Prediction and detection of primary microcracks in carbon fiber reinforced polymer under load

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Abstract. Carbon fiber reinforced polymers (CFRP) are widely used in the manufacturing of critical parts and structures in the aerospace industry due to the combination of low density, high strength, and stiffness. Production of parts and structures with pre-predicted properties is a difficult task provided significant anisotropy of physical properties and complex microstructure. The solution to this problem has to be based on the correct mathematical model describing the behavior of parts and structures made of CFRP under operational loads. Moreover, experimental data on physical, mechanical, and thermophysical properties and their change depending on the number of loading cycles has to be implemented. In view of the above, prediction of the occurrence and development of microcracks in the material becomes significant. The aim of this article is to develop algorithms for prediction and detection of primary microcracks in CFRP under loading using fiber Bragg grating (FBG) sensors and multiscale mathematical modeling. The results of measuring the primary residual deformations in the plates made of CFRP at the manufacturing stage by embedded FBG sensors and testing its performance under loading was presented. Multiscale mathematical modeling of a numerical experiment performed to evaluate the occurrence of areas of primary microcracks in CFRP under loads. It is demonstrated that splitting of peaks of resonant wavelengths of embedded FBG sensors indicates the occurrence of primary damage and microcracks.

1. Introduction
High-strength and high-modulus carbon fiber reinforced polymers (CFRP) are widely used to create light, strong structures of aviation and rocket space vehicles [1 – 5]. CFRP exposed to significant thermal and type of other types of loading during operation. CFRP have high stiffness, strength properties, low coefficients of temperature expansion, and low density. Due to microstructural features and different fiber laminates, CFRP are anisotropic materials. In addition, CFRP characteristics depend on the adhesive strength at the fiber – matrix interface.

Due to these features, it is a very important part of scientific work, to study the behavior of CFRP and identify the conditions which lead to the occurrence and development of microcracks. Traditionally, various strength criteria such as Mises, Tsai-Wu, Goldenblat – Kopnov, Tsai-Hill, Hashin, Hoffman, maximum deformations, maximum stresses are used to evaluate the parts and different structures made of CFRP. However, the main forms of the damage mechanism of CFRP laminates are fiber-matrix debonding, intralaminar and interlaminar matrix cracks, and fiber breakage. In view of the above, prediction of the occurrence and development of microcracks in the material becomes significant. The research in this area
involved scientists in the USA, Japan, Germany, Great Britain, France, China, the Russian Federation, and other countries [6 – 9]. However, those studies are devoted to mathematical modeling of delamination in polymer composites or modelling of representative volume elements at the level of «fiber – matrix», where the process of occurrence of microcracks is caused by the development of critical stresses and deformations in the components of the material.

That is why many fatigue life prediction models, which are based on experimental data, statistical approach, damage mechanics, or numerical modeling, have been proposed so far. However, there have been few studies on the prediction of crack initiation in CFRP laminates under fatigue loading because it is difficult to evaluate experimentally or analytically the initiation behavior of a crack under fatigue loading. A different model was proposed to predict transverse crack initiation in cross-ply and quasi-isotropic CFRP laminates under fatigue loading based on the Walker model [10, 11]. The paper [11] proposed a probabilistic slow crack growth model to predict the initiation and multiplication behavior of transverse cracks in CFRP laminates under fatigue loading. The influence of fiber bridging on delamination failure in multidirectional composite laminates with different thickness scales is characterized, and the dependence of fiber bridging significance on laminate thickness as well as loading regime is investigated in paper [12]. Furthermore, different numerical models have been developed to predict fiber-bridged quasi-static delamination growth in composite laminates [13–15].

At the paper [16] a multi-scale model for estimating the micro residual stresses during the curing process for polymer-matrix composites has been set up. The results show there is a significant difference in the calculation of micro residual stresses by introducing the effect of the multi-scale model. M. Maiarùa et al. proposed a novel computational model to determine the effects of the cure cycle on the mechanical response of polymer matrix composites. Virtual testing is performed using the commercial codes and program ABAQUS have been used as the finite element method solver, supplemented by user written subroutines, that model the curing process and the mechanical response including the onset of damage and subsequent failure [17].

In general, it is necessary to state that the monitoring of microcracks occurrence and evolution in the parts of polymer composite materials under operating loads is the important challenge.

