Effect of internal technological defects and loading waveform on CFRP fatigue life

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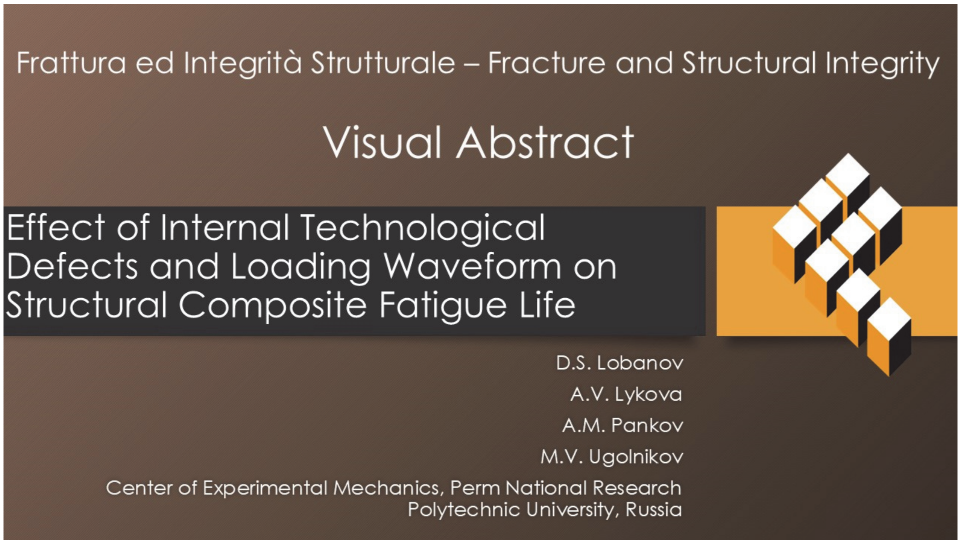
Frattura ed Integrità Strutturale – Fracture and Structural Integrity

Visual Abstract

Effect of Internal Technological Defects and Loading Waveform on Structural Composite Fatigue Life

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INTRODUCTION

Polymer composite materials are increasingly being prioritized in the design and manufacture of critical components in the aerospace industry due to their unique properties and advantages over traditional materials [1, 2]. However, the implementation of composites necessitates the development of manufacturing technologies [3]. The production process for composite parts can introduce various defects that may adversely affect the operational and strength performance of the final product.

To identify various technological defects in composites, the most commonly used methods include ultrasonic testing [4-6], X-ray inspection [7], thermography [8, 9], acoustic emission testing [10], and fiber optic sensors [11, 12]. These techniques help mitigate potential risks from defects during production, but there are some defects which impact on operational and strength characteristics may not always be severe. Thus, further research in this area remains relevant.

Various approaches are used to study the impact of defects on material properties, including computer modeling and experimental studies. Computer modeling enables predicting material behavior with defects under different operating conditions. It is possible to calculate stress and strain distributions within the material through numerical methods and assess its strength and rigidity [13, 14]. Experimental studies involve testing actual material specimens with various types of defects, providing more precise data on material behavior. These experiments can include tensile, compressive, bending, torsional, and other types of loading tests [15-17].

There are several methods for creating composites, with prepreg technology currently being the most widely used. During the manufacturing process with this technology, various defects can arise, including wrinkling, dry spots, internal delamination, foreign inclusions, cracks, voids, and other imperfections. These defects can significantly diminish both the static and fatigue strength of the product. Therefore, understanding the effect of defect size, geometry, and location on the mechanical properties of materials is crucial [18]. The ASTM E2533-09, Standard Guide for Nondestructive Examination of Polymer Matrix Composites Used in Aerospace Applications, is a key regulatory document that defines these defects in composites.

Research [19-21] also indicates that the loading cycle waveform can significantly influence the pattern of damage accumulation in a material. Certain waveforms may lead to more uniform damage accumulation, potentially extending the material's life. Conversely, other waveforms can cause rapid damage accumulation in specific materials, adversely affecting their fatigue properties.

This study builds upon previous research [22, 23], which examined static tests of CFRP specimens with introduced technological defects (such as wrinkles and dry spots) under tension and compression. The research utilized systems such as acoustic emission and digital image correlation to identify the locations of defects and assess their impact on the mechanical properties of CFRP.

