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MONITORING REINFORCED CONCRETE BUILDING STRUCTURE TECHNICAL CONDITIONS BASED ON THE USE OF QUASI-DISTRIBUTED FIBER-OPTIC SENSORS

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ABSTRACT: Construction and safe operation of buildings and structures in complicated geological conditions, in the conditions of dense development, is a vital issue for large, densely populated cities. Systems of monitoring the technical condition of the supporting structures of buildings based on the use of fiber-optic sensors have been developed. Fiber-optic sensors operate on a new method of controlling the parameters of a light spot using a hardware-software complex. The proposed monitoring system is quasi-distributed and can determine the damaged and most stress-strained sections of the supporting reinforced concrete structures of buildings at the stage of their occurrence and take preventive measures to protect them. The monitoring system can perform the function of measuring pressure on the building structure and establish the damage zone and signal in case of a sharp change in parameters during the structure destruction. Using this system, it is possible to monitor the technical condition of building structures of the underground and aboveground parts of buildings and to monitor their integrity in real-time. A four-channel hardware-software complex has been developed that uses the physical principles of measuring pressure on a concrete beam, as well as changing the refractive index during micro bending of an optical fiber of the G.652 type, which can be expressed through changing the light spot incident on the surface of the photodetector. The dependence of additional losses in an optical fiber on the applied force at a light wavelength of 650 nm has been obtained.

Keywords: Defects and damage, Building structures, Monitoring, Fiber-optic sensors, Soil

1. INTRODUCTION

For the safe operation of buildings and structures in the conditions of dense urban development, one of the topical issues is selecting the base of the building and carrying out the underground cycle work. Since earthworks can cause soil subsidence and cracks around the built-up area, as well as affect the existing buildings and structures (uneven subsidence of the base, subsidence, and destruction of foundations, the aboveground part of the building) [1, 2], to protect buildings, scientists have carried out a lot of studies of the supporting structures of the foundation of the adjacent building [3-5].

Disasters associated with the development of deep pits occur mainly due to improper control of groundwater [3, 4]. Decreasing the groundwater level in the area of Bangkok (Thailand) caused not only subsidence of the soil but also affected the bearing capacity of the soil around the piles [5].

Defects and damage to load-bearing building structures are found both in buildings and structures in operation and newly built ones. The incorrect design of the soil base leads to defects and damage to the foundations, which in turn affects the technical condition of the aboveground part of the building or structure [6-8].

If to consider tunnel construction, then one of the causes of accidents (10 %) in the course of tunneling are unfavorable hydro-geological conditions, groundwater or heavy rainfall, and loose soil layers; the other subjective reasons are non-compliance with the construction technology (30 %) [6]. In Shanghai (China), a 13-story building collapsed due to the impact on the foundation structures of 10 m high accumulated dirt from one part of the building and the development of underground pits for a garage on the other side [7]. After 30 years of operation, in a five-story residential building in Athens, sloping cracks began to appear in the transverse load-bearing walls of the building, distortions of the door frames due to the incorrect design of the foundation structures, as well as the impact of the underground cycle, works in the course of constructing another five-story building next to the existing building [8]. In work [9], the technical condition of bored piles is studied due to the presence of a structural defect in one pile.

The search for defects and damage to foundations is sometimes associated with various difficulties since the foundation is hidden in the ground and usually, the detection of defects is carried out by manual excavation. The number of pits for examining the foundation is assigned depending on the size of the structure in the plan and its design solution.

The search for new methods of controlling defects and damage to building structures at the stage of construction or operation of buildings is a very topical issue at present. There are methods of studying the properties of foundation soils directly within the depth of foundations and under their sole, as well as to the depth of the compressible thickness [10].

Qian et al. [11] propose a piezoceramic-based passive probing approach for detecting typical failures in concrete piles. Xingsen et al. [12] present the technology of geological exploration, the principle of which is based on the seismic scattering profile used to detect defects in the foundation of a power transmission tower.

