Degradation of elastic characteristics of the CFRP used in the design of a gas turbine engine as a result of high-cycle fatigue damage

M.Sh.Nikhamkin, D.G.Solomonov
Aircraft Engines Department, Perm National Research Polytechnic University, Komsomolsky prosp., 29, 614000, Perm, Russian Federation
Solomonov1198@yandex.ru

Abstract. Carbon fiber reinforced polymers (CFRP) are increasingly being used in heavily loaded parts of aircraft engines. CFRP fan blades, vanes must successfully resist fracture due to high-cycle fatigue. One of the consequences of fatigue damage is a decrease in the rigidity of the material and a drop in the natural vibration frequencies of parts. These effects are of interest when developing fatigue fracture models and predicting durability. The purpose of this article is to develop a method and obtain experimental data on the decrease of elastic characteristics of CFRP as a result of progressive fatigue damage. The developed technique consists of two stages. During the first one, the natural frequencies and eigenmodes of the samples during their fatigue testing are experimentally obtained. During the second stage, the four elasticity parameters of the CFRP laminate monolayer are identified via the natural frequencies. The inverse numerical/experimental technique for material properties identification is applied. The dependences of elastic characteristics on the relative fatigue life are obtained as experimental results of both modal and fatigue tests. The results can be useful in studying the fatigue behavior of the examined materials and in creating methods for calculating fatigue life.

Introduction

Carbon fiber reinforced polymers (CFRP) are increasingly being used in heavily loaded parts of aircraft engines. Examples include fan blades, vanes, engine nacelle parts and others. These parts are subject to a complex set of static loads and cyclic vibration loads. It is not possible to ensure the reliability of these parts unless sufficient high-cycle fatigue resistance is provided [1, 2]. The use of CFRP in heavily loaded engine parts is difficult due to insufficient experimental data on the accumulation of fatigue damage. The diversity of these materials (fibers, binders, reinforcement patterns, process parameters) makes the problem even more complex.

Different studies of the fatigue failure of composites have shown that the gradual accumulation of fatigue damage is accompanied by a decrease in the stiffness of the material. The decrease in stiffness during fatigue damage is indirectly manifested in a change in the natural frequencies of structures and samples. This effect manifests itself both in metals and in composite as shown in [3–5].

Gradual drop in the resonant frequency due to a drop in sample stiffness were observed during fatigue tests on a resonant machine [5]. More complete data on natural frequencies decrease was obtained in [3] using methods of experimental modal analysis. It was concluded that modal testing is an effective nondestructive testing method that can be applied in order to estimate the fatigue life of composite
laminates. A significant decrease (up to 30%) in the bending stiffness of samples from the orthotropic and quasi-isotropic laminate was experimentally discovered by the authors of [6].

In recent years, numerous models of fatigue damage accumulation have been developed, designed to predict the durability of composite structures [3, 7 - 9]. The practical application of these models requires the availability of experimental data on the degradation of material properties with the accumulation of fatigue damage. Studies [10-12] contain experimental data on changes in the Young modulus of composite materials under fatigue damage. The results show a slight drop in Young module during the first stage of fatigue, followed by a stage with a slow stable decrease in \( E/E_0 \) (\( E \) is a current Young modulus, \( E_0 \) is its initial value) to the stage of its sharp drop and final destruction. The authors of [12] report on the phenomenon of material stiffness, where the modulus of specimen elasticity can increase during the initial stages of fatigue loading at a certain orientation of the fibers. The results mentioned relate to characteristics of specific multi-layer laminates, but not to the characteristics of a monolayer.

The purpose of this article is to develop a method and to obtain experimental data on decrease of elastic characteristics of a fiber-reinforced laminate monolayer as a result of progressive fatigue damage. The use of laser vibrometry for experimental modal analysis gives an appropriate opportunity.

1. Experimental technique

The object of this study is a polymer composite that consists of variously oriented identical monolayers and is reinforced with carbon fabric. A monolayer of laminate is considered orthotropic. Four parameters characterize the elastic properties of the monolayer: Young modules in the directions of warp (index 1) and weft (index 2) \( E_{11} \) and \( E_{22} \), respectively, shear module \( G_{12} \) and Poisson's ratio \( \nu_{12} \). The task is to determine the change in these parameters with an increase in the number of fatigue loading cycles \( N \).

The research methodology contains two steps. During the first one, natural frequencies and eigenmodes of the samples are experimentally obtained during their fatigue testing. The dependence of the natural frequencies on the number of loading cycles \( N \) is determined. During the second stage, the obtained natural frequencies are used to solve the problem of identifying the mentioned four parameters of elasticity.

