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## TESTING OF AN OPTOELECTRONIC SYSTEM OF DISTRIBUTED FIBER-OPTIC SENSORS FOR MONITORING AND DIAGNOSING THE STATE OF BUILDING STRUCTURES

**Abstract.** This article discusses distributed systems of fiber-optic sensors based on Bragg fiber gratings for monitoring and diagnosing the state of building structures, which allow periodic measurements and monitoring of the state of engineering structures, assess trends in their technical condition and thereby facilitate the identification of possible threats. The paper presents the results of experimental tests of an optoelectronic system of distributed fiber-optic sensors based on fiber Bragg gratings. The distribution of deformations has been estimated. The results of the study show that shape changes can be reliably detected using all installation methods and fiber optic sensors before significant cracking occurs in the cement.

**Keywords.** Distributed fiber optic sensors, fiber Bragg gratings, monitoring, building structure.

### Introduction.

One of the main types of fiber sensors are sensors based on fiber Bragg gratings [1, 2]. Such grating is Bragg mirror, namely, periodic structure of the refractive index, made directly in optical fiber core, with length of about 1 cm. Such structure reflects light in narrow spectral range. Gratings are recorded on special photosensitive optical fibers due to the so-called photorefractive effect [3]. Another type of point sensors are sensors using Fabry-Perot interferometers [4]. Fabry-Perot interferometers consist of two reflectors located on each side of optically transparent medium. With appropriate distance between the reflectors, the transmittance of the interferometer is high. Distance changing leads to drop in transmittance. When reflectors are highly reflective, the reflectance is very sensitive to changes in wavelength or distance between reflectors.

Standard design of point sensor, based on Fabry-Perot interferometer is described in [4]. Fabry-Perot interferometers are attractive for use in sensors, since they make it easy to establish connection with measured physical or chemical quantities [4]. In sensors, based on Mach-Zehnder interferometers [4], coherent radiation of single-mode (simultaneously in relation to transverse and longitudinal modes) laser is injected into a single-mode fiber and, using a fiber-optic splitter, is divided into two beams of approximately equal intensity. A kind of sensor, based on Michelson interferometer was proposed by SOFO [5,6].

### Materials and methods.

Mounting the sensor along the monitored object is critical to ensure that voltage is transferred from the structure to the sensor cable. Stress behavior within building structures usually varies depending on material properties, loading conditions, etc. Therefore, sensors must

be placed not only in suitable locations, but also using suitable installation techniques according to project requirements. Rotation and twisting measurements are important for monitoring various types of cable systems and mechanical structures [7, 8], and even in textiles [9]. The article [10] presents a method using simple and homogeneous Bragg gratings to track the forces acting on metal wires, which are elements of mechanical structures. Figure 1b shows a steel rod reinforced with carbon fiber, the condition of which is monitored by sensors with a fiber Bragg grating (FBG - fiber Bragg grating).

The sensitivity of systems of this type is most often evaluated using static and fatigue tests. On figure 1b shows the so-called smart steel cables with embedded carbon fiber cores and installed FBG sensors. The system proposed in this work was subjected to tensile tests in order to determine the sensitivity of the measuring system. The obtained results show the stability of the measurements and the accuracy is higher than the measurements using strain gauges.

