

## Research Article

# Numerical Analysis of the Effect of Microscale Components Interaction on Measurements of Fiber Optic Strain Sensors Used in Composite Structures

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The paper investigates the influence of structural components of a composite material on the strain values measured by using an embedded optical fiber with Bragg gratings. The effect of composite plies and intermediate epoxy layers on the transfer of deformations from the measured object to the optical fiber was studied taking into account various methods of the fiber attachment and surrounding media configurations. A numerical estimation of the effect of the longitudinal and transverse components of the strain tensor on the wavelength of the reflected spectrum is performed.

## 1. Introduction

Laminate polymer composites by their nature are complex objects to study due to inherent anisotropy as well as significant dependence of properties on temperature and manufacturing technology. In some cases, properties of a composite material as a part of structure cannot be determined on standard samples, and the influence of technological factors, such as characteristics of the components of the material (fibers, fabric, matrix, etc.) and the parameters of technological processes makes a tangible contribution to the characteristics of the final product. However, in the very principle of creation of a laminate composite material or structure as a combination of individual components, one can find a solution to the problem of its reliability ensuring. Particularly, it is possible to produce a material with the ability to diagnose its condition during testing and operation using nondestructive monitoring systems [1–3]. Development of such monitoring systems includes integration of the sensors into materials and structures, collection of data from sensors, data processing

using various algorithms for extracting requested measurements, and prediction of durability of a structure.

A reliable monitoring system requires installation of a distributed network of sensors. Existing technologies allow to create highly sensitive, reliable, and miniature sensors that can be embedded in composite structures during or after the manufacturing stage. Up to now, electric, piezoelectric, acoustic, thermal, electromagnetic, and other sensors, fixed at certain points of the analyzed structure, have often been used as sensors of embedded control [4–7]. Such sensors are used to passively (i.e., without the possibility of influencing the process) monitor disturbances caused by events resulting in occurrence of damage (for example, quick release of acoustic signals or heat), as well as to capture various types of external influence on the structure (for example, vibration, loading, and interactions with the surrounding media). The measurements of reliable sensors should not be significantly affected by the presence of noise and vibration, as well as electromagnetic fields [8].

One of the most used basic elements of internal strain monitoring systems is fiber optic sensors (FOS). Currently,

fiber optic sensors are used as an alternative to traditional strain gauges, including laboratory testing of structures made of polymer composite materials. FOS have a high degree of resolution in terms of the measured parameters, small dimensions, long service life, resistance to corrosion, and electromagnetic interference. Optical fibers are also quite flexible, durable, and heat-resistant and can be easily embedded in laminate composites [3, 9–25]. Existing technologies allow to embed fiber optic sensors directly into the composite material during the technological cycle of manufacturing of composite structures without significant influence on its mechanical properties [26], since the size of optical fibers is relatively small compared to reinforcing fibers [15, 27]. This makes it possible to manufacture composite structures with an integrated sensor system for measurement of strain state at all stages of the structure's life cycle. The monitoring system created this way will allow to evaluate technological stresses during manufacturing process, control the degradation of material properties during its long-term storage when exposed to environmental factors (humidity, ultraviolet radiation, etc.), register damage accumulation under operational loads and additional external influences (shock, vibration, and overload), and predict residual life.

Depending on the requirements of the monitoring system, various types of FOS have been designed. One of the most popular solutions is optic sensors with fiber Bragg gratings (FBGs), which provide periodic change in the refractive index of the core of an optical fiber created using optical radiation [17, 28, 29]. While the light wavelength is an absolute parameter, the signal from the Bragg grating can be processed in a way that its information remains immune to the fluctuations along the optical path. Thus, FBGs offer an autoreference and absolute measurement scheme. The technology based on FOS with Bragg gratings has shown great potential for solving monitoring problems in various industries. For instance, they have been widely used in aircraft structures [30–34]. Besides, fiber optic sensors on Bragg gratings were also employed to monitor the state of wind generators [35, 36], the performance of geotechnical objects [37, 38], different civilian structures such as high-rise buildings, bridges, and tunnels.

Measurement of strains is one of the main tasks when using FOS in composite materials. Numerous studies on the features of strain measurement with the use of FOS with Bragg gratings, as well as the specific practical problems of measuring strains in composite materials, are addressed, for instance, in [13, 30, 39–47]. For existing composite structures, FOS can be attached to the surface of the structure, while for new structures, these sensors can be embedded in the structure without affecting structural integrity.

