Global Scientific Review
A Peer Reviewed, Open Access, International Journal
www.scienticreview.com
Volume 8, October 2022
ISSN (E): 2795-4951

Analyzing the Results of Monitoring the Situations that May Occur in Emergency Situations of Bridges Through Various Optical Sensors

Abdazimov Shavkat Xakimovich,
Zuhriddinov Hayotbek Qaxramonjon o'g'li
Tashkent State transport University

Annotation: Structural health monitoring (SHM) is currently an extremely effective and vital safeguard measure. Because of the fiber-optic sensor's (FOS) inherent distinctive advantages (such as small size, lightweight, immunity to electromagnetic interference (EMI) and corrosion, and embedding capability), a significant number of innovative sensing systems have been exploited in the civil engineering for SHM used in projects (including buildings, bridges, tunnels, etc.). The purpose of this review article is devoted to presenting a summary of the basic principles of various fiber-optic sensors, classification and principles of FOS, typical and functional fiber-optic sensors (FOSs), and the practical application status of the FOS technology in SHM of civil infrastructure.

Keywords: fiber-optic sensors; structural health monitoring; distributed fiber-optic sensor; optical time-domain reflectometer; civil engineering

Introduction. Real-time SHM for major engineering structures can timely identify the cumulative damage of the structure and evaluate its service performance and life, and establish a corresponding safety early warning mechanism for early warning of possible disasters, which is not only of great scientific significance for improving the safety and reliability of the structure, but also can reduce the cost of operation and maintenance of the structure. It has become the inevitable requirement of the future engineering, and also a tough issue to be solved urgently [1,2,3].

SHM is an important application of intelligent material structure in practical engineering, which can monitor the "health" state of the structure on-line. It uses embedded or surface-bonded sensors as the nervous system to sense and predict internal defects and damage in the structure. The overall and local deformation, corrosion, brace failure, and other factors of the structure can be evaluated by the SHM system. When there is a sudden accident or dangerous environment, it can restore the whole structural system to the best working state through adjustment and control. Of course, the structure can protect itself and survive in times of danger by automatically changing and adjusting the shape, position, strength, stiffness, damping or vibration frequency of the structure.

Typical Fiber-Optical Sensors (FOSs) (*Crack Sensors*). FOSs are extensively used in various fields [4]. The FOSs used for crack detection mainly including grating sensors and distributed fiber-optic sensors. Crack detection FOSs are mainly used for the stability of reinforced concrete structures. They have a wide range of applications in the health and stability of bridges, buildings, tunnels, and highways.

In crack detection, an important challenge is that it is difficult to monitor the number and depth of cracks in concrete structures due to the uneven and complex materials. A distributed crack fiber sensor based on optical time-domain reflection, which does not need to pre-determine the position of the crack, and realizes the coverage monitoring of all cracks. The short light pulse is used as the light source, and the backscattered light power is measured by OTDR. The formation of the crack is related to the bending angle of the optical fiber, and the bending leads to the loss of optical power. The relationship curve between backscattered power and light propagation distance decreases sharply at the crack. From this, the crack opening can be determined. One of the advantages of distributed optical fiber sensing is that it can monitor every point distributed along the optical fiber [5], thus it can accurately correspond to the location of the crack. Subsequently, on the basis of locating the crack position, Neha Niharika proposed a novel “S”-type optical fiber layout to increase the sensitivity while maintaining the distributed characteristics of the sensing system. Moreover, with the “S”-type fiber layout suggested by the solution, the sensitivity of crack openings is increased by 1.43 dBm/mm. In 2015, Gerardo Rodríguezdemonstrated a method based on the optical backscattering reflectometer (OBR) to measure the generation, location, and width of cracks in concrete structures. A lot of uncertain structural damages are shown through cracks, thus the crack location and width are vital parameters. This OBR system can obtain continuous strain with higher spatial resolution and precision, and the experimental data calibrate the nonlinear model of the concrete slab, which can predict the crack location and width of different parts of the specimen. In 2018, Linked In and Yaming Li designed a new type of line crack sensor based on linear macroscopic bending loss of optical fiber. The sensor system overcomes the nonlinear relationship between macroscopic bending loss and crack opening displacement (COD), and verifies the simple linear relationship between macroscopic bending loss and COD of the optical fiber by using crack transfer device with gears.