Fiber-optic methods for measuring twist and coil have several important advantages, such as resistance to external conditions (variable temperature or electromagnetic field), relatively easy placement of sensors on structures, and the ability to simultaneously measure in many places [10]. There are many methods for optical measurement of rotation and torsion [11]. Sensors using optical fibers include the following: systems based on Sagnac loop and optical connectors [12], Sagnac interferometer and optical fibers with elliptical polarization PM (PM-polarization maintaining) [13], single-mode fiber coupler [14], long-period fiber LPFG optical gratings (LPFG: long period fiber gratings) [15], polarization-maintaining FBG gratings [16], and simple simple FBGs [17]. Recently, inclined structures of NIRB have become very popular in applications for measuring rotation, twist, and other dimensions [18, 19]. These gratings use the SOP-state of polarization (SOP-state of polarization) effect of applied light on the spectral characteristics of cladding modes [20]. This is due to the fact that the LISG grating deprives the optical fiber of cylindrical symmetry [21] and, thus, makes it possible to detect changes in the polarization orientation of the incoming light. NVRBs have all the advantages of classical FBG technologies, the most important of which are insensitivity to changes in the electromagnetic field and small size. An additional advantage of NIBS structures is the large number of cladding modes visible in a relatively narrow spectral range. Interrogation systems using classical FBG gratings [22] or direct laser signals [23] can also be used to detect the spectral shift that occurs in inclined FBG structures. The region of the spectral characteristics of the NISG grating corresponding to the cladding modes changes under the influence of many factors, for example, the refractive index [24], the force that causes the structure to bend [25], changes in the liquid level on which the grating is located [26, 27, 28], and also temperature and structure elongation [29].

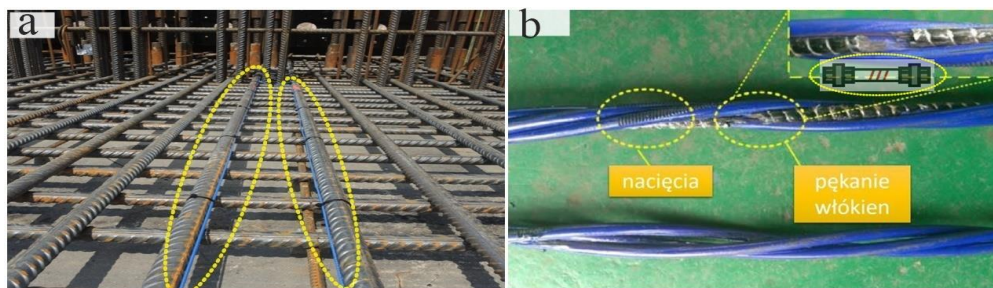


Figure 1 - Sensor installation methods: (a) Application along the rebar. (b) steel cable controlled by FBG sensors

For concrete structures, it can be used both inside the structure and along the surface. However, the monitoring results vary significantly depending on the installation location and the type of cable used with embedded carbon fiber rods and clamp-on FBG sensors.

Reinforced concrete objects allow direct application of the sensor inside the structure, where either bare fibers or thin cables can be glued with appropriate adhesives to the surface of the stylus or inside the grooves to assess the deformation of the stylus. behavior. Stronger sensor cables can be attached to reinforcing bars with cable ties to fix the concrete load. The reinforcement itself also has the advantage that the cable is better protected during the pouring process, especially in the case of high concrete delivery pressures.

Terrestrial cable applications with embedded carbon fiber rods and clamp-on FBG sensors in civil engineering are particularly useful for downstream equipment and monitoring. Flexible, for example, densely buffered sensor fibers can be individually guided along a surface to cover conspicuous areas such as surface cracks and the like. The use of a cable with embedded carbon fiber rods and surface-mounted FBG sensors in construction is especially advantageous for downstream instrumentation and monitoring. Flexible, for example, densely buffered sensing fibers can be individually directed along the surface to cover areas of interest, such as areas of surface cracks or the like.

As shown in Figure 3c, the fiber can be directly bonded to the surface using adhesive solutions that also protect the optical fiber from mechanical stress and provide higher strength in practical conditions.

Sensor installation technology not only affects monitoring capabilities, but may also be limited due to practical circumstances on site. The implementation of the sensor must be appropriate for the construction process itself and may be limited due to lack of installation time or access barriers. Therefore, proper coordination with the building contractor is essential for the successful installation of the sensor.