This paper is devoted to a numerical study of interaction of the optical fiber and Bragg grating with the surrounding elements taking into account different types of sensors attachment on the measured surface.

The paper structure is as follows. Section 2 contains general information about working principles of fiber optic strain sensors with the Bragg gratings, including main relation that enables transformation of wavelength

measurements into values of strain. Section 3 introduces the numerical model that was used in this work to study interaction of the sensor with the adhesive composition and substrate. Details of the finite element models are presented. Comparison is made between the strain values on the surface of the object (without the sensor) and the strain values in the sensor core. Section 4 investigates the effect of deformations of the surrounding media on the wavelength of the reflected spectrum from the Bragg grating. Conclusions summarize the obtained results.

## 2. Operation Principle of Fiber Optic Strain Sensors

The operation principle of fiber optic strain sensors on the Bragg gratings is based on a comparison of the wavelength of the light transmitted to and reflected from the Bragg grating [19]. When the fiber is in a deformed state, the grating period and, accordingly, the wavelength of the reflected light change. The relation between shift of the reflected spectrum wavelength on the strain tensor components and temperature of the optical fiber is as follows:

$$\frac{\Delta\lambda}{\lambda} = \varepsilon_{11} - \frac{1}{2}n^2(p_{11}\varepsilon_{22} + p_{12}(\varepsilon_{33} + \varepsilon_{11})) + K_T\Delta T, \quad (1)$$

where  $\varepsilon_{ij}$  is the strain tensor,  $n$  is the optical fiber refractive index,  $p_{11}$  and  $p_{12}$  are Pockels' coefficients of the elastic-optical tensor, and  $K_T$  is the thermal expansion coefficient. When the temperature is constant, the last term becomes negligible ( $\Delta T = 0$ ). An important feature of the Bragg gratings is that, as can be seen from equation (1), the wavelength of the reflected spectrum depends on the deformations in all three directions.

The key issue that arises when using fiber sensors on Bragg gratings to monitor strains in composite structures is at what extent the data obtained from the sensor correspond to the real strains of the environment, and in particular, the structural element which is being monitored. It is obvious that the configuration of the microstructural elements of the laminate composite structures, such as the orientation of the layers, the thickness of the epoxy resin layer, and the methods of mounting the sensors on the surface, can introduce errors in the measurements and, ultimately, influence the readings of the sensors.

## 3. Numerical Model of the Interaction of the Sensor with the Adhesive Composition and the Substrate

When using fiber optic strain sensors with Bragg gratings in structures made of polymer composite materials, an important issue is the analysis of the interaction of the sensors with the surface of the object. The accuracy of strain measurement depends on the extent to which the surrounding medium is reliably capable of transferring strains of the object to the sensor. Under the real operating conditions, a fiber optic sensor is usually exposed to influence of microscale components of the structure, such as the surrounding adhesive composition (a resin pocket arising

TABLE 1: Elastic mechanical properties of the composite ply.

$E_x$ (GPa)	$E_y$ (GPa)	$E_z$ (GPa)	$\nu_{xy}$	$\nu_{yz}$	$\nu_{xz}$	$G_{xy}$ (GPa)	$G_{yz}$ (GPa)	$G_{xz}$ (GPa)
60	8.1	60	0.2	0.2	0.14	3.2	3.2	4.1

during production) or plies of a composite material, the effect of which must be considered when interpreting sensors measurements.

In order to study the mechanical interaction of the fiber optic sensor with the surrounding microstructural elements and to estimate the error introduced by these elements into the values of the deformations measured by the sensor, finite element 3D models of a fiber optic sensor with a Bragg grating attached in various ways to a deformable macroscopic object were created. In order to assess the effect of each of the main structural elements on the transferring of strains into the optical fiber, model problems were investigated, where the components of layered composites—composite fabric and epoxy binder—were used as the intermediate medium between the measured object and the fiber. As a reference object, the surface strains of which was to be measured, an isotropic 7 mm thick plate with mechanical properties  $E=70$  GPa and  $\nu=0.35$  was used. The boundary conditions were specified in the form of distributed pressure applied from below while the edges were simultaneously stretched to both sides. The maximum vertical displacement of the plate was 1 mm, and displacements of points on each edge were 0.5 mm.

