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Fiber optics based system of monitoring load-bearing building structures

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Abstract. Inspection of the technical condition of load-bearing structural elements of buildings and structures in the process of their construction and operation is an important issue at the present time. A fiber-optic monitoring system is proposed as a solution to the problem of early diagnostics of defects and damage to load-bearing building structures. We developed a scheme for testing fiber-optic sensors, which make it possible to control the stress-strain state of monolithic reinforced concrete structures. For testing, a series of monolithic concrete beams of rectangular cross section were reinforced with fiber optics during their manufacturing. The values of mechanical stresses and deformations arising in beams under loading were determined. Using the tested samples as an example, it was established that the proposed fiber-optic monitoring system (FOMS) makes it possible to control stresses and deformations (and to predict the appearance and growth of cracks) in various building structures. The main element of the system is a hardware-software complex capable of estimating the parameters of a light wave at the output of the optical fiber. The distance from the installation site of the data processing unit to the measurement point can cover the area of 30 km. At this, fiber-optic sensors operate without additional power supply from a laser with the power of up to 30 mW. The proposed monitoring system has a low cost of one measurement point, it is easy to install, which is a good alternative to the electronic beacon-recorder device and the development of optical digital technologies in construction.

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1. Introduction

At present, as the number of buildings and houses are increasing it is important to provide their sustainability. Possible solution to this task is the development of the integrity monitoring system. The improvement of the semiconductor and digital technologies made the building of the monitoring system easier and more effective. The relevance lies in the fact that there is well-known problem of sudden collapse of structures after their long-term operation. The solution requires developing methods and tools for diagnosing the state of building structures. In addition, with the consideration of the Industry 4.0 objectives the proposed technologies must be digital and energy efficient. This is a rather serious challenge for scientists and developers who create new diagnostic and monitoring tools in construction.

The operation of the buildings depends on many factors. From the practice it is known that every integrity deviation in the monolithic reinforced concrete elements and structures can lead to the potential destruction of the whole building. Visual inspections, as well as with the use of nondestructive testing means, showed the presence of hidden slowly developing or already formed and growing cracks in the body of the building structure. The technical inspection can establish the parameters of the defects and identify the causes of their occurrence. Cracks have certain geometric dimensions and are also characterized by the speed of development, which is quite important when assessing the danger to the integrity of the structure of a building or structure.

Therefore, it is much more efficient not to control already formed cracks but to take preventive measures for determining the state of stress and deformation changes in structures and identifying emergency zones where cracks arise from stress concentration.

The simplest method of crack opening control is installing gypsum, cement, glass beacons on the cleared surface on both sides of the crack that is currently used but is obsolete and does not meet present day requirements.

The unique properties of optical fiber allow its use, as a distributed sensor, and the optical fiber (OF) must be built into the monolithic reinforced concrete structure at the stage of its manufacture. The OF application provides a number of advantages [1]. In contrast to the copper wire OF is energetically passive, because it does not transmit electrical signals. An important point is that OF should contain a protective sheath of plastic to protect the glass filament from moisture, which may be contained in the reinforced concrete building structure, such as foundations. The selected object of research is optical fiber of G.652 standard, which is quite common in telecommunications systems and mass-produced by various countries, which provides a fairly low cost per linear meter. The OF also has sufficiently high reliability and durability, it is not susceptible to electromagnetic interference. The main hypothesis is the research of the G.652.D standard optical fiber application as a tool for the early diagnostics of the building structural elements destruction, because of the propagating inside its core light wave parameters dependance from mechanical impact. The obtained data can be further fixed using a hardware-software complex and converted into numerical values of the crack growth.

As shown by the analysis of the literature and the results of various years of research, the problem of cracking in monolithic reinforced concrete structures remains unsolved and creates many problems in the operation of buildings and structures [1–9]. The source of cracks is quite a serious danger, since it can be hidden from visual control, and the process and speed of crack growth can be quite rapid. It may also be noted that in the world there are enough examples of destruction of buildings and structures with cracks, sometimes, unfortunately, with tragic consequences. So far there are no effective tools to ensure monitoring of the cracks in monolithic reinforced concrete structures in real time for a long time without interruption. This will allow revealing the centers of crack formation at early stages, to identify their location and to take measures for their elimination. The analysis of the literature also showed that in some cases the cause of failure of monolithic reinforced concrete structures are errors made by designers. In the source [1] the collapse of buildings at the stage of construction connected with the violation of the technology of concrete production, weak reinforcement or incorrectly chosen distance between the columns are considered. There are examples when fully constructed buildings collapsed with terrible consequences and loss of life. The author does not give an example that a monitoring system was used, capable of detecting the danger of collapse at an early stage.

The analysis of the literature and the results of research in different years demonstrates that the problem of cracking in monolithic reinforced concrete structures remains unresolved and creates many problems in the operation of buildings and structures [1–9]. The source of cracks is a serious danger, because it can be hidden from visual inspection, and the process and the rate of crack growth can be fast. It may also be noted that in the world there are enough examples of destruction of buildings and structures by cracks, sometimes, unfortunately, with tragic consequences. In addition, currently, there are no effective means for continuous real-time monitoring of the technical condition of monolithic reinforced concrete structures without interruption in long periods. This will allow to reveal the centers of cracking at early stages, to determine their location and to take measures on their elimination. The analysis of the literature has also shown that in some cases the cause of failure of monolithic reinforced concrete structures is errors made by designers. Source [1] considers the problems associated with the collapse of buildings at the construction stage due to violation of the technology of concrete production, weak reinforcement or improperly chosen spacing between the columns. There are examples where fully constructed buildings have collapsed with terrible consequences and loss of life due to saving construction materials and their poor quality, as well as the lack of technical supervision and control over the constructed buildings. In Turkey, where residential buildings with reinforced concrete frame are mainly located in seismically active areas, design errors in building structural systems including low reinforcement and low column height, high beam reinforcement, non-seismic connections of steel parts and poor concrete quality have resulted in thousands of deaths and huge economic losses in earthquakes (1999 and 2011) [2].

On the other hand, in the Gaza Strip (Israel) many construction projects are being built in a short time, especially after the Gaza war in 2014 [3]. The analysis of this source revealed that the leading factors of the building destruction are primarily the human factor that can be described as violations of construction technology or the use of low-quality materials. The violation of the technology can be distinguished to preparation of the foundations and deviations from the vertical axis of the building; insufficient reinforced concrete structures; absence of technical supervision and the use of expired materials, using rusty or reused reinforcing steel or materials that are not suitable for the application. In the work [4], authors analyzed the sources of the bridge damages. The most valuable ones are wrong calculations of the wind load and errors in the technology of construction or repair work. Paper [5] describes the problem of defects, failures and accidents in the construction of buildings in the Czech Republic. Particular attention is paid to defects and malfunctions that have resulted in death or serious injury (to people or animals), safety hazards or serious property damage. There are considered failures of load-bearing structures, i.e. such states of structures that do not meet their functional requirements during their operation.

