Registration of the Creep Behavior by Embedded and Surface Mounted FOSS

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Abstract. Epoxy resins are widely used to connect various structural elements made of polymer composite materials. The integrity of the critical components depends on the strength and durability of such compounds. At the same time, epoxy resins have pronounced viscoelastic properties. An experimental study was conducted of the possibility of using fiber-optic strain sensors to register the viscoelastic behavior of materials. The fiber Bragg grating (FBG) was used as a sensor. The main objectives of this study were: registration of material creep (growth of strain with time at constant external load) and subsequent (after removal of load) recovery of strain using surface mounted and embedded fiber-optic strain sensors.

1. Introduction
The use of polymer composite materials as structural materials requires long-term stability of their size and strength. Under various operating temperature and mechanical loads, polymer composite materials can exhibit pronounced viscoelastic behavior, which requires additional research [1]. One of the most common ways to experimentally study the viscoelastic behavior is to test materials at high temperatures, when materials exhibit their viscoelastic properties more vividly, which can significantly reduce the test time [2–4]. Material creep failure is the result of a combination of such phenomena as the breaking of bonds of material fibers (for fiber composites), shearing and cracking of the binder, the formation and growth of voids. In addition, in polymer composites, such parameters as polymer / fiber or polymer / particles interfacial strength affect the material creep failure. Temperature, stress level and time are also crucial factors affecting the viscoelastic behavior of polymer composite materials. The influence of these factors is used to describe the behavior and prediction of the polymer composite materials failure [5–8].

Significant amount of studies of the viscoelastic behavior of composite materials, in particular, of layered composites, have been conducted in the military and aerospace industries [9]. In [10], a literature review is presented about the most relevant studies of the creep behavior of materials, specifically designed for use in civil engineering infrastructure. These studies focus both on the experimental characterization of materials and on the development of analytical models. Special attention is paid to flexural and compression loads, which were used in most studies on the creep phenomenon of composites with different reinforcement structures. Using of the materials exhibiting viscoelastic properties for structural design, requires to take into account a number of features [11].

Epoxy resins are widely used to connect various structural elements and the integrity of the critical components depends on the strength and durable characteristics of such compounds. At the same time, epoxy resins exhibit viscoelastic behavior that require determination, both in laboratory tests and during operation. Fiber optic strain sensors (FOSS) have a great prospect of use for registration of the mechanical behavior of laboratory samples and joints in structures made from epoxy resins during long-term testing. They are small in size, can be embedded in the samples or junctions, or mounted to the surface. It is also possible to place several sensors on one fiber and to record data for a long period of time.
This paper presents the results of an experimental study of the possibility of using fiber-optic strain sensors to register the viscoelastic behavior of materials. The fiber Bragg grating (FBG) was used as a sensor. Experiments on creep and strain recovery were carried out on an epoxy sample with an embedded and surface mounted FBGs. The main objectives of this study were: registration of material creep (growth of strain with time at a constant external load) and subsequent (after removal of the load) recovery of strain using fiber optic strain sensors and comparing the data for two types of sensor placement on the object.

2. Description of the experiment

For testing, epoxy resin sample was made. Two Bragg grating strain sensors were used to measure the strains of the sample. One of the sensors was embedded into the sample during its manufacture. The second was mounted to the surface of the sample using adhesive bonding. The sensor layout is shown in Figure 1.

![Figure 1](image1.png)

Figure 1. The scheme of location of optical fibers with FBG on a epoxy resin sample.

The technology of making a sample from epoxy resin was as follows. A silicone mold with a 200×10×5 mm hole, for the subsequent pouring of epoxy resin with a hardener, was made (Figure 1.). Two technological cuts along the edges of silicone mold were created. They are designed for centering the position and fixing the optical fiber with FBG in the mold. After positioning of the optical fiber in this silicone mold, a mixture of epoxy resin and hardener is poured in proportions determined by the manufacturer of the epoxy resin. This mixture is left for 24 hours at a temperature of 23°C for curing.

![Figure 2](image2.png)

Figure 2. Silicone mold for making samples.

It is known that when a Bragg grating is subjected to a transverse load, as a result of the birefringence phenomenon, the peak of the reflected spectrum splits. The Bragg wavelength, which is subsequently used to calculate the strain, is determined by the maximum value of the spectrum. Thereby if the peak is bifurcated, difficulties may arise in the reliability of strain determination. This problem is common for FBGs embedded in the composite material, when during the technological process the optical fiber in the zone of Bragg grating loses a cylindrical shape. During experiments with epoxy samples, carried out in the framework of this study, such problem was not observed. Further, Figure 3 shows the reflected Bragg grating spectra: before embedding into the sample (black line) and after embedding under the tensile load (blue line).
Figure 3. Reflected FBG spectra before embedding and after embedding under the load.

The second fiber with FBG was glued to the sample surface after the epoxy resin had hardened using cyanoacrylate glue. Patch pieces were made for fixation of the sample, the scheme and photos are shown in Figure 4 and 5. The patch pieces have two technological holes for attaching the sample and for hanging the load.

Figure 4. Experimental diagram of the sample with mounts.  
Figure 5. Sample mounted for testing.

In the experiment several stages of loading and unloading were carried out in order to study the reaction of the Bragg grating, as well as the sample itself in time. The scheme of the experiment stages of the viscoelastic behavior registration of an epoxy sample is presented in Figure 6.
Figure 6. The scheme of the experiment stages of the viscoelastic behavior registration of an epoxy sample.

The experiment was carried out for 171 hours. During this time, the sensor readings were taken with a frequency of 1 measurement per second using an interrogator FS 2100. At the first stage (I), a constant load $F_c$ was applied to the sample for 121 hours. Strains recorded by the sensors at this stage are presented in Figure 7. For convenience, the sensor readings of each of the experiment stages are presented from the zero time value corresponding to the beginning of this stage.

Figure 7. Strain measurements depending on the time under constant load of the sample for embedded FBG (s00) and glued on the surface (s01).

Then, at the second stage (II) the load was removed and the sample was in a free state for 25 hours. The process of decreasing of the strain in time, recorded by the sensors is shown in Figure 8.
Figure 8. Strains depending on the time after removing the load for FBGs embedded in the sample (s00) and glued on the surface (s01).

At the third stage (III), a constant load $F_c$ was applied to the sample again for 22 hours (Figure 9).

Figure 9. Strains depending on the time under constant load for FBG embedded in the sample (s00) and glued on the surface (s01).

And at the final stage of the experiment (IV), the sample was in the free state for 3 hours (Figure 10).
Figure 10. Strains depending on the time after removing the load for FBGs embedded in the sample (s00) and glued on the surface (s01).

Analysis of the results showed that the embedded fiber-optic sensor (s00) and placed on the surface (s01) demonstrate minor differences in the readings. Thus, the maximum difference in the strains recorded by the sensors in the first stage was 13%; in the second - 7%; in the third - 13.2%; in the fourth - 4%.

3. Conclusions
The experimental study of the viscoelastic behaviour registration using fiber-optic strain sensors based on the Bragg gratings was done. A sample of epoxy resin with FOSS embedded and placed on the surface was fabricated for experiment.

The experiments made it possible to track the strain growth with time under the constant load which is characteristic for creep material behaviour and the strain reduction over time after the load was removed using the sensitive elements. The maximum difference between the readings of the embedded sensor and glued on the surface was 13.2%.

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