Bulgarian Society for NDT
International Journal "NDT Days"
Volume V, Issue 3, Year 2022
ISSN: 2603-4018
eISSN: 2603-4646

Features of the Development of Continuous Non-destructive Testing Systems and Monitoring of Stress-strain State of the Bearing Elements of Building Structures

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Abstract
This article presents a theoretical analysis and structure of non-destructive testing and monitoring system of load-bearing structures of buildings and constructions based on piezoresistive sensors, introduction and active use of which will significantly increase the level of ensuring the safety of people in buildings and structures of various purposes. A list of buildings and structures subject to mandatory equipping with non-destructive testing systems is given.

Keywords: automated non-destructive testing, stress-strain state monitoring, building structures, control technology.

1. Introduction

Every year, the speed and volume of construction of objects for various purposes is significantly increasing both in the Republic of Belarus and in the Republic of Azerbaijan, which is due to economic growth of the countries and development of industry. New cultural, healthcare and sports facilities, residential areas and industrial enterprises adorn the architectural appearance of our countries. Modern engineering structures are complex technical objects that include both unique architectural innovations and advanced automation tools for control and condition monitoring with the ability to predict further changes. During their life cycle, the components of building systems are exposed to various kinds of impacts, both planned (operational loads, natural and climatic changes) and unplanned (anthropogenic) impacts from the environment and external infrastructure, including emergency situations, which is especially typical for structures located in cramped conditions of large cities and seismically hazardous areas (Figure 1).

Analysis of statistical data shows that a large number of emergency situations associated with destruction of buildings and structures occur due to disfunction of the elements of main load-bearing structures. Destruction of the building structures of buildings and constructions cause significant economic damage and are often accompanied by loss of life. At the same time, it is quite difficult to identify signs of an emergency state of the elements of main load-bearing structures of buildings and constructions by visual inspection [1–4].

The analysis showed that the main causes associated with destruction of buildings and structures are: increased loads on the load-bearing structures of buildings and constructions that have been in operation for a long period of time; the impact on structures of natural and anthropogenic factors, such as temperature drops, wind and snow loads, vibrations, accidents, fires, as well as terrorist acts (explosions). It should be noted that non-compliance with the technologies for erecting buildings and structures can also lead to a violation of the integrity of their structures. For example, incomplete filling of joints with mortar and poor-quality monolithing of abuts does not ensure uniform load distribution between building structural elements, and use of prefabricated reinforced concrete products with through cracks, spalls, and bare reinforcement reduces the bearing capacity of individual elements of building structures up to 40% in some cases, which leads to a significant increase in the probability of violation of the integrity of a building or structure [5, 6].

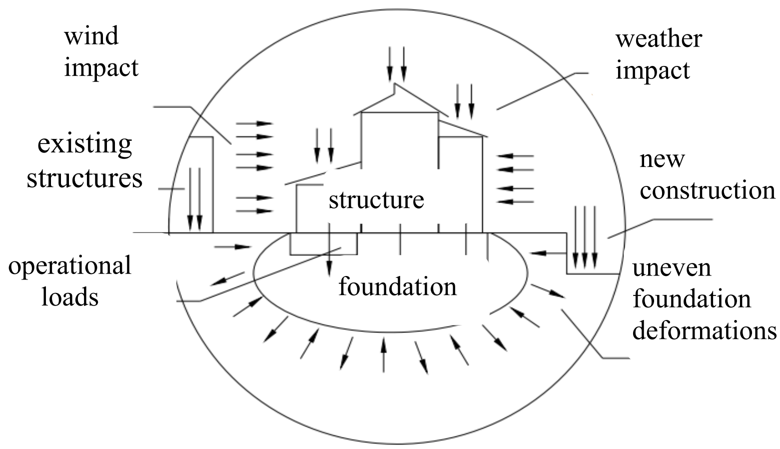
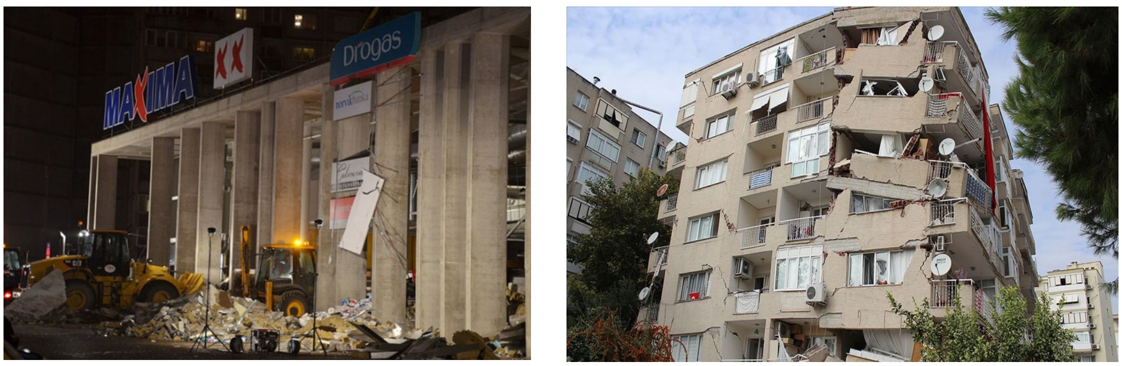