However, to gain a more comprehensive understanding of material behavior under real operating conditions, it is essential to conduct cyclic tests. These tests assess the material's fatigue life and evaluate how different loading waveforms affect its ability to endure repeated stresses without degrading its properties.

This study aims to evaluate the impact of internal defects, such as dry-spot and wrinkling, on the fatigue life of CFRP under triangular and sinusoidal loading waveforms.

MATERIAL AND METHODS

An experimental research program was developed and performed to investigate the impact of internal technological defects on the fatigue life of structural CFRP under various cyclic loading waveforms.

Specimens of structural CFRP (carbon-fiber-reinforced polymer laminate VKU 60) were made from prepreg VKU with using an epoxy binder (VSE-58) based on the autoclave molding technology. The lay-up scheme was [0/90]10. Specimens were made with the incorporated defect simulators. The primary technological defects included internal delaminations (dry-spot) with a circular shape and wrinkling (Z-shaped bends of the inner layer). The defects were positioned at the geometric center of the specimen, as illustrated in Fig. 1. Drafts of the specimens with geometric sizes are shown in Fig. 1a. The location of defects within the layer pack is shown in Fig. 1b. As embedded defects (dry-spot), a technological release film (special insulation sheet) was artificially inserted.

To determine the cyclic loading parameters, all groups of specimens were first tested for quasi-static tension: (1) specimens without a defect, (2) specimens with the dry-spot defect in the form of a circle with a diameter of 10 mm, and (3) specimens with the wrinkling defect across the entire width of the specimen and a height of 10 mm. Three specimens from each group were tested. Tensile tests were conducted using an Instron 5982 electromechanical testing system (100 kN). The loading rate during tensile tests for all specimen groups was 2 mm/min. The results of the static tension tests are presented in Tab. 1.

Based on the results of the quasi-static tests, a fatigue life test program was developed for all series of CFRP specimens under different waveforms. Fatigue life tests were conducted using an MTS Landmark 370.10 servohydraulic system, with a maximum load of 100 kN and a frequency of 30 Hz, under sine and triangle waveforms, as shown in Fig. 2a. The appearance of the test system is depicted in Fig. 2b.

Cyclic loading parameters were set as follows: frequency of 10 Hz, stress ratio $R = 0.1$, and a ratio of maximum stress in the cycle to the ultimate strength of the material $\sigma/\sigma_{\text{в}} = 0.44\text{-}0.75$ (Tab. 2). The average maximum stress values for each group of specimens were used as the ultimate strength (see Tab. 1). The failure criterion was defined as either a 50% reduction in maximum load from cycle to cycle or the destruction of the specimen into parts.

