Use of monitoring system in Ekaterinburg

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Abstract. The monitoring of buildings and structures condition, as well as the timely implementation of corrective actions aimed at the elimination of adverse factors, are the most important aspects that shall be addressed at the construction stage. The usage of monitoring systems makes it possible to monitor the building condition and above that to implement more efficient design solutions in the prospective projects using the results of the analysis of the acquired and design data. In this work the review of a monitoring system installed in a high-rise building located in Ekaterinburg is given. The paper describes the analysis of the natural oscillation frequency and the logarithmic decrement of fundamental tone acquired with the help of accelerometers, and compares the values with the acceptance limits. The process of converting data acquired by strain gauges for the determination of the stress-strain condition of the bearing structures is analysed. The process of comparison of data obtained by the monitoring system of a high-rise building is described. The necessity of the application of the monitoring system is analysed.

1. Introduction

The large-scale construction of high-rise buildings in Russia started in the last decades. Design and construction of such buildings are very specific processes. The reliability and safety of such buildings are the issues of the topmost priority for the design development, construction, and further condition monitoring. The first examination of the technical condition of high-rise buildings and structures is carried out within two years after the commissioning. Further examinations are carried-out at least every 10 years [1]. The monitoring is conducted in accordance with the plan approved by a customer. The aim of the monitoring is to detect changes in the stress-strain condition of the bearing structures at the early stage. According to the requirements of GOST 31937-2011 "Buildings and structures. Rules for carrying-out examination and monitoring of technical condition" the general technical condition examination shall include the visual examination of bearing structures in order to approximately assess the condition category, the measurement of dynamic parameters of the structures, and the preparation of a building data sheet [2].

2. Application of a monitoring system as exemplified by a high-rise building in Ekaterinburg

The "Champion park" is one of the Ekaterinburg high-rise residential complexes. At this moment the second phase of the project is being completed, and the third phase is commenced. The complete residential complex will have a huge infrastructure including an underground parking, shops, restaurants, sports facilities for children and adults, fitness centers, etc (Figure 1, 2).

Figure 1. "Champion park" residential complex. Final appearance.

Figure 2. "Champion park" residential complex. Progress of works.

All buildings of the complex are similar type frame-and-core structure buildings consisting of a central rigid core, solid reinforced concrete columns, and flat-slab floors.

Upon the completion of the first stage of construction, the first building has been equipped with structured monitoring and utility control systems (SMUCS) [1]. The SMUCS system allows reducing the risk of occurrence of emergency situations treating the safety of people, including the emergency caused by changes in the stress-strain condition of the bearing structures (bearing structures condition monitoring system – SCMS). The SCMS monitors the parameters characterizing the bearing capacity of the building structures with the purpose of preventing situations in which the values of these parameters exceed maximum allowable levels [3].

The SCMS of the 1-st building of "Champion park" complex includes the following equipment: inclinometers, accelerometers, surface-mounted strain gauges, and a weather station. The system sensors are protected from weather and physical effects, connected to a continuous power supply source, and installed in hard-to-reach place. The system continuously collects data from the devices connected to the network, processes the acquired data, and displays the results on the operator's screen. All measured parameters and data processing results are recorded in a common database. Accumulated information is used as a basis for the assessment of general dynamic behavior of the building and the prediction of strain development. The design (limit) values of monitored parameters are determined using a computer model of the building developed in the finite-element software tool LIRA-SAPR [16-20] (Figure 3).