The analysis of defects and damages to public buildings in Botswana [6] showed that structural defects in building structures accounted for 73 % of total repair costs. To prevent building structures defects and damages, authors recommend implementation of quality assurance programs throughout the life cycle of building objects, especially at the design and construction stages. In work [7], studies were carried out to identify factors contributing to the occurrence of structural defects in load-bearing structures that occur during construction in Malaysia, especially in the Penang region, to minimize the time and cost. In article [8], the authors consider the hidden defects of the building, the causes of their occurrence and ways to prevent them. As the possible main factors, the human factor during the design stage as well as load created by people, environmental conditions, water concentration and leaks in the premises and violation of the governmental rules and standards are considered.

The analysis of defects and damages in the building structures made of monolithic reinforced concrete in the Republic of Kazakhstan appeared due to several reasons. First of them is practical absence of the domestic regulatory framework for the design and construction of high-rise and unique buildings including those with multifunctional purposes. Second is the little experience in the design and construction of high-rise buildings. Third is the violation of the technologies of concrete, formwork, construction and installation works, including those under extreme conditions; low quality of building materials, structures and products; deviation from the project [9]. Roof collapses of such underground structures as tunnels, mine roads, power plants and oil storage facilities can result in catastrophic injury, loss of life and significant financial loss. Major accidents have occurred in such civilian infrastructures as the collapse of the West Virginia rail tunnel in 2009, the collapse of the tunnel in Hangzhou, China in 2008, and the collapse of the subway tunnel in Cologne, Germany in 2009 [10].

To assess the strength and continuity of concrete and reinforced concrete structures, various non-destructive testing devices are used. The existing methods of continuous diagnostics of the strength of reinforced concrete structures have a certain complexity and require a certain amount of expensive preparatory work [11–13]. For instrumental inspection of buildings and non-destructive testing. One of them can be called a fairly well-known method of instrumental examination using non-destructive flaw detector IPS-MG4, this device allows to set the strength parameters of reinforced concrete and masonry structures, and also has a number of functions to control the homogeneity of concrete. There are several analogues with identical functions and almost similar technical characteristics used for the express quality control of concrete and mortar with the shock-pulse method (GOST 22690).

The relevance consists in developing and searching for new methods of the early diagnostics of deviations from standard working parameters of the building structures based on fiber-optic technologies and methods of computer processing the images of color spots using a hardware-software complex. This will allow real-time informing of the building structure technical condition and taking timely measures to prevent emergencies. The possible solution to the problem can be the early diagnostics of defects and damages of building structures with the application of a fiber-optic monitoring system (FOSM).

In the age of digital technologies, various electronic monitoring systems have been developed, which, among other things, allow detecting integrity faults of buildings and structures for the growth of cracks in monolithic concrete and reinforced concrete structures. This problem is quite serious and occurs in various cases, especially when construction technology is violated. Accordingly, the development of effective tools for early diagnostics of distributed and significant objects is very relevant.

The goal of this article is to research the conditions of the building to further develop the a real-time monitoring system based on the fiber-optic sensor for monolithic reinforced concrete structures. This will detect the centers of crack formation and establish their dislocation place in the foundation structure.

The task is to develop a monitoring system of the distributed or quasi-distributed type that in comparison does not use electricity in sensitive elements, with the lowest possible cost of one point-by-point measurement instrument. The cost is important for the subsequent implementation of the monitoring system in the construction industry. At this, a single-mode fiber is used as a guiding system for transmitting the measurement data and a sensor simultaneously over a greater distance with the lowest energy consumption compared to the existing systems of monitoring the building structure technical condition.

To monitor the technical condition of buildings and structures, tensometric, acoustic piezoelectric transducers, molecular-electronic, fiber-optic strain gauges [14] are successfully used. Among them the most widespread are electrical sensors: strain gauges in the form of thin rectangular foil strips with labyrinth wiring diagrams. The disadvantages of strain gauges are limited length (up to 800 m), a large number of cables, and the cost.

Fiber optic strain sensors (FOSS) have been developed based on the improving the technical characteristics of optical gauges. The principle of this system operation is refraction of a light beam in an optical fiber that has a sharp bend.

One solution of the problem is early diagnosis of defects and damages of building structures is a fiber-optic monitoring system (FOMS). The idea is to use G.652.D standard single-mode optical fiber as a distributed sensor, as it has several advantages in comparison with twisted-pair copper and its cost is several times lower. The task is to develop a monitoring system of a distributed or quasi-distributed type without applying electric signals, with the lowest possible cost for point-by-point measurement instrument. The cost of implementing a monitoring system in the construction industry is a crucial consideration. Specifically, the use of a single-mode fiber as both a guiding measurement data transmission system and a sensor is being explored in this case.

Optical fiber (OF) allows to transmit signals with high efficiency over long distances with a low attenuation coefficient at minimal energy consumption. OF has also sufficiently high reliability and durability, it is not susceptible to electromagnetic interference.

A scientific analysis of the works of foreign authors who work with optical fiber and develop fiber-optic sensors has been carried out. Similar problems exist in the mines of China, Russia and India, where rock displacement and pressure must be controlled. At the moment, a lot of research is related to the developing monitoring systems to control the geotechnical condition of mine workings, where optical fiber is used as a sensor. The condition of the coal mines can be inspected by different values, for example the temperature of the coal seams or pressure of mine water in the rocks. The system proposed by researchers from China for coal mine has been successfully tested and proved to work in coal mine conditions. In their development, Bragg gratings are used [15]. The application of FOS with Bragg gratings is not always economically justified, primarily due to the cost of the elements, such as an optical spectroanalyzer.