### Results and discussion.

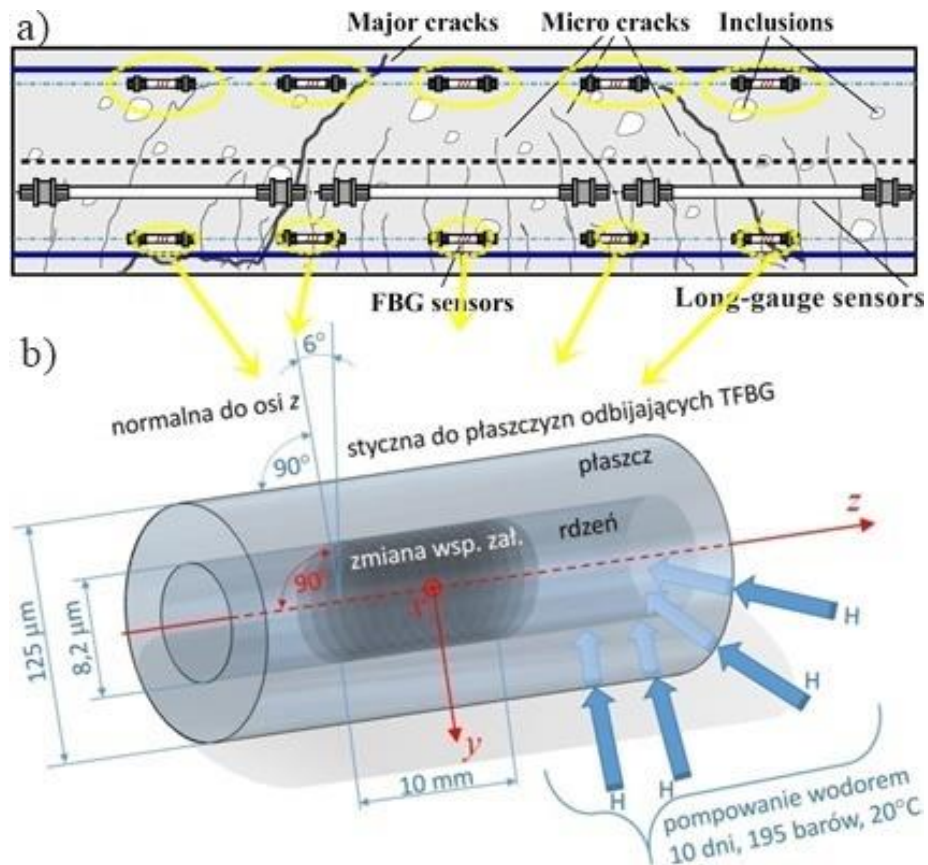


Figure 2 - Cross sections of  $I_{AV}$  averaged intensity distribution  $I_{AV}$  along z axis

Concrete structures in civil engineering are usually affected by local inhomogeneities such as inclusions or cracks that arise as a result of the construction process itself or the loads during operation. Thus, the location of the strain gauge inside the concrete, as well as the appropriate length of the gauge, is important for data interpretation (figure 2a). Large-diameter strain gauges are capable of capturing the overall behavior of a structure, but their capabilities are limited to detecting local defects. FBG sensors located along the structure, or point sensors with a shorter sensor length, can provide local deformation response at selected locations, however with the disadvantage that events between the sensing elements can be missed. The function of distributed probing of cable systems with built-in fiber rods and clamp-on FBG sensors basically allows both comprehensive registration of deformation behavior without gaps and localization of local defects.

Fiber optic sensors generally transmit strain (and temperature) values along the longitudinal axis of the installed sensors. If two or more measurement lines are placed inside a structure with the same geometry in a well-known arrangement (figure 2a), strain values can be used to derive curvature characteristics along the object that result from potential bending orthogonal to the direction of perception.