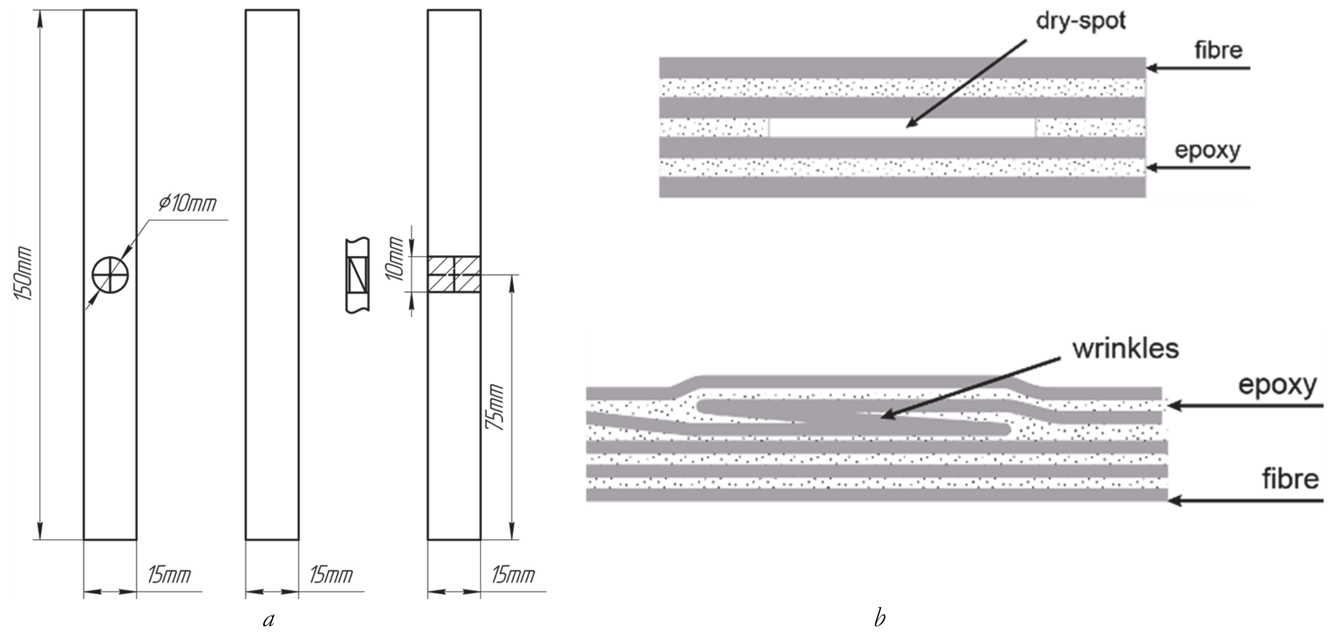


Figure 1: Scheme of specimens *(a)* with internal defects *(b)* "dry-spot" and "winkles" [25].

Defect	Maximum load, kN	Maximum stress, MPa
Without defect	26.1	801
Dry-spot, a circle	25.9	801
Wrinkles	23.8	712

Table 1: Results of static tensile tests of CFRP specimens.

№	Defect	$\sigma/\sigma_\text{в}$	Waveform cycle	R
1	Without defect	0.56	triangle	0.1
2	Without defect	0.64	triangle	0.1
3	Without defect	0.44	triangle	0.1
4	Without defect	0.48	sinus	0.1
5	Without defect	0.56	sinus	0.1
6	Without defect	0.44	sinus	0.1
7	Dry-spot	0.56	sinus	0.1
8	Dry-spot	0.64	sinus	0.1
9	Dry-spot	0.75	sinus	0.1
10	Dry-spot	0.70	sinus	0.1
11	Dry-spot	0.64	triangle	0.1
12	Dry-spot	0.75	triangle	0.1
13	Dry-spot	0.70	triangle	0.1
14	Dry-spot	0.70	triangle	0.1
15	Wrinkles	0.65	sinus	0.1
16	Wrinkles	0.70	sinus	0.1
17	Wrinkles	0.75	sinus	0.1
18	Wrinkles	0.70	triangle	0.1
19	Wrinkles	0.75	triangle	0.1
20	Wrinkles	0.65	triangle	0.1

Table 2: Loading parameters of specimens.

