JAES | JOURNAL OF APPLIED ENGINEERING SCIENCE | www.engineeringscience.rs

ISTRAŽIVANJA I PROJEKTOVANJA ZA PRIVREDU

Indexed by

INTEGRAL MONITORING OF HIGH-RISE BUILDINGS WHILEN MINIMIZING THE NUMBER OF SENSORS

Tolmacheva Valeriya Mixajlovna
Southwest State University, Faculty of Construction and Architecture, Department of Industrial and Civil Construction, Kursk, Russia

Plotnikov Alexey Nikolaevich
The Chuvash State University named after I.N. Ulyanov, Faculty of Civil Engineering, Department of Building Structures, Cheboksary, Russia

Ivanov Mikhail Yurievich
The Chuvash State University named after I.N. Ulyanov, Faculty of Civil Engineering, Department of Building Structures, Cheboksary, Russia

Amelin Vasilij Yurievich
Southwest State University, Faculty of Construction and Architecture, Kursk, Russia

Key words: *sensor, monitoring, deformation, forces, rigidity, deflection, frequency, inclinometer, strain gage, accelerometer*

doi:10.5937/jaes0-29432

Cite article:
Tolmacheva V. M., Plotnikov A. N., Ivanov M. Yu. & Amelin V. Yu. [2020]. Integral monitoring of high-rise buildings whilen minimizing the number of sensors. *Journal of Applied Engineering Science*, 18(4), 649 - 664.

Online aceess *of full paper is available at: www.engineeringscience.rs/browse-issues*

Istraživanja i projektovanja za privredu
Journal of Applied Engineering Science

Original Scientific Paper

doi:10.5937/jaes0-29432

Paper number: 18(2020)4, 741, 649 - 664

INTEGRAL MONITORING OF HIGH-RISE BUILDINGS WHILE MINIMIZING THE NUMBER OF SENSORS

Tolmacheva Valeriya Mixajlovna[1], Plotnikov Alexey Nikolaevich[2], Ivanov Mikhail Yurievich[2], Amelin Vasilij Yurievich[3]***

[1]Southwest State University, Faculty of Construction and Architecture, Department of Industrial and Civil Construction, Kursk, Russia
[2]The Chuvash State University named after I.N. Ulyanov, Faculty of Civil Engineering, Department of Building Structures, Cheboksary, Russia
[3]Southwest State University, Faculty of Construction and Architecture, Kursk, Russia

Considered current issues of automatic monitoring of high-rise buildings. A review of currently implemented monitoring methods is given. An analytical study of the effect of the ratio of the rigidity of the vertical and horizontal structural elements of buildings of various structural systems on the deformation of the vertical axis of the building was performed. The basis of the research is the solution of the differential equation of the elastic vertical axis of the building. By finding the extrema of the deformation function of the vertical axis, critical points of control of its angles of rotation are determined. As a result of the study, it was concluded that it is advisable to minimize the number of control points, with limited control at certain critical points. The position of the control points dividing the vertical axis of the building through ¼ of its length at the corners of the perimeter of the floors has been determined. It is shown that minimization is necessary due to difficulties in processing and analyzing big data (Big Data). As a result of the traditional manual calculation with the accepted design methods, it was found that the box-barrel structural system has the greatest deformations, the frame-link frame with the stiffness core has the smallest deformations, and outriggers do not always allow to radically increase the building stiffness. Studies were conducted on computer models of the same types of buildings, which confirmed this dependence. However, here the maximum rigidity was shown by the cross-wall model. This testifies to the features of modeling buildings in various ways and confirms once again the need to monitor not only high-rise buildings, but all non-standard ones. It is concluded that it is necessary to accumulate data on the deformations of buildings using automatic monitoring methods. It is shown that information on the technical condition of the building is complemented by information on the longitudinal deformations of vertical structures - columns, stiffness cores, measured by tensiometers on concrete, as well as dynamic stiffness, determined by the natural oscillation frequency of accelerometers. The principle of sensor grouping and the need to use integrated, integrated monitoring are shown.