The substrate consists of 5 composite plies with a thickness of 0.2 mm. The properties of a single ply are shown in Table 1.

The optical fiber is placed in the layer of adhesive binder (0.1 mm thick), which is also present in one of the models as a layer for attaching components to the surface of the measured object. The modulus of elasticity of the binder is 3 GPa, and the Poisson's ratio is 0.35.

The optical fiber is heterogeneous in its composition and consists of a quartz core with a diameter of 0.12 mm and a polyimide protective shell with a thickness of 0.03 mm. The properties of the quartz core are  $E=71.4$  GPa and  $\nu=0.17$ ; the properties of the polyimide shell are  $E=2$  GPa and  $\nu=0.35$ . In the numerical simulations, the stress-strain state was analyzed in the quartz core of the fiber where the Bragg grating (10 mm long) is located (Figures 1 and 2). It was assumed that the fiber is placed along the surface (in the direction of stretching) and the Bragg grating is in the center of coordinates. It is assumed that the presence of the Bragg grating does not alter the properties of the fiber.

The sketches of the considered models are presented in Figures 1 and 2 (all units are in mm).

Three-dimensional numerical models of the proposed calculation schemes were implemented using the finite element method in Abaqus software. Figure 3 demonstrates the finite element model according to the scheme in Figure 2. The composite plies, the adhesive layer, and the substrate were modelled with 8-node linear hexahedral elements (C3D8R). In each composite ply, the adhesive layer between plies and the substrate comprise one solid

element in the thickness direction. In total, 2500 elements were used for the composite plies and 500 elements for the adhesive layer together with the substrate. The adhesive layer between composite plies and the substrate comprises one solid element in thickness direction and 500 elements in total. The optical fiber, including the core and the shell, as well as the surrounding epoxy layer was modelled using 6-node linear triangular prism elements (C3D6), 36200 in total. The elements' sizes were chosen to be corresponding to dimensions of the microstructural component. The contact conditions between the surfaces of the microstructural components preserved hard contact normal behavior and rough tangential behavior.

According to the results of the calculation, a comparison was made between the strain values on the surface of the object (without the sensor) and the strain values in the sensor core.

Figure 4 shows the values of component 11 of the strain tensor in the core of an optical fiber, directed along the  $X$ -axis (coaxially with the applied tensile load). The values are given in the zone of the proposed placement of the Bragg grating (from  $-5$  to  $5$  mm in the  $X$  coordinate) when the sensor is attached to the surface (Figure 1), between the adhesive substrate and composite ply above and below, and between two composite plies secured to the surface via an adhesive layer (Figure 2). For comparison, strains on the pure surface with no structural elements are also shown.

The obtained results confirm that the way of fixing of the FOS on the surface of the object has a significant effect on the deformation response in the fiber. The smallest deviation from the reference values of strains (about 3%) was predictably obtained in case when the sensor is directly fixed on the surface, although insignificant contribution from the adhesive layer is nonetheless present. A more noticeable deviation was obtained when the composite ply was applied to the sensor from above, as well as when the sensor was attached to the composite ply. The greatest difference from strains on the measured object was obtained when the sensor interacts with both composite plies from above and below (more than 10%).

These results indicate that, in each specific case, the introduction of corrective parameters when measuring the deformation characteristics is required for a preliminary assessment of the interaction of the sensor with the media.

The graphs in Figures 5–7 show the influence of the components (composite plies and adhesive layer) which interact with the sensor and the measured object, on the strain values on the surface of the object. Values are presented along the entire length of the surface and of the optical fiber (edge effects are present).

The method of fixing of FOS also affects strains on the surface of the object. Thus, in addition to adjacent environment, the components providing attachment of the sensor can have an impact on the stress-strain state in the measurement zone.