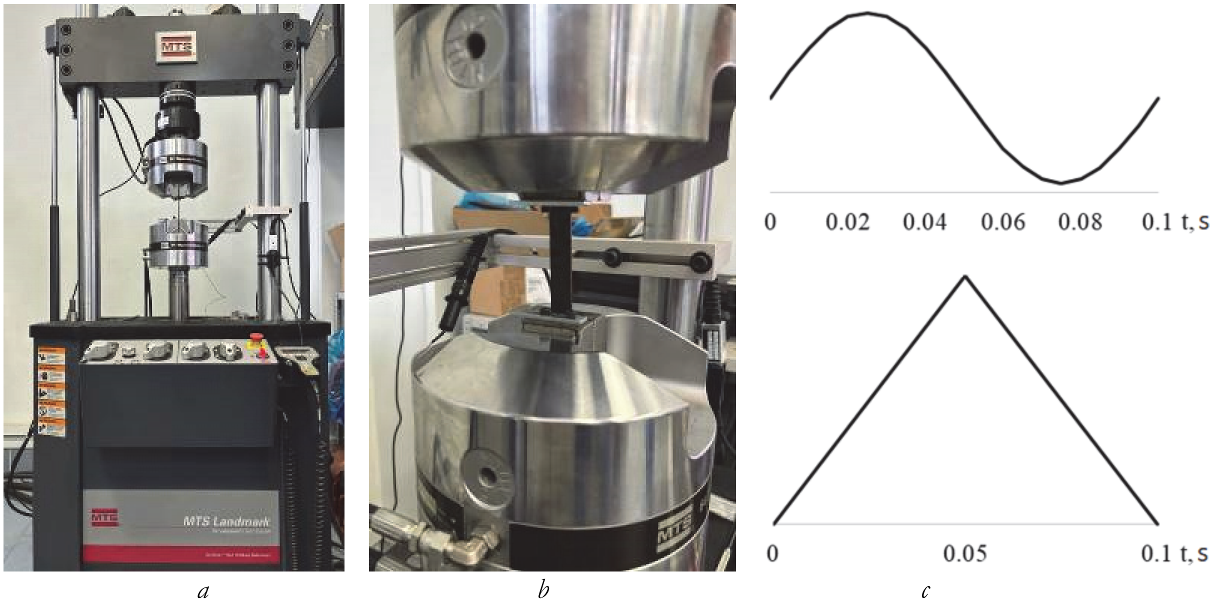


Figure 2: a – MTS Landmark 370.10 system; b – fatigue testing; c – waveforms of cyclic loading (sinus, triangle).

RESULTS AND DISCUSSION

Based on experimental data, the influence of critical internal defects on the fatigue life of a polymer structural composite material was assessed for triangular and sinusoidal waveforms.

The influence of cycle waveform on the fatigue life of specimens with various defect types was assessed by plotting tensile fatigue curves, which are displayed in Figs. 3-5. Open points signify runouts, meaning specimens that were tested but did not reach failure due to having achieved the test limit. The lines in the figures represent a power law approximation of the test data.

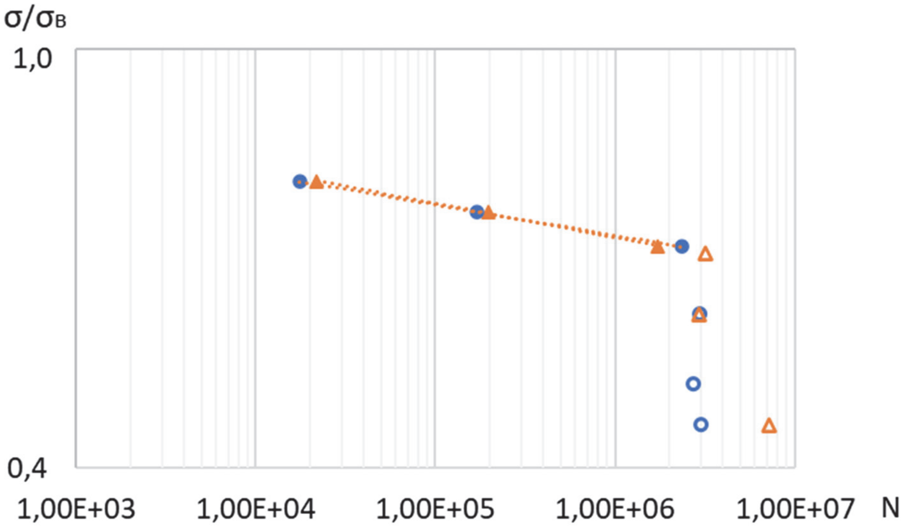


Figure 3: Fatigue curves for defect-free specimens for different waveforms: ● indicates sinusoidal, ▲ indicates triangular; open points correspond to runouts.

When comparing the curves for specimens without defects, with the dry-spot defect, and with the Z-shaped wrinkling defect, no effect of waveform (sinusoidal/triangular) on the fatigue life of structural CFRP was observed. In carbon fiber

plastic, during fatigue tests, damage accumulates such as matrix cracking, delamination and fiber damage, while in metals the accumulation of damage is mainly associated with the movement of dislocations, which requires much less energy. This is probably why the influence of the cycle shape for carbon fiber reinforced plastics is less pronounced than for metals.
Therefore, to study the effect of defects on tensile fatigue life, the results from specimens tested with sinusoidal and triangular cycle shapes were combined.