Key words: sensor, monitoring, deformation, forces, rigidity, deflection, frequency, inclinometer, strain gage, accelerometer

INTRODUCTION

For high-rise buildings, the construction of which is carried out throughout the world, a necessary requirement during the operation is an automatic permanent monitoringof the technical condition [1] to [3]. However, there is no complete methodology for creating and conducting automatic monitoring [4] to [6]. On some objects, the full scope of control of dynamic parameters is realized, the continuous installation of accelerometers, the definition of building deformations is minimized [7] to [9]. On other objects, a chain of inclinometers is established - measurement points are located along the entire vertical of the building, but often the measurements of deformations are carried out only along its most rigid area - the core of rigidity [10] to [12]. As a result of the application of a large number of sensors and the receipt of a significant amount of data over time, the operation service faces the problem of analyzing this volume [13] to [15]. This is despite the fact that automatic monitoring is an expensive procedure [16] to [18]. However, areas remote from the center of the building, but affecting its rigidity, remain uncovered.

In a number of works it is noted that various constructive solutions of high-rise building systems have common mathematical dependencies that determine their deformation[19] to [21], in particular, from wind static load [22] to [24]. The ratio of the stiffness parameters of the vertical and horizontal bearing elements also affects the operation of the building as a whole [25] to [27]. It is known that during operation with varying degrees of intensity, the state of buildings changes: performance is limited and the reliability of structures is reduced [28] to [30]. A number of reasons lead to this: a change in the nature of the conjugation between structures, a change in the physical properties of materials, and also a change in shapes and sizes.

When monitoring high-rise buildings, techniques are used based on the application of the main group of sensors - strain gauges, inclinometers and accelerometers [31] to [33].

*325573@mail.ru

With the help of accelerometers, which are often used in high-rise buildings, they measure dynamic parameters, observing which over time, one can obtain information on the rigidity of the object as a whole [34] to [36]. As many authors write, the registration of vibrations requires a rather complex pre-processing on the structure model [37] to [39]. A feature of dynamic (seismometric) techniques is that the observation schemes can be quite simple (up to one point). In addition, they provide an opportunity to control not only the magnitudes of accelerations, but also make it possible to judge the joint work of the building and the foundation grounds and to identify previously unknown phenomena. Various forms of building vibrations are shown in Fig. 1.

The amplitude-frequency characteristics (AFC), manifested during the operation of the building, are influenced by the rigidity of the construction of a complex cross section of the building in plan, the types of elements joints. When the properties of concrete change, with the formation and development of cracks, a change occurs in the frequency of vibration shapes in vertical elements [40].

In connection with the foregoing, the task of rational placement of sensors and the principle of analyzing their data is very relevant and requires a series of studies. Mathematical methods for analyzing the stress-strain state of high-rise buildings, taking into account the patterns of operation of carrier systems, allow us to solve the urgent question of reducing the number of sensors needed to monitor high-rise buildings.

The purpose of this work is to justify the rational placement of sensor groups in high-rise buildings based on the differential functions of the vertical axis.

The task of research is to solve the differential equation of the elastic axis of the building with different stiffness ratios of vertical and horizontal structural elements with finding characteristic extremes corresponding to changes in the axis curvature, as well as determining zones of possible reduction in stiffness recorded by dynamic characteristics.

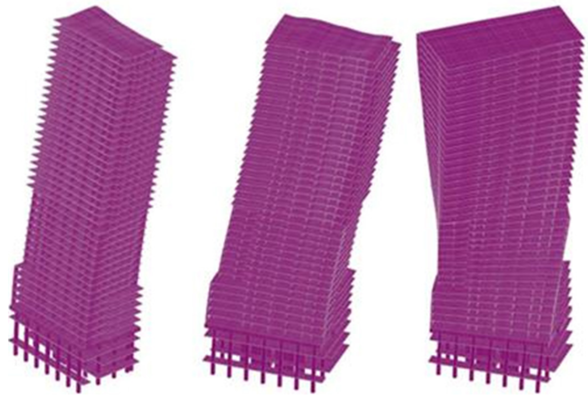

Figure 1:Forms of vibrations of the building

METHODS

From the analysis of the extrema of the deformation function of the vertical axis of the building [41], [42] while maintaining the horizontal plane of the floors [43], the main characteristic monitoring points necessary to minimize the number of sensors in high-rise buildings are determined.