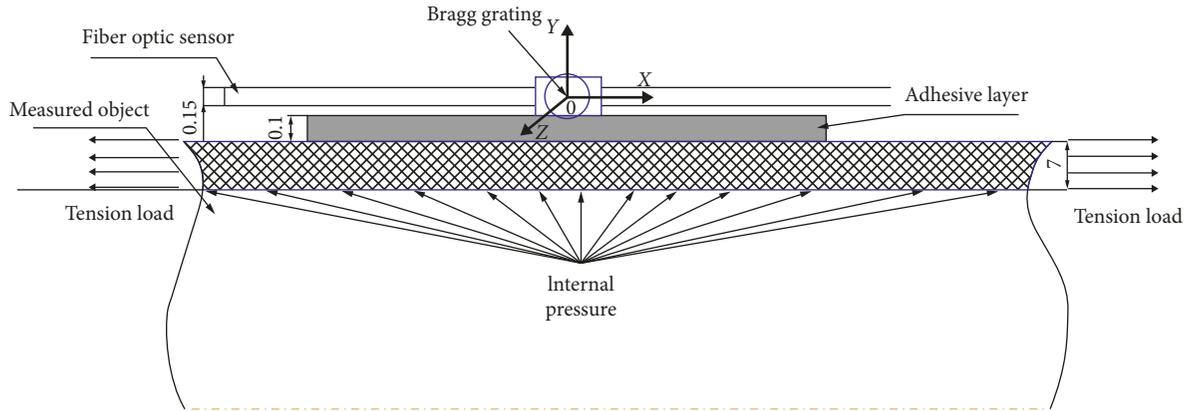


FIGURE 1: Model scheme for calculation of strains transferred from the measured surface through the adhesive layer to FBG.

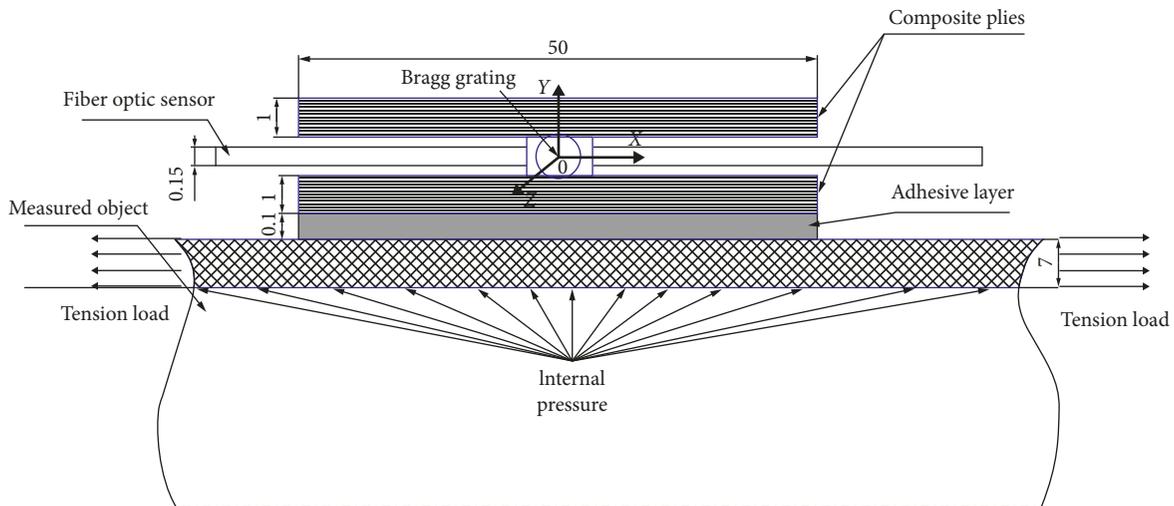


FIGURE 2: Model scheme for calculation of strains transferred from the measured surface through the composite plies and adhesive layer to FBG.

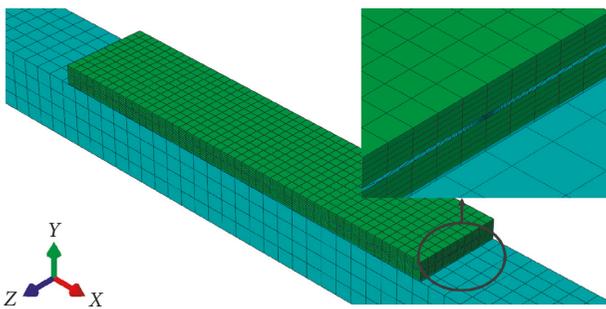


FIGURE 3: Finite element model corresponding to the scheme in Figure 2.

