Experimental Study of Fatigue Damage Accumulation in Laminated Carbon Reinforced Fiber Plastics

Mikhail Sh Nihamkin, Danil G Solomonov * and Andrey A Voronkov
Perm National Research Polytechnic University, Komsomolsky ave., 29, 614000, Perm, Russian Federation
E-mail: * solomonov1198@yandex.ru

Abstract. It is necessary to achieve high fatigue strength in order to apply carbon reinforced fiber plastics (CRFP) for critical elements subjected to vibration. Gradual accumulation of fatigue damage is accompanied by changes in the material stiffness and natural frequencies. The purpose of this work is to found experimental data on the change of the elastic characteristics of layered CRFP as fatigue damage accumulates. The object of the study is standard samples made of unidirectional carbon/epoxy fiber with different layering schemes. The samples were subjected to fatigue tests under cyclic tension with constant amplitude. The test of each sample was stopped several times at different loading stages to execute experimental modal analysis and non-destructive inspection of the appeared defects. The found natural frequencies were used to solve the inverse problem of identifying the elastic parameters of the laminate monolayer: two Young's modulus, shear modulus and Poisson's ratio. As a result, the dependences of these parameters on the relative fatigue life were obtained. These dependences, together with the results of non-destructive testing, can be used to describe the process of fatigue damage accumulation and for the subsequent development of methods for the fatigue life prediction.

1. Introduction
The regularities of fatigue failure of layered carbon fiber reinforced plastics (CFRP), methods for predicting fatigue life have been of interest to researchers for more than 50 years [1-2]. This interest is driven by the application of carbon fiber plastics in structures subjected to vibrations. It is enough to list such high-load critical products as the an airplane wing, a fan blade of aircraft engine or a rotor blade of a wind turbine [3-6].

It is known that the accumulation of fatigue damage, changes in the microstructure lead to a decrease in the rigidity of the material. This manifested in a change in the elastic characteristics of the material and in a change in the natural vibration frequencies of the parts. The decrease in natural frequencies in cast iron samples is described by Damir (2007) [7]. Elastic properties evolution of flax/epoxy composites under fatigue loading is studied by Liang (2014) [8]. Experimental data on the decrease in stiffness and natural frequencies in fiberglass and carbon fiber plastics are presented in papers [9-13]. The authors of the article [14] experimentally found a decrease in the bending stiffness of carbon fiber samples by 30%. A number of publications [7, 9, 10, 12] suggest using the reduction of natural vibration frequencies and residual stiffness to predict fatigue life. The articles [8, 11, 15, 16] present experimental data on the decrease in Young's modulus as fatigue damage accumulates. It is found a rapid decrease in the Young's modulus at the first stage of fatigue, followed by a stage with its stable slow decline to the stage of its sharp decrease just before the fracture. To study the modal parameters decrease of laminated fiberglass and carbon fiber plastics, an experimental modal analysis of samples was performed at different numbers of loading cycles in [12, 17]. The authors [18] investigated the change in the Poisson's ratio and established its sensitivity to the accumulation of fatigue damage in fiber-reinforced plastics. The authors [8, 11, 19] propose models for the accumulation of fatigue damage using experimental data on changes in the stiffness of the material.
The purpose of present research is to found experimental data on the change of the elastic characteristics of layered CRFP as fatigue damage accumulates. It should be emphasized that the task is to study four elastic parameters of the laminate monolayer: two Young's modulus, shear modulus and Poisson's ratio.

2. Experimental technique

The research methodology consisted of three main stages. At the first one, the material samples were subjected to fatigue tests. The test of each sample was stopped several times at different loading stages to perform experimental modal analysis and non-destructive inspection of the appeared defects. The natural frequencies and natural modes of the samples were obtained at this stage. The dependence of the natural frequencies on the number of loading cycles was determined. At the second stage, the obtained natural frequencies were used to solve the inverse problem of identifying four elastic parameters of the laminate monolayer. At the last stage, the obtained dependences of the elastic characteristics were compared with the results of non-destructive testing.

