Investigation of the dynamic behavior of CFRP with an embedded smart layer based on fiber-optic sensors

A Tikhonova*, A Anoshkin, M Baranov, A Nikiforov, N Sajenkov and P Pisarev

Department of Mechanics of Composite Materials and Structures, Perm National Research Polytechnic University, 29 Komsomolski avenue, 614990, Perm, Russian Federation

*E-mail: shgs-kt@pstu.ru

Abstract. Currently, special interest arises in the use of various systems for monitoring the state of structures during operation. Structures during operation, as a rule, experience dynamic loads. As a result, the monitoring system must correctly and accurately record this response. Most modern monitoring systems use fiber-optic sensors. Embedding fiber optic sensors directly into the structure of composite structures is a difficult task due to the fragility of the fiber. The team of authors has developed a prototype of the Smart-layer, which allows for safe implementation into structures made of carbon fibre reinforced polymer. However, the issue of decrypting the data obtained from the Smart layer is an urgent and laborious task. The paper presents the results of studies on the registration and interpretation of the dynamic response obtained from the Smart-layer embedded in carbon fibre reinforced polymer specimens under dynamic loading of the specimens. The results of field experiments on dynamic loading of samples were compared with model values. In the course of the study, good agreement was found between the model and experimental results.

1. Introduction

At present, during the operation of aircraft and aerospace structures that, as a rule, experience dynamic loads, special attention must be paid to issues related to the safety and reliability of such structures. This is achievable only with a constant scheduled inspection of the structures in operation by non-destructive testing methods, which is expensive, or using the so-called systems for monitoring the state of structures.

The creation and use of monitoring systems in structures made of carbon fiber reinforced polymer (CFRP) in the literature is devoted much attention [1-3]. Fiber-optic sensors (FOS) based on Bragg gratings are usually used as sensing elements. This is due to the fact that optical fibers are sufficiently flexible, strong, heat-resistant and can be easily embedded in multilayer composites [4-5]. Along with this, such sensors have a rather small size (the diameter of the optical fiber is 0.2 mm), which allows their implementation in various designs negligible reducing the physical and mechanical characteristics (PMC) [6].

However, when FOS is introduced directly into the structure of a layered composite, a number of difficulties arise: the complexity of locating the sensitive element in the structure, ensuring the integrity of the FOS at the exit from the polymer structure. When solving the problem of ensuring the integrity of the FOS, the authors in [7] investigated the possibility of providing a uniaxial stressed state of the FOS based on the use of a capillary tube in the area of the fiber Bragg grating, which protects the grating from transverse deformation. This made it possible to use the well-known dependences [8] between the measured value of the Bragg wavelength shift and the longitudinal deformation. With the help of
software packages, the authors studied the geometric and mechanical parameters of the capillary tube. On the basis of numerical analysis, it was found that the capillary tube does not affect the elastic modulus. However, the presence of a cavity in the capillary led to an increase in stress concentration.

Another possible solution to the problems described above is to use the so-called Smart-layer. Smart-layers are mainly manufactured using two technologies: 3D printing with engineering plastics and gluing dielectric printed circuit boards onto epoxy adhesives.

In [9] the authors described the technology for creating its Smart layer, in which a network of fiber optic sensors was imprinted into the plastic on a 3D printer. This technology of creation allows ensuring the integrity of the sensors and can be used for surface monitoring of structures. However, the authors used the following materials: PLA plastic (FDM technology) and methacrylate resin (SLA printing). Thus, the authors faced two problems, namely, the impossibility of diagnosing structures exposed to high temperatures (PLA plastic deforms at 60°C), and incomplete curing of Smart packaging made using SLA printing technology due to the multi-stage manufacturing process. It should be noted that the manufactured Smart packages have a thickness of about 3.2 mm.

Then the technology for creating its Smart Layer, in which a network of piezoelectric sensors was placed between a polyimide films and glued together with epoxy resin has been considered in [10]. This technology of creation allows ensuring the integrity of the sensors and can be used for surface monitoring of structures. However, it has some limitations when introducing sensors directly into CFRP structures, since polyimide films have poor adhesion to CFRP and the thickness of such a layer reaches 2-4 mm, which can significantly affect the physical and mechanical characteristics (PMC) of such structures.