#### 4. Evaluation of the Effect of Environmental Deformations on the Wavelength of the Reflected Spectrum

In the ideal case of uniaxial ( $X$ -axis) stretching of an optical fiber that does not interact with the environment, the components  $\epsilon_{22}$  and  $\epsilon_{33}$  of the strain tensor are expressed in terms of the Poisson's ratio of the optical fiber and the strain tensor component  $\epsilon_{11}$ . This case can be implemented, for example, when

the fiber is fixed in two points at the measured surface. Then, the axial deformation of the optical fiber will be exactly the same as the deformation of the surface of the object. Substituting the physical properties of the most commonly used types of optical fibers into expression (1), the following relationship can be obtained:

$$\frac{\Delta\lambda}{\lambda} \approx 0.78\epsilon_{11}. \quad (2)$$

However, calculation of strain values using this relation may result in an increasing error when the tangential stress has significant influence. The calculations were performed that allow to compare the values of the ratio of the reflected spectrum to the wavelength  $\Delta\lambda/\lambda$  using expression (1) and the approximate formula (2). These results for the Bragg grating zone are presented in Figures 8–10.

It has been established that, with more rigid fiber fixing (between two plies), the difference between the results obtained using the two methods for calculating the change in the wavelength of the reflected spectrum is only about 1%. In the case when the fiber is fixed on the surface using the adhesive layer, this difference increases up to 10%. The influence of components 22 and 33 of the strain tensor

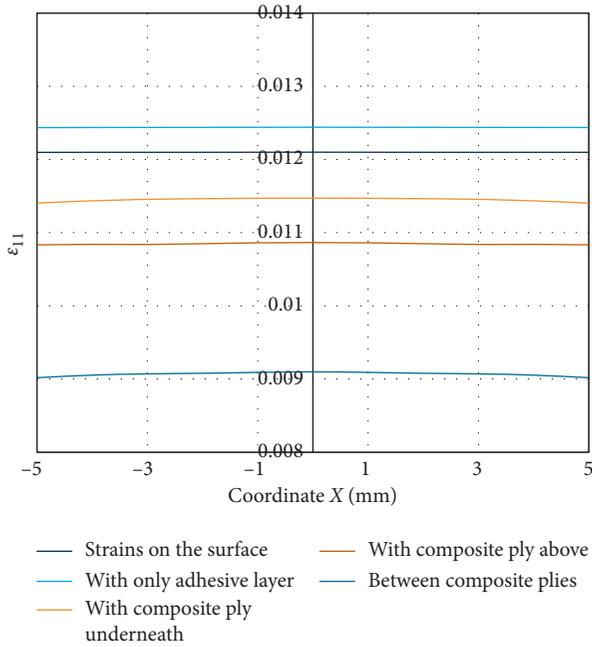


FIGURE 4: Comparison of strain values  $\epsilon_{11}$  in the Bragg grating zone, obtained with different configurations of fiber surroundings.

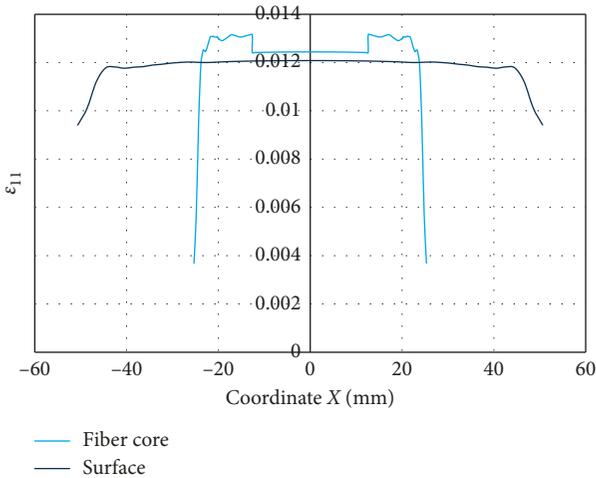


FIGURE 5: Strain value  $\epsilon_{11}$  in case when the fiber is attached to the surface through the adhesive layer.

becomes more significant when the mechanical properties of the environment decrease.