There is an example of a fiber-optic monitoring system capable of measuring the pressure on the coal face. The article [16] presents a detailed description of this system and the results of its testing. In the source [17] a distributed fiber-optic sensor and data processing unit are considered. The sensor is designed to monitor the stress-strain state of rocks of coal mine workings, capable of automatically monitoring the geotechnical condition of underground workings. The rock pressure can reach the value of 400–500 MPa. There is no need to use this sensor because the racks are already equipped with rock pressure monitoring system and this sensor performs a duplicate function. However, there is no information about its performance. In [18] information about the use of Bragg gratings for the creation of distributed fiber-optic sensors capable of measuring the deformation of the rock massif is presented. It may be noted that there is no example of their use in the coal industry because of the complexity and high cost. There are two interesting publications [19] and [20], which are devoted to the use of Bragg gratings to create a distributed FOS (DFOS). These articles contain only theoretical information without the results of practical research and testing in mine conditions, but the basis of any scientific work must be a well-planned and set experiment. In this case, the experiment was not conducted, and the system was not tested in practice. The very idea of using optical fiber as a sensor for monitoring the geotechnical condition of coal mine rocks is very relevant, as it allows to achieve a high level of safety. The light wave propagating along the core cannot become a source of fire or explosion of the mine atmosphere. In [21] the information on tests of already ready-to-use fiber-optic sensors based on Bragg gratings, which allow to measure deformations of the rock mass, is presented. The authors claim to have conducted tests in coal mines and received positive results. Tests were conducted in a coal mine in China.

There is a similar article [22], which also mentions that there were successful tests of DFOS based on Bragg gratings. This sensor allows monitoring the geotechnical condition of mine workings of coal mines of one of the Chinese mining companies, but there is no information about its practical application yet. Despite the high cost of sensors based on Bragg grids, some researchers continue to work, although other directions have already appeared. For example, research is already underway into the use of long-period optical gratings, which would be unambiguously more advantageous to use due to the absence of devices for analyzing the optical spectrum in the measurement chain. There are papers that consider only Bragg gratings [23], and the proposed developments are only at the stage of laboratory samples, which are not subject to commercialization due to the problems discussed above. Therefore, it is necessary to look for a way to simplify the fiber-optic sensor and reduce its cost. An optical interferometer could be a feasible solution as it is relatively inexpensive for both the sensor and data processing unit, yet offers high measurement accuracy. However, this method faces several significant issues that prevent its utilization in monitoring the structural integrity of monolithic reinforced concrete foundations in buildings. Since the measurement process is greatly and adversely affected by the temperature changes of the optical fiber [24]. The influence of temperature is also characteristic of sensors based on Bragg gratings and it is quite a serious problem of occurrence of noise in the measuring channel and output of false measured values [25]. There is also a mention of attempts to solve these problems arising during the application of the FOS with Bragg gratings. In the mentioned work to measure the mechanical parameters with the various strain gauges. On the other hand, the system cannot be used for long time and the main information carriers are electrical signals. In the work [27] authors suggest using fiber optic sensors instead of them, while some problems of using optical fiber are considered. According to the known literature, the foundation of the system for developing the computational device of the monitoring system can be formed for any application [28]. In the source [29] some issues on the use of Bragg gratings and problems in their use are considered. An article [30] proposes a simplified design of a pressure sensor. There are several articles that contain the results of research related to the control of displacement of rocks in a mine, using fiber-optic sensors [31], refers to the OF application to inspect the pads of the quarry [32].

The industry produces an electric string load cell "Autograph-1.2", which is installed already in the place of the formed crack. The length of the wire from the sensor to the data processing unit is not more than 800 meters, which sometimes limits the scope of its application, also the sensor itself has a rather high cost for a single point of measurement.

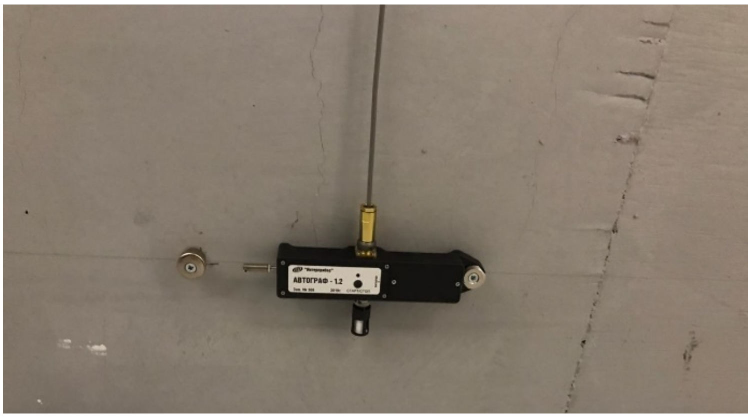

Figure 1. Electronic beacon-recorder “Autograph-1.2” mounted in the beam crack.

Many articles, papers are discovering the problem of the technical condition monitoring for the monolithic reinforced concrete building structures. Timely detection of cracks and crack growth monitoring are important [33]. A publication devoted to the description of methods for assessing the destruction of reinforced concrete was found [34].

There is a problem of effective control of monolithic structures including foundations in which cracks form (Fig. 2). In many cases, extended objects are not available for inspection. The growth of cracks in the foundation is the reason of the building walls destruction that in future threats with the collapse. The experience of using OF to control rock displacement demonstrated the possibility of the determination of the stress-strain state change in the structure at the early stages of the stress concentrators formation and initiation of cracks. OF can be built into the body of the foundation and stay in it during the entire service life. In contrast to the copper pair of a string sensor, in which the length of the guide system is limited to 800 meters, OF can transmit measurement data over the distance of more than 50 km, while energy consumption is only a few milliwatts. The FOMS can use existing fiber-optic telecommunication networks to transmit data within the city or over longer distances. The design of the FOS is simpler, and it will have a lower cost compared to a string sensor.

Figure 2. Cracks in the foundation.

If to install the FOSs in the body of the foundation during its mounting or to fix them on its surface, then there can be timely detected the centers of destruction. The problem of diagnosing the state of concrete structures is relevant and is considered by various researchers. It is especially important to detect the problem at the early stages of crack development. There are works [35] and [36], connected with the development of methods of monitoring the technical condition of reinforced concrete electrical signals and magnetic fields. As a result of the review, it can be said that at the present moment the greatest interest and relevance is acquired not by electrical, but by optical measurement systems. There are the results of similar studies of fiber-optic sensors, which are buried in the ground and used in security systems [37]. The main advantage of the proposed system in comparison to the existing ones is integration of the G.652.D standard single-mode optical fiber with the hardware and software complex [38]. Another differentiating factor lies in the methods employed for processing signals from the FOS. Additionally, preliminary testing of fiber-optic sensors embedded in reinforced concrete beams has been carried out [39]. The fundamental of the process of the fiber-optic sensors have also been discussed and presented in an earlier source [40].