2.1. Investigated samples

The object of the study is unidirectional carbon/epoxy fiber with different layering schemes. Samples with a length of 250 mm and a width of 255 mm, recommended by the ASTM D 3479 standard [20], were examined. All samples were made of 6 identical layers of unidirectional carbon/epoxy fiber and had a thickness of about 1.2 mm (Figure 1).

Two types of samples made from were studied. The first type had a laying scheme 0/-45/45/45/-45/0. The laying scheme of the second type of samples differed by 90°, that was 90/45/-45/-45/90. Thus, in the samples of the first type in the outer layers, the fibers were laid along the loading axis of the sample, and in the samples of the second type – across it (Table 1). The tensile strength of the samples of the first type was 3.6 times higher than that of the samples of the second type. Two samples of each type were examined.

| Table 1. Dimensions and laying scheme of samples. |
|-----------------------------------------------|
| Layering scheme | Type 1 | | Type 2 |
| Sample № | 0/-45/45/45/-45/0 | 90/45/-45/-45/90 |
| Width, mm | 24.96 | 24.96 | 25.01 | 25.02 |
| Thickness, mm | 1.19 | 1.2 | 1.21 | 1.22 |

2.2. Fatigue tests

Fatigue tests were carried out in accordance with ASTM D 3479 standard [20] using the Testronic-50 resonance testing machine [21]. A tensile mode cyclic loading with a constant stress amplitude and asymmetry ratio of 0.1 was realized. The loading frequency was 40 Hz. The temperature of the sample was monitored using an infrared camera. Although the loading was carried out with a relatively high frequency, the temperature did not exceed 20°C.

The load amplitude $\sigma_a$ was chosen so that the life time $N$ of the samples was about 1 million cycles. For this purpose, the fatigue curves obtained in advance were used (Figure 2). The relative stress $\sigma_{rel}$ amplitude (the ratio of the amplitude $\sigma_a$ to the tensile strength) was 0.64 for the first type of samples and 0.3 for the second type.
2.3. The modal tests technique and elastic parameters identification

The purpose of modal tests was to obtain the natural frequencies and natural modes of the samples. The modal tests of each sample were performed before the fatigue tests and several times during the fatigue tests after a different number of loading cycles.

The method of scanning laser vibrometry was used. The sample was attached to a rigid frame on thin elastic. Samples vibrations were excited by an acoustic shaker and recorded using a scanning laser vibrometer PSV-400-3D. Thus, the tests were performed without contact of the equipment with the sample. This made it possible to determine with high accuracy the first 8 natural frequencies in the range up to 2000 Hz. The technique of modal tests of samples is described in more detail in [22-24].

The natural frequencies of the sample are used to determine the characteristics of the laminate monolayer: the two Young’s modulus $E_{11}$ (1-fiber direction) and $E_{22}$, the shear modulus $G_{12}$, and the Poisson’s ratio $\nu_{12}$. For this purpose, a mixed numerical experimental technique was used [21-23]. The determination of the mentioned elastic parameters was considered as an inverse problem of identification based on the results of modal tests. Within its framework, the root-mean-square deviation of the calculated values of natural frequencies from the experimental data was minimized. The calculated values are obtained using finite element modal analysis. The desired parameters of the monolayer elasticity were considered as optimization parameters. A more detailed description of the method for identifying elastic parameters is given in [24-27].

2.4. The non-destructive testing technique

In parallel with the modal analysis, non-destructive testing of samples was carried out by ultrasound at different stages of fatigue failure. ФФ Harfabg VEO flaw detector with a piezoelectric converter on a PE-5.0M32E0.8 phased array and a SONATEST T1-25.4 TOD direct prism was used. The pulse frequency emitted by the PEP is 5 MHz, and the number of converters in the phased array is 32 pieces.