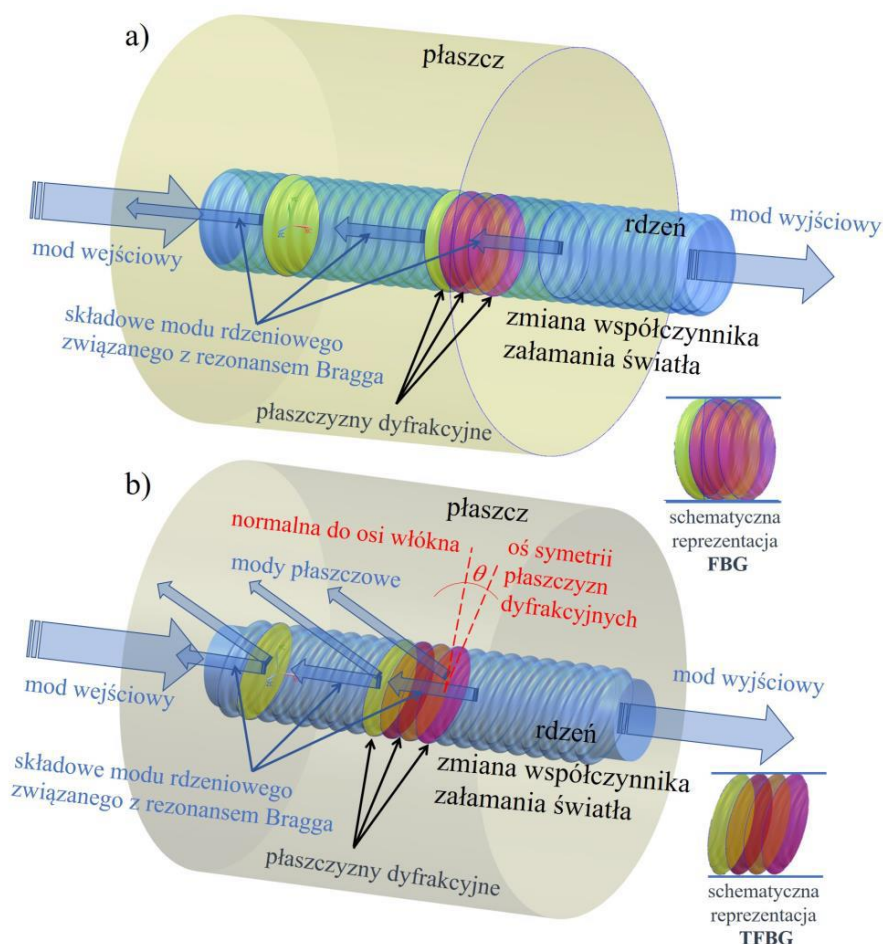


Figure 3 - Schematic representation of diffraction planes of Bragg structures: a) FBG type, b) TFBG type

In the case of energy coupling between individual modes in an optical fiber with a periodic structure, the wave vectors have a direction consistent with the symmetry axis of the fiber. This direction is also known as wave vector of periodic structure. It can also be written that in the case of energy coupling between individual modes, e.g. mode  $m$  and mode  $n$ , the condition

of phase matching between these modes is met, which we will write in the form of two equations:

$$k_m = k_n + k_B, \quad (1)$$

and at the same time

$$k_m = k_n - k_B. \quad (2)$$

If the wave vector of the Bragg structure  $\vec{k}_B$  has no direction, then the wave number  $k_B$ , which is its measure, does not have one distinguished sign. In equations (1) and (2),  $k_m$  denotes the wave number of the  $m$ -th mode, while  $k_n$  refers to the wave number of the  $n$ -th mode, where the values of the wave numbers for individual modes are a function of the effective refractive index and are determined by the following relationship:

$$k_i = \frac{2n}{\lambda} n_i, \quad (3)$$

where  $n_i$  is the value of the effective refractive index for  $i$ -th mode, with a wavelength equal to  $\lambda$ . In turn, the wave number of the Bragg structure is equal to:

$$k_B = \frac{2n}{\Lambda_B}, \quad (4)$$

where  $\Lambda_B$  is the period of the structure measured along the axis of symmetry of the fiber on which it is written. In the case of structures with diffraction planes not tilted in relation to the normal to the fiber axis (Figure 3), the light entering the structure is reflected directly in the opposite direction on its individual planes, which is visible on the spectral transmission characteristics as the main minimum corresponding to the reflected core mode. According to equations (1)-(2), such reflection occurs for waves whose wavenumber of the Bragg structure is equal to twice the wavenumber of the core mode  $k_m$ . Therefore, in the spectral characteristics of such a structure there is a single main peak with the largest amplitude. At the same time, it is a clear main minimum in the transmission characteristics and the corresponding maximum in the reflection characteristics (Figure 4).