The stiffness of the elements and the compliance of the mates determines the distribution of internal forces in the main bearing elements, as well as their redistribution under external influences and loads (Fig. 2). These parameters depend on their stress-strain state, characteristics of the materials used, operating conditions [44], [45].

Due to the compliance of numerous seams, the rigidity of the overlapping discs and the coating is significantly reduced compared with the solid monolithic overlap [46, 47, 48]. This reduction is allowed to take into account by introducing a lower value of the initial modulus of elasticity of concrete with a constant ratio between the moduli of shear and elasticity equal for precast ceilings with a

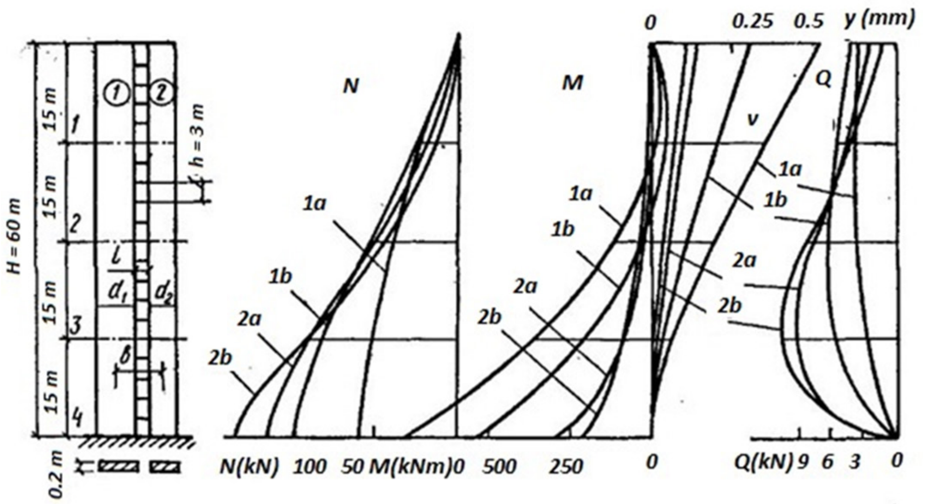

Figure 2: Distribution of deformations and efforts at the height of the building.
Plots of longitudinal forces (N), bending moments (M), transverse forces (Q), deflection (v) of the coupled system with ratios of the reduced stiffness characteristics between the individual vertical elements

quality seal of joints in the range of 0.15-0.25.

A change in the compliance of overlapping disks leads to a change in their effect on the redistribution of forces between vertical subsystems. The harder the disk and its mates with vertical elements, the smaller the difference in horizontal displacements it allows, and with absolutely hard disks all points of vertical structures in the level of floors would have the same horizontal displacements.

Deformations depend on the ratio of the stiffness of the vertical and horizontal elements of the frame (Fig. 3). Dependencies are presented in graphical form in the literature on the theory of deformation of high-rise buildings [37], [38], where the characteristic points of fracture are found through ¼ of the height of the building.

In a building, floors are shear connections, possessing real stiffness, depending on the design. They prevent the free bending of the vertical stiffeners. In this connection, the strain line of the vertical stiffeners becomes S-shaped, i.e. has two curvatures in the plane, in space, respectively, four. In Fig. 4 shows the operation of the shear connections, depending on their design.

The basic formulas for defining the deflections obtained by P.F Drozdov [41].

Horizontal movement (deflection) in any section of the bearing system or structure in the adopted coordinate system:

$$v(x)=\int_x^H \alpha dx = v_s(x)+\frac{n\cdot B_a}{\left(\lambda^2\cdot B_u\cdot\sum B\right)}\cdot \left\{q\cdot\left[ch\lambda H-ch\lambda x+\beta\cdot\left(sh\lambda H-sh\lambda x\right)+ +(1-a)\cdot\left(1-\frac{x}{H}\right)\right]\cdot\lambda^{-2}+M_h(H \right. \quad (1)$$