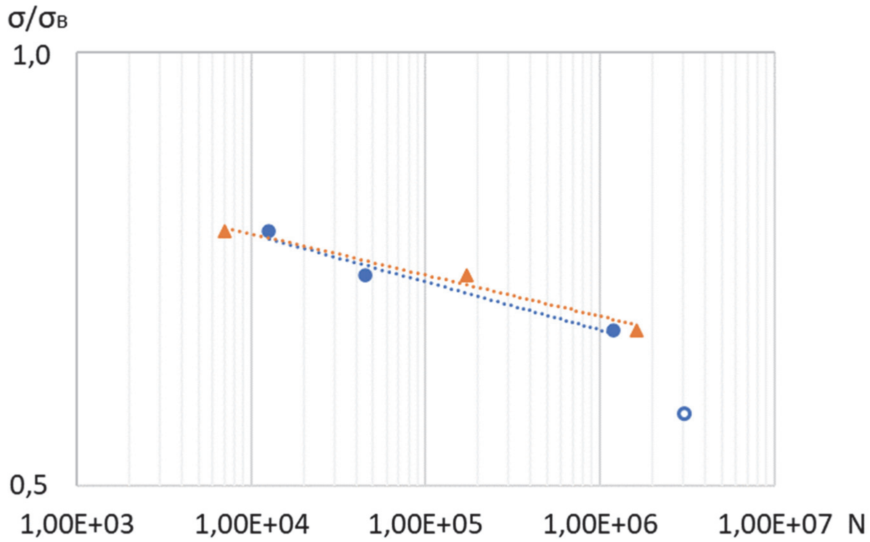


Figure 4: Fatigue curves for specimens with the dry-spot defect for different waveforms: ● indicates sinusoidal, ▲ indicates triangular; open points correspond to runouts.

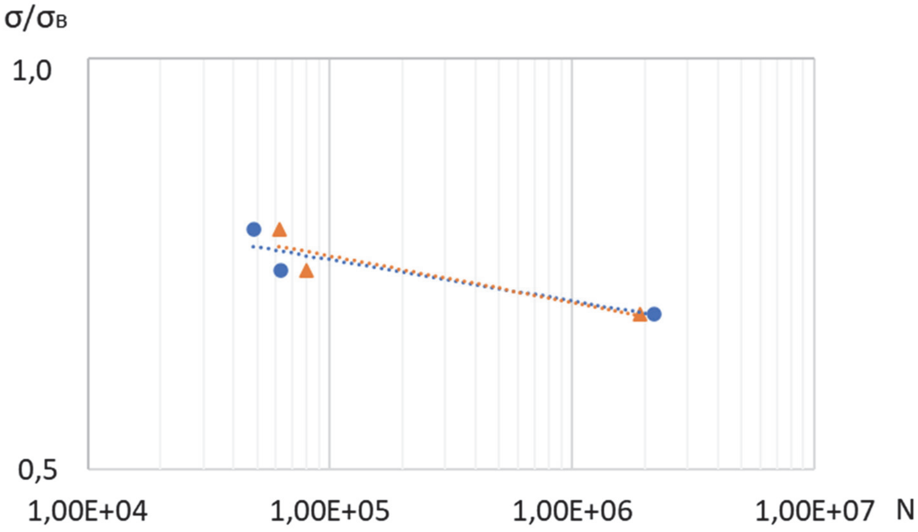


Figure 5: Fatigue curves for specimens with the Z-shaped wrinkling defect for different waveforms: ● indicates sinusoidal, ▲ indicates triangular.