Tempereture Sensors. In the past few decades, with the rapid construction of buildings, bridges, and dams, researchers have focused on the health monitoring of concrete structures. The temperature effect of the concrete structure is closely related to its structural health [6,7]. Temperature monitoring determines the quality, thermal resistance, and cold resistance of the concrete structure. At present, the more matured technology is the distributed optical fiber temperature sensing. Different from local optical fiber sensing, distributed sensing can realize the test of thousands of data points by a single sensor.

In the earlier period, Y. J. Rao proposed an optical fiber Fabry–Perot sensor based on wavelength multiplexing, which can be used to simultaneously measure the static strain, temperature, and vibration of SHM. It can be surface mounted or embedded to realize distributed temperature sensing. Different from most studies focusing on the influence of the surrounding environment on the temperature change of concrete structures, Xiaotian Zou designed a Fabry–Perot optical fiber temperature sensor to study the temperature change in the hydration process of concrete, and derived the temperature curve (as shown in Figure 1), which is used to calculate the apparent activation energy (Ea) and hydration heat (H(t)) of concrete, which can help us better understand the hydration of cement. When cement is mixed with water, an exothermic chemical reaction occurs to generate hydration heat. The data obtained through experiments show that when the water-to-cement (w/c) ratio is 0.4, 0.5, and 0.6 respectively, the peak temperature of the concrete specimen is 51.42 °C, 52.88 °C, 55.08 °C. The early temperature changes caused by hydration heat at different water-cement ratios are related to the temperature stress and cracks of the concrete structure. Therefore, during the hydration process, the temperature trend of the cement and the maximum temperature is crucial. These parameters can be used to predict future structural health.

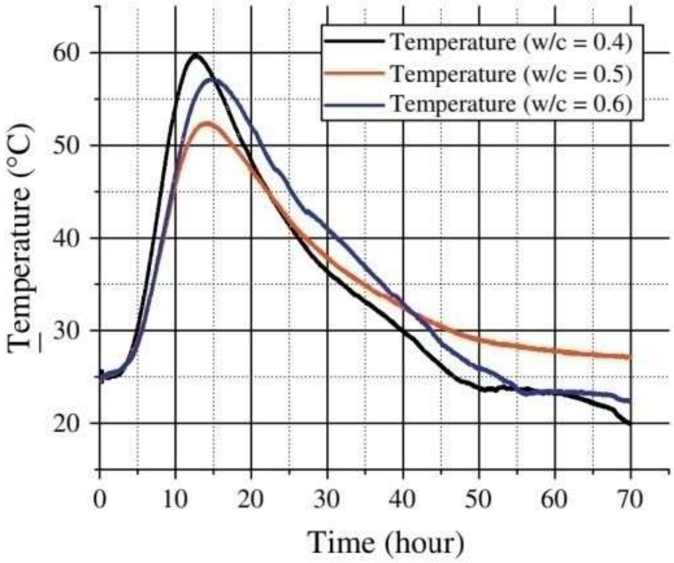

Figure 1. Concrete hydration experiment with water versus cement ratio 0.4, 0.5, and 0.6 using the thermocouple

In addition, distributed temperature sensing (DTS) plays an important role in controlling and monitoring the cracks in concrete structures. In large concrete structures (such as large bases, bridges, dams, etc.), the hydration process heats the concrete structure after pouring large pieces of concrete. The outer surface of the concrete cools down faster than the inner surface. Because of the poor thermal conductivity of the concrete, a large temperature gradient is generated on the surface and inside. The uneven expansion of concrete caused by early temperature differences can cause thermal tensile stress on the surface. In the later period, it is constrained and deformed by the adjacent concrete or rock mass, which produces a tensile force on the constrained surface. When the tensile force exceeds the tensile strength, thermal cracking occurs [8]. Ouyang used the DTS system to provide crack control ideas for mass concrete structures in reservoir projects. This Raman-based DTS system usually consists of a DTS unit with an integrated OBR interrogation unit and multiplexer, computer, power supply, and optical cable. They are covered by a graded-index multimode optical fiber with a refractive index of 50 µm and a coating layer with a diameter of 125 µm, and the outer layer is covered with low-density polyethylene. Each fiber optic cable is connected to the DTS unit through a pigtail (Figure 2). The pigtail is a short length of optical fiber with a dedicated connector at one end to protect the fiber core wire and paired with the channel of the multiplexer; the other end uses a fiber fusion splicer to fuse it with the optical cable. Through the inverse analysis method based on temperature simulation, the temperature measurement value in the concrete block is used as the basic data to determine the thermal performance of the cast-in-place concrete. Based on thermal stress simulation using thermal characteristics, the cracking risk of each concrete block is predicted and evaluated in a temperature control mode related to time-varying construction and environmental condition, greatly improving the efficiency of temperature adjustment and crack control in the construction of mass concrete.