The authors in [11] used a photopolymer resin for the manufacture of so-called smart packages capable of protecting fiber lines from harsh environmental influences and suitable for implementation in concrete structures. The smart packages produced were examined with surface and embedded structural monitoring in concrete. However, the thickness of such packages reaches about 50 mm and can be suitable for surface mounting and introduction into reinforced concrete structures.

Thus, at present there are several limitations for the implementation of various Smart layers and packages in CFRP structures, namely, poor adhesion of layers to CFRP; large thickness, capable of lowering the PMC of structures; low melting point of the layer, which can lead to a change in the location of the fiber line. In order to solve the above problems, the educational, research and development center of Aviation composite technologies of PNRPU team has developed a prototype of a Smart-layer, which consists of fiber-optic sensors and a high-temperature polymer film, which allows ensuring the integrity of optical leads and basing accuracy when directly introduced into a CFRP structure. The developed prototypes of Smart-layers have proven themselves well under quasi-static loads, which is described in detail in [12]. The purpose of this work is to test the developed system for monitoring the state of structures under dynamic loading of CFRP specimens. For the correct interpretation of data from FOS during dynamic loading, a method has been developed for determining and decoding information in the data stream on reduction of mechanical strength and structural failure under dynamic loading.

2. Experimental methodology
To conduct mechanical tests on dynamic loading, samples were made of carbon fiber reinforced plastic with a Smart layer introduced at the manufacturing stage. To carry out mechanical tests for dynamic loading, the samples were made from 20 layers of an equal-strength prepreg with a reinforcement scheme (0/90), with a Smart layer introduced at the manufacturing stage. The developed Smart layer is embedded between the 10th and 11th layers of CFRP prepreg, as shown in figure 1. Samples were made by the autoclave method using a unique research facility "research complex for scientific and technological research in the field of creating products made of polymer composite materials". Samples for tests were made according to the following technological regime: heating up to 180°C at the rate of 3°C/min, holding at a given temperature for 5 h at a pressure of 7 bar, and cooling to 40°C at the rate of 3°C/min.
Fiber-optic sensors with a polyimide coating were fabricated for the SMART layer by Inversion Sensor Co. As a consequence, the experimental temperatures range from -200 to 350°C. The FBG was 5 mm long, the resonance wavelength was 1520 nm, the reactance was 70.49%, the peak width was 0.195 nm, and the side-peak suppression was 9.6 dB.

![Figure 1. Layout scheme for the Smart layer (dimensions are in mm).](image1)

Laboratory tests of CFRP specimens with an embedded Smart layer make it possible to evaluate their mechanical behavior in a resonant vibration mode, as well as to record the occurrence of damage in the material under dynamic loading. Before carrying out dynamic tests, to obtain a complete picture of the stress-strain state, additional fiber-optic sensors and strain gauges (for measuring longitudinal deformations) are mounted on the surface of the samples. The layout of the sensors on the sample surface is shown in figure 2.

![Figure 2. Scheme of FOS placement on the sample surface: 1 – FBG 301, 2 – FBG 201, 3 – FBG 101, 4 – strain gauge, 5 – sample fixation zone, and 6 – load fixation zone.](image2)

Dynamic loading of the samples was carried out on an experimental setup (figure 3a), which is an electrodynamic vibration stand V-850-400 with a power amplifier and a control system based on an ARM-4M power regulator. Figure 3b shows a diagram of the experimental setup. The sample was fixed on a cantilever on a vibration stand. On the sample to reduce the frequency of the resonant vibration mode in the first bending form at a distance of 182 mm from the rigid attachment, a weight of 183.72 g is installed.

To control the state of CFRP specimens during dynamic loading, a developed monitoring system is used, which includes: a monitoring object with an embedded Smart layer; interrogator ASTRO X321 for registration of readings obtained from FOS; copyright software for primary decoding of information in real time and software for recording, storing and displaying the received data on changes in deformation fields.
Figure 3. Experimental setup: appearance (a) and diagram (b): 1 – test sample, 2 – clamping device, 3 – electrodynamic vibrator V850-400, 4 – pneumatic system control unit, 5 – power amplifier, 6 – MBS-9 microscope, 7 – OFV-525 laser vibrometer sensor head, 8 – laser controller vibrometer OFV-5000, 9 – regulator ARM-4M, 10 – frequency meter, 11 – cycle counter, 12 – oscilloscope.