2. Methods

Given the need to develop highly efficient means of remote monitoring load-bearing reinforced concrete structures including columns, floor slabs and coatings, walls, flights of stairs and foundations, the aim of the experimental studies were solving the problems discussed above [12, 33–36]. The basis of The proposed monitoring system that inspects the condition of the monolithic reinforced concrete structures including floors with pre-stressed beams is the fiber-optic technology based on monitoring changes in the parameters of a light wave passing through an optical fiber under mechanical action. Fiber-optic sensors that are based on the optical fiber standard G.652.D allows to simultaneously solve two important problems: reduce the cost and ensure the length of the measurement channel within 30 km. The advantages of fiber-optic sensors have already been discussed previously and outlined [37–40]. The diameter of the glass filament is 125 µm, which is covered by a protective layer of acrylic and plastic. The final diameter is about 1 mm.

The experiment was carefully planned, first of all the fiber optic sensor test scheme was prepared. A data processing unit was specially designed, to which the sensors were connected. The idea was to simulate the real situation when the optical fiber is inside a monolithic reinforced concrete structure to reproduce as accurately as possible the real conditions of foundation loading and load measurement. The optical fiber was placed inside the concrete beam, and it was secured to the reinforcement with plastic clamps. The optical fiber was impacted mechanically as the beam was destroyed with the all parameters of the of the propagating light wave were recorded using a hardware-software complex. The method proposed below makes it possible to control the stress-strain state of a concrete structure and, in this case, of a concrete beam. Before a crack forms, a zone of mechanical stress concentration is formed, which can be fixed by means of a fiber-optic sensor and also establish the place of the crack formation, which is very important, since the foundation may be hidden under the soil layer and inaccessible for visual inspection. This method implies that the optical fiber will be installed inside the foundation structure at the stage of its erection, and the fiber ends should have optical connectors to connect the measuring device. In [40, 41] there is already information on how measurements are made and how the fiber takes the load. The hardware-software complex (HSC) receives information from fiber-optic sensors, then processes it and outputs a numerical value of load changes on the beam, as well as changes in its stress-strain state. The mechanical action on the OF changes the parameters of the light wave passing through the OF and falling on the sensitive multi-pixel photodetector. The HSC processes the data according to the algorithm developed and converts the changes in the parameters of the light wave into changes in the pattern of pixels. The higher the load on the beam, the greater the transition of pixels from black to white state. Further the microprocessor outputs the numerical value of the measured value.

Fig. 3 shows a general view of reinforced concrete beams laboratory samples that simulate various monolithic reinforced concrete structures. The beams use G.652.D standard optical fiber that is identical in its characteristics and was attached to the reinforcement at the stage of its manufacturing. Its ends were released to the outside. The fabricated samples are made with transverse dimensions of 40x40 mm, the length of 160 mm, using cement of PC-400 D.0 grade, Volsky sand. Concrete beams were stored within 28 days in water according to the GOST. The hardening conditions are natural.

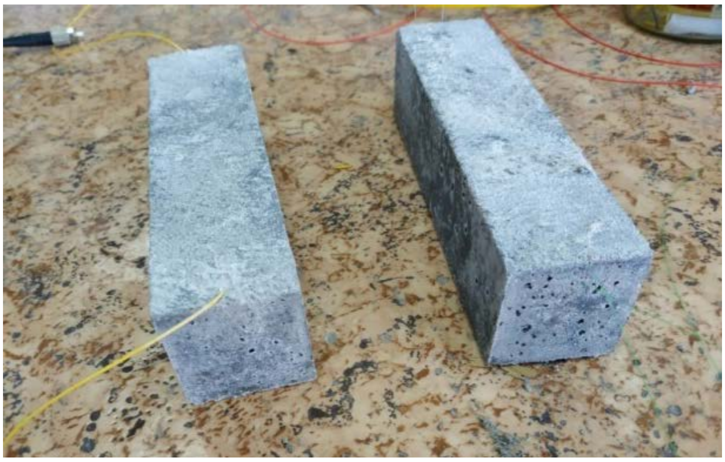

Figure 3. Laboratory samples.

The result of the research was the establishment of numerical values of mechanical stresses and strains that occurred in the body of the beam when the load increased. The beam was subjected to fracture and a crack was formed in it, this process was also recorded by the APC. The beam was divided into three equal parts and contained three sensors. The determination of the crack formation place was considered.

Accordingly, 6 optical fibers, three working and three reserve, were embedded in the reinforced concrete beam at the manufacturing stage. Optical connectors of the SC PhysicalContact type are installed at both ends of the fiber optic sensors, which facilitates switching with the guiding system for transmitting optical signals and control devices.

The proposed method implies that an optical OTDR (Optical Time Domain Reflectometer) is used to obtain a more accurate distance to the location of the formed crack in extended objects. The scheme of the experiment and measurement is shown in Fig. 4. The diagram shows that the beam was terminated into three zones, which are marked with Roman numerals I-III. The use of the reflectometer is economically justified only on long objects over a distance of 500 meters, in other cases the HSC is able at a distance of 200 meters to ensure an accuracy of crack detection within 3 meters. At a distance of 100 meters it is already 1.5 meters. The main disadvantage of the measurement scheme is the inability to determine the exact location of the crack without the use of a reflectometer (Fig. 4). HSC monitors various parameters, including additional losses of optical power, which according to a linear function increased proportionally to the increase of the mechanical load. The fiber optic sensors were pre-calibrated using an automatic strain gauge with AID-4 strain gauges. The HSC performs all measurements in real time and saves the results in the computer memory. As a source of loading was used testing machine MII-100, which is used to conduct static bending tests (serial number 239, inv. number 2235, certificate of verification GVL-2-03-1800003). The bending strength parameter of the beam was measured in kgf/cm^2. Load rise rates of 5 kg/s were selected. Concrete beams of rectangular section of 40x40 mm and length of 160 mm participated in the tests. A VIAVI (JDSU) Smart Pocket OLP-38 optical wattmeter and a Smart Pocket OLS-34 light wave emitter were used as measuring instruments. Switching with fiber-optic sensors is made by means of optical connectors and optical connectors of CS type. Optical wavelength of 1310 and 1550 nm is used.

During the experiments the load applied to the center of the concrete beam was increasing smoothly until its destruction or a crack was formed in it. The appearance of the test bench is shown in Fig. 5. The generator of the coherent light is the semiconductor laser 1 (SmartPocket OLS-34/35/36) connected through the optical connector to optical fiber 2. The optical fiber is inside beam body 3, and its ends go out for connection to the measuring system. MII-100 is capable of developing pressure up to 100 kgf/cm^2, in the Figure it is marked by position 4. The direction of the force vector application is indicated by the F arrow. The pressure on the beam is carried out through device 5. The beam is located on two stationary supports 6, thereby forming two support points for fracture tests. The fracture of the beam occurs in its middle. One end of the optical fiber is connected with the optical connector to the SmartPocket OLP-38 optical power meter, indicated by position 7, which measures the level of additional losses that occur when exposed to the optical fiber. The mechanical impact on the center of the beam causes the development of mechanical stress and deformation, this impact is transmitted respectively to the optical fiber, in which the refractive index changes and the phase of the light wave propagates, which is recorded by photo-detector 4.