The test samples are cut from CRFP plates laminate with a length of 250, and a width of 25 (Figure 1). Such specimens are recommended by ASTM standard D 3479 for polymer composite fatigue tests. Carbon-epoxy plate is reinforced with an equal-strength carbon fabric. Laying scheme is \([0/45/90/-45/0/45/90/-45/0/45/90/-45/0/45/90/-45/0]\). The sample weight is 35g.

The specimens were tested for high-cyclic fatigue under cyclic tension. The test technique is based on the requirements of the ASTM standard D 3479. It involves testing under cyclic tension while maintaining a constant amplitude and average load value. The electro resonant fatigue test machine Zwick Amsler HFP 5100 was used [13, 14]. It enables fatigue testing of up to \( 10^8 \) cycles in a reasonable amount of time. Loading frequency is about 45 Hz. Additional air cooling is provided to prevent sample heating.

Fatigue tests of samples was stopped several times to perform the modal tests. The first modal test of each sample was carried out before fatigue tests. The modal tests were performed by the scanning laser vibrometry technique [15-17] using a laser vibrometer PSV-400-3D. The principal advantage of
the technique is the non-contact measurement and the ability to find a large number of eigenmodes and natural frequencies with high accuracy. The sample was suspended on a rigid frame on thin elastic threads (Figure 2). Its oscillations were excited by an acoustic speaker. It created acoustic loading of the sample, which varies in time according to a harmonic law with a frequency that continuously increases from 0 to 6400 Hz. The scan grid included 165 nodes. For each sample at least three tests are carried out. The following loading parameters were realized during fatigue tests: asymmetry ratio $R=0.1$, temperature 20°C. The fatigue stress amplitude for the set of examined samples was 15-30% higher than the fatigue limit. The lifetime of the $N_f$ samples under these conditions was 0.9 - 2.5 million cycles. Fatigue tests were terminated after visible macroscopic cracks or delamination appeared in the sample. The results of the experimental stage of the study are the natural modes of vibration of the samples and the values of the natural frequencies $f_{ei}$ at different values of the relative fatigue life $N/N_f$ (where $N$ is a current number of loading cycles and $N_f$ is a total number of cycles until failure).

2. Finding parameters of elasticity

Finding the four aforementioned parameters of elasticity of a monolayer $E_{11}$, $E_{22}$, $G_{12}$ and $v_{12}$ is considered in this study as the inverse identification problem using the results of modal tests. In the framework of this approach, a mixed numerical experimental technique (MNET) was used [18-20]. It includes an optimization procedure for identifying the mathematical model of a sample from experimental data on its natural frequencies. The optimization is carried out by selecting four characteristics of the elasticity $E_{11}$, $E_{22}$, $G_{12}$ and $v_{12}$, ensuring the minimum discrepancy between the set of $m$ calculated and experimental natural frequencies ($f_{ci}$ and $f_{ei}$):

$$I(E) = \sum_{i=1}^{m} \alpha_i \left( \frac{f_{ci}(E) - f_{ei}}{f_{ei}} \right)^2 \to \min$$

(1)

Here $E$ is the vector of identified parameters of elasticity $E_{11}$, $E_{22}$, $G_{12}$ and $v_{12}$, $\alpha_i$ are weighting coefficients.

The calculated values of natural frequencies $f_{ci}$ are the results of finite element (FE) modal analysis of examined samples. The task is reduced to solving the eigenvalue $\omega$ problem:

$$\det[\mathbf{K} - \omega^2\mathbf{M}] = 0$$

(2)

Here $[\mathbf{K}]$ and $[\mathbf{M}]$ are stiffness and mass matrixes; the stiffness matrix includes identifiable elasticity characteristics.
The FE model of the sample consists of about 1000 shell elements. It is a four-node element with six degrees of freedom at each node. The FE calculation uses shell elements. This type of element allows you to model a layered material consisting of orthotropic multidirectional layers, rigidly connected to each other. Four parameters of elasticity $E_{11}$, $E_{22}$, $G_{12}$ and $\nu_{12}$ are to be set in each layer in the FE modal analysis. The quasi-random search method was used to solve the optimization problem. The quasi-random search procedure includes 50 realizations. This technique is described in more detail in [19, 20]. As it is shown in [19, 20], the described method for determining elasticity characteristics provides a 1% margin of error when determining Young’s moduli, and a 5% margin when it comes to the shear modulus and Poisson’s ratio.