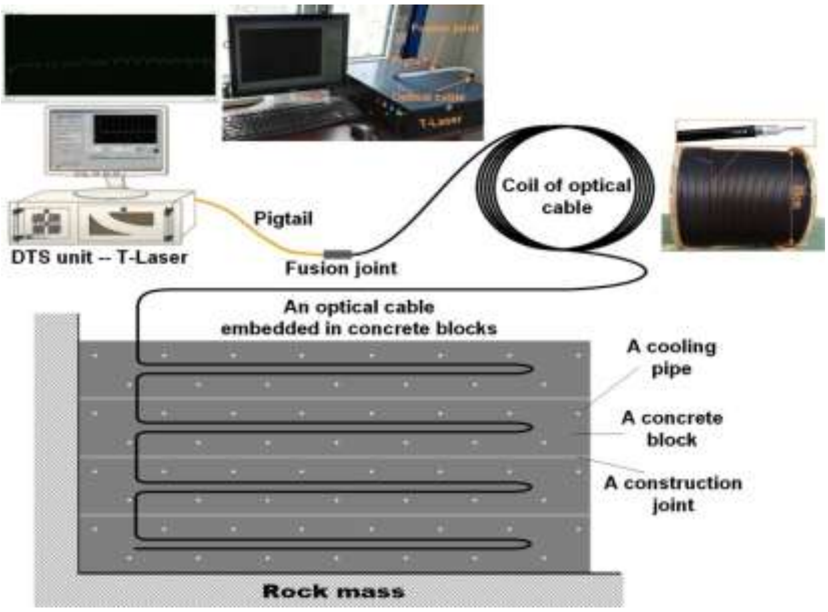

Figure 2. The diagram of the distributed temperature sensing (DTS) system.

Although distributed temperature sensing technology has matured, the point sensors are more suitable for monitoring the temperature of a limited measurement point. The point FOS technology can be developed owing to the unique advantages provided by the use of optical fiber connecting the measuring location to the interrogating unit [9,10]. Moreover, low cost and mature packaging technology are also the advantages of point FOS widely used in temperature measurement in the industry.

Strain Sensors. In the SHM process, the density information in the structure can be used to identify the degree of deformation. In other words, when the strength of the structure is greater than the externally applied stress, the structure has higher stability. Therefore, it is important to identify the stress (load) or strength (damage) applied to the structure to ensure the health of the structure. In recent years, there have been many reports on the application of FBG and distributed fiber-optic sensor (DFOS) to structures performance monitoring, many of which are based on the FOS to measure the internal strain of structures.

In 2016, Sridevi. S reported an etched Bragg grating sensor (eFBG) coated with reduced graphene oxide (rGO), which significantly improved the sensitivity to strain and temperature because the interaction between the propagating light and the rGO film coated on the optical fiber is enhanced. In this study, the strain sensitivity of the eFBG sensor with rGO coating was 5.5 pm/με, which was about five times that of the bare FBG sensors and the resolution was 1με. The high aspect ratio, excellent flexibility, and ability to withstand strains up to 30%, as well as a higher temperature coefficient of resistance (TCR) than tungsten and platinum, make graphene suitable for manufacturing highly sensitive and durable strain and temperature sensor. Because of its small size, FOSs can be placed on the surface of a structure or embedded inside a structure. When light propagates in an optical fiber, the transmitted and reflected light is modulated by its amplitude, phase, frequency, or polarization state. If the structure is affected by strain, then these parameters will change. The most commonly used FBG sensors and DFOS can't provide multi-parameter sensing. Monssef Drissi Habtiet proposed to use a new type of sine wave sensor positioning to solve this problem. When the sensor is embedded inside the structure, the sinusoidal alignment model displays the multi-parameter strain more clearly than the linear model (Figure 3). When FOS is embedded in a large structure, it is difficult to identify multiaxial strain. If the direction of the applied strain is random, the linearly aligned FOS cannot distinguish the strain coordinates. Therefore, multi-axial strain with distributed FOS sinusoidal alignment in epoxy viscose fiber-reinforced composites is the best solution. Linearly arranged FOS can only detect transverse strain, while sinusoidally arranged FOS can provide linear, shear, and transverse strain information. As shown in Figure 4a, under similar boundary conditions, the strain value collected by the linearly aligned FOS is 1300 μm/m, and the strain value collected by the sinusoidally-aligned FOS is 600 μm/m. The strain range of linear alignment is 55% higher than that of sinusoidal structure. However, the advantage of sinusoidal alignment is that a shear strain of 100~250 μm/m (as shown in Figure 4b) can be detected when the torsional load is applied, so it can work under bending loads. Considering that the strain range should be close to the linear configuration of FOS while maintaining the torsional load strain sensing. The collected strain value reaches 1050 μm/m (as shown in Figure 4c) after extending the sinusoidal alignment period, which makes the difference between the strain values of the linear configuration and the sinusoidal configuration reduced to 20%. It is fully proved that it is possible to realize DFOS multi-parameter strain sensing without affecting strain.