Tran et al. [13] present a simple analytical method of determining the stress-strain state of reinforced concrete beams subjected to biaxial bending. The cross-section of the beam is divided into numerous elements, after which the stress-strain state in the center of these elements is analyzed. The results of this method are compared and verified with the 3D finite element method.

One of the ways to solve the problem of determining the stress-strain state of building structures is the use of quasi-distributed fiber optic sensors (DFOS) embedded in the reinforced concrete foundation of a building or structure under construction. Using these sensors, it is also possible to monitor the technical condition of foundations that are in long-term operation.

DFOS can be used for monitoring, telemetering, and controlling various stationary objects, including extended ones (dams, pipelines, reservoirs, embankments, quarries, bridges), as well as reservoirs and earthquake-prone areas. This is a fairly wide area and the prospect of their application, but this article will consider only one aspect related to the monitoring of defects and damage to foundations.

Fig.1 shows a photograph of the reinforced concrete foundation and the crack formed. In the course of the survey, several dozens of construction sites in the city of Nur-Sultan (Kazakhstan) were surveyed, and dozens of photographs of similar damage were taken.

The existing methods of controlling and monitoring do not provide a solution to this problem.

For example, one of the modern means of controlling the development of cracks is the use of an electronic beacon-registrar "Autograph-1.2" installed on a crack of any building structure. The measured parameters are transmitted via the cable over a distance of several hundred meters to the data processing unit and the data storage server.

The basis of the presented work was the earlier work that proved the advantage of using FO for building various monitoring systems [10]. The experience of using FO to control rock displacement has shown that it is possible to determine the change in the stress-strain state of a structure at the early stages of stress concentrators formation and the crack initiation.

FO can be built into the body of the foundation and stay in it during the entire service life. There is a positive experience of using FO as sensors of pressure and displacement of rocks operating in hazardous conditions in coal mines [14].

Over time, various kinds of cracks form in monolithic reinforced concrete structures of buildings. This phenomenon is a danger associated with the destruction of foundations and the collapse of load-bearing structures.

It is difficult to control the formation, growth, and opening of cracks since the structures of the foundations are largely hidden and not available for observation. This leads to the fact that the actual technical condition of the structure remains unknown.

Fig. 1 Cracks in the foundation

When analyzing the papers published in journals included in the knowledge-intensive databases Web of Science and Scopus, a fairly high scientific interest from researchers from around the world was found. A fairly large volume of publications is associated with the development of systems for monitoring building structures and controlling crack growth. Certain methods of nondestructive testing of defects are proposed, which make it possible to identify damaged areas in a reinforced concrete structure [15]. There is the rmation on developing methods of assessing reinforced concrete destruction and controlling the development of cracks during bending based on the response of electrical parameters [16]. It is especially important to detect the problem at the early stages of crack development. Guo et al. [17] present a method of monitoring the concrete structure state is presented that is based on electromechanical impedance. The theoretical foundations for the development of cracks in the walls of buildings due to the settlement of foundations [18-20], as well as methods of nondestructive testing concrete strength [21], were studied. Previous studies aimed at developing the ems of monitoring based on fiber-optic sensors to control the displacement of rocks show that it is possible to determine changing the stress-strain state of reinforced concrete structures.

Table 1 Advantages and limitations of fiber optic sensors

Advantages of fiber optic sensors	Limitations of fiber optic sensors
1	2
Ability to multiplex parameters	Certain complexity in data processing and fiber optic conductor switching
A low percentage of signal attenuation and a significant length of the measurement channel	Occurrence of temperature disturbances and the phenomenon of fading
Resistance to electromagnetic interference.	The fragility of optical fibers and premature aging in contact with water.
No electrical signals are used in measurements	
Longevity	
1	2
Fire safety	
High sensitivity and wide measurement range	
High accuracy	
Wide signal bandwidth for fast information transfer	
Possibility of creating a distributed monitoring system	

