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The Analysis of the Stress-Strain State in the PCM–optical-Fiber System

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Abstract. Fiber-optic strain sensors (FOSS) perfectly suit for organizing a measuring system of polymer composite materials (PCM) due to small dimensions, measurement accuracy, and the possibility of both placing optical fibers on the surface of the object under study and embedding them into the structure of a composite material. One of the main problems arising in the evaluation of the mechanical state of a structure using optical fibers is the correspondence of the measured strain in the optical fiber to the actual strain in the composite material. In this study, the efficiency of strain transfer from the initial material to the optical fiber placed on the surface or embedded in the PCM structure at various ratios of the mechanical properties of composite materials to the optical fiber properties are investigated. The discrepancy zone of strains in the optical fiber and in the initial material is estimated. For optical fibers placed on the surface of the material, the issue of gluing of the optical fiber along its length is considered.

INTRODUCTION

The combination of composite materials and optical fibers has great prospects for creation of reliable structures able to assess the mechanical state during operation. High specific strength of composite materials, a wide range of testing the obtained mechanical properties, organization of various laying schemes, weaving, a wide choice of reinforcing fibers and binder, as well as a manufacturing process that allows creating large parts with a minimum number of connecting elements are among the main advantages of composite materials. Besides, structures made of composite materials experience different operational loads and can have a high level of responsibility. Fiber-optic strain sensors (FOSS) perfectly suit for organizing a measuring system of polymer composite materials (PCM) due to small dimensions, measurement accuracy, and the possibility of both placing optical fibers on the surface of the object under study and embedding them into the structure of a composite material. One of the main problems arising in the evaluation of the mechanical state of a structure using optical fibers is the correspondence of the measured strain in the optical fiber to the actual strain in the composite material. It is well known that, when strain is measured on the surface of a material, the quality of strain transfer is affected by the thickness of the adhesive layer and its properties.

Issues related to the quality of strain transfer to optical fiber are discussed in a number of studies. For example, the authors of [1] theoretically and experimentally showed how FOSS based on Bragg gratings can be used as a valuable tool for monitoring of composite structures during operation, as well as for obtaining internal stresses and strains in laminates. It was experimentally found and theoretically proved that the transverse load on the sensor causes the reflection spectra of the grating to be divided into two peaks and that the bandwidth between these peaks contains information about transverse strain. The paper [2] describes the behavior of fiber-optic Bragg grating (FBG) subjected to transverse and axial strains, both for single-mode optical fibers with low birefringence and for polarization-stabilized optical fibers. The authors focus on some issues that remain open regarding the grating response to transverse loading in experiments on diametrical compression. The results indicate the need to create an

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adequate model that is going to describe the transfer of stresses from the matrix to the embedded fiber for a satisfactory interpretation of the measured data.

In [3], an analytical model of an adhesive layer for an FBG on a substrate was developed in order to predict strain transfer from the substrate to the FBG, while the substrate is under external influences. The results show the effect of the adhesive layer on the strain transfer from the substrate to the FBG near the two ends of the FBG. It is possible to improve the strain transfer through the bonding layer using glue with a high shear modulus. The authors of [4] carried out a series of experiments with FBG sensors embedded in graphite and epoxy composite structures. Here, the strain-optical behavior of embedded FBG sensors is studied and a quantitative discussion of the results of the data from the embedded sensors is given. A new method for making independent strain and temperature measurements using an FBG embedded into polymer samples for tensile tests was presented in [5]. The FBG strain and temperature sensitivity were separated using two single-mode FBG sensors embedded into the sample material at a certain angle.

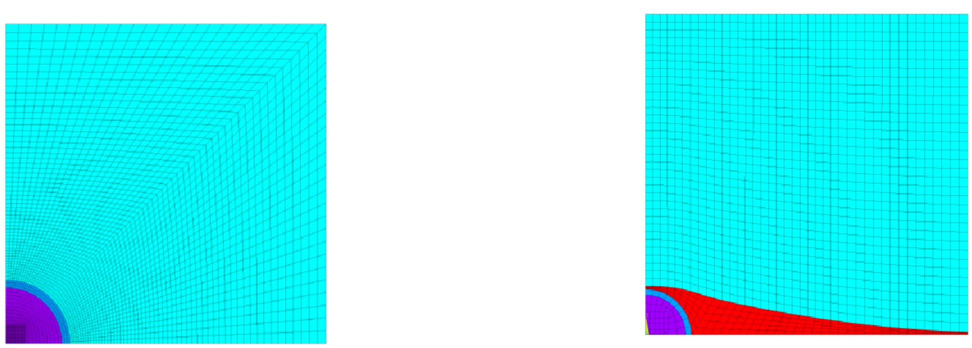
This paper is devoted to a numerical study of the correspondence between the strains realized in an optical fiber and strains in a composite material both when the sensor is located on the surface of the sample under study and when it is embedded into the PCM structure. The purpose of using FOSS is to measure the strain components in the direction of the axis of the optical fiber. However, the change in the resonance wavelength of a Bragg grating that is not in the free state is affected not only by the strain component along the axis of the optical fiber, but also by the transverse components of the strain. In addition, it is important to determine the efficiency of the strain transfer from the initial material to the optical fiber.