### 5. Conclusions and Discussion

In this work, some particular cases of the interaction of a strain fiber optic sensor with components of a composite material have been studied using finite element modelling. The problem statement included several variations of the FOS attachment to the surface of the measured object, with different elements of the composite structure forming the media surrounding the optical fiber. Numerical results regarding the influence of the components of the composite structure on the transfer of strains from the object being measured to the optical fiber were obtained.

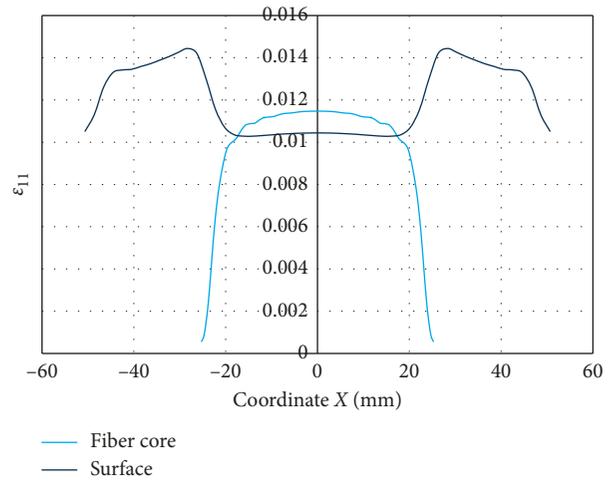


FIGURE 6: Strain value  $\epsilon_{11}$  in case when the fiber is located on the composite ply and attached to the surface through the adhesive layer.

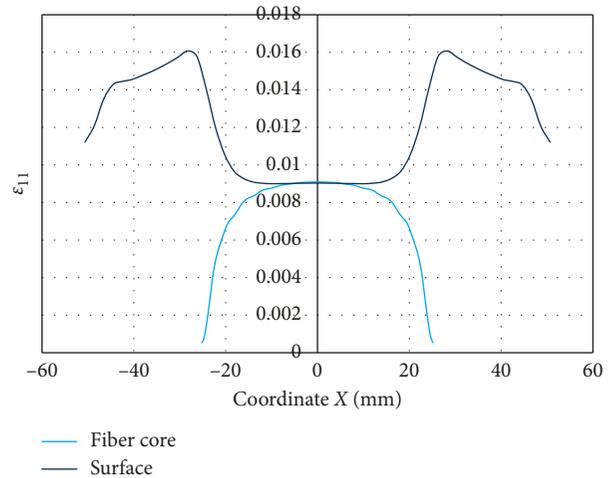


FIGURE 7: Strain value  $\epsilon_{11}$  in case when the fiber is located between the composite plies and attached to the surface through the adhesive layer.

Comparison was made between the strain values on the surface of the object and the strain values in the sensor core. It was shown that the media in between the FBG sensor and the measured object may introduce deviations to the strain values that should be taken into account when interpreting the strain sensor's measurements. The effect of the surrounding media on the wavelength of the reflected spectrum from the Bragg grating in some cases may bring out an error when ignoring the tangential constituents in the stress-strain state in the vicinity of the optical fiber. Consequently, when interpreting the readings of fiber optic sensors embedded between the layers of the composite according to the relation (1), it is necessary to take into account all components of the strain tensor. When inserted between layers, the fiber does not deform freely in the transverse plane, and its radial deformation in a nontrivial way depends on the interaction between the fiber and the environment. Thus, it is impossible to uniquely obtain indications of axial strains  $\epsilon_{11}$  using the

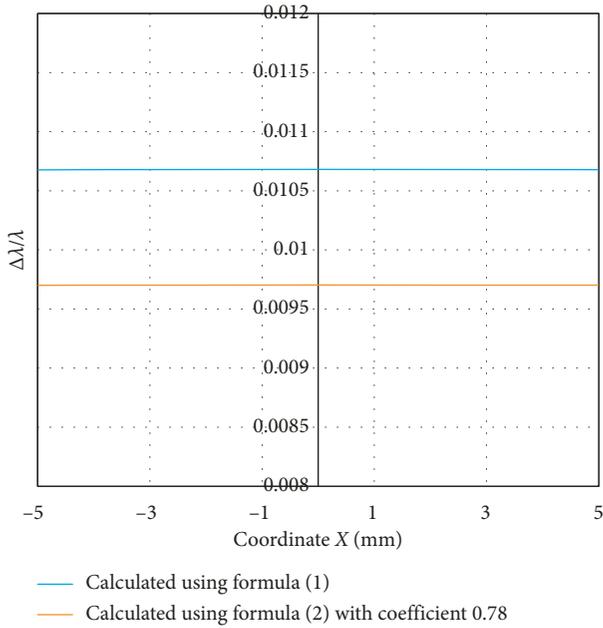


FIGURE 8: Estimated value  $\Delta\lambda/\lambda$  when the fiber is attached to the surface through the adhesive layer.