The methods of nondestructive testing proposed below will make it possible to establish the zones of crack initiation at the early stages of the stress concentrator formation. An optical fiber (OF) can be built into the body of the foundation and stay in it for the entire service life. The existing monitoring systems have a rather high cost of one measurement point and a limitation on the distance from the data processing unit to the sensor. The length of the line should be no more than 800 meters. The use of optical fibers will increase this distance to 30 km, while the energy consumption for data transmission is only a few milliwatts. The design of the FOS is simpler, and it will have a lower cost compared to a string sensor. Table 1 shows the advantages and limitations of fiber optic sensors.

An OF can be placed in the body of the foundation during its construction or fixed on its surface. When the foundation is deformed and destroyed, the impact will be exerted on the OF, which will be fixed and have a numerical expression in units of measurement. This makes it possible to detect the centers of destruction promptly.

The problem of diagnosing the stress-strain state of building structures is relevant and is considered by various researchers. The fundamental difference of the idea from the analogs existing in the world consists in the development of a hardware-software complex capable of working with a single-mode optical fiber [22] and analyzing the data obtained by changing the pixels of a light spot incident on the surface of a television matrix. The use of a single-mode optical fiber makes it possible to increase the distance significantly from the installation site of the FOS to the data processing unit.

2. RESEARCH SIGNIFICANCE

Timely monitoring of the technical condition of load-bearing building structures for the presence of defects and damage is important for the safe operation of buildings and structures. Now scientists from many countries of the world are carrying out studies aimed at solving an important problem: an adequate assessment of the technical condition of building structures and the development of new methods of nondestructive testing. One of the ways to solve this problem is the development of distributed fiber-optic systems for controlling and monitoring load-bearing building structures. Fiber-optic sensors are already successfully used in various industries and are currently of great relevance.

3. METHODOLOGY

3.1 Preparing Prototypes of Beams

The preliminary work was carried out to prepare a solution of cement using brand PC-400 D.0, Volsky sand. In the course of concrete beams formation, fiber-optic sensors were laid that were fixed to the reinforcement using plastic ties. 12 cement beams 40x40 in size were made on a span of 100 mm (Fig. 2). After formation in a metal formwork, cement beams were placed on a vibrating table to compact the mortar. The conditions of the solution hardening were selected naturally within 28 days in water according to GOST 310.4-81 types of cement. Methods of determining ultimate strength in bending and compression.

Standard fiber-optic patch cords used in telecommunication systems with SC-type quartz connectors with the 2.5 mm ferrule were selected as sensors. Patch cords are made using single-mode optical fiber 9/125 µm (Corning, USA) with a low "water peak" standard ITU-T G.652.D. The optical fiber had a vinyl sheath and a plastic protective coating about 1 mm in diameter. The beams were tested and brought to failure using a hydraulic measuring press PGI-500 serial number 166 (made in Russia). PGI - 500 undergoes periodic testing and has a verification certificate VL-2-03-18000654. This press was used in the building materials laboratory for strength testing and for testing concrete beams for compression by generating a variable force value from 0 to 500 kN (50986 kgf).

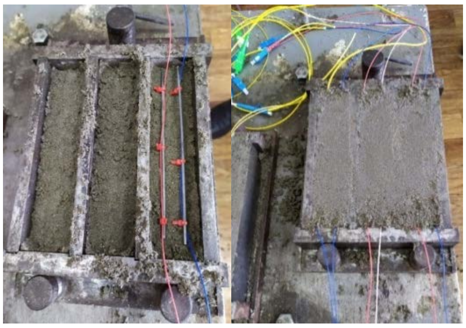


Fig. 2 The process of manufacturing cement beams

3.2 Selecting Measuring Means

To control the compression force and other parameters, there is a liquid crystal display. The tests were carried out by the conditions of GOST 310.4-81 Cements. Methods of determining ultimate strength in bending and compression. The temperature in the laboratory room varied within the range of 24-25 °C.