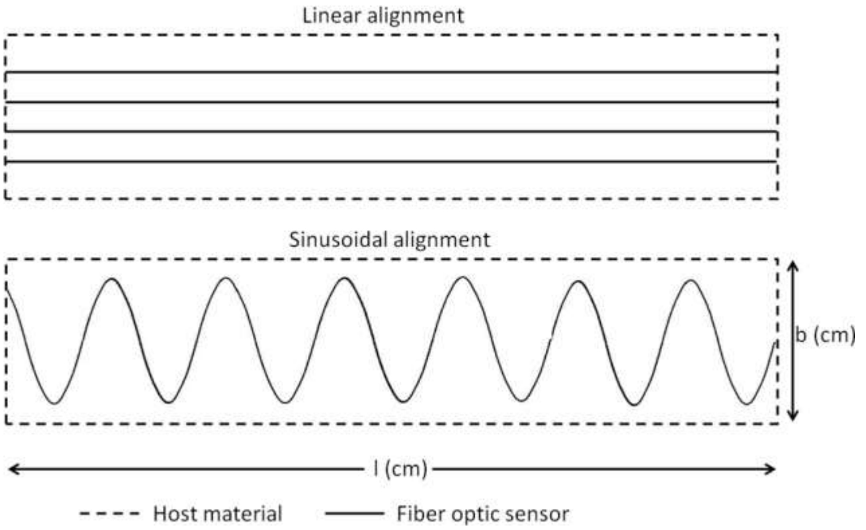

Figure 3. Fiber-optic sensor (FOS) installation method for a reference surface area.

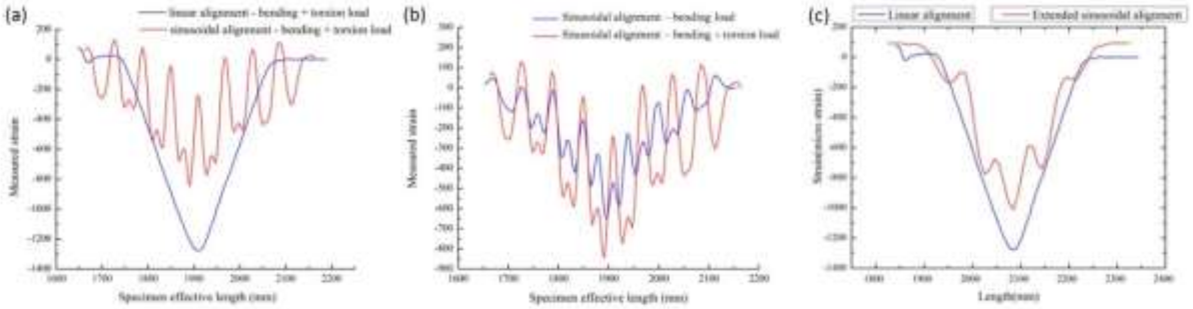

Figure 4. (a) Linear vs. sinusoidal alignment, bending + torsional load; (b) sinusoidal alignment, bending load with torsion vs. without torsion; (c) linear vs. extended sinusoidal alignment, bending load.