2. Goals and Object of study

The production of parts and structures with pre-predicted properties is a difficult task provided significant anisotropy of physical properties and complex microstructure. That is why the direction of creating smart carbon fiber reinforced polymer has started to develop actively [18 – 20]. It is worth noting the following areas of scientific work:

- Detection of residual technological deformations in the parts from polymer composite materials.
- Detection of deformations and correct temperature in the structures made of polymer composite materials under operating loads.
- Monitoring the occurrence and evolution of microcracks in the parts of polymer composite materials under exploitation loads.

Traditional non-destructive testing techniques, such as eddy-current, magnetic-particle, radiographic, ultrasonic, digital radiography are used to monitor the damage state of CFRP in order to control damage and identify types of defects. That is why strength monitoring, such as that can be achieved using fiber Bragg grating (FBG) sensors, is more in accordance with the need for future development parts and constructions for aerospace applications made from CFRP [21, 22].

The aim of the scientific work is to develop algorithms for prediction and detection of primary microcracks in CFRP under loading using FBG sensors and multiscale mathematical modeling.
The unidirectional CFRP plates consist of 12 layers (reinforcement – carbon fiber UKN–M–6K (UMATEX Co., Russian Federation), matrix – epoxy, volume fraction of carbon fiber was 0.62) that are the object of the current study. Carbon fiber UKN–M–6K properties are presented in table 1.

The carbon fiber prepreg was used to make the plates. The dimensions of the CFRP plates were: length – 200 mm, width – 40 mm, thickness – 1.8 mm. In these plates FBG sensors with wavelengths of 1560, 1570, and 1575 nm were embedded between the six and seventh layers. The FBG sensors were embedded in the longitudinal and transverse directions. The FBG sensors embedded in the CFRP were copper coated or polyimide coated. The diameter of the FBG sensors is 90 μm.

| Number of Filaments | Density (g/cm³) | Tensile Modulus (GPa) | Tensile Strength (MPa) | Elongation (%) |
|---------------------|----------------|-----------------------|------------------------|---------------|
| 6000                | 1.75           | 225                   | 3500                   | 1.5           |

It is important that FBG sensors were embedded in CFRP with minimal distortion of the microstructural of layers. As seen in figure 1, the FBG sensor is located along the carbon fibers and provides minimal distortion of the microstructural of layers. However, if the FBG sensor is located across the carbon fibers different pores may occur.

![Figure 1](image1.png)

**Figure 1.** The microstructure of CFRP in the area of the FBG sensor:
(a) – The FBG sensor is located along the carbon fibers
(b) – The FBG sensor is located across the carbon fibers.

### 3. Experimental data

First, it is necessary to measure the various properties of the component materials of the CFRP. For elementary carbon fibers, the measured properties were: the elastic modulus, the elongation, tensile strength. For the matrix: the elastic and shear modulus, and the tensile and compressive strength. Also, for glass fibers with FBG sensors: the elastic modulus, the elongation, tensile strength.

In the next step, the FBG sensors were embedded into the green body of plate of the prepreg with carbon fibers and epoxy matrix. After this, the autoclave curing cycle was done. The mold subjected by a vacuum pressure was introduced in autoclave connected at the autoclave vacuum system. Autoclave cycle steps are: heat the mold at 80°C for 30 min; dwell at 80°C for 60 min; heat the mold at 1°C/ min. ramp rate to 150°C;
dwell at 150°C for 180 min.; cool the part at 2°C/min. During polymerization process of the plates, the residual strains and temperatures up to 150°C were measured using embedded FBG sensors. Residual strains have to use for preloading the geometrical model plate of CFRP under stage of the mathematical modelling.

Then, under flexural test of unidirectional CFRP plates was measured indications of longitudinal FBG sensors for each step of loading: 150 N, 220 N, 290 N, 360 N, 430 N (figure 2). The long-beam test was performed by maintaining a span-to-thickness ratio of 80:1 and using a loading roller and supporting rollers of 10 mm and 20 mm radii respectively. All CFRP plates were loaded to failure on a machine UTS110-M after setting the velocity of the loading head to 1 mm/min.

![Figure 2. Indications of a longitudinal FBG sensor (1560 nm):](image) (a) For each step of loading during flexural test of unidirectional CFRP plate, and (b) Flexural test.

![Figure 3. (a) Indications of FBG sensors, and (b) Diagram of loading up to 600 N during flexural test of unidirectional CFRP plate.](image)
Figure 3 illustrates the indications of FBG sensors and diagram of loading up to 600 N during flexural test of unidirectional CFRP plate. It is seen how primary microcracks and delamination in CFRP plate under loads were occurred.