The beam moved along the axes OX=0 m; OY=0 m; OZ=0 m when pressure was applied. Before starting the experiments, the integrity of the fiber-optic sensors was checked, and the parameters of additional losses were set using a Smart Pocket OLP-38 optical power meter (JDSU, USA) and a Smart Pocket OLS-34/35/36 (JDSU, USA) optical radiation source. All the fiber-optic sensors remained undamaged after the beams were covered and dried.

In the experiments, a solid-state InGaAs semiconductor laser (CLASS IIIB) with a wavelength of 650 nm ±10 nm and power of 20 mW was used as a radiation source. The data processing unit has four measuring channels.

Four CMOS photo-matrices with a graphics processor for each channel separately for signal preprocessing were used as a photodetector. The experiments involved two fiber-optic sensors and two measuring channels. For final data processing, a personal computer with software was used.

Fig. 3 shows the process of experimenting using a hydraulic measuring press PGI-500 and fiber-optic sensors to monitor the technical condition of reinforced concrete building structures and foundations.

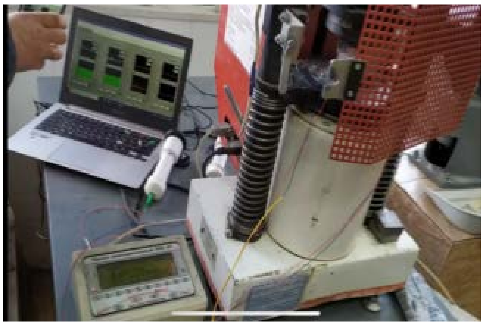


Fig. 3 Carrying out testing with the use of hydraulic measuring press PGI – 500.

3.3 Method of Carrying Out the Experiment

To carry out the experiments, a measuring layout was developed (Fig. 4). The layout operates as follows: a laser beam with a wavelength of 650 nm from source 1 that is coherent enters optical splitter 2. Then it is divided into two beams in the proportion of 50/50 in terms of radiation power. If there are more channels, then the beam is divided into each channel accordingly.

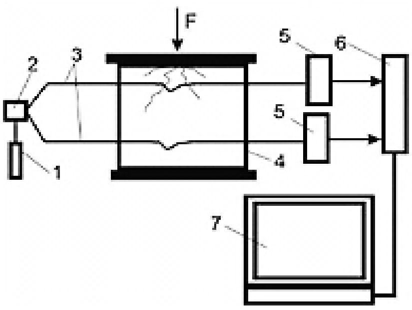


Fig. 4 Measuring layout of the experiment

The laboratory sample can work simultaneously with four measuring channels. Two fiber-optic sensors 3 are connected to the optical splitter and were previously built into the body of concrete beam 4. Photo-detector 5 based on a CMOS photo-matrix, is installed at sensor 3 output. Photo-matrix 5 captures all the changes in the intensity of the light wave that is formed when a force is applied to the body of beam 4 up to its destruction. The higher the force ap**p**lied to the concrete beam, the more significant the change in the shape of the light spot incident on the surface of photo-matrix 5.

Accordingly, it is possible to convert numerically the change in the intensity of the light spot incident on the surface of the photo-matrix installed at the output of the fiber-optic sensor into relative units of additional light wave losses. With the help of PGI-500 measuring instruments, the measuring system was calibrated and adjusted. Measurements were carried out simultaneously on two channels to eliminate measurement errors. The graphics processor of each channel is independent and performs preprocessing of the measurement data. Through matching devices 6, each channel is connected to a personal computer 7 that is equipped with software for the operation of the entire system as a whole, as well as the issuance of information in real-time.