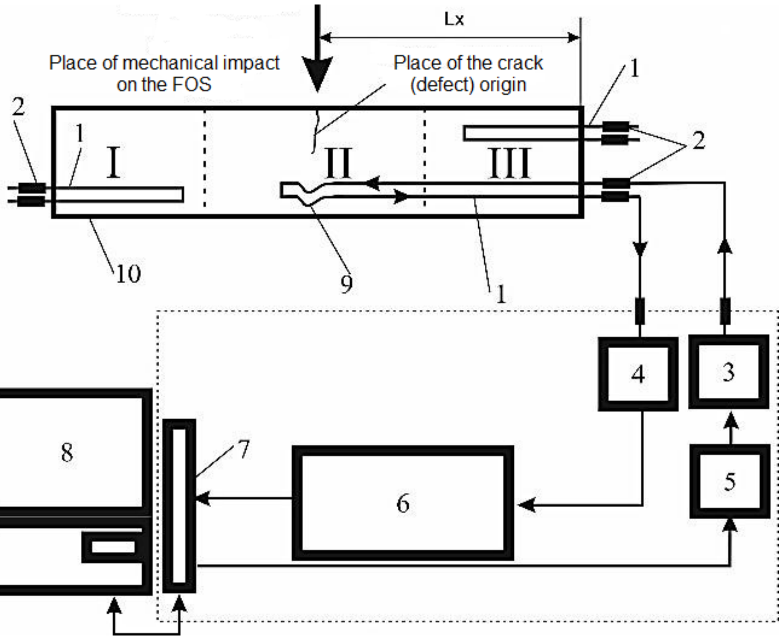

Figure 4. The structural scheme for the mechanical stresses values measurement and determination of the defect location: 1 – optical fiber, 2 – optical connectors of the SC brand, 3 – semiconductor laser with a system of controlling its pumping, 4 – photo-detector, 5 – device for controlling laser pumping, 6 – device for preliminary processing of the received data, 7 – device for matching, 8 – personal computer, 9 – place of microbending, 10 – beam.

Figure 5. Testing machine MII – 100 (two-support bend): 1 – radiation source; 2 – optical single-mode fiber in a protective sheath; 3 – beam; 4 – testing machine MII-100; 5 – area of pressure application; 6 – stationary support; 7 – optical power meter.

It was recorded that when the load on the concrete beam increased, the value of additional optical losses in the OF increased in proportion to the increase of the load, with a linear law predominating. Mechanical impact on the OF caused a change in the properties of the light wave passing through the OF, and changes in light intensity were also recorded.

Part of the optical power is lost when microbending occurs [41]. This makes it possible to detect the magnitude of mechanical effects on the beam with sufficiently high accuracy through changing the magnitude of additional losses. One important fact can be noted that the OF remained undamaged and continued to perform its functions, while in the place of the formed crack a slight deformation of the fiber is preserved, it will allow using a refractometer to accurately determine the location of the beam damage.

During the experiments, some conditions were set. The magnitude of loading should not exceed 16 kgf/cm^2, with a load of 0 to kgf/cm^2 at the beginning of the experiment. Two ranges of light wave 1310 and 1550 nm) were used. The temperature in the room where the experiments were conducted was fixed at 25 °C. The movement of the beam was excluded (OX = 0 m; OY = 0 m; OZ = 0 m). To process and approximate the data, the capabilities of Microsoft Excel were used. Each measurement during the experiment was carried out 30 times. The number of necessary repetitions of experiments to achieve a sufficient reliability equal to 0.95 was chosen according to the recommendations of the source [43]. The coefficient of variation was also determined. Also to process the results of the experiments was used Wolframalpha program, which is publicly available and is an interactive system for processing the results of various experiments, as well as helps in working with arrays of data.

The main limitation of the proposed system is the need to install sensors directly in the body of the foundation structure itself. In this regard, the use of this system for other building structures requires the use of another type of sensors. The SNO can be installed directly in the body of the foundation or attached to its side surfaces. When using the HSC in practice it should be understood that for each building structure it is necessary to configure the HSC separately and to calibrate it. The proposed monitoring system can be adapted to monitor the technical parameters of any monolithic reinforced concrete structures, such as walls, bridge abutments, slabs and hydraulic structures. At the moment this system represents a laboratory specimen, on which positive results are received, which allow to assume its practical introduction, but for this purpose comprehensive industrial tests are required which will be realized in the future. The main purpose of the research was not to determine the strength characteristics of concrete, but to investigate the response of the optical fiber to the deformation of concrete. The limitations of the test machine, as well as the purpose of the experiment, were taken into account in conducting the experiment.

3. Results and Discussion

The results of the experiments were processed and presented in the graphs of Fig. 6 and 7. These graphs represent only part of the data obtained. Different values were obtained in different wavelength ranges of 1310 and 1550 nm, but the principle of linearity of measurement was maintained in both occasions. The results were obtained by measuring the additional losses in the OF when it is deformed. It should be understood that the fiber is subjected to microbending and the well-known photoelastic effect occurs, which was recorded. The measurement scheme is presented earlier in Fig. 4. In the graphs of Fig. 6 and 7, which show how the additional optical power loss varied with the step-by-step increase in the load on the concrete beam during its bending tests. It is known that loading in the center of the beam causes changes in mechanical stresses and deformations, and the beam begins to deflect, concrete layers and reinforcing bars affect the fiber-optic sensor located inside the beam. The step-by-step increase in load leads to the failure of the beam and the formation of a crack. The instrumentation and the HSC recorded that at the moment of failure there is a small spike in additional losses and a short-term increase in losses. This moment remains in the memory of the HSC and if necessary, can be retrieved from it. The graph of Fig. 6 reflects the dependence of the additional losses at a wavelength of 1310 nm, the graph in Fig. 7 reflects the growth of additional losses at a wavelength of 1550 nm. At the same time, loading in both cases was performed in the same way and with the same step. The experiments with OF without a protective shell showed its greater sensitivity to a lower load, but at the same time there was a big problem of its damage, since the glass filament is quite fragile. Therefore, the use of protective sheathless fiber is not recommended because the sensor can be easily damaged. In all cases, the fiber with the protective sheath remained intact and without visible damage.

