A new criterion for determination S-N curve of CFRP under tension

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Abstract. The article is devoted to development of fatigue failure criterion of the CFRP specimen under fatigue tension loading. The main goal of the current study is to develop a quantitative failure criterion for fatigue damage of a specimen with open hole under tension. In response to this problem, the influence of the following parameters on the stability of the criterion and on its application was determined experimentally: manufacturing technology of a material, the loading conditions during testing. The usage of the failure criterion of thickening in the hole zone made it possible to obtain S-N curve while using the classical criterion does not allow to get a S-N curve at some cases. The application of developed failure criterion of thickening made it possible to reduce the standard deviation of the logarithm of \( S_{\log}N \) durability. The dependence of the matrix damage area around the hole from the endurance at different loading levels was obtained according to the results of NDT method.

1. Introduction
The work is devoted to the second stage of experimental studies on the development of a failure criterion for fatigue tensile testing of carbon fiber reinforced polymer composites (CFRP). On the first stage [1] a method of monitoring of the specimen thickening in the hole zone during fatigue tensile tests was developed and applied. The main goal of the study is to develop a quantitative failure criterion for fatigue damage of a specimen. The influence of the following parameters on the stability of the criterion and on its application was determined experimentally: manufacturing technology of a material, the loading conditions during testing.

2. Background
The main documents regulating the static and fatigue testing of CFRP are currently the national standards: GOST, ASTM, EN and others. The existing list of standards is dominated by standards for static testing rather than fatigue testing of various types of specimens. For example, in the list of test standards (ASTM D4762), which contains several tens of standards, there are only three fatigue test methods – ASTM D7615, ASTM D3479 and ASTM D6115. The strength, reliability and durability of the aircraft structure is largely determined by the bearing capacity of the mechanical joints. The destruction of structures in most cases begins with the hole surface in the longitudinal and transverse joints. In such places, the material operates in a complex strain-stress state, while taking significant static and dynamic loads. To ensure the strength of the mechanical joint, it is necessary to estimate the safe allowable unit stress level in critical zones of the structure according to the strength and crack toughness. In this case, it is necessary to take into account the influence of climatic factors and material features, using existing models of CFRP failure and a definite set of fatigue characteristics of the structure material. When obtaining these fatigue characteristics of the material, the researcher is faced with the
problem of the existence of a large number of types of fracture (modes). They depend both on the material and on the stacking sequence of the material, as well as on the type of loading. This work is devoted to the study of the fatigue characteristics of specimens with an open hole.

Fatigue testing of open hole or filled hole specimens is one of the most common in evaluating the fatigue characteristics of composite materials. When manufacture of specimen with a hole, it's necessary to give attention to the quality of the hole. CFRP mechanical drilling can affect the strength of the material. According to the TsAGI experience, the low quality of the hole manufacturing leads to a slight decrease in strength and, sometimes, to a catastrophic decrease in fatigue characteristics. For example, during drilling due to violation of the tool replacement time as it is worn out, breakouts and delamination of the material were produced in the hole zone, which led to a significant standard deviation of the logarithm of $S_{lgN}$ was in the range $1.0 \div 2.0$. The typical values of $S_{lgN}$ for CFRP is in the range $0.15 \div 0.3$. With such a range of characteristics, obtaining of $S$-$N$ curve of material becomes almost impossible. The increased dispersion is associated with damage to the material on the sides of the hole. This is confirmed by research by many authors. For example, in [2], the effect of various drilling parameters on the quality of hole manufacturing is obtained. It is worth noting that due to CFRP anisotropy during drilling of the hole, formation of microcracks, fiber breakout, delamination, cracking, and temperature degradation of the material are received. To assess these damages, the parameter $F_d$ (figure 1) was used:

$$F_d = \frac{D_{\text{max}}}{D_0},$$

where $D_{\text{max}}$ – maximum area of the delamination zone, mm; $D_0$ – drill bit diameter, mm.

![Figure 1. CFRP delamination due to drilling](image)

(a) typical damage (b) determination of the delamination parameter of the material.

As a result, authors determinate that the values of the parameter $F_d$ lie in the range $1.05 \div 1.25$. Similar results were obtained in articles [3,4]. In [3] the case of manufacturing a hole using a laser machine was considered. As a result, the values of the stratification parameter $F_d$ lie in the range $1.35 \div 1.58$. In [4] the value of $F_d$ lie in the range $1.12 \div 1.23$. These initial damages affect the fatigue characteristics starting from the load level of 30% of the ultimate strength [3] and should be taken into account when obtaining the $S$-$N$ curve of the material.