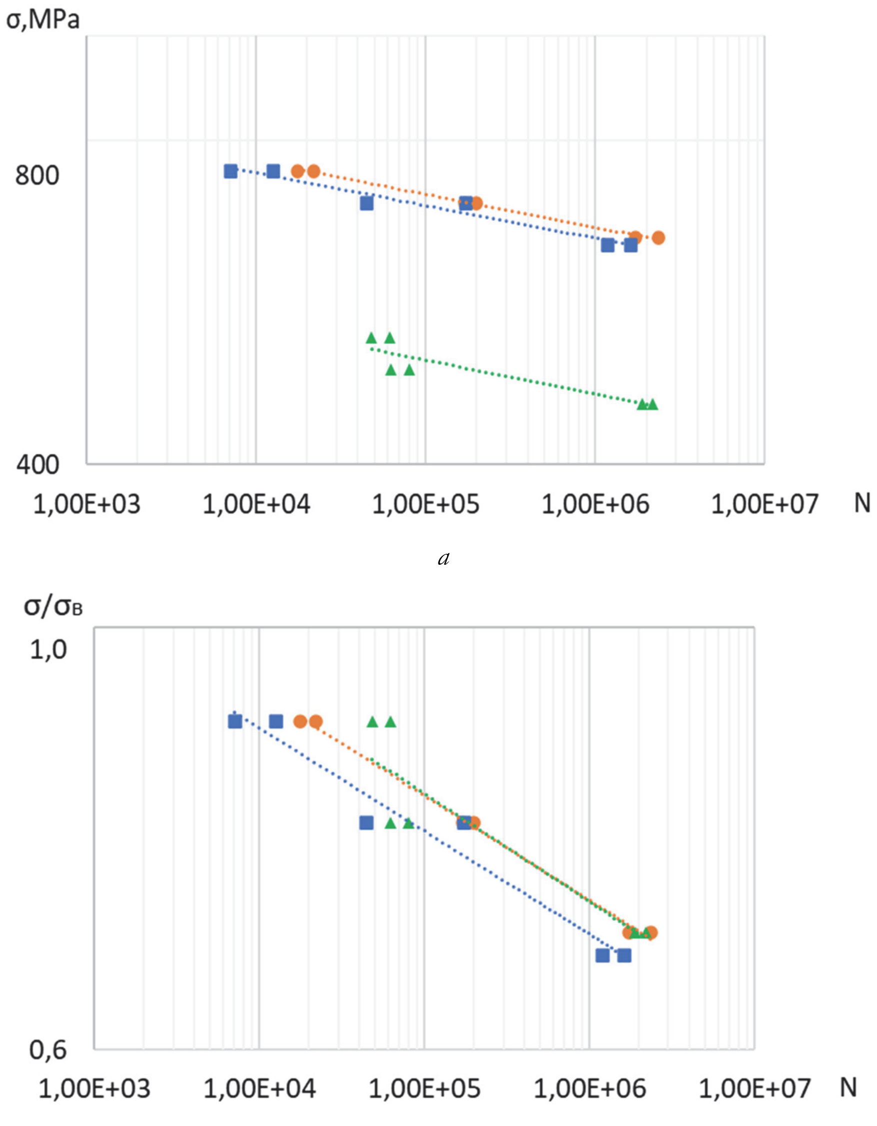
The results of the fatigue tests were used to plot fatigue curves that demonstrate the influence of defect types on the fatigue life of CFRP. Fig. 6 displays combined fatigue life curves for various defect types, shown in absolute and relative values. For each group of specimens, its corresponding ultimate strength was used.
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 [24, 25]. The Basquin function can be expressed as follows:

$$\sigma(N) = a * N^{-b} \tag{1}$$

For a numerical comparison, the Basquin equation parameters were determined for both defect-free specimens and those with technological defects. The results are presented in Tab. 3.

Defect	a	b
Without a defect	1017	0.0308
Dry-spot	988	0.0304
Wrinkles	722	0.0319

Table 3: Basquin equation parameters for fatigue curves.



a

b

Figure 6: Fatigue curves in absolute (*a*) and relative (*b*) values: ● indicates defect absence, ■ indicates dry-spot, ▲ indicates Z-shaped wrinkling.

Since the parameter *b* is approximately constant within the range from 7000 to 2×10^6 cycles, a variation in the parameter *b* by 0.0015 results in a difference of less than 1% in the calculated stresses. Therefore, it can be assumed that the decrease in stresses at a fixed fatigue life due to defects can be estimated by the ratio of the parameters *a*. It is found that with the delamination (dry-spot) defect, the stress decreases by approximately 3%, and with the wrinkling defect, it decreases by about 29%. Similarly, the drop in fatigue life at constant stresses for the dry-spot defect is calculated. The decrease in life at the same stress level is approximately 2.5 times over the entire range considered (Fig. 6a). For samples with the wrinkling defect, a quantitative comparison of fatigue life is not possible because their ranges of applied stresses do not overlap. When fatigue life curves are constructed in relative values (Fig. 6b), the effect of the wrinkling defect on the fatigue life of CFRP is practically unobserved. This indicates that for this material, the drop in fatigue properties due to the wrinkling defect corresponds to a reduction in strength properties.

To evaluate the effect of defects on cyclic durability in both low-cycle and high-cycle fatigue tests, the effective stress concentration factor can be used as an analogy. This factor is derived by comparing the fatigue limits of specimens with and without stress concentrations. In this study, internal technological defects in CFRP specimens are considered as stress concentrators. To observe the differences in material behavior across the entire durability range, the coefficient of the effect of internal technological defects on fatigue resistance (k_f) will be calculated. This coefficient is defined as the ratio of the stress amplitude of a defect-free specimen to that of a specimen with a defect for the same level of fatigue life. The calculations will be performed in a range from 3×10^3 to 3×10^6. Fig. 7 illustrates the relationship between the calculated parameter (k_f) and fatigue life (N) for specimens containing defects such as dry-spot and Z-shaped wrinkling.

