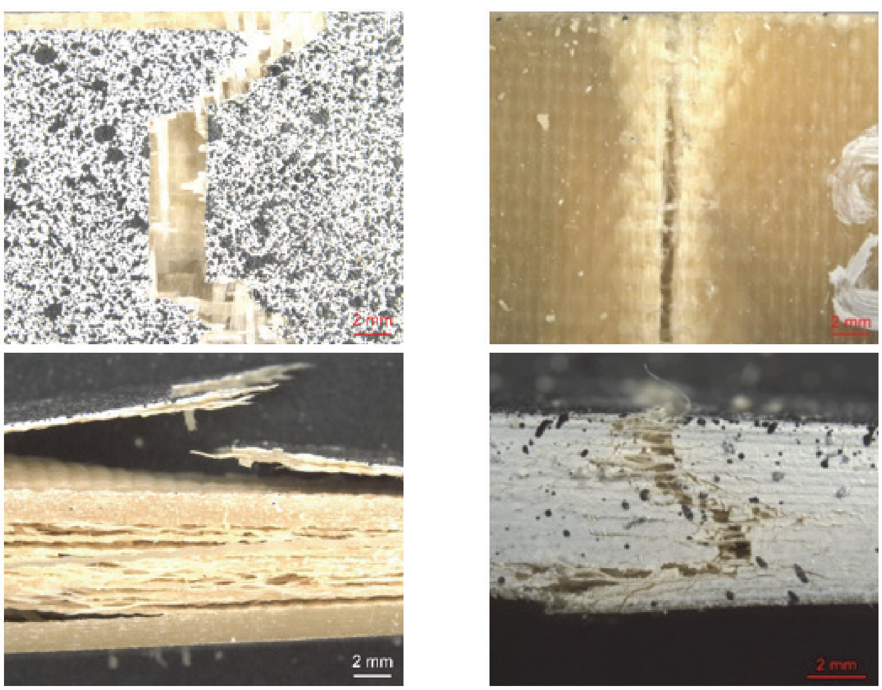


Figure 6: Effective stress concentration coefficient versus fatigue life for samples with defects: ▲ - scratch, ♦ - dent 10 kN, ■ – dent 15 kN

The failure sites of GFRP samples with operational defects were analyzed after quasi-static tension and fatigue testing. Photos of the samples after static testing are shown in Fig. 7. For samples with a scratch, failure occurred both in the grip region due to fiber rupture and in the defected area due to interlayer delamination, followed by rupture of the loaded layers (Fig. 7a). In samples with a dent, failure was caused by fiber rupture at the defect site, accompanied by local delamination and transverse separation of layers (Fig. 7b).



a *b*

Figure 7: Representative images of failed GFRP samples after quasi-static tensile testing: (a) with a scratch, (b) with a dent.

Representative images of failed samples after fatigue tests are shown in Fig.8. Analysis of the fracture surfaces indicates that failure occurs in the area of the applied operational defect due to fiber rupture.

Based on the photo of the fractures from the side, it was noticed that the crack (initiation of failure) begins from the surface of the defect, then grows under the defect and is accompanied by normal separation of layers (yellow areas), and the breakage of the samples occurs due to inertia from the bending of the sample with delamination (red zone).

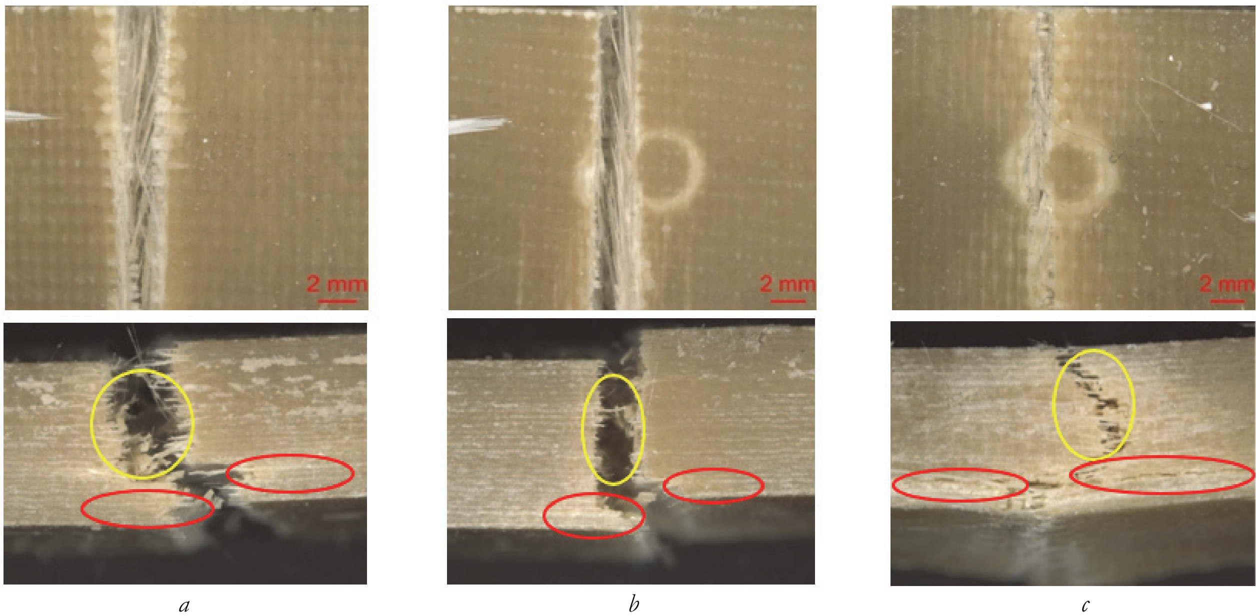


Figure 8: Representative images of failure sites in GFRP samples after fatigue testing: (a) scratch, (b) 10 kN dent, (c) 15 kN dent.

Conclusions

We developed methods to introduce external defects that simulate operational damage, such as scratches and dents. A series of experiments was conducted to investigate the effect of these defects on the elastic and strength properties of the composite using GFRP samples. New data were obtained on how operational defects, specifically scratches and dents, influence the fatigue life of the GFRP samples.

The fracture surfaces of samples with operational defects were examined after tensile and fatigue tests. It was found that during cyclic loading, failure occurs predominantly at the sites of the applied defects, whereas under quasi-static tension, samples may fail either in the working section or in the grip region.

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