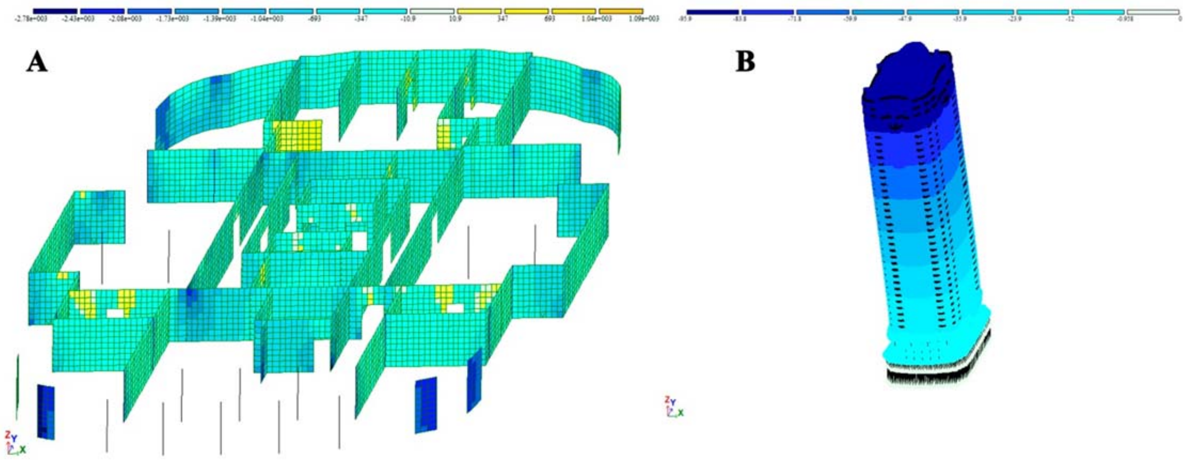

Figure 3. Determination of limit values in LIRA-SAPR: **A-** stresses in element (t/m^2). B- The deviation of the building structures from vertical position (mm).

2.1. Indications of inclinometers

The inclinometers detect the deviation of the building structures from vertical position. The sensors are mounted on brackets on the core structures. The inclinometers are able to measure their inclination along the X and Y axes with the accuracy of up to 2.5 mm per 1 km, and can generate real-time inclination signal through a serial port with the frequency of 1 Hz. The indications of the inclinometers are transmitted in the form of voltage signals with the voltage U. These indications are automatically recorded in the SCMS database. The inclinometer output voltage U can be converted into X and Y rotation angles using the polynomial transformation method. The table of maximum and minimum values of measured parameters (Table 1), generated in the result of the transformation, is then compared with the limit values obtained by means of the finite-element software analysis [4].

Table 1. Extreme values of inclinometer indications obtained during the analyzed period of time.

Sensor No.	Indication ID	Value ID	Initial sensor indication, V	Max. sensor indication, V	Min. Sensor indication, V
300080	6101	3 (Y)	1.428	1.452	1.405
		2 (X)	1.232	1.255	1.209

2.2. Indications of accelerometers

A triaxial seismograph ZETLAB BC1313 is installed at the 35-th floor of the building for analyzing the vibration power spectrum. A seismic recorder ZETLAB ZET 048-I is provided for recording the data. Dynamic performance parameters are individual for every building. The variation of natural frequency spectrum may indicate the change of the stiffness properties of building structures due to the accumulation of damages, and changes in the soil condition and interface between the soil and a pile foundation. The continuous monitoring of vibration properties includes analyzing the building vibration spectrum and assessing the natural frequencies of the building. Then, after every measurement, the frequency of the first mode of vibration is compared with the reference value. The first mode of vibration is usually the most dangerous and corresponds to the degree of freedom in the lowest stiffness direction. The reduction of the first natural frequency value by 5% may indicate the structural damage, stiffness variation, or variation of stiffness ratios [5]. However, such variation cannot be considered sufficient evidence of changes in the technical condition of the building, because apart from these factors environment and subsoil (the parameters of which are changing depending on the season) also have a great effect on the dynamic properties [6]. Taking the abovementioned into account, has been decided during the examination that it makes good sense to carry-out additional manual analyses of the frequency spectrum during the first year of the SCMS operation; and, in case the maximum allowable (limit) levels of monitored parameters are exceeded, perform the visual examination of the building for structural defects.

The data obtained are processed in the "Fundamental tone" software tool. The period of vibration is determined using the indirect measurement method involving the recording of building vibration along three perpendicular axes. The values of the period are calculated basing on the result of measurements along the corresponding axis. The calculation is based on the building vibration power spectrum analysis [7]. The vibration period and the logarithmic decrement of the building natural frequency fundamental tone are determined according to the GOST R 54859-2011.

The acquired data are automatically recorded in text files. When analyzing the data, the highest value is compared with the limit values of deviation parameters.

During the analysis of the data obtained from the accelerometers installed in the 1-st building of "Champion park" complex it has been found that the indications of sensors exceed the limit values. The short-time increase or decrease of the natural vibration frequency can be caused by maintenance works carried-out at the mechanical floor or by strong wind gusts observed at that time. To prevent such temporary conditions from affecting the analysis it was decided to collect statistical data during

10 subsequent measurement cycles and, in case the value of the first mode (period) of vibration is within the reference limits, exclude the affected data from the collected sample [8-14].

In the result of the analysis of data collected during 10 subsequent measurement cycles, it was found that the measured values are within the allowable range. Therefore, the previously-obtained values exceeding the limits were removed from the total sample.