The presented hardware-software complex is capable of measuring pressure on elements of building structures, as well as determining the impact zones and crack dislocation. When reinforced concrete building structures and foundations are deformed, quasi-distributed fiber-optic sensors will inevitably be affected, which will subsequently be recorded by the hardware-software complex of the technical condition monitoring system, with increasing the mechanical load on the beam, the mechanical effect on the optical fiber increases, which causes additional losses of the light wave passing through its core. All the measurements are made in real-time.

4. RESULTS AND DISCUSSION

The experiments were planned, and the results obtained were processed according to the known methods and recommendations taken from work [14]. The total number of experiments was 12, while measurements were carried out on two channels simultaneously. Justification of the required number of repetitions is carried out to ensure sufficient reliability of the results of experimental studies. It is established based on the K_{var} coefficient and the required degree of accuracy. A numerical study was carried out using the Microsoft excel program, with the help of which the graph of the additional losses in the FO dependence on the applied force at the light wavelength of 650 nm was guarded (Fig. 5). Microsoft Excel allows processing the results of experiments to work with data arrays. The confidence probability was p=0.95, and the Student's distribution quantile was t=1.098 for a given confidence probability with the number of degrees of freedom n k = n − k (n, k is the number of suspicious observations). The relative measurement error was δ = 2.69 %.

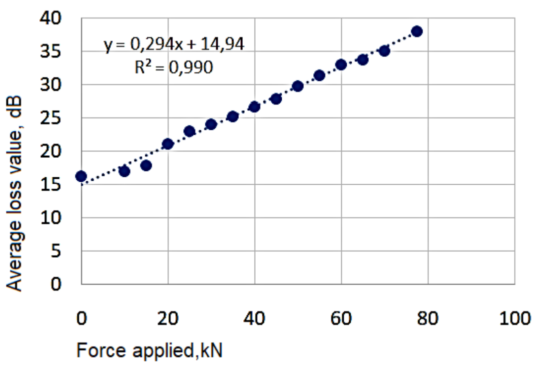


Fig. 5 Dependence of additional losses in the FO on the force applied with the light wavelength of 650 nm.

The control method is based on the use of the photo-elastic effect that occurs with the impact on the OF, with subsequent processing changes in the parameters of the light spot incident on the surface of the photo matrix installed at the exit from the OF using a hardware-software complex. This method allows establishing changes in pressure on the elements of building structures and the deformations that occur in them, as well as determining the zones of impact and the distance to the place of cracks. Optical reflectometry (OTDR) is used to determine a more precise location of damage to the OF and its deformation and, consequently, the deformation of the building structure itself. In this study, the task was to find a way or method to determine the presence of a crack in the structure, for which the OF was used that was built into the beam and perceived all the mechanical effects.

This led to changing the parameters of the light wave under mechanical action on the structure. In contrast to the known methods that use the OF to determine various physical parameters, the proposed method has differences in the algorithms of processing the parameters of a light wave using the hardware-software complex. The fundamental difference is the presence of a CMOS Photomatix and a graphics processor that allows detecting all the changes in the pixels of the light spot and converting them into numerical values. This method has advantages over a single-pixel photodetector because it allows using a photo matrix with a resolution of Full HD 1920x1080. Preliminary work was carried out to calibrate the FOS using strain gauges and an automatic strain gauge AID-4. The error of strain measurement of strain gauges should not exceed Δll= 1 μm/m in the range of ±5% (±50000 μm/m).

There were problems associated with the low sensitivity of the fiber-optic sensor placed in the beam body at the initial moment of the force application. A significant deviation and non-linearity were also noted in the force range from 0 to 20 kN. Then the curve was more linear until the destruction of the beam. At the moment of destruction, a surge in the value of additional losses was noted, based on which it could be judged that the applied force caused the appearance of a crack in the beam body and its destruction. This requires further studying to develop a method of diagnosing the occurrence of cracks in the foundation body. These problems will be solved over time with the help of hardware and software to achieve higher accuracy at the initial stages of impact on the fiber optic sensor.