Based on the data obtained from the FBG sensors, it is proposed that with an increase in the load, splitting of the peaks of the resonance wavelength, which indicates the occurrence of primary microcracks and delamination.

4. Numerical modelling

The next step to develop algorithms for prediction and detection of primary microcracks in carbon fiber reinforced polymers under loading used multiscale mathematical modeling. For mathematical modelling geometrical model of CFRP plate at flexural tests and representative volume element was built. Materials properties are presented in tables 2 and 3.

| Density (g/cm$^3$) | Tensile Modulus (GPa) | Poisson’s Ratio | Tensile Strength (MPa) | Compressive Strength (MPa) |
|-------------------|-----------------------|---------------|------------------------|--------------------------|
| 1.02              | 4                     | 0.3           | 95                     | 84                       |

Table 3. High-strength steel (loading head and the supports).

| Density (g/cm$^3$) | Tensile Modulus (GPa) | Poisson’s Ratio | Tensile Strength (MPa) | Compressive Strength (MPa) |
|-------------------|-----------------------|---------------|------------------------|--------------------------|
| 7.8               | 200                   | 0.3           | 390                    | 370                       |

The CFRP plate and representative volume element CFRP, the loading head and the supports were simulated using 3D SOLID 186 elements and program ANSYS. The total number of finite elements used was:

- CFRP plate with FBG sensors 328624 (element size for plate – 0.1 mm, element size for FBG sensors – 0.006 mm). Types of element: 10 noded tetrahedron – Tet10, 20 noded hexahedral – Hex 20 and 15 noded prismatic – Wed 15;
- Representative volume element CFRP 1415063 (element size for carbon fiber – 0.0008 mm, element size for matrix – 0.001 mm). Types of element: 20 noded hexahedral – Hex 20 and 15 noded prismatic – Wed 15;
- The loading head and the supports 24572 (element size – 2 mm). Types of element: 10 noded tetrahedron – Tet10, 20 noded hexahedral – Hex 20 and 15 noded prismatic – Wed 15.

INTER 204 elements (element size – 0.0002 mm, 3D 16-node quadratic interface element) can simulate an interface between two surfaces and the subsequent delamination process, when used with SOLID186 elements [23]. The frictionless contact model represented by element types CONTA 174 and TARGE 170 was used to simulate the contact between the loading head and the plate of CFRP and between the plate and supports. In addition, in the geometrical model of CFRP plate was embedded FBG sensors (figure 4). Representative volume element was the area with FBG sensor located in the center of the carbon fibers yarn.

Total deformation in CFRP plate with integrated FBG sensors at flexural test was determined. The results of numerical modeling are in good agreement with the results of experimental data on the values of total displacement.
Figure 4. Geometrical model of CFRP plate at flexural tests (left) and representative volume element (right).

Figure 5. Damage in CFRP plate with integrated FBG sensors at flexural test.
Microcracks and delamination.

In this work virtual testing is performed using the commercial codes and program ANSYS have been used as the finite element method solver, supplemented by user written subroutines, that Hoffman’s model including of damage and subsequent failure. Hoffman’s model [24] for damage initiation and evolution was used to identify the regions within the CFRP plate or representative volume element at which tensile or compressive damage in the fiber and matrix was initiated. The damage evolution law is known as Continuum Damage Mechanics method that models gradually increasing damage and defects. This is defined in terms of the fracture energy dissipated during the damage process.

The failure in CFRP plate with integrated FBG sensors at flexural test under different loading was presented. It was possible to predict the appearance of primary microcracks and delamination at the level of the CFRP plate. Due to numerical modelling a primary fracture region occurred in the FBG sensor was detected (figure 5).
In addition, a primary fracture region occurred in the matrix near FBG sensor. Multiscale mathematical modeling of a numerical experiment to evaluate the occurrence of areas of primary microcracks in CFRP under loads was performed. Failure criteria in representative volume element of CFRP plate with integrated FBG sensors at flexural test under loading up to 510 N was detected. Based on mathematical modeling, it was found that in representative volume element of CFRP plate with integrated FBG sensors at flexural test under loading microcracks occur in the matrix also in the regions between the carbon fibers and near the sensor (figure 6).