2.3. Indications of strain gauges

The strain gauges allow monitoring the stress-strain behavior of the bearing structures. In the "Champion park" complex, the strain gauges are installed on the bearing columns and solid bearing walls at different levels of the building (Figure 4).

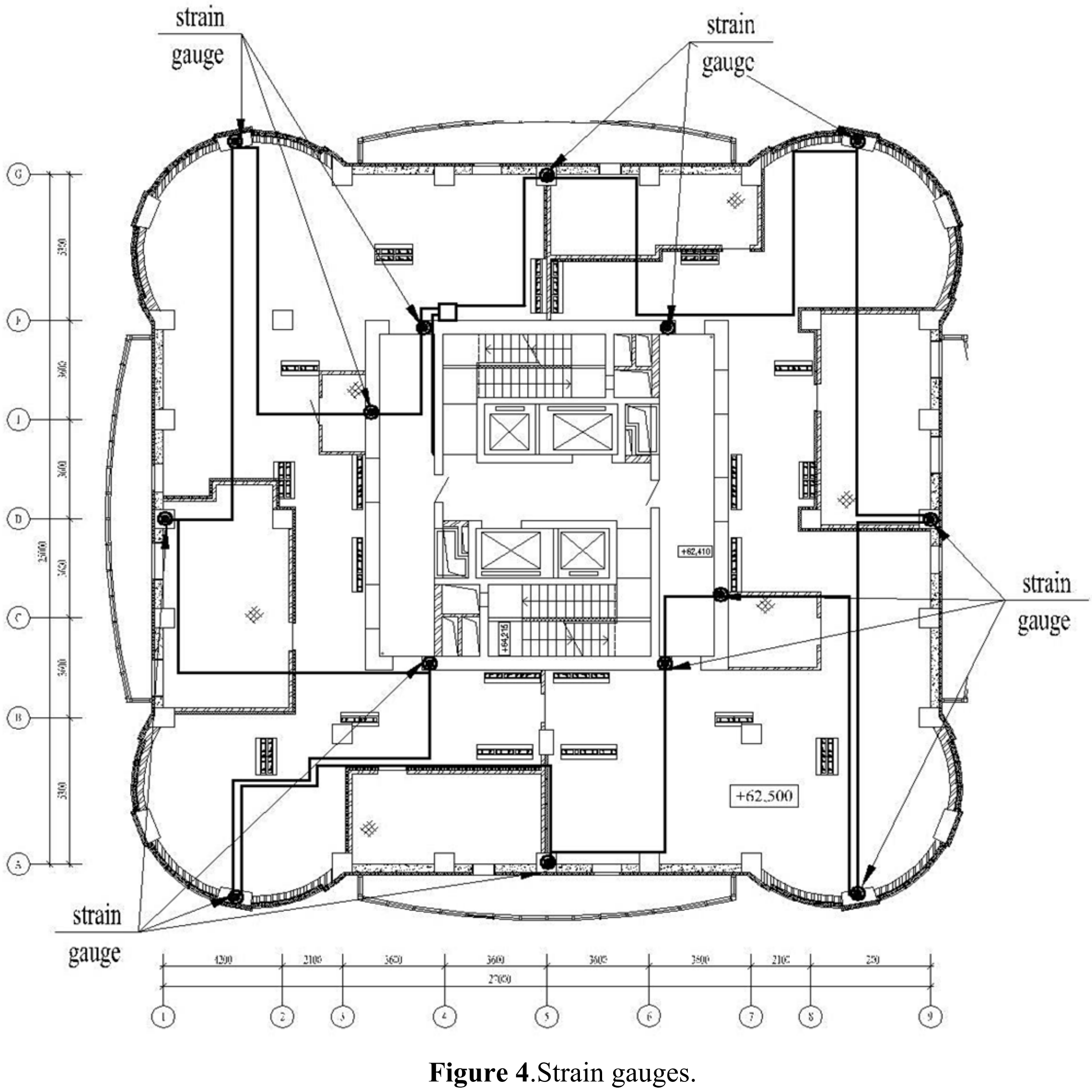

Figure 4.Strain gauges.