Since 1998, Froggatt et al. [11,12] used optical frequency-domain refractometer (OFDR) to demonstrate distributed static strain measurement for the first time. The potential of its high spatial resolution in strain measurement has attracted widespread attention. OFDR uses a swept frequency laser interferometer to generate the relationship between strain or temperature and sensor length, with FBG or Rayleigh scattering as the source signal [13,14]. With the rapid growth of demand for dynamic disturbance measurement in the oil and gas, aerospace, and geophysics industries, OFDR's method of realizing distributed vibration measurement has also been widely used. In 2015, Stephen T. Kreger's team developed and demonstrated a novel optical phase-based vibration detection and mapping technology based on the data of OFDR's optical fiber sensing system. The result proves the potential of OFDR instrument for accurate, high spatial resolution, distributed vibration sensing in a dynamic environment, and is suitable for structural monitoring applications where modal frequency may be a health indicator. Since the optical fiber made of amorphous silica can be regarded as a naturally produced chaotic Bragg grating, the local reflection spectrum will also change with changes in strain or temperature [15]. Correlate the locally defined reference spectrum with the current spectrum to obtain the measured value of the frequency shift, from which the measured value (strain or temperature) can be derived. This kind of strain/temperature quantitative interrogation method has been proved in the SHM of civil, industrial, and aerospace structures.

Recently, femtosecond (FS) laser have attracted attention because of their extremely high peak power values, high spatial resolution, and ultra-short duration. Using FS laser to write gratings in optical fibers has quickly become a popular tendency. Yinan Zhang proposed a FS laser micromachining method to manufacture a diaphram-based optical fiber Fabry–Perot interferometric (FPI) sensor for pressure measurement at high temperature. The sealed cavity of the diaphragm-based FPI sensor has an ultra-thin film (diaphragm) near the cutting optical fiber. The function of the diaphragm is to form interference as a mirror. The diaphragm would deform and alter the interference pattern when the environmental pressure changes. Therefore, the sensor can be used for pressure sensing [16,17].

The significance of utilizing FS laser is: (1) The laser polished surface helps eliminate the external reflection of the diaphragm surface, so that the sensor is not affected by changes in the refractive index of the environment; (2) the cavity length of FPI can shorten to further reduce the cross-sensitivity to temperature; (3) the thickness of the diaphragm can be controlled to meet the specific requirements for pressure sensitivity and measurement range. These advantages prove that the FS laser is an effective micromachining tool for manufacturing fiber optic equipment.

Conclusions. In the past few decades, since SHM has come into our sight, it has been an important direction in the development of large-scale civil engineering. The emergence of new technology brings not only function and convenience, but also technical improvement and problems. In recent years, the development and application of optical fiber sensing technology in the field of SHM are more and more mature and stable. In this review, the working principles of FPFOS, FBG sensor, OTDR and LPFG sensor are introduced, and the distributed fiber-optic sensing technology is widely discussed and reviewed, especially in civil engineering structure. Then several classical functional sensors in civil engineering are described, including crack sensors, temperature sensors, and strain sensors. After that, the latest applications of different FOS in large-scale civil engineering such as bridges, buildings, and tunnels are reviewed. These works are related to the design of the sensor, the implementation technology, experimental results, and sensor performance. In addition, we keep eyes on the development of new fiber-optic technology. Also, we briefly summarize the difficulties faced by FOS in the field of SHM and predict its future development direction. There is still a lot of work to be done if FOS is to become a comprehensive, definite, and high-level feasible solution in SHM applications.

References

1. Li, M.; Ranade, R.; Kan, L.; Li, V.C. On Improving the infrastructure Service Life Using ECC to Mitigate Rebar Corrosion. In Proceedings of the 2nd International Symp. on Service Life Design for Infrastructure, Delft, The

Netherlands, 4–6 October 2010; pp. 773–782.