Fig. 6 shows the interface of the hardware-software complex and the pictures from the computer screen that show how the intensity change of the light wave is controlled.

One of the results of the study is the development of a hardware-software complex of the technical condition monitoring system, which evaluates the change in the parameters of the light spot of an incident light wave on the surface of the matrix photo-matrix. Pixel analysis of changes in the spot area and its intensity is performed. All the changes are recorded in the computer memory and based on the analysis, the result of changing pressure on the concrete beam is given. The program can clearlyressure fluctuations in real-time and give numerical values of its changes. There are also separate visible bursts that are interference.

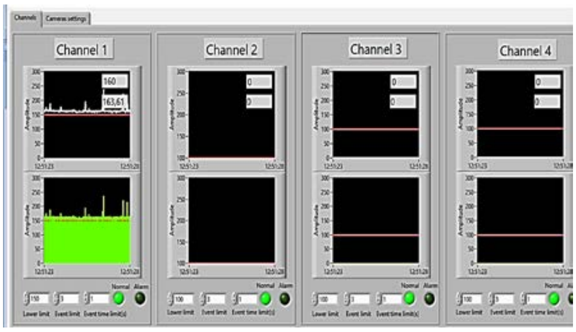


Fig. 6 Developed four-channel hardware-software complex

In Eq. (1), values of additional losses and optical refractive indices in optical fiber depend on mechanical action and temperature:

$$\frac{\Delta q}{q} = \frac{1}{q\left(\frac{dq}{qT}\right)k\Delta T} + \frac{\delta q}{q}. \quad (1)$$

Here q is an additional loss of the optical fiber; Δq is the additional loss changing;

$\left(\frac{dq}{qT}\right) \cdot k$ is a partial derivative of the temperature dependence of losses in the optical fiber;

δq is the additional loss indicator changing due to photo-elasticity.

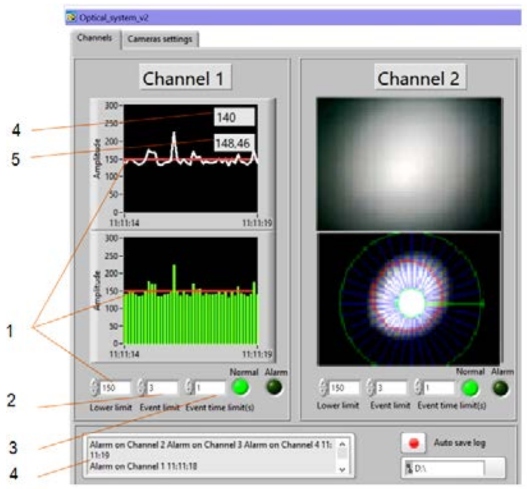
When developing a hardware-software complex, the NI LabVIEW program for graphical stream programming was used. The user, when programming in LV, sets the sequence of actions and the data transformations using a block diagram. LV uses the "G" graphical programming language, which is built on the dataflow architecture. In such a language, the order of executing operators is formed not by the system of their following but by the presence of the data flows at the inputs of these operators.

The LV program is considered a virtual device (VD) consisting of two interconnected parts: a block diagram that describes the logic of the virtual device; a front panel that is the virtual device interface. On the front panel, there are input-output facilities: these are various buttons, switches, scales, light bulbs, and others. They are used to control and communicate with the VD. To take numerical indicators of the load on the OF, two counters can be adapted to measure various parameters. The first one gives the instantaneous value of the measured value of the applied force (pressure, stress, strain), and the second one gives the average value that can be set. Fig. 7 shows the interface of the hardware-software complex and its positions during configuration.

The physical foundations of measuring pressure on a concrete beam were based on changing the refractive index during micro bending of the G.652 type optical fiber, which can be expressed in terms of changing the light spot incident on the photodetector surface.