3. Results and discussion
In the course of mechanical tests, the dependence of the change in the natural vibration frequency of the sample on the number of loading cycles was obtained, shown in figure 4. The graph was plotted according to certain values of the natural frequencies of the sample after a certain number of loading cycles. The approximating function for the resulting data array is a 4th degree polynomial.

Figure 4. Graph of changes in the natural vibration frequency of the sample depending on the number of cycles.

Analyzing the obtained dependence, it can be concluded that the most significant drop in the natural frequencies of the specimens’ vibrations occurs during the first stage of loading, i.e. during the first 100000 dynamic loading cycles. The drop in the natural frequency of the samples is associated with a decrease in the rigidity of the sample due to the formation and evolution of defects of various kinds.

Figure 5 shows diagrams of changes in the wavelength deviations of embedded fiber optic sensors from time the vertical axis in the diagram corresponds to the value of the deviation of the resonant wavelength in nanometers, the horizontal axis is the time in seconds.
Figure 5. Diagrams of FOS wavelength deviation readings based on the results of dynamic tests.
It should be noted that the surface-mounted strain gauge and additional fiber lines peeled off from the sample surface after the first loading cycle, which can be explained by insufficient adhesion of the sample surface and the used epoxy resin. Thus, the readings from these sensors are not provided.

The points forming a sharpened diagram (figure 5) were recorded by an interrogator with a frequency of 100 Hz. Accordingly, from each loading cycle, on average, 2 points were obtained, since the vibration frequency of the sample was about 45 Hz. Therefore, the sampling frequency is insufficient to reliably construct an approximating oscillation function at each of the loading cycles and to determine the maximum vibration amplitude for each of the loading cycles. However, since dynamic loading occurs over a long period of time and a large number of loading cycles, it is possible to assess the overall trend of deformation and temperature. It should be noted that the temperature change occurs due to the appearance of the thermo-optical effect. Diagram 5 shows the boundaries of the sections of the dynamic loading stages (thin center lines in orange). In addition, the color chart highlights areas of practical interest for further analysis.

The data obtained from the experimental diagrams of the FOS responses indicate a proportional shift in the values of the wavelength deviation indices in the positive direction along the vertical axis. The values corresponding to the process of proportional growth of the minimum and maximum readings of the FOS information responses are highlighted in green curves. This effect is due to the fact that the sample, when exposed to a dynamic load, begins to heat up due to the release of heat (the work of internal forces). Due to the fact that FOSs respond not only to deformation, but also to temperature changes due to the thermo-optical effect, a proportional shift of the data array to the positive side along the vertical axis is observed. This assumption is confirmed by the fact that the intensity of change in the maximum and minimum indicators decreases by the end of the loading stage, due to the onset of thermal equilibrium. Local maxima and minima of FOS wavelength deviations (figure 5, zones highlighted in red) indicate the appearance of defects in the structure of the material of the samples, which correlates with the data on the drop of the natural frequencies of the sample during the first loading cycle.

For a more detailed analysis of the dynamic behavior of the sample and the initiation of defects in the intervals between loading stages, ultrasonic nondestructive testing was carried out using a HARFANG VEO ultrasonic flaw detector with a sensitive element on a phased antenna array. This flaw detector allows you to determine the defectiveness of the structure by changing the vibration amplitudes of ultrasonic waves (A-scans, figure 6, and S-scans, figure 7).

Analyzing the scans obtained (figure 6, figure 7), it was found that the dimension of the defect in thickness increased with an increase in the number of cycles, which indicates an increase in the signal amplitude (figure 6a and figure 6b), and the dimension of the defect between the 1st and 2nd stages of loading increased by 7 mm (figure 7a, figure 7b), the delamination after the 1st loading cycle was 12 mm (figure 7a). It should be noted that defects originated in the upper layers in the sample embedment, i.e. in the area of maximum stresses. After the 3rd loading cycle, the sample was removed from the testing machine and ultrasonic NDT was performed. In this case, it was found that the delamination reached 42 mm (figure 7c), and the region of the onset of nucleation corresponded to the middle of the embedding of the sample.