The study of these issues is carried out using numerical simulation methods. The results on the efficiency of the strain transfer from the initial material to the optical fiber placed on the surface or embedded in the PCM structure at various ratios of the mechanical properties of composite materials to the optical fiber properties are obtained. The discrepancy zone of strains in the optical fiber and in the initial material is estimated, which makes it possible to give recommendations about the location of distributed FOSS embedded into the composite material. For optical fibers placed on the surface of the material, incomplete gluing of the optical fiber along its length is considered. In this case, the area of the strain sensor should remain free from gluing.

STRAIN TRANSFER TO OPTICAL FIBER EMBEDDED INTO MATERIAL

The actual strain in a composite material is assessed by the strain measured with optical fiber when using embedded FBGs. The strain field in a sample with an embedded optical fiber under uniaxial tension in the direction of the fiber was studied. Three cases were considered: an optical fiber with and without protective coating is embedded into a host material; the variant which takes into account the distortion of the layers of a composite material when incorporating an optical fiber (resin pocket).

The size of the model was chosen in such a way as to exclude the influence of the boundaries on the obtained results. The analysis of the stress-strain state of the presented models is considered within the framework of the static problem of the theory of elasticity. The finite-element representation of the models is shown in Fig. 1.



(a) (b)

FIGURE 1. Finite element representation of the considered models: material with embedded optical fiber and protective coating (a); material with embedded optical fiber, protective coating and resin pocket (b)

Numerical simulation is carried out in the isotropic approximation of the materials under consideration, which are as follows: host material ($E = 26.3$ GPa, $\nu = 0.14$), polyimide coating ($E = 2.7$ GPa, $\nu = 0.31$), quartz ($E = 71.4$ GPa, $\nu = 0.17$), and epoxy resin ($E = 3.2$ GPa, $\nu = 0.35$).

In the case of the uniform strain field along the length of the embedded optical fiber, a complete transfer of axial strain from the host material to the optical fiber is realized, with the exception of the output zone near the boundary of the sample. The size of this zone depends on the ratio of the elastic modulus of the host material and the optical fiber. To evaluate this effect, numerical calculations are carried out for different elastic moduli of the material into which the optical fiber is embedded in the isotropic approximation.

The increase in the discrepancy zone occurs when the value of the elastic modulus of the composite material (E_{comp}) moves away from the elastic modulus of the optical fiber (E_{opto}). This conclusion is shown in Fig. 2, which shows the dependence of the size of the zone of mismatched strain, represented in the number of optical fiber radii (R_{opto}).

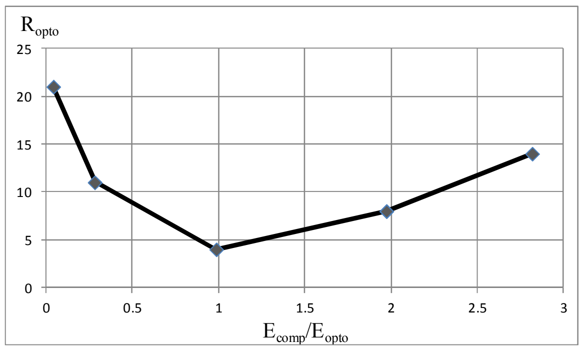


FIGURE 2. Dependence of the size of the zone of non-coinciding strain on the ratio of the elastic moduli of the initial material and the optical fiber

The minimum size of the zone is achieved when the modulus of elasticity of the host material approaches the elastic modulus of the optical fiber. Thus, it is necessary to take into account imperfect transfer of strain to the optical fiber in the boundary zone, as in the case of a material with a low elastic modulus or when the elastic modulus of the host material is significantly higher than that of the optical fiber.

SURFACE MOUNTING OF OPTICAL FIBER

The purpose of using fiber-optic strain sensors is to measure the strain components in the direction of the axis of the optical fiber. However, the change in the resonance wavelength of a Bragg grating not in the free state is affected not only by the strain component along the axis of the optical fiber, but also by the transverse components of the strain, hence the strain coefficient for recalculating strain from the Bragg wavelength shift for free optical fiber ($K_\varepsilon = 0.78$) is not always valid.