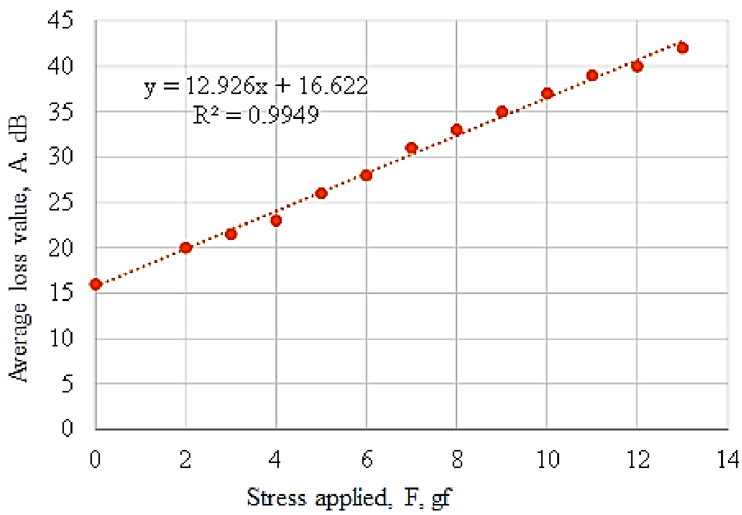

Figure 6. Optical fiber with the wavelength of 1310 nm loss value with a step-by-step increase of bending load.

For each experiment, the reliability and accuracy evaluation criteria were selected. Using the recommendations of the source [43], the necessary number of measurements was selected. The parameters at which the required reliability was achieved were selected. For example, for the graph in Fig. 6, the Student coefficient has a value of 2.098 with a confidence interval of 0.94. In addition, the calculation of the accuracy of the measurements was performed and the absolute error was determined to be 2.32 and the value of the relative error was 3.87 %.

As it was mentioned before, the difference of the graph presented in Fig. 7 consists in other values of additional losses, formed in OF from mechanical impact on it. Analyzing the dependence of the optical power loss presented in Fig. 7, which is called additional, because it is formed during microbending of the OF and differs from the straight section of the OF not affected by the mechanical impact. The experiment was performed using a wavelength of 1550 nm. The load was identical and increased in steps similar to the experiment with a wavelength of 1310 m. A pattern was found that as the wavelength increased, the losses decreased with the same mechanical load on the OF.

For example, for the graph in Fig. 7, the Student coefficient has a value of 2.091 with a confidence interval of 0.94. The measurement accuracy was also calculated and the absolute error was determined to be 3.01, as well as the relative error, which was 2.97 %.

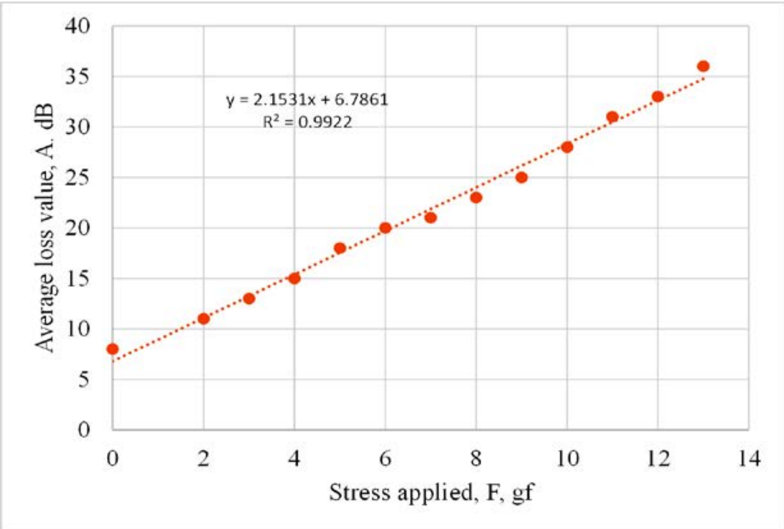

Figure 7. Optical fiber with the wavelength of 1550 nm loss value with a step-by-step increase of bending load.

The FOMS presented below is able to control the loading and growth of cracks in various building structures. The FOMS is able to work with monolithic reinforced concrete and steel building structures. So far, the laboratory sample is capable of registering a change in the loading of the structure only at four points. Fig. 8 shows the program window, which allows controlling four sensors simultaneously. The number of measuring channels and sensors is theoretically unlimited, but in practice there are limitations associated with the number of cores of the fiber optic cable. As stated above, an important element of the monitoring system is the HSC, which performs an assessment of the parameters of the light wave passing through the core, when a microbend occurs, the properties of the light wave change and, first of all, the phase of propagation of the intensity. When a microbend occurs, part of the light wave travels beyond the shell into the environment. The greater the microbending or mechanical impact on the OF, the more energy of the light wave escapes to the outside. A multi-pixel photodetector is installed at the end of the fiber, which captures all changes in the light spot and converts them into a numerical value of the measured quantity, such as mechanical load or pressure. As the graphs in Fig. 6 and 7 have shown, the higher the load, the greater the additional losses of optical power, which was recorded by the HSC program.

HSC monitors many parameters of the light spot falling on the surface of the sensitive photodetector. The program analyzes the shape of the light spot, its reduction with increasing load, the change in shape in each segment and the number of formed white pixels, which grew with proportional to the load on the beam. After processing all the data and making certain adjustments for external interference, numerical values are given. The HSC also has an alarm function, in case of changes in the parameters and their growth, the operator is given a signal indicating the zone of load change. The APC window shown in Fig. 8 contains a number of important functions, which can be used to perform its adjustment. Designed and used in experiments HSC contains four independent channels capable of working at a distance of up to 5 km. In the experiments only two channels were used to achieve a certain guarantee of reliability of the obtained results. Measured parameters are displayed in various forms. The instantaneous value of the measured quantity and the averaged value are displayed. There are also two information windows with the oscillogram of the measurement process and the representation of the measured value as a separate bar. The operator manually sets the measurement limits and starts the monitoring system in operation. The individual bursts are specifically recorded and shown. As can be seen on the screen, external vibrations from the machine are also recorded. Each channel reacts differently because of the different settings and sensitivity. The instrument readings, the swashplate is sufficiently successful in interference control that even with a deliberate impact on the beam there is no interference and the difference between the averages is negligible. The HSC is able to recognize interference and perform averaging of the measured values.

All the measurement parameters are stored in the computer memory. On the right there is an enlarged view of the measuring channel during operation, which shows the case of oscillations during the appearance of noise and subsequent impact on the sensor. It is seen that the noise generated by the laser presents a single peak, and the effect presents a more stable and time-consuming section of the diagram.