The hardware-software complex can determine the received data and exclude false responses. The system can control changing pressure by changing the level of additional losses, and changing the intensity of the light wave incident on the surface of the photodetector; intelligent processing of the spot image allows tracking changes in the intensity of individual pixels.

As a result of the studies, a concept was formulated for constructing and using the proposed system of monitoring the technical condition of reinforced concrete building structures and foundations using quasi-distributed fiber-optic sensors.



a b

Fig. 7 Interface of the hardware-software complex: 1 - threshold value, 2 - number of responses, 3 - period of the response time, 4 - average amplitude value, 5 - instantaneous amplitude value, 6 - response time fixation window

The layout of the sensors is shown in Fig. 8. At the moment, four control zones can control from 1 to 500 m, respectively. The total length of the controlled zone can reach 2000 m.

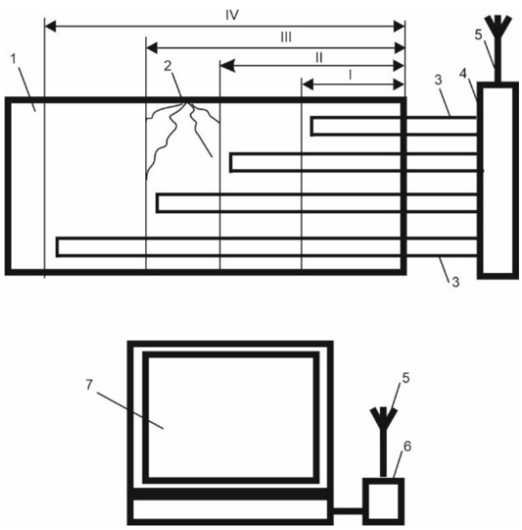


Fig. 8 Layout of the sensors

The layout works as follows. Fiber-optic sensors are attached to the reinforcement at the stage of the foundation casting. It is also possible to fix them on the existing surfaces of building structures and foundations. According to the proposed layout, a crack appears in foundation body 1. It grows and leads to its partial destruction. Installed fiber optic sensors 3 that capture these changes and transmit the data to data preprocessing unit 4that is based on a Raspberry Pi mini-computer with a switch and a radio modem. The radio modem through antenna 5 provides the data transmission via cellular channels to the central computer. The information is transmitted to the antenna of radio modem 6 installed on central computer 7. The computer has rather low hardware and software requirements: I3 processor and higher, 8 GB of RAM, Windows 7, and a higher operating system. Fiber-optic sensors can reach a length of up to 30 km, which allows you to organize a data transmission channel over optical fiber in a straight line. In this case, fiber optic sensors are both a measuring part and a guiding data transmission system. In laboratory conditions, a data transmission channel with a length of 10 km was tested using a coil with a single-mode optical fiber of the G652 standard with a diameter of 9/125 terminated with SC/UPC-SC/UPC connectors, while the laser power was 20 mW.

5. CONCLUSIONS

The use of a single-mode optical fiber of the ITU-T G.652.D standard for nondestructive testing of defects in load-bearing reinforced concrete building structures is a promising trend since fiber-optic sensors developed on its basis have sufficiently high accuracy, measurement speed, and good linearity of characteristics. The hardware-software complex can determine the received data and exclude false responses.

All the changes are recorded in the computer's memory and based on the analysis, the result of changing pressure on the building structure is given. There has been developed a hardware-software complex of a technical condition monitoring system that evaluates changes in the parameters of a light spot of an incident light wave on the surface of a photo-matrix with a pixel analysis of changes in the area of the spot and its intensity.

The method will allow establishing the expected location of defects (cracks) and damage to building reinforced concrete structures, which cannot be used by the existing methods of nondestructive testing concrete strength. It is possible to obtain the values of mechanical stresses and strains in real-time by storing the obtained data. It is planned to expand the number of control zones and increase the number of measuring channels to improve the accuracy of detecting a defect in a building structure. It is also required to improve the software to increase the noise immunity of the measuring channels of the monitoring system.

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