The difference in the number and degree of excitation of the cladding modes between the FBG and TFBG structures is explained by the aforementioned phenomenon of shaping the light beam in these structures. The light introduced into the optical fiber with a simple periodic structure and propagating in its core falls on individual FBG planes at right angles to these planes and is reflected in the opposite direction, i.e. backwards, and this reflection is also directed to the optical fiber core. In the case of TFBG structures, in which the mesh planes are tilted at an angle relative to the normal to the fiber axis, the reflections on such planes direct part of the light to the cladding, and not, as in the case of FBG, only to the core. This results in the phenomenon of light coupling to the cladding modes that meet the phase matching condition, and they propagate backwards, i.e. in the direction opposite to the direction of propagation of the introduced light. Small minima appearing on the FBG transmission characteristics are caused by limiting the structure only to the core of the optical fiber.

In most cases, periodic changes in the refractive index are produced only in the core of the fiber. This is because it is the core of the fiber that is photosensitized and when recording the structure, e.g. when using light from the UV range, the refractive index in the core changes mainly. Therefore, in the place where the FBG-type structure is formed at the core-cladding boundary, there is a change in the effective value of the refractive index, which leads to poor diffraction of light towards the cladding. The solution leading to the reduction or even elimination of this type of phenomenon is to subject the entire optical fiber to the process of photosensitization, i.e. both the core and the cladding.

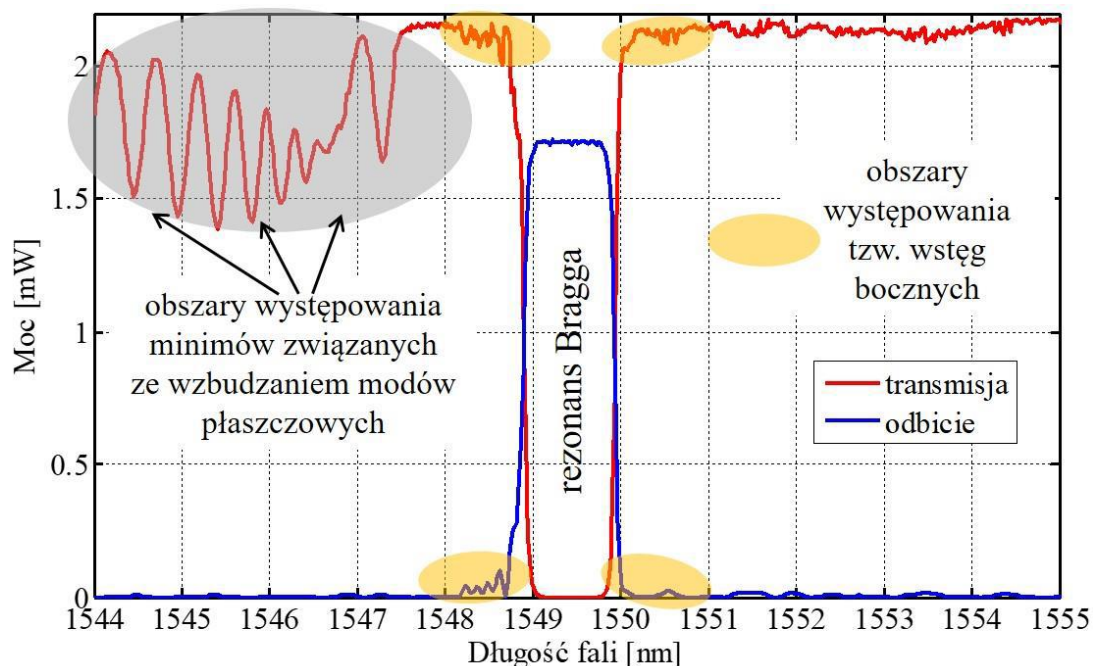


Figure 4 - Measured Spectral Characteristics of Fiber Bragg Structures of the FBG Type