![Figure 6. Damage in representative volume element of CFRP plate with integrated FBG sensor: (a) At flexural test, and (b) Microcracks in matrix.](image)

The multiscale mathematical modeling of a numerical experiment was carried out to evaluate the occurrence of areas of primary microcracks region in CFRP under loads. It was shown that the results are in good agreement with the experiment.

5. Discussion

Based on the above, the correctness of the performed mathematical modeling assessment acquires importance. It is necessary to compare experimental data and numerical simulation results in the following parameters: maximum displacement of the plates during the flexural test compared to the modeling, also the primary microcracks region (table 4).

| Density (g/cm$^3$) | Total displacement (mm) | Force (N) | Detect primary microcracks |
|-------------------|-------------------------|-----------|---------------------------|
| Experiment        | 19.2                    | 507       | Primary fracture region occurred near the FBG sensor |
| Numerical modelling | 19.18                   | 510       | Primary fracture region occurred near the FBG sensor, also in epoxy matrix: fiber-matrix debonding, intralaminar and interlaminar matrix cracks |
As Table 4 shows, the results of numerical modeling are in good agreement with experimental data but append it in primary microcracks regions. These results are of particular interest for further research in microcracks prediction and propagation in the volume of composite materials.

6. Conclusions

Algorithms for prediction and detection of primary microcracks in CFRP under loading using FBG sensors and multiscale mathematical modeling were developed.

The results of measuring the primary residual deformations in the plates made of CFRP at the manufacturing stage using embedded FBG sensors, and their testing under loading were presented.

Multiscale mathematical modeling of a numerical experiment to evaluate the occurrence of areas of primary microcracks in CFRP under loads was performed.

It is demonstrated that the occurrence of primary damage and microcracks is indicated by the peaks splitting of the resonant wavelengths of the embedded FBG sensors.

References
[1] Zimin V N, Koloskov I M, Meshkovsky V E and Usyukin V I 2001 Trans. Mod. and Sim. 30 497–504
[2] Reznik S V, Prosuntssov P V, Mikhaylovskiy K V 2018 IOP Conf. Series: Materials Science and Engineering 1134 012048
[3] Irving P E, Soutis C 2019 Polymer composites in the aerospace industry (Sawston: Woodhead Publishing)
[4] Mikhaylovskiy K V, Baranovski S V 2018 Vestn. Mosk. Gos. Tekh. Univ. im. N.E. Baumana, Mashinostr. 5 15–28
[5] Gorodetsky M A, Mikhaylovsky K V, Reznik S V 2019 IOP Conf. Series: Materials Science and Engineering 683 012075
[6] Shokrieh M M et al. 2012 Comput Mater Sci. 65 66–73
[7] Farmand-Ashtiani E, Cugnoni J, Botsis J 2015 Int. J Solids Struct. 55 58–65
[8] Dimitrienko Y I, Sborchikov C V and Sokolov A.P. 2013 Mech. Comp. Mater. Constr. 19(3) 365–383
[9] Mikhaylovskiy K V 2010 Vestn. Computer. and Inform. Technol. 11 (77) 17–22
[10] Hosoi A, Kawada H 2018 Materials 11 1182 16
[11] Ogi K, Yashiro S 2009 J. Jpn. Soc. Compos. Mater 35 212–220
[12] Liaojun Y et al. 2018 Composites Part A. 115 175–186
[13] Shokrieh M M, Heidari-Rarani M 2011 Mater. Sci. Eng. A. 529 265–269
[14] Stutz S, Cugnoni J, Botsis J 2011 Compos. Sci. Technol. 71 443–449
[15] Farmand-Ashtiani E et al. 2015 Compos. Sci. Technol. 119 85–92
[16] Zhenyi Y et al. 2018 Composites Part B. 155 49–61
[17] Maiaria M et al. 2018 Composites Part B. 149 285–295
[18] Andreades C, Mahmoodib P, Ciampaa F 2018 Composite Structures 206 456–466
[19] Takeda S, Okabe Y, Takeda N 2008 J. of Int. Mater. Sys. and Struct. 19 437–444
[20] Minakuchi S, Takeda N 2013 Photonic Sensors 3(4) 345–354
[21] Mikhaylovskiy K V, Bazanov M A 2016 Constr. From Comp. Mater. 2 54–58
[22] Raffaella D S 2015 Sensors, 15, 18666–18713
[23] Ansys Inc. 2011 Ansys Mechanical APDL Element Reference (Canonsburg: Ansys Inc.)
[24] Hoffman O 1967 J. of Comp. Mater. 1 200–206