The analysis of the analytic model was performed for the assessment of a steady state stress-strain condition. Since the stresses in the analysis performed in the LIRA-SAPR software package are located in the central part of a bearing element, and the values obtained by the gauge are measured on its surface (Figure 5), the following equation is used for the comparison of the values:

$$\sigma = \frac{N}{A} \pm \frac{Ne_x l_x}{I_y} \pm \frac{Ne_y l_y}{I_x} \quad (1)$$

where: σ - normal stress; N – longitudinal force; A – cross-section area; e_x – eccentricity of longitudinal force N relative to cross-section center of mass along x axis; e_y - eccentricity of longitudinal force N relative to cross-section center of mass along y axis; l_x, l_y - distances from cross-section center of mass to gauge along x and y axes equal to half of column size; I_x, I_y - cross-section inertia moment relative to axes x and y.

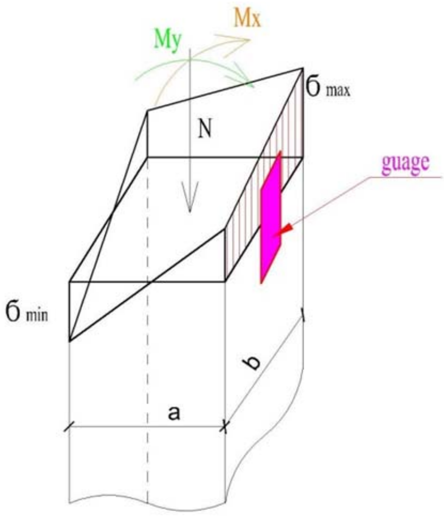

Figure 5. Determination of max. stresses in element

Relative strain is determined using the following equation:

$$\varepsilon_t = \frac{\sigma}{E} \quad (2)$$

where: ε_t – relative strain; E – concrete strain modulus equal to $\frac{E_b}{1+\varphi_{b,cr}}$ (cl. 6.1.15 of SP 63.13330.2012 regulations), where: E_b – initial concrete elasticity modulus equal to 38000 MPa for B50 concrete grade. $\varphi_{b,cr}$ – concrete creep coefficient taken as 1.6 for concrete grade B50 and above. All stress and relative strain values obtained in the result of the analysis are summarized in the table (table 2).

Table 2. Strain values measured by a strain gauge and corresponding full-load stresses in the gauge location on the edge of a bearing element.

Strain gauge No.	N, kN	e_y, m	σ, MPa	ε_t, m*10^{-6}
4	5130	0.0266	7.44	509
5	3600	0.0266	5.22	357
6	3570	0.07	6.33	434

Since the strain gauges are surface-mounted, they are installed on structures in steady-state stress-strain condition, it is impossible to assess the values of the structure stresses existing before the installation of the gauge i.e. the inherent stress and strain and temporary loads that are already acting on the structure. Therefore all subsequent variations of gauge indications are related to the changes of temporary loads: live load, wind load, and snow load [15].

In the tables given below the extreme indications of the gauges located at the 20-th floor level in με and Hz are given (Table 3). The values of gauge indications are obtained by means of converting the analogue signal from the gauges (frequency of string vibration induced by an electromagnetic coil). The frequency value is converted to strain by means of the following correlation formula:

$$\varepsilon = G \cdot F^2 \tag{3}$$

where: F – actual string vibration frequency received from telematics recorder;
G – manufacturer's coefficient calculated for a standard strain gauge basing on the gauge size and enclosure material properties (density and elasticity modulus). The coefficient for the gauges made by SITIS G = $4.479 \cdot 10^{-9}$ s^2.

Table 3. Extreme values of additional gauge strain and corresponding additional stress values in the gauge location.

Gauge ID	Gauge No. acc. To diagram	Location	Limit compression strain, με	Limit tension strain, με	Initial frequency value	Min. frequency value	Max. frequency value
300057	6	20th floor (ID 67151)	98.09	100	828.627	815.31	841.99
300058	5		136.19		835.836	817.44	849.09
300061	4		129.18		813.608	795.69	827.21

The analysis of the gauge indications showed that the values measured during the monitoring cycle are within the allowable limits.

3. Conclusion

The monitoring of technical condition of buildings and structures and the timely adoption of measures aimed at the elimination of factors affecting this condition are one of the main issues that shall be addressed when constructing a building. The outcome of the monitoring in the form of appropriate report shall contain sufficient data for assessing the condition of building structures and justifying the adoption of appropriate measures. The monitoring systems installed in the first building of the "Champion park" complex make it possible to assess the stress-strain condition of the bearing structures, monitor the maximal inclination of the building from vertical position under external loads, and assess the influence of newly constructed buildings (phases 2 and 3) on the bearing structures of the existing building. The continuous monitoring allows registering unexpected negative effects, variations in the stress-strain behavior of the structures, and causes of such variations.

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