3. Results and discussion

3.1. The results of the modal testing

As a result of the modal testing, the natural frequencies and natural modes of each sample were obtained before and during the fatigue tests. In the range up to 3000 Hz, the type 1 samples had 6 bending and 2 torsional modes. The type 2 samples in the same range had 6 bending and 2 torsional modes as the type 1. The difference in natural frequencies between samples of the same type did not exceed 4.7%. The natural frequencies of bending modes of type 2 specimens are 50% lower than that of type 1 specimens.

Torsional modes had 5% difference between 1 and 2 type. Figure 3 shows the natural frequencies and natural modes of the type 2 sample as an example.
Figure 4 shows an example the graphs of changes of the natural frequencies with fatigue time. The abscissa axis is the relative time \( N/N_f \) (\( N \) is the number of loading cycles, \( N_f \) is the number of cycles before failure). The axis of the ordinate is the relative frequency \( f/f_0 \) (\( f \) is the natural frequency, \( f_0 \) is its value before fatigue tests). It could be seen, that the decrease in both torsional and bending natural frequencies with an increase in the relative fatigue time has the same appearance. Quantitatively, they also were the same. With a relative fatigue time of 0.9 the natural frequency decrease was about 14%. For other natural frequencies of type 2 samples, this observation was valid too. The change in the relative natural frequencies with the relative fatigue time for type 1 samples had some quantitative differences. The decrease in the relative frequency of bending vibrations was about 2 times less than for type 2 samples.

3.2. The result of the elastic parameters identification
The result of identifying the elastic parameters of laminate monolayer at different stages of fatigue damage accumulation is graphs of changes in these parameters with fatigue operating time. Figure 5 shows the dependences of the Young’s modules \( E_{11} \) and \( E_{12} \) and the shear modulus \( G_{12} \) on the relative
fatigue operating time $N/N_f$. The values of the elastic parameters are related to their values before the fatigue tests. All elastic parameters decrease as fatigue damage accumulates.

The direction of fibers laying of the outer layers of the type 1 samples coincided with the longitudinal axis of the sample and the direction of the load. The direction of fibers laying of the outer layers of the type 2 samples was perpendicular to the longitudinal axis of the sample and the direction of the load. For the first type of samples, the $E_{11}$ modulus decreased faster than for type 2 samples, and the $E_{22}$ modulus decreases slower. The load directed along the fibers of the outer layer causes their destruction (samples of type 1). The load directed across the fibers of the outer layer (samples of type 2) causes the destruction of the matrix. As a result, the $E_{22}$ modulus decreases faster in type 2 samples.

3.3. The result of the non-destructive testing

Figure 6 shows an example of S-scan of the sample before (Figure 6a) and during fatigue damage accumulation. S-scan after running-in of 0.3 of relative fatigue life is shown in Figure 6b. Presence of a numerous signals between the first and the second bottom signals indicates the occurrence of cracks in the polymer matrix. Figure 6c shows an S-scan of the sample after 0.71 of relative fatigue life. It is seen the formation of delamination, as well as the growth of cracks in the structure of the material. These data confirm that the reason for the decrease in the elasticity parameters is the accumulation of fatigue damage.
Conclusion
The study of changes in the elastic characteristics of a monolayer during the accumulation of fatigue damage during tests for cyclic stretching on the basis of $10^6$ cycles for two types of samples of unidirectional layered carbon fiber with different laying scheme was carried out. The dependences of two Young's modulus, shear modulus and Poisson's ratio on the relative fatigue life were obtained. These dependencies reflect the accumulation of fatigue damage in the samples as shown by non-destructive testing.

The rate of accumulation of fatigue damage in a unidirectional carbon fiber monolayer depends on the direction of fiber laying in relation to the load pressure. If the load was directed along the fibers, the $E_{11}$ module decreases 1.3 times slower than when loaded across the fibers. The $E_{22}$ module was reduced by 1.6 times in a similar situation. This fact should be taken into account in models of fatigue damage accumulation in laminates with unidirectional layers.

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