Fig. 1. Scheme of interaction between the elements of the "foundation – structure" construction system and the environment of the city

Recent emergencies associated with the sudden collapse of, for example, schools in Mogilev Region (Krasnopolye, 2004 and Krichev, 2014), the Transvaal Park dome (Moscow, 2004), the bridge on Akhsu River (Azerbaijan, 2009), the automobile overpass (Minsk, 2022), the pool roof in Perm Territory (Chusovoy, 2005), Basmanny Market and the water park (Moscow, 2006), the section of the airport in France (Paris, 2005), the roofs of skating rinks in Germany and Austria (2006), the roof and part of the wall of MAXIMA Shopping Center (Riga, 2013) (Figure 2, a), the five-storeyed residential house in Ukraine (Lutsk, 2018), the seven-storeyed residential building in Azerbaijan (Baku, 2019) (Figure 2, b), brought the issues of monitoring the technical state of load-bearing structures during the operation of buildings and constructions to one of the first places in the system of integrated safety of building objects functioning. At the same time, special attention should be paid to safety issues during construction of high-rise buildings. Analysis of statistical data shows that the number of people died during collapse of buildings with a height of more than 25 floors is 3-4 times higher than the number of people died in buildings with no more than sixteen floors.

To date, in order to timely detect violations in operation of the supporting structures of buildings and constructions and carry out repair measures, it is necessary to regularly conduct surveys that require time and money. Periodic inspection of buildings, their certain zones and types of structures with an assessment of their technical state and clarification of the further operation mode must be carried out with involvement of specialized organizations.

Replacing routine preventive and repair work, as well as labor-intensive manual studies with continuous non-destructive testing will significantly reduce the costs associated with maintaining the life cycle of complex structures of buildings and constructions. In this regard, there is a need for reliable systems of non-destructive testing of the technical state of structures that can automatically process data, evaluate the technical state and signal the need for human intervention. Use of such systems for non-destructive testing and monitoring of the technical state of structures during construction of the Sochi-2014 Olympic Venues is of interest. So, all the main Olympic Facilities of the coastal cluster (Bolshoy Ice Palace, Ice Cube Curling Center, Adlerarena Indoor Skating Center, Iceberg Winter Sports Palace, Shaiba Ice Arena, Fisht Olympic Stadium) were equipped with automated systems of non-destructive testing and monitoring of the stress-strain state of supporting structures which took into account the location of the facilities in a seismically hazardous area. However, used non-destructive testing and monitoring systems are characterized by a very small set of equipment and complexity. Nevertheless, the obtained results confirmed the prospects for introduction of automated system for non-destructive testing and monitoring of the stress-strain state of load-bearing structures on constructions with large-span coatings [7].



(a) (b)

Fig. 2. Photos of the places of building structures collapse

Systems of both periodic and continuous non-destructive testing are currently being actively developed and implemented at critical facilities, which allows us to conclude that the era of using the tools of automatic recognition and prediction of the technical state of buildings and structures has come.

The aim of the paper is the theoretical analysis and development of the structure of continuous non-destructive testing and monitoring system of the stress-strain state of the supporting structures of buildings and constructions based on piezoresistive sensors.

2. Results and discussion

Strain gauges of various types are used to control the dynamics of stress development in structural elements. The most widely used are strain gauges with resistive sensors (resistance strain gauges) built on the basis of the ability of conductors to change their resistance when stretched or compressed [8].