2. Knott, J.F.; Elshaer, M.; Daniel, J.S.; Jacobs, J.M.; Kirshen, P. Assessing the Effects of Rising Groundwater from Sea Level Rise on the Service Life of Pavements in Coastal Road Infrastructure. *Transp. Res. Rec. J. Transp.Res. Board* 2017, *2639*, 1–10.
3. Gul, M.; Catbas, F.N. Structural health monitoring and damage assessment using a novel time series analysis methodology with sensor clustering. *J. Sound Vib.* 2011, *330*, 1196–1210.
4. Suppasri, A.; Mas, E.; Charvet, I.; Gunasekera, R.; Imai, K.; Fukutani, Y.; Abe, Y.; Imamura, F. Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami.*Nat. Hazards* 2013, *66*, 319–341.
5. Linderman, L.E.; Mechitov, K.A.; Spencer, B.F., Jr. TinyOS-based real-time wireless data acquisition framework for structural health monitoring and control. *Struct. Control Health Monit.* 2013, *20*, 1007–1020.
6. López-Higuera, J.M.; Cobo, L.R.; Incera, A.Q.; Cobo, A. Fiber Optic Sensors in Structural Health Monitoring. *J. Light. Technol.* 2011, *29*, 587–608.
7. Zou, X.; Chao, A.; Tian, Y.; Wu, N.; Zhang, H.; Yu, T.Y.; Wang, X. An experimental study on the concrete hydration process using Fabry–Perot fiber optic temperature sensors. *Measurement* 2012, *45*, 1077–1082.
8. Torres, B.; Paya-Zaforteza, I.; Calderón, P.A.; Adam, J.M. Analysis of the strain transfer in a new FBG sensor for Structural Health Monitoring. *Eng. Struct.* 2011, *33*, 539–548.
9. Lau, K.-T. Structural health monitoring for smart composites using embedded FBG sensor technology. *Mater.Sci. Technol.* 2014, *30*, 1642–1654.
10. Čápová, K.; Velebil, L.; Včelák, J.; Dvořák, M.; Šašek, L. Environmental Testing of a FBG Sensor System for Structural Health Monitoring of Building and Transport Structures. *Procedia Struct. Integr.* 2019, *17*, 726–733.
11. Shimada, Y. Development of Optical Fiber Bragg Grating Sensors for Structural Health Monitoring. *J. LaserMicro Nanoeng.* 2013, *8*, 110–114.
12. Lan, C.; Zhi, Z.; Ou, J. Monitoring of structural prestress loss in RC beams by inner distributed Brillouin and fiber Bragg grating sensors on a single optical fiber. *Struct. Control Health Monit.* 2014, *21*, 1–14.
13. Zuhriddinov Hayotbek Qaxramonjon o'g'li, "OPTIK TOLALI DATCHIKLARNING BOSHQADATCHIKLARDAN FOYDALANISHDAGI AFZALLIKLARI" «ОБРАЗОВАНИЕ И НАУКА В XXI ВЕКЕ». Выпуск №25 (том 4) (апрель,2022). Дата выхода в свет: 30.04.2022.http://mpcareer.ru. 445-449bet.
14. Mirsagdiyev Orifjon Alimovich, Zuhriddinov Hayotbek Qaxramonjon o'g'li, "QISHLOQ XO'JALIGIDA NAMLIK DATCHIKLARIDAN OQILONA FOYDALANISH USULLARI" Journal of Advanced Research and Stability ISSN: 2181 -2608. www.sciencebox.uz/482-484 bet.2022y.
15. Zuhriddinov Hayotbek Qaxramonjon o'g'li, "ANALYSIS OF SAFETY IN CONSTRUCTION SITES USING OPTICAL SENSORS" WEB OF SIENTIST: INTERNATIONAL SCIENTIFIC RESEARCH JOURNAL. ISSN: 2776-0979, https://wos.academiascience.org/index.php/wos/article/view/1850. 131-140 bet.
16. Zuhriddinov Hayotbek Qaxramonjon o'g'li, "MA'LUMOTLARNI OPTIK

DATCHIKLAR YORDAMIDA YETKAZISH VA O‘LCHASH TIZIMLARINI ISHLAB CHIQISH” Iqtisodiyotni raqamlashtirish sharoitida korporativ boshqaruv modellarining transformatsiyasi xalqaro ilmiy-amaliy anjumani. 10.24412/cl-36899-2022-1-237-241.

17. Zuhriddinov Hayotbek Qaxramonjon o’g’li, “HOZIRGI ZAMONAVIY RIVOJLANAGAN DAVRDA OPTIK DATCHIKLARDAN FOYDALANIB TURLI SOHALARDAGI HAVFLARNI OLDINI OLISHNI O’RGANISH” Iqtisodiyotni raqamlashtirish sharoitida korporativ boshqaruv modellarining transformatsiyasi xalqaro ilmiy-amaliy anjumani. 10.24412/cl-36899-2022-1-231-236.