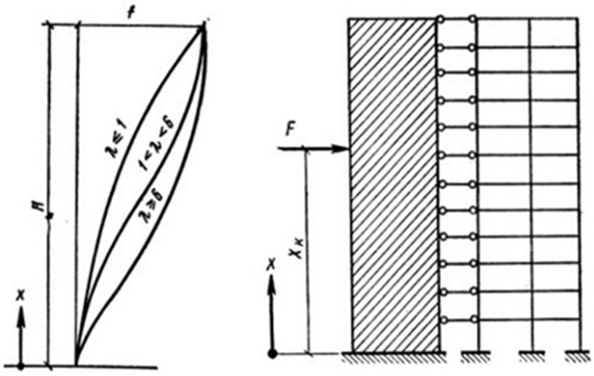

Figure 3: Distribution of deformations over the height of the building, depending on the stiffness of the vertical elements. λ - stiffness characteristic of vertical diaphragm elements (core), with a value less than 1 - more rigid vertical elements, more than 6 - more flexible

where - where the number of simply connected doubly connected structures; H - building height; q - single wind load; B_u - flexural stiffness; B_a - stiffness for one vertical design; $\sum B$ - total stiffness of columns (walls) and hardness cores; x- characteristic break point; a - conditional value equal to 0.3; $v_s(x)$ – deflection in the section x of the bearing system or structure with absolutely rigid jumpers or bolts, equal to the load distributed according to the trapezium law:

$$v_s(x)=\frac{-q\cdot H^4}{120\cdot B_u}\cdot\left[4\cdot a+11+(a-1)\cdot\left(\frac{x}{H}\right)^5+ +5\cdot\left(\frac{x}{H}\right)^4-5\cdot(3+a)\cdot\frac{x}{H}\right] \quad (2)$$

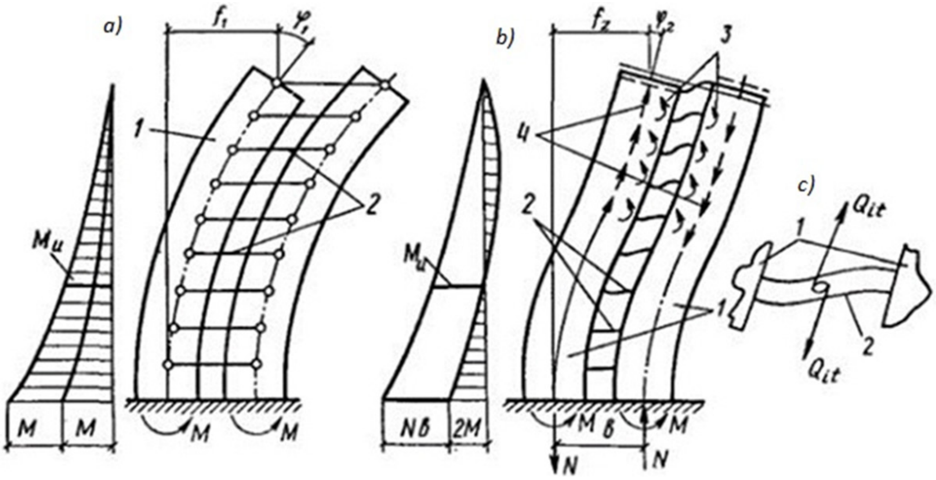

Figure 4: Scheme of the shear connections
a - swivel (extremely theoretical), b - real (with intermediate rigidity), c - detail of the bond deformation (overlap); 1 - pillars (diaphragms, stiffening cores), 2 - connections (overlap) 3 - bending moments, 4 - transverse forces Qi transmitted to stiffeners

β - conditional value equal to:

$$\beta = \frac{E_2 F_2}{E_1 F_1} \tag{3}$$

where E_2 - the modulus of elasticity of the vertical element (core stiffness); F_2 - sectional area of a vertical element (hardness core); E_1 - the modulus of elasticity of a vertical element (columns or walls); F_1 - sectional area of a vertical element (columns or walls);

λ - conditional value equal to:

$$\lambda = \sqrt{\frac{kB_u}{s\sum B}} \tag{4}$$

where s - conditional value equal to:

$$s = \frac{hl^3}{12B_u b} \tag{5}$$

where h - floor height; l - jumper length; b - lintel width; k - conditional value equal to:

$$k = \frac{1+\beta}{b(E_2 F_2)} \tag{6}$$

M_h – bending moment with a trapezoidal horizontal load diagram:

$$M_h = \frac{-(a+2)\cdot q\cdot H^2}{6} \tag{7}$$

Find the first derivative of the deflection line and equate it to zero:

To determine the characteristic points, high-rise buildings were installed with a different structural system [49], [50], in which the coordinates of the extremes were determined from formulas (8) [51], [52].

$$v'(x) = \frac{H^4\cdot q}{120\cdot B_u}\cdot\left[\frac{20\cdot x^3}{H^4} - \frac{5\cdot a+15}{H} + \frac{5\cdot x^4(a-1)}{H^5}\right] - \frac{B_a\cdot n}{\sum B\cdot B_u\cdot\lambda^2}\cdot \tag{8}$$

$$\left[\frac{q\cdot\left[ch\lambda x - ch\lambda H + \beta(sh\lambda x - sh\lambda H) - (a-1)\cdot\left(\frac{x}{H}-1\right)\right]}{\lambda^2} - \frac{q\cdot x^2(a+2))}{6} + \right.$$

Building 1 with a frame-coupled frame, with a monolithic reinforced concrete core stiffness (height 118.75 m; 26 floors). Location: Moscow, Prospekt Vernadskogo, p. 10 (Fig. 5). Projected building. Sensors are located on floors 1, 6, 12, 18, 23.

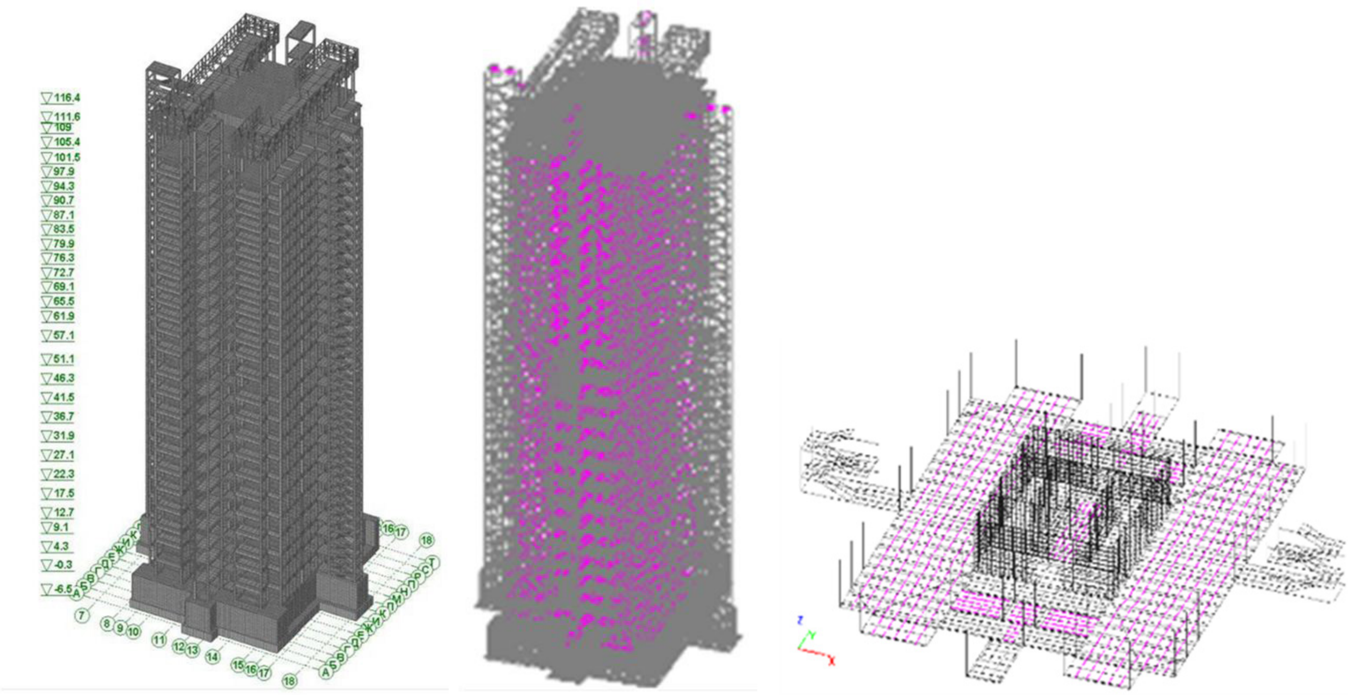

Figure 5: Settlement model of a building with a frame-coupled frame

Building 2 with a cross-wall structural system (height 136.81 m; 44 floors). Location: Moscow region, Krasnogorsk, Pavshino (Fig. 6). Sensors are located on floors 1, 11, 22, 33, 44.

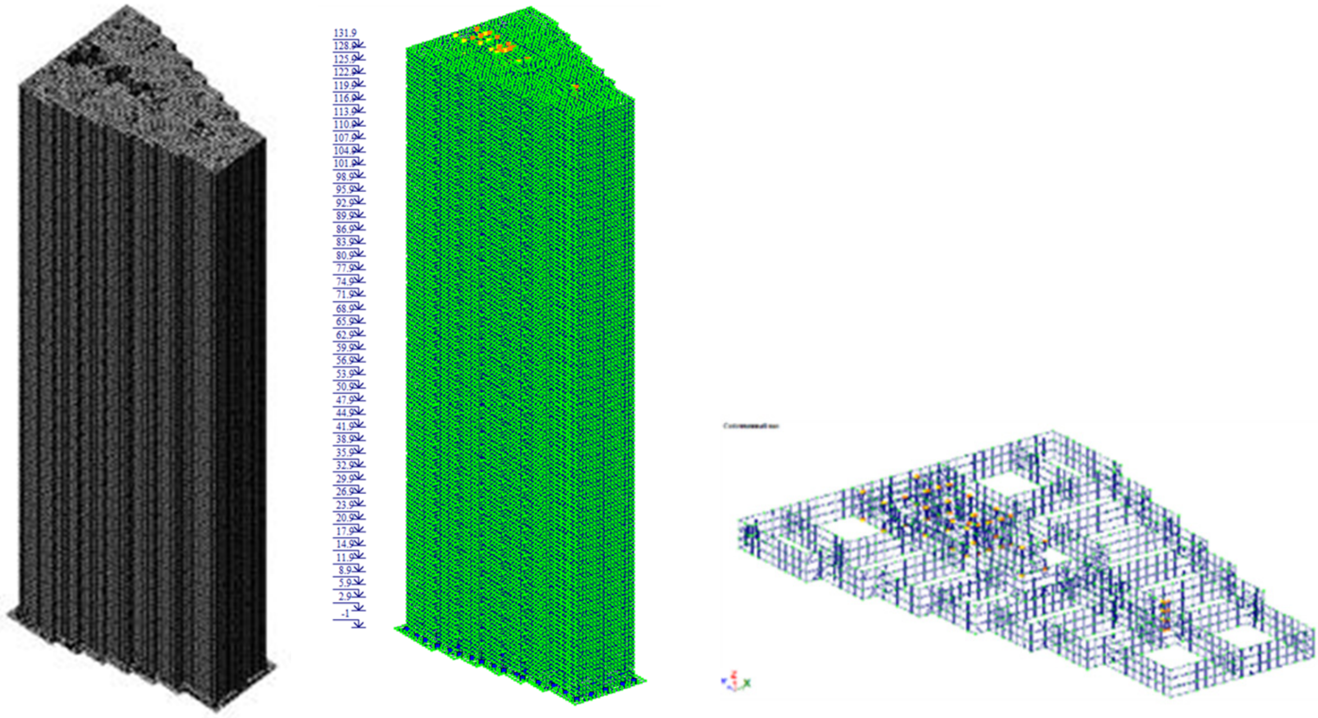

Figure 6: Settlement model of a building with a cross-wall system

Building 3 box-stem structural system with outrigger floors (height 103.5 m; 23 floors). Projected building(Fig. 7). Sensors are located on floors 1, 6, 12, 18, 23.