### Conclusions.

This article presents the capabilities of various types of sensors and distributed fiber-optic sensors based on Bragg fiber gratings were evaluated during load tests of cement beams, where various installation methods were used to attach sensors along the reinforcement, inside concrete or on the surface of the structure. Installations with distributed sensors based on Bragg fiber grating.

The results show that shape changes can be reliably determined using all installation methods and sensor fibers before significant cracking occurs in the cement. Estimates of various technologies show that spatial resolution limitations or interpolation between the points of detection of the FBG really limit the accuracy of the distributed shape determination method.

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## ҚҰРЫЛЫС КОНСТРУКЦИЯЛАРЫНЫҢ МОНИТОРИНГ ЖӘНЕ ДИАГНОСТИКАЛАУ ҮШІН ТАРАТЫЛҒАН ТАЛШЫҚТЫ-ОПТИКАЛЫҚ ДАТЧИКТЕРДІҢ ОПТИКАЛЫҚ-ЭЛЕКТРОНДЫҚ ЖҮЙЕСІН ТЕСТІЛЕУ

**Аңдатпа.** Бұл мақалада инженерлік конструкцияларының күйін мезгілімен өлшеуге және мониторинг жасауға, олардың техникалық жағдайының тенденцияларын бағалауға және сол арқылы ықтимал қауіптерді анықтауды жеңілдетуге мүмкіндік беретін құрылыс конструкцияларының күйін бақылау және диагностикалау үшін Брэгг талшықты торларына негізделген талшықты-оптикалық датчиктердің таратылған жүйелері қарастырылады. Жұмыста Брэгг талшықты торларына негізделген таратылған талшықты-оптикалық датчиктердің оптоэлектрондық жүйесінің эксперименттік сынақтарының нәтижелері келтірілген. Деформациялар таралуын бағалау жүргізілді. Зерттеу нәтижелері цементте айтарлықтай жырықтар пайда болғанға дейін барлық орнату әдістері мен

талшықты-оптикалық сенсорларды қолдану арқылы пішіннің өзгеруін сенімді түрде анықтауға болатынын көрсетеді.

**Түйінді сөздер.** таратылған талшықты-оптикалық датчиктер, талшықты Брагг торлары, мониторинг, құрылыс құрылымы.

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## ТЕСТИРОВАНИЕ ОПТИКО-ЭЛЕКТРОННОЙ СИСТЕМЫ РАСПРЕДЕЛЕННЫХ ВОЛОКОННО-ОПТИЧЕСКИХ ДАТЧИКОВ ДЛЯ КОНТРОЛЯ И ДИАГНОСТИКИ СОСТОЯНИЯ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ

**Аннотация.** В данной статье рассмотрены распределенные системы из волоконно-оптических датчиков на основе брэгговских волоконных решеток для контроля и диагностики состояния строительных конструкций, которые позволяют проводить периодические измерения и контроль состояния инженерных конструкций, оценивать тенденции их технического состояния и тем самым облегчать выявление возможных угроз. В работе приведены результаты экспериментальных испытаний оптоэлектронной системы распределенных волоконно-оптических датчиков на основе волоконных решеток Брэгга. Проведена оценка распределения деформаций. Результаты исследования показывают, что изменения формы могут быть надежно определены с использованием всех методов установки и волоконно-оптических датчиков до того, как в цементе произойдет значительное растрескивание.

**Ключевые слова.** Распределенные волоконно-оптические датчики, волоконные брэгговские решетки, мониторинг, строительная конструкция.

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