Figure 8. Program interface: 1 – threshold value, 2 – number of triggers, 3 – trigger time period, 4 – average amplitude value, 5 – instantaneous amplitude value, 6 – response time fixation window.

Separate bursts in the measurement data array appear due to the vibro-acoustic effect on the OF from the electromechanical part of the MII-100N testing machine. The program has a number of settings that allow dealing with incoming external interference, which can affect the accuracy of the measurement, as well as the results reliability.

The program window in the setup mode, where the image of the light spot is on the left, and the results of the analysis of changing the pixel pattern are on the right, is presented on the Fig. 9. The left part of the figure shows the light spot, which is formed on the surface of the Full HD photomatrix, which is the measurement body. The photodetector is a matrix, which is installed on the end of the optical fiber. On the surface of the photomatrix a light spot is formed, which can be referred to the well-known Poisson's spot. This spot of light has a fairly bright central part and a darker part closer to the edge of the spot. The middle is very bright and usually has, as observations have shown, about one-third of the entire area of the spot. The rest of the light spot profile looks darker. The transformation process is rather complicated and is performed by the program automatically, but some moments should be explained separately. The photodetector records all changes of the light spot. It also converts the image into a negative and then analyzes the number of white pixels formed on the background of the OF shell. The more the load on the beam and therefore directly on the sensor itself, the more changes in the light spot. The spot loses intensity and becomes less bright with increasing mechanical impact on the OM. In the negative image the white zone increases, unlike when there was no load, the spot was completely black. When the load increases, the transition of pixels from black to white is observed. As shown in Fig. 9, the left side shows a positive image of the spot, but the right side is its negative. With increasing load on the screen in the right part the white ring increases in size and at the break of the OV becomes the maximum occupying almost the entire window.

This is a rather serious problem that has to be dealt with. At the output, a stepped profile is formed that is described by the Gaussian distribution.

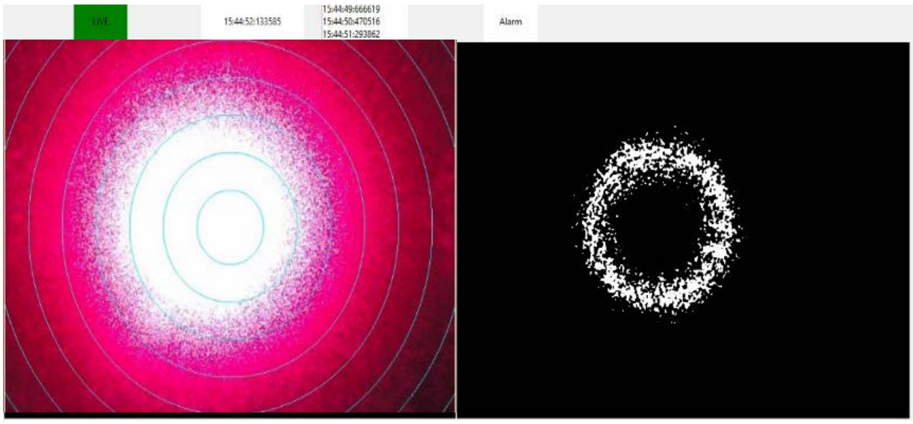

Figure 9. The program window in the setup mode.

From the output of the optical fiber the light spot falls on the high-resolution television matrix surface. The core glows more intensely, and the shell is less intense. The spot can slightly change its shape with changes in temperature and fluctuations in the light generator frequency. In order to negate all the noise from laser is the coherency and the possible error of 5 nm and the varying power from 10 to 30 mW. With increasing the load on the structure, the pressure on the OF increases proportionally. As the result the propagating light wave properties changes. The measurement of the values were performed by the television matrix, and the hardware-software complex converts them into numerical measured value. Fig. 10 shows changing pressure on the OF that is converted into changing the pixelized image of the light spot. In comparison with the previous Figure, there is observed increasing the number of white pixels and decreasing the number of black ones. Additionally, the graph of the white pixels number dependence from the pressure on the OF is presented on the Figure. The number of dark pixels unlike the white ones decreases with the pressure growth. If the load is removed from the optical fiber, then the white pixels amount will decrease as presented in Fig. 10.

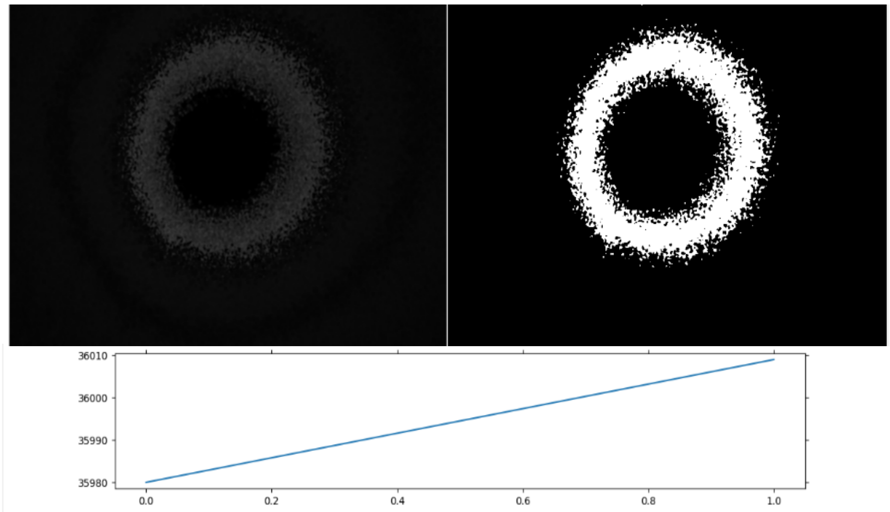

Figure 10. Changing the spot with increasing pressure on the OF.

When the laser is unstable, the operation of the entire FOMS is disrupted. For this occasion, the HSC has the function of learning and distinguishing time peaks, when the frequency of the radiation source light wave deviates. When mechanical impact is done on the optical fiber, the pixel pattern changes in the direction of increasing white color, and additional losses that can be converted into numerical values of the displacement or deformation parameters increase, respectively.

Fig. 11 shows a photo of a FOMS laboratory specimen in the setup mode. The presented specimen has four measuring channels but only two were used in the experiment to compare the results and to refine them. The Figure also shows that both channels produce the same parameters and diagrams. Preliminary adjustment of the program made the elimination of the reaction to changing the frequency of the radiation source possible.