As we can see, this sensor consists of a base which a conductive layer forming a curve is applied on; the thickness of conductor is increased on the bends to reduce the sensitivity to stretching perpendicularly to the main axis. The main axis runs along the curve direction lines (horizontally) and the sensor stretching along this direction causes the maximum change in sensor resistance. On top, the sensor is covered with a layer of transparent laminate which protects the resistive layer against damage. The sensor also has marks indicating the axes directions which simplify its installation, and usually passing through the center of the sensor at angles of 90°±45° relative to the main axis of sensitivity. Usually, several strain gauges or systems of sensors, the axes of which intersect at different angles or run in parallel, are used in automated non-destructive testing and monitoring systems. Therefore, sensors that have several strain gauge elements located at a certain angle are usually used to simplify installation.

Continuous monitoring systems of load-bearing structures of buildings and constructions, which contain strain gauge sensors for monitoring the stress-strain state of a structure, have a clear advantage over the currently used non-destructive testing equipment [9], since a continuous stream of data obtained using a large number of sensors placed at different points of the structure is carefully analyzed using special software and compared with the permissible technical parameters of the object controlled.

Use of continuous monitoring systems in buildings and structures with a massive stay of people, as well as at complex production facilities, will provide the necessary accurate information about the state of facility from the moment it is erected, and, most importantly, in elimination of emergency situations, such as fires.

Strain gauges developed to date as part of continuous monitoring systems make it possible to automatically measure the real value of stresses arising in structure at installation point; to track the dynamics of stress buildup process in main structural elements of construction throughout the entire stage of building operation; to evaluate performance of structure as a whole and effectiveness of applications of materials used; to detect critical and pre-emergency conditions; to control the yielding of buildings and structures.

Strain gauges of the non-destructive testing and monitoring system are installed on the main structural elements of buildings and constructions which include the following:

- structures or their elements, destruction or inadmissible deformations of which can lead to a decrease in the safety of building operation, as well as the progressive destruction of building as a whole;
- structures that provide spatial rigidity, immutability and stability of construction.

Today, technical solutions in the field of communication equipment allow data transmission over existing electrical networks which does not require additional work on equipping of communication channels, for example, using radio signals.

It should also be noted that the continuous monitoring of the stress-strain state of buildings and structures is not limited solely to the task of alerting the maintenance services about an impending emergency. The monitoring system constantly captures the state of structure and allows making a decision in advance on unscheduled repairs (if there are facts of violations of control elements) or, on the contrary, to carry out a limited repair cycle (in case of obtaining satisfactory data), which becomes especially relevant for buildings with a long service life and requiring major repairs.

The analysis of the papers [10–12] made it possible to develop a list of buildings and structures which, in our opinion, must be equipped with continuous monitoring systems:

1) technically complex facilities: river ports; airports with a main runway length of 1,800 m or more; bridges and tunnels; subways; large industrial facilities;

2) high-rise buildings and unique structures: capital construction projects, the project documentation of which provides for at least one of the following characteristics (height of more than 75 meters, spans of more than 100 meters, availability of a cantilever of more than 20 meters, complete or partial deepening of the underground part lower than planning mark of the earth by more than 10 meters); availability of structures and structural systems for which non-standard calculation methods taking into account physical or geometric non-linear properties are applied or special calculation methods are developed;

3) objects with mass stay of people. Buildings in which 500 or more people can stay at the same time are considered objects with a mass stay of people;

4) hotels with more than 100 rooms.

It should also be noted that there is a high need for systems of continuous automated non-destructive testing and monitoring of the stress-strain state of the objects of space-rocket, aviation and military purposes. The concept of continuous automated non-destructive testing system presented herein fully meets the requirements for modern monitoring systems both in the Republic of Belarus and the Republic of Azerbaijan, and in other foreign countries.

3. Conclusion

Introduction and active use of continuous non-destructive testing systems of stress-strain state of building structures at all stages of the process of construction and operation of buildings and structures of various purposes will significantly increase the level of ensuring the safety of people staying there. Introduction of these systems is a tool for safety, reliability and a reasonable economic approach in modern construction. It should be noted that keeping a log for regular registration of the state of a controlled structure is actually drawing up a Health Passport of a specific structure which will be the only reliable document indicating the degree of real reliability of main structural elements. Development of these systems in the future will make it possible to predict the technical state of all infrastructure facilities, from heat supply systems to environmental indicators.

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