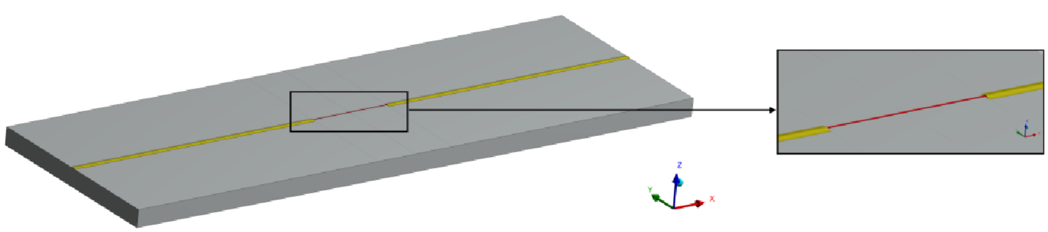


FIGURE 3. The model of a PCM sample with an optical fiber glued to its surface

For optical fiber placed on the surface of the material, incomplete gluing of the optical fiber along its length is considered. In this case, the area of the strain sensor should remain free of adhesion. Such scheme helps to minimize the influence of the surrounding material on transverse strains in optical fiber. A sample of PCM with the dimensions $150 \times 50 \times 4.38$ mm was considered as the object of the study. On the surface of the sample, an optical fiber is placed through the adhesive bond. The adhesive connection is absent in the area where the location of the fiber-optic strain sensor is assumed (Fig. 3).

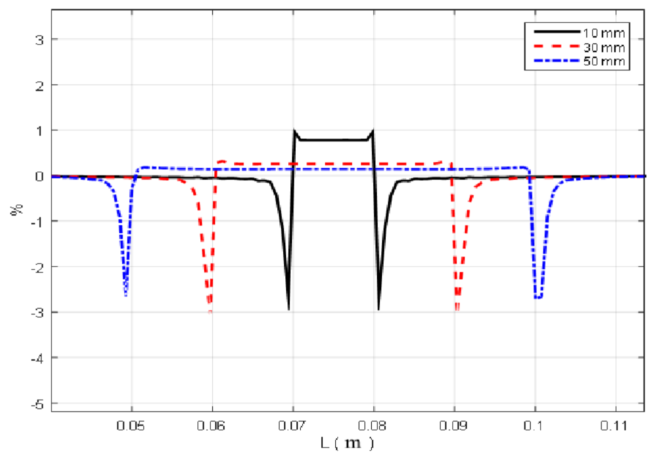


FIGURE 4. Difference in the axial strain in an optical fiber with nonuniform gluing compared to complete gluing in a free region for different lengths of the region free from adhesive bonding

The obtained numerical results showed the efficiency of the analyzed scheme for the reduction of transverse strains; however, in the region without adhesive bonding there is a slight difference in the axial strain in the optical fiber compared to the composite material. In addition, in the transition zones from the glued joint to the zone without it, a strain concentrator is observed. The distribution of axial strain in an optical fiber in a free region for different lengths of the free region is shown in Fig. 4.

CONCLUSION

Two configurations of optical fiber placement on the composite material have been studied: optical fiber embedded into the structure of the host material; surface mounting of optical fiber, when the area of the strain sensor remains free from adhesive bonding. In case of embedded optical fiber, it has been shown that strain transfer from the host material to the optical fiber is satisfactory, except the area close to the boundary. This zone depends on the ratio between the elastic modulus of the host material and that of the optical fiber. The numerical simulation of the stress-strain state of the surface-mounted optical fiber shows that leaving the area of the strain sensor without adhesive bonding leads to an insignificant change in the measured strain.

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REFERENCES

1. J. A. Guemes and J. M. Menéndez, Compos. Sci. Technol. **62**, 959–966 (2002).
2. F. Bosia, P. Giaccari, J. Botsis, M. Facchini, H. G. Limberger, and R. P. Salathé, Smart Mater. Struct. **12**, 925–934 (2003).
3. C. C. Cheng, Y. L. Lo, B. S. Pun, Y. M. Chang, and W. Y. Li, J. Light. Technol. **23**, 3907–3915 (2005).
4. Y. Fan and M. Kahrizi, Sensors Actuators, A Phys. **121**, 297–305 (2005).
5. G. Pereira, M. McGugan, and L. P. Mikkelsen, Polym. Test. **50**, 125–134 (2016).