3. Experimental procedure

To define the $S$-$N$ curve fatigue tests of CFRP specimens with a size of $210 \times 36$ mm and a 6 mm open-hole were conducted. Specimens made from two materials were tested. Fatigue tests were carried out on electrohydraulic machines by sinusoidal loading with stress ratio $R = 0$. $R$ is the ratio of the minimum to maximum cycle stress amplitude. The maximum amplitude stress of the cycle varied in the range $0.8 \div 0.95$ of the ultimate tensile strength. Monitoring the state of the material during the tests was carried
out using an Sitescan D-20 ultrasonic flaw detector. The thickening of each specimen in the hole zone during loading was monitored using a specially designed and manufactured sensor, shown in Figure 2 (a). A typical diagram of the change in sample thickness in the hole zone from number of cycles is shown in figure 2 (b).

![Figure 2. (a) thickening monitoring device mounted on the specimen (b) a typical diagram of the dependence of the thickness of the specimen in the hole zone on number of cycles.](image)

4. Results and discussion
At the first stage, the dependence of the delamination area in the hole zone on the number of cycles was evaluated. Figure 3 shows the experimental data for two batches of specimens.

![Figure 3. Dependence of the delamination area around the hole on the number of cycles.](image)

At different number of cycles, each sample was stopped and ultrasonic testing was carried out, the results of which determined the shape and area of delamination around the hole. Figure 4 shows photos of the typical delaminations by ultrasonic testing in the process of fatigue loading. It is worth noting that the data approximation for both materials shows good convergence and the dependence of the delamination area on the number of cycles in the studied load range can be considered linear. The main reason for the appearance of delamination is the relatively low strength of the polymer matrix compared to the carbon
fiber. Over the past half century, the strength of carbon fiber has grown significantly, and the properties of the matrix have changed slightly. Therefore, if earlier delaminations appear mainly due to an improperly selected technical process, which led to increased porosity, unadhesiveness, low adhesive strength of the fiber-matrix interface, etc., now they are often the main mode of fracture of high-quality CFRP even in the absence of loads from the plane, which does not allow to use the maximum strength properties of the fiber.

Figure 4. Specimens delamination areas, estimated by NDT method.

The problem of delamination is compounded by the lack of reliable methods for detecting them, which is related to the nature of the appearance of delamination: microcracks appear in the beginning, which practically do not reduce the strength characteristics of the material, the union of which into a macrocrack has an explosive, brittle nature. In addition, the exponent of the $S$-$N$ curve for fractures by the delamination mechanism has significantly lower values compared to fracture forms along the fiber. The fracture of specimens with a free hole according to the delamination mode when determining the tensile $S$-$N$ curve leads to a number of problems: it is impossibility to produce a $S$-$N$ curve for the destruction of the specimen — a sample with extensive delamination does not reduce the residual strength; the need for continuous monitoring of the state of the sample, which in the absence of an automated procedure leads to increased dispersion of fatigue properties. It becomes the most critical, since according to the existing procedure [5] the value of $S_{gh}$ is definitive in the designation of safety factors in determining the life characteristics of an aircraft structure. The duration of the durability structure tests required to certify the design depends on this procedure.

At the second stage of the work, the application of different values of the developed criterion ($\Delta_{del}$) was evaluated. The specimen was considered destroyed when the thickening of the specimen in the hole area reached a predetermined value $\Delta_f = \Delta_{del}$, where $\Delta_f$ is the current value of the thickening, %.

The fracture criterion $\Delta_{del}$ is measured in % of the initial thickness of the specimen.

The obtained experimental results are presented in table 1. $S_{gh}$ is the dispersion of the $S$-$N$ curve fatigue characteristics using the corresponding criterion, $CV$ is the coefficient of variation of the specimen delamination area determined using the corresponding criterion. Using the value of the criterion below 0.5% is impractical due to the fact that at such values it is not possible to define the delamination in the hole area by NDT method. Values higher than 0.75% cannot be used due to the fact that the thickness of the sample does not increase by such a value even with number of cycles of $10^7$ cycles. Of the remaining options, the most stable results were shown by the fracture criterion equals to the specimen thickening by 0.7% of the initial thickness in the hole zone.
Table 1. Experimental results depending on the value of the fracture criteria and the scattering of durability and delamination area

| $\Delta_{\text{del}}, \%$ | $S_{\text{lg}N}$ | $CV, \%$ |
|------------------------|-----------------|---------|
| 0.50                   | 0.32            | –       |
| 0.63                   | 0.20            | 39      |
| 0.70                   | 0.17            | 26      |
| 0.75                   | –               | 25      |

5. Conclusions
The second stage of the study was carried out, as a result a criterion for fracture of a specimen under fatigue tensile loading was developed and tested. The use of the value of the fracture criterion $\Delta_f=0.7\%$ made it possible to obtain the tensile $S$-$N$ curve and reduce the standard deviation of the logarithm of the $S_{\text{lg}N}$ durability to a level of $0.17 \div 0.32$. A linear dependence of the delamination area around the hole on the number of cycles was obtained for different loading levels according to the results of ultrasound studies.

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