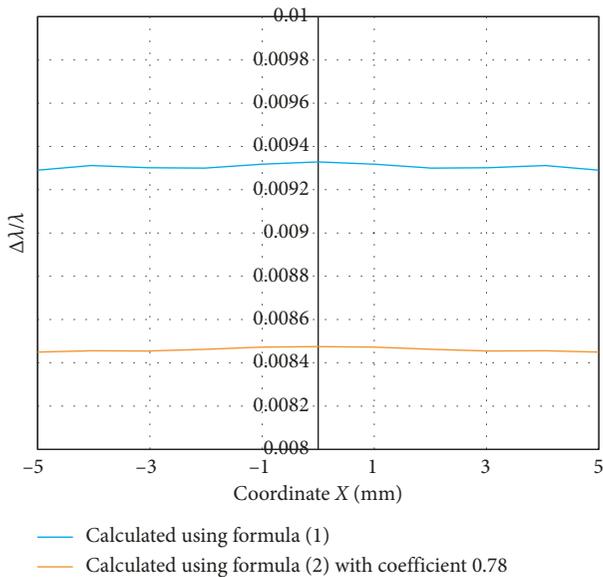


FIGURE 9: Estimated value  $\Delta\lambda/\lambda$  when the fiber is located on the composite ply and attached to the surface through the adhesive layer.

relation (1), and in order to determine the remaining components, a number of linearly independent measurements must be made at the same coordinate point.

There are several approaches to achieve that, both experimental and theoretical. The main technological approaches are based on the imposition of two gratings with different periods [39, 48], application of the sensor with superposition of two gratings of the same length inside the fiber core surrounded by two concentric shells [49], and using the Bragg grating recorded in a birefringent optical fiber [50, 51].

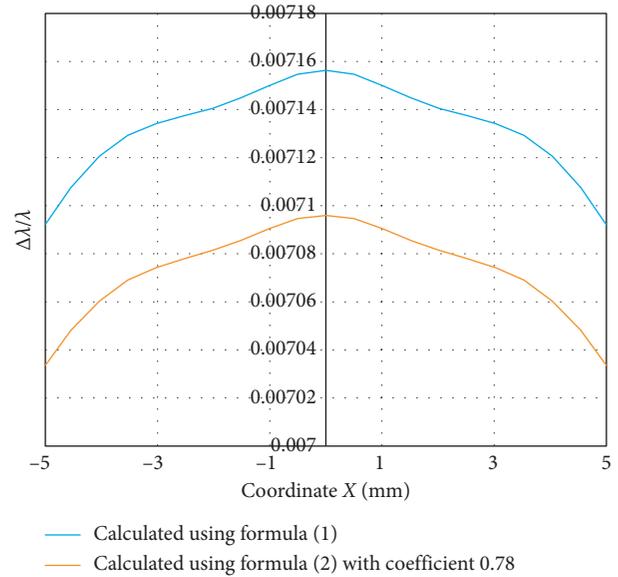


FIGURE 10: Estimated value  $\Delta\lambda/\lambda$  when the fiber is located between the composite plies and attached to the surface through the adhesive layer.

One of the theoretical approaches aimed at solving the problem of determining axial strains in the optical fiber inside a complicated environment is associated with development of the theory of strain transfer, which is used to establish a quantitative relationship between strains in a measured object and an optical fiber, and is aimed at minimizing the transfer error deformations and an increase in the measurement accuracy of sensors [44–47].

From the point of view of the manufacturing process, when developing schemes for monitoring structures with the help of FOS, both the method of attachment and the properties of the microstructural elements surrounding the sensor should be considered. In particular, it is necessary to minimize the thickness of the adhesive layer and optimize its properties in such a way to ensure the least impact on the transfer of strains from the measured object to the optical fiber.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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