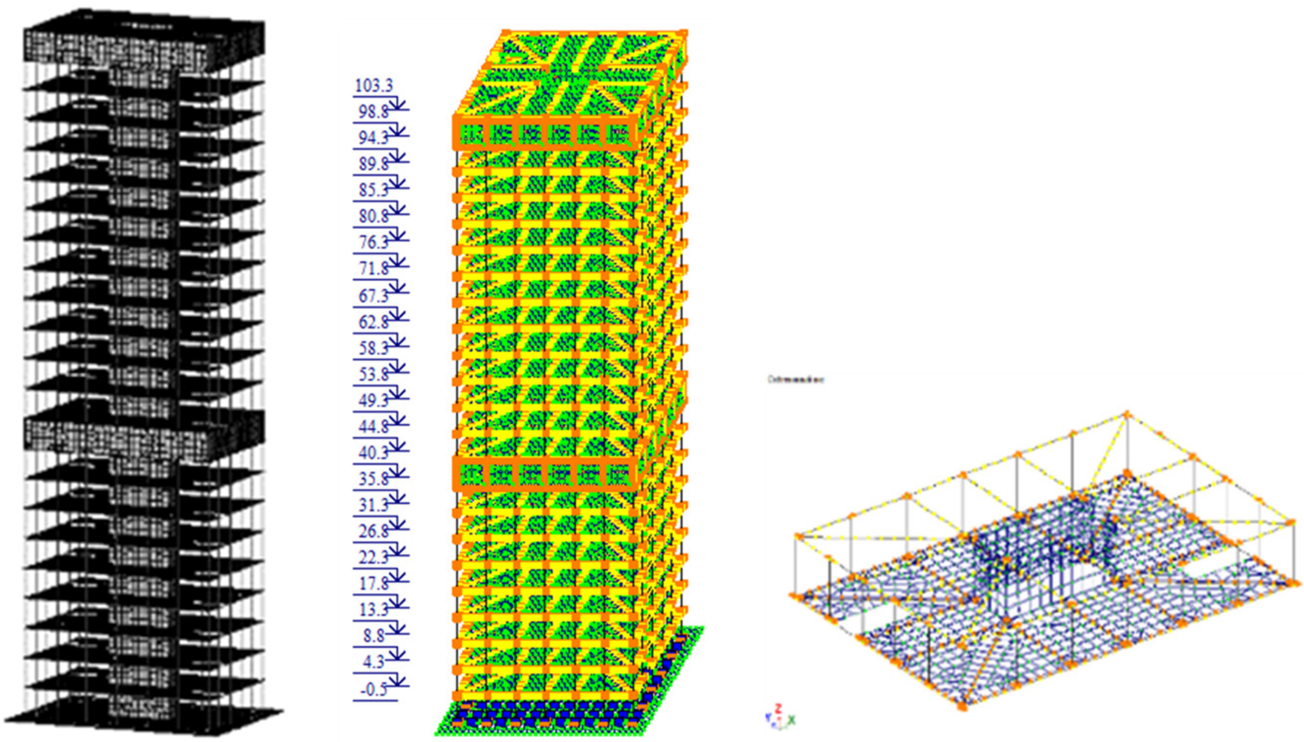

Figure 7: Settlement model of a building with a box-and-barrel system

Building 4 shell structural system with outrigger floors (height 100 m, 25 floors). Projected building (Fig. 8). Sensors are located on floors 1, 6th 12, 18, 25.

As a result of the calculation, control points located through ¼ of the building height are determined.