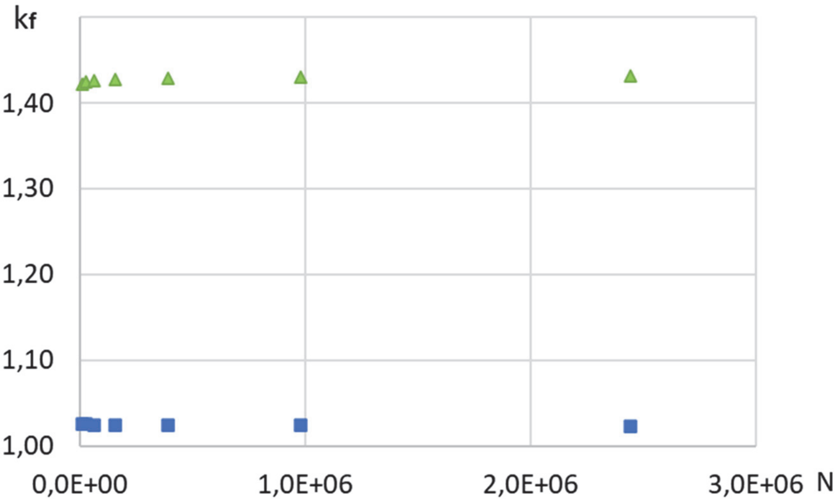


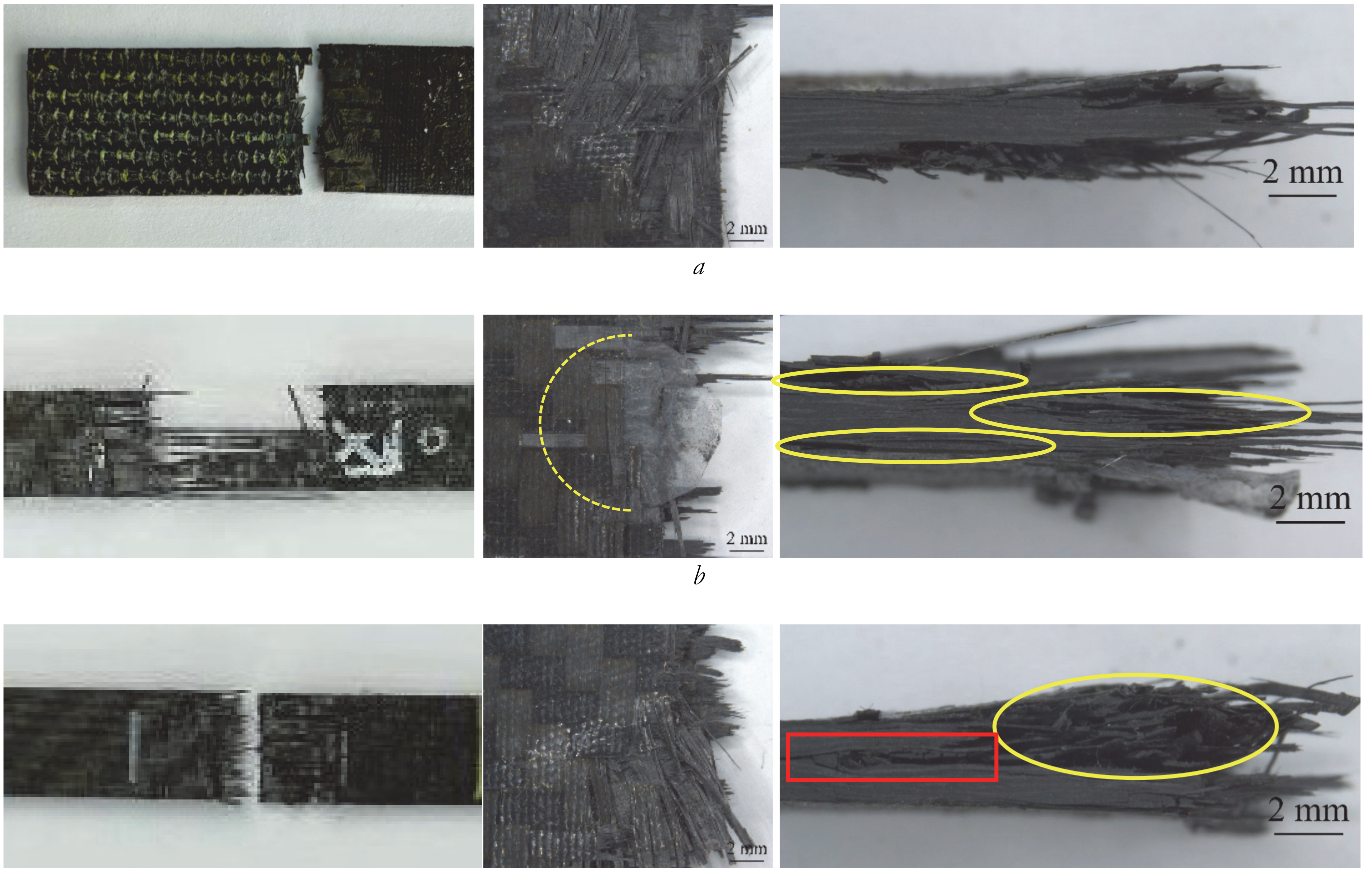
Figure 7: Dependence of the coefficient of the effect of internal technological defects on fatigue resistance: ■ indicates specimens with dry-spot, ▲ indicates specimens with Z-shaped wrinkling.