During the increase of the pressure, a uniform increase in the deformation parameters of the beam is observed. Because of the occurrence of a photo-elastic effect caused by microbending additional losses in the OF increase. Theoretically, there is limitations of the number of channels by the number of strands of the fiber-optic communication cable. The approximate maximum number of measurement channels is 64.

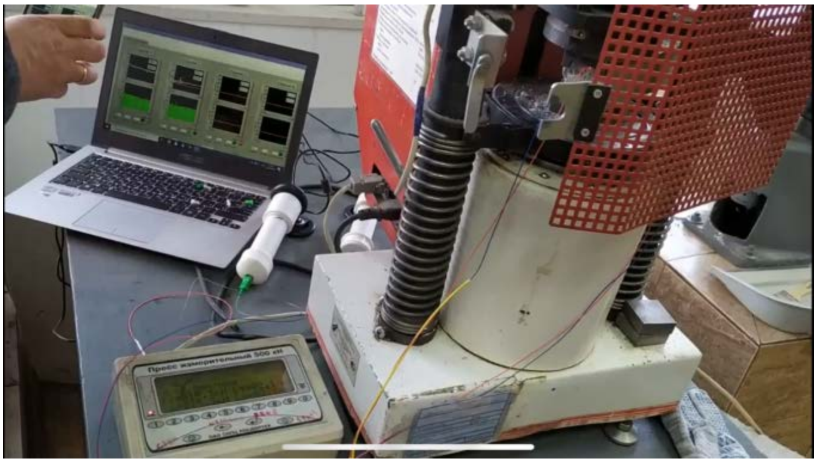

Figure 11. FOMS laboratory specimen.

The FOMS is used in testing concrete beams for compression and bending. When the beam is broken, the optical fiber in most cases remains undamaged and makes it possible to determine the parameters of further crack growth and its dislocation. Thus, it is possible to use this system for monitoring the technical condition of monolithic reinforced concrete structures. In contrast to the known methods of constructing FOS based on interferometers, reflectometers, and Bragg gratings, the proposed FOMS has a simpler design and a lower cost per measurement point. This system has lower energy consumption compared to electric string sensors. The radiation source is common for all the measuring channels, and the television matrix is installed separately for each channel. The hardware-software complex is installed on a personal computer.

Experiments have shown that the G.652.D standard single-mode optical fiber is capable of handling a measurement channel length of up to 30 km, in contrast to the G.651 standard multimode fiber, which was experimented with earlier. The 30 km long sensor can cover almost any need in the construction industry, as there are no such long foundations. Industry-proposed strain gauge monitored cracks can operate at distances up to 800 meters from the data processing unit, which is not always convenient in real construction conditions. The use of the previously considered strain gauge is limited, since it is installed over the already formed crack. Also, this sensor is much more expensive to produce. As for the OV standard G.651 is earlier in its production and is suitable for use at distances up to 1 km. Losses in this type of fiber are quite significant in contrast to the OF standard G.652, and it was excluded from further development as unpromising. The fiber optic sensor at a length of 30 km consumes power equal to 30 mV. Measured attenuation of OF standard G.652 does not exceed 0.22 dB per km. The use of fiber-optic sensors will make it possible to build a distributed or quasi-distributed system for monitoring the technical condition of monolithic building structures. To create a fully distributed monitoring system, an OTDR must be added to the existing HSC. The lower cost is provided using the OF, low energy consumption, a simpler sensor design.

Compared to the other methods of periodic control that are currently used and discussed earlier, the FOMS works in real time, therefore, it can control the process of crack formation at the early stages of their development, because fiber optic sensors are built into the design itself.

An important difference is also the development of an original hardware-software complex that uses intelligent processing of the data received from fiber-optic sensors, which reduces the likelihood of obtaining false data when the temperature changes or when some other external interference occurs. This work is based on the preliminary scientific groundwork and the results obtained in the development of the system for monitoring the technical condition of the reinforced concrete lining of mine workings and used out-of-the-box work is the modernization of the already considered HSC in [41]. In the process of research a number of upgrades and improvements were made, which improved the noise immunity of the measurement channels. The results of the research coincided with previous studies, which were carried out earlier and concerned the development of the monitoring system of the technical condition of the reinforced concrete lining of mine workings [42]. The proposed monitoring system is able to recognize at an early stage the process of load changes and the occurrence of stress concentration in the monolithic building structure. Accordingly, at an early stage to inform the user of the beginning of the process of formation and growth of cracks in the foundation. The use of fiber-optic sensors makes it possible to create a distributed and quasi-distributed monitoring system, which is unattainable when using string strain gauges, which are able to monitor parameters only in one point.

4. Conclusions

1. The above experimental studies allowed developing a test scheme and a laboratory prototype of the system for monitoring the technical condition of monolithic building structures made of reinforced concrete.

2. Concrete beams with embedded fiber-optic strands of G.652.D standard were used in the experiments. The values of mechanical stresses and deformations arising in the beam during its loading were determined and places of defect (crack) appearance were established.

3. The research was conducted to study in detail the processes of propagation of light waves with lengths of 1310 and 1550 nm through the core of an optical fiber at the moment of application of external mechanical load to a concrete beam into which an optical fiber of standard G.652 was embedded at the pouring stage. We also measured additional losses of optical power during step-by-step loading. The experiments showed that it is possible to measure, with sufficient accuracy and linearity, the magnitude of the load on the concrete beam, through the measurement of the additional optical power loss in the OV formed by microbending.

4. The developed HSC is the fundamental basis of the monitoring system, which is intelligent and capable of learning. The HSC can transform and convert the values of mechanical impact on the beam into the numerical value of mechanical stress–strain parameters with high accuracy. Future studies will be done to improve the HSC in the field of machine learning algorithms, to increase the level of its adaptation to various conditions of operation of monolithic reinforced concrete structures and to increase the level of noise immunity of measurement channels.

5. A limitation of using the proposed system is the need to install sensors directly inside the structure, so to assess the technical condition of other load-bearing monolithic reinforced concrete structures, which will require adaptation and small changes in the technical characteristics of the sensors.

6. In the process of the experiment, it was found that the use of single-mode fiber optics of G.652 standard makes it possible to significantly increase the distance from the sensor to the data processing unit within 30 km, which increases the capabilities of this method and determines its present relevance. Switching from 650 nm to 850 nm wavelength will increase the distance from the data processing unit to the FOS.

7. Presented FOMS is a new generation monitoring system, based on fiber-optic technology, where OF is both a means of data transmission and a sensitive element at the same time.

8. FOMS are relatively simple and cheap, as they do not use fiber-optic measuring systems based on interferometer, reflectometer and Bragg gratings.

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