The areas of the “out-of-the-box” readings of the wavelength deviations received from the sensor #2 (figure 5, highlighted in orange) are associated with the manifestation of the birefringence effect inside the FBG. This effect is a consequence of uneven deformations of the FOS in the radial direction during autoclave molding of CFRP. For a more detailed understanding of the process of accumulation of defects during dynamic loading, mathematical modeling of the corresponding loading is carried out.
4. Mathematical modeling of dynamic loading of the sample

To simulate the behavior of a CFRP specimen under dynamic loading, an algorithm for resource prediction has been developed. The resource means the number of cycles until the first fatigue failure and the total number of operating cycles. The algorithm is based on the use of kinetic equations of damage accumulation with a scalar damage function. The algorithm assumes that a multilayer composite structure consists of a set of reinforcing layers and adhesive layers located between the reinforcing layers. The external load is assumed to be cyclically changing according to the harmonic law. In this case, it is assumed that fatigue failure occurs only in the adhesive layers. The algorithm is implemented in the finite element package Ansys.

At the first step of loading, after calculating the general stress-strain state for the entire sample, for each finite element of the adhesive layers, a nonlinear equation is solved:

\[ N_b(\sigma_y) = \frac{1}{w(\sigma_y)} , \]  

and the number of cycles to failure is determined. The minimum value among all finite elements is the number of cycles before the first act of fatigue failure of the composite structure. After this event, the

![Figure 6. A-scans of samples after the 1st (a) and 2nd (b) loading cycles.](image)

![Figure 7. S-scans of samples after the 1st (a), 2nd (b) and 3rd (c) loading cycles.](image)
corresponding element of the adhesive layer is considered to be destroyed and the elastic and shear moduli are reduced in it.

In the course of mathematical modeling, the kinetics of accumulation of fatigue damage was investigated, shown in figure 8.

![Figure 8](image-url)

Figure 8. Kinetics of damage accumulation: after 29537 (a), 56624 (b), and 96857 (c) cycles.

Analysis of the kinetics of damage accumulation showed that fatigue fracture of the composite specimen begins in the region of attachment and arises in the adhesive layer between the first and second layers. The total operating time before the onset of fatigue failure at a given cycle amplitude is 29537 cycles (figure 8a) while with an increase in the number of cycles, the size of the fracture region increases and the defect propagates into the central adhesive layers of the sample.

It should be noted that in the model, upon reaching 96857 cycles (figures 8b-8c), a significant accumulation of defects occurs, leading to destruction. Within the framework of modeling, it was obtained that significant destruction in the structure of the sample occurs at 96857 cycles, according to the testimony of the testing machine – the first 100000 cycles, according to the results of FOS – 2300 sec, which corresponds to 100000 cycles (figure 8a). Thus, we can conclude that the results obtained correlate well and, at a given loading, defects nucleate in the material structure by 30000 cycles (figure 8a) and by 10000 cycles their evolution occurs, leading to damage and destruction of samples.

5. Conclusion

Thus, in the course of the research, mechanical tests were carried out on the dynamic loading of a CFRP specimen with an embedded Smart layer, the dependence of the change in the natural vibration frequency of the specimen on the number of loading cycles was obtained. The FOS readings were processed and decoded, and it was found that during the first loading cycle a drop in natural frequencies occurs, which indicates the initiation and evolution of a defect structure, the thermooptical effect and the effect of FBG birefringence were recorded, which indicates nonuniform deformations of the FOS in the radial direction.

For a detailed study of the origin of a defect structure, a mathematical model for predicting the resource was developed, implemented in the Ansys finite element package. Within the framework of mathematical modeling, it was established that fatigue fracture is formed in the region of sample fixation...
and occurs in the adhesive layer between the first and second layers at cycle 29537, with further growth into the central layers of the CFRP sample, which is in good agreement with experimental data.

Based on the results obtained, it can be concluded that the developed Smart-layer does not distort the original signal and makes it possible to register the change in deformation fields during the dynamic loading of the samples. Thus, the use of Smart layers in structures for aviation and aerospace purposes will increase the safety and reliability of such structures during long-term operation.

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