The graph indicates that the effect of each defect is consistent across the entire durability range, with no significant differences observed in high-cycle and low-cycle regions.

Fig. 8 displays typical photographs of specimens with different types of defects after fatigue testing.

Notably, similar to static tensile tests, specimens without defects typically failed near or within the grips, while those with internal technological defects failed in the working zone. In particular, during static tensile tests, specimens with delamination (dry-spot) defects failed in the grip region, whereas those with wrinkling defects failed in the working region along the defect boundary. Fig. 8b illustrates a circle of fluoroplastic film representing a dry-spot defect, with its continuation inside the specimen marked by a yellow dashed semicircle.

The fracture surface analysis of CFRP specimens with internal technological defects revealed that defect-free specimens failed by transverse tearing near the grips, where additional mechanical impacts occurred (Fig. 8a). Specimens with dry-spot defects experienced internal delamination at the location of the embedded defect (Fig. 8b, yellow ellipses), followed by subsequent fiber fracture. Specimens with a Z-shaped wrinkling defect exhibited multiple delaminations across the thickness of the specimen in the defect area (Fig. 8c, yellow ellipse), which led to the development of a longitudinal main crack between the 5th and 6th layers (Fig. 8c, red rectangle) where the defect was embedded, resulting in the fracture of the loaded fibers.



a

b

c

Figure 8: Typical photographs and fracture surfaces of failed specimens: a) without defect; b) with the dry-spot defect (circular shape); c) with the wrinkling defect (Z-shaped layer bend).

CONCLUSIONS

New experimental data on the effect of loading waveform and internal technological defects (such as dry-spot and wrinkling) on the fatigue life of VKU CFRP under cyclic tension have been obtained. Fatigue curves were constructed based on cyclic tensile tests for various waveforms and defects. The study finds that:

- Internal technological defects, particularly wrinkling, significantly reduce the fatigue life of CFRP. At a fixed fatigue life, stress levels decreased by approximately 3% for specimens with delamination (dry-spot) defects and by about 29% for specimens with Z-shaped wrinkling defects. Similarly, for fixed stress levels, the fatigue life of specimens with dry-spot defects decreased by about 2.5 times compared to defect-free specimens across the entire range considered.
- The type of loading waveform (sine vs. triangle) does not significantly influence the fatigue life of both defect-free and defected CFRP specimens.
- The reduction in fatigue properties corresponds to a decrease in the material's strength properties for wrinkling defects.
- Fracture surface analysis after static and cyclic tests revealed that dry-spot defects lead to a change in the failure mechanism of CFRP. During fatigue tests, failure initiates from delamination, followed by fiber fracture in the defect area.

In the next stage, the authors plan to study the fatigue life of material specimens with defects under complex cycle shapes and negative stress ratios.

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