3. Results and discussion

The first time the modal test of the sample was performed before fatigue testing. The frequency range of up to 5000 Hz was investigated and 8 eigenmodes were found. The eigenmodes and corresponding natural ones for one of the examined samples prior to fatigue tests are given in Table 1. The values of the natural frequencies $f_{i0}$ ($i$ is the serial number of an eigenmode) of the sample before the start of fatigue tests are given. The eigenmodes of other samples are the same as those shown in Table 1. It can be seen that 5 bending and 3 torsional eigenmodes were excited in the studied frequency range.

| $i$ | Eigenmode | Natural frequency $f_{i0}$, Hz |
|-----|------------|-------------------------------|
| 1   |            | 319                           |
| 2   |            | 568                           |
| 3   |            | 1557                          |
| 4   |            | 1702                          |

Fatigue tests of each sample were stopped several times to perform a modal test. The modal test was performed for the last time after termination of fatigue tests, $N/N_f = 1$. A slight decrease in all investigated natural frequencies was found as well as an increase in the number of loading cycles $N$. Figure 3 shows a typical change in the natural frequencies of a sample during its fatigue test. The ratio of the current value of each $i$-th of the natural frequencies $f_i$ to its initial value $f_{i0}$ is plotted as a function of the life ratio $N/N_f$. 

| $i$ | Eigenmode | Natural frequency $f_{i0}$, Hz |
|-----|------------|-------------------------------|
| 5   |            | 2791                          |
| 6   |            | 3146                          |
| 7   |            | 4137                          |
| 8   |            | 4787                          |
All eight studied natural frequencies gradually reduced during fatigue testing. Their values decreased just before the fatigue failure of samples by 6-7%. The natural frequencies corresponding to the first bending and the first torsional eigenmodes reduced slightly more than others. The natural frequencies’ tendency to decrease indicates a decrease in material rigidity due to the accumulation of fatigue damage during testing. The experimental data on the decrease in natural frequencies of the samples is consistent with that presented in [5, 6].

Each sample’s characteristics of the composite E monolayer were determined using the obtained natural frequencies. For each number of loading cycles N the MNET procedure described above was used. As a result, elasticity characteristics of the monolayer are obtained as functions of N. It is convenient to use dimensionless values:

$$\bar{E}_{11} = E_{11}/E_{110} ; \bar{E}_{22} = E_{22}/E_{220} ; \bar{G}_{12} = G_{12}/G_{120} ; \bar{\nu}_{12} = \nu_{12}/\nu_{120} ; n = N/N_f$$

(3)

Here $E_{11}$, $E_{22}$, $G_{12}$ and $\nu_{12}$ are the current values of Young modules, shear module and Poisson's ratio; $E_{110}$, $E_{220}$, $G_{120}$ and $\nu_{120}$ are their initial values.

Figure 4 shows evolution of elastic characteristics of the laminate monolayer obtained for one of the samples as dimensionless functions $\bar{E}_{11}(n), \bar{E}_{22}(n), \bar{G}_{12}(n)$ and $\bar{\nu}_{12}(n)$. The Young module $E_{11}$ decreases in three stages similarly to the general behavior of composite materials loaded in fatigue [12]. An initial stage with rapid stiffness reduction is followed by an intermediate step with a steady but slow decrease and a final acceleration before specimen failure. This decrease for the studied samples was at about 10% immediately before the destruction. Conversely, the $E_{22}$ module increased by about 8% because of early loading cycles and then decreased by 15 compared to the initial value. Similar stiffness effects have been reported by several authors for some traditional composite materials [12].

4. Conclusion

The experimental data obtained in this paper on the decrease in natural frequencies and evolution of elasticity characteristics of carbon plastics relates to the field of a large number of loading cycles (more than 1 million cycles). The dependence between the dimensionless elasticity characteristics and the relative fatigue life for the laminate monolayer is experimentally studied. The dependence
quantifies the process of fatigue damage accumulation. It appears that this experimental data can be used in the development of mathematical models and techniques for estimating the fatigue life of studied materials. The developed technique can be used to obtain similar data for other fiber-reinforced laminates.

References
[1] Kelly A. The engineering triumph of carbon fibre. Composites and nanostructures, 2009, №1, pp. 38 – 49.
[2] Mandall J.F., Samborsky D.D., Cairns D.S. Fatigue of composite materials and substructures for wind turbine blades: Sandia report SAND 2002-0771. Sandia National Laboratories, USA, 2002, 279p.
[3] Abo-Elkhier M., Hamada A.A. El-Deen B. Prediction of fatigue life of glass fiber reinforced polyester composites using modal testing. International Journal of Fatigue. 69 (2014). PP.28–35.
[4] Wang J., Tan N., Zhou S., Sun Q. Experimental Study on High-Cycle Fatigue Behavior of GFRP-Steel Sleeve Composite Cross Arms. Advances in Civil Engineering. 2018, 12 p.
[5] Cesnik M., Slavic J., Boltezar M. Uninterrupted and accelerated vibrational fatigue testing with simultaneous monitoring of the natural frequency and damping. Journal of Sound and Vibration. V. 331 (2012). Pp. 5370-5382.
[6] Michel S.A., Kieselbacha R., Martens H.J. Fatigue strength of carbon fibre composites up to the gigacycle regime (gigacycle-composites). International Journal of Fatigue. V.28 (2006). Pp.261–270.
[7] Patel A.G., Shah D.S., Patel D.C. A review of progressive damage analysis and fatigue life prediction for degraded e-glass FRP material. International Journal of Technical Innovation in Modern Engineering & Science. V.4 (2018). Issue 12. Pp. 295-299.
[8] Naderi, M. and A. Maligno, Fatigue life prediction of carbon/epoxy laminates by stochastic numerical simulation.Composite Structures, 2012. 94(3): p. 1052-1059.
[9] Barbero, E.J. and M. Shahbazi, Determination of material properties for ANSYS progressive damage analysis of laminated composites. Composite Structures, 2017. 176: p. 768-779.
[10] Reis P.N.B., Ferreira J.A.M., Costa J.D.M., Richardson M.O.W. Fatigue life evaluation for carbon/epoxy laminate composites under constant and variable block loading Composites Science and Technology. V. 69 (2009). Pp.154–160.
[11] Karahan M., Lomov S.V., Bogdanovich A.E., Verpoesta I. Fatigue tensile behavior of carbon/epoxy composite reinforced with non-crimp 3D orthogonal woven fabric. Composites Science and Technology. V.71, Issue 16. Pp. 1961-1972.
[12] Liang S., Gning P.B., Guillaumat L. Properties evolution of flax/epoxy composites under fatigue loading. International Journal of Fatigue, Elsevier,2014,63,pp.36-45
[13] Nikhamkin M.Sh., Sazhenkov N.A., Samodurov D. Fatigue testing method of test coupon and structurally equivalent samples of carbon fiber reinforced polymer for gas turbine engine parts and assemblies. Solid State Phenomena. 284 SSP (2018). Pp. 43-47.
[14] Nikhamkin M.Sh., Sazhenkov N. A., Samodurov D. Fatigue fracture of fiber reinforced polymer honeycomb composite sandwich structures for gas turbine engines. Journal of Physics: Conference Series, 843 (1) (2018). Article № 012029.
[15] Stanbridge A.B. Ewins D.J. Modal testing using a scanning laser Doppler vibrometer. Mechanical Systems and Signal Processing. V.13 (1999). № 2. Pp. 255-270.
[16] Nikhamkin, M., Bolotov, B. Experimental and finite element analysis of natural modes and
frequencies of hollow fan blades (2014) Applied Mechanics and Materials, 467, pp. 306-311.
[17] Grinev M.A., Anoshkin A.N., Pisarev P.V., Shipunov G.S., Nikhamkin M.Sh, Balakirev A.A., Konev I.P., Golovkin. Experimental and numerical research of the dynamic response of composite outlet guide vane for aircraft jet engine. PNRPU Mechanics Bulletin,(4)(2016). Pp.106-119.
[18] Sol H, Hua H, De Visscher J, Vantomme J, De Wilde WP. A mixed numerical/experimental technique for the nondestructive identification of the stiffness properties of fiber reinforced composite materials. J. Independent Nondestructive Testing and Evaluation.V.30(2) (1997). Pp. 85–91.
[19] Nikhamkin M. Sh., Sememnov S. V., Solomonov D. G. Application of Experimental Modal Analysis for Identification of Laminated Carbon Fiber-Reinforced Plastics Model Parameters. Proceedings of the 4th International Conference on Industrial Engineering. ICIE 2018. Lecture Notes in Mechanical Engineering. Springer, Cham. 2019. Pp. 487-497.
[20] Nikhamkin M. Sh., Sememnov S. V., Silberschmidt V.V., Solomonov D. G. Identification of elastic parameters of laminated carbon fiber plates using experimental modal analysis. ARPN Journal of Engineering and Applied Sciences. V.14. № 12 (2019). Pp.2279 – 2285.