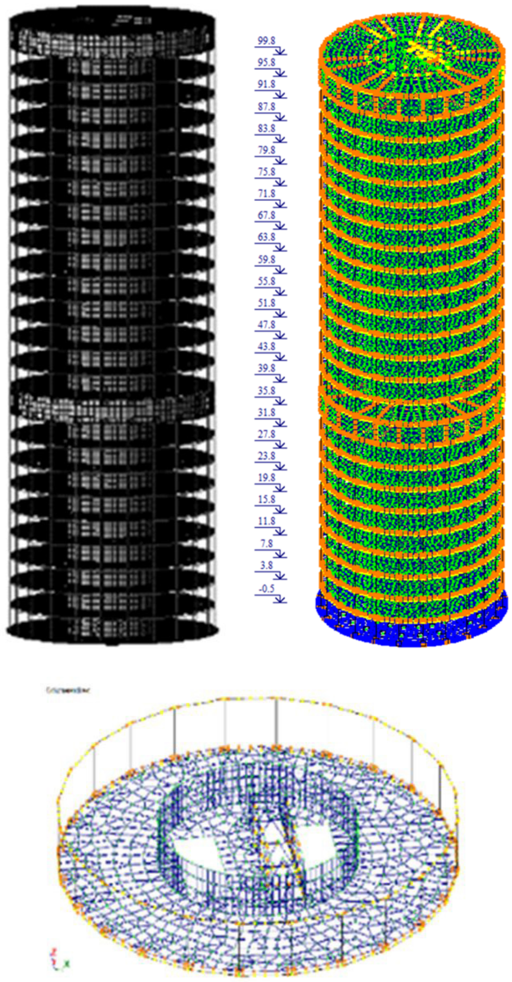

Figure 8:The design scheme of the building and floor plan

RESULTS AND DISCUSSION

According to the formulas presented in the works of P.F. Drozdov [41], [42] made a manual calculation of horizontal displacements in the overlap levels, and also obtained the calculated models of the finite element method in the software complexes of Lira SAPR and SCAD. Deformations of buildings are shown in Fig. 9, and the results of the calculation of horizontal displacements – in Table. 1.

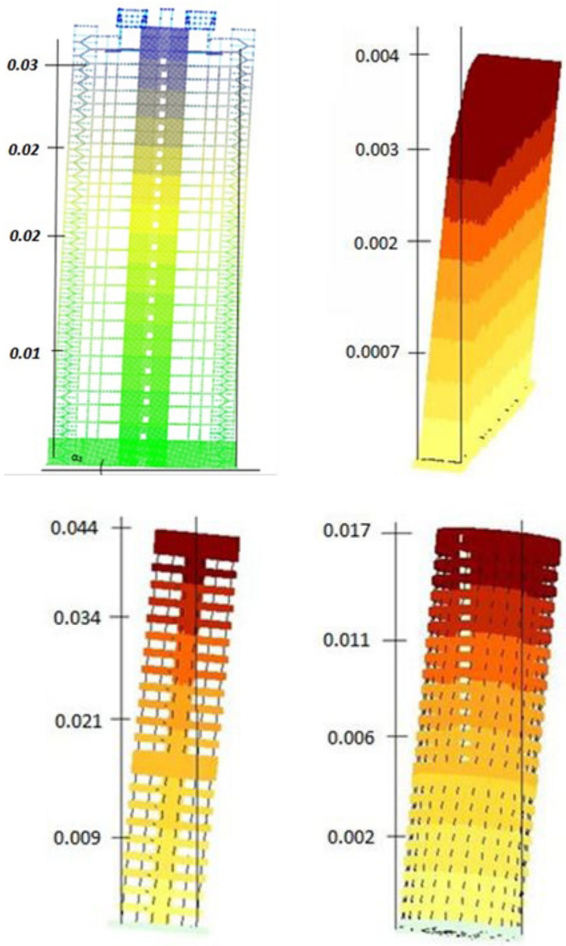

Figure 9: Deformations of buildings of various structural systems from wind static load according to the calculation results

Table 1: The results of the calculation of the horizontal displacements of the structure

Section	x/H	Frame-bond frame (1)		Cross-wall system (2)		Box-stem system (3)		Shell system (4)	
		V(x), mmanual calculation	V(x), mcomputer calculation	V(x), mmanual calculation	V(x), mcomputer calculation	V(x) , mmanual calculation	V(x), mcomputer calculation	V(x), mmanual calculation	V(x) , mcomputer calculation
0	0	0.01246	0.03	0.1363	0.004	0.3236	0.044	0.25	0.017
1	1⁄4	0.008494	0.02	0.1052	0.003	0.2494	0.034	0.181	0.011
2	1⁄2	0.004695	0.02	0.0721	0.002	0.1700	0.021	0.125	0.006
3	3⁄4	0.001613	0.01	0.0227	0.0007	0.08353	0.009	0.065	0.002
4	1	0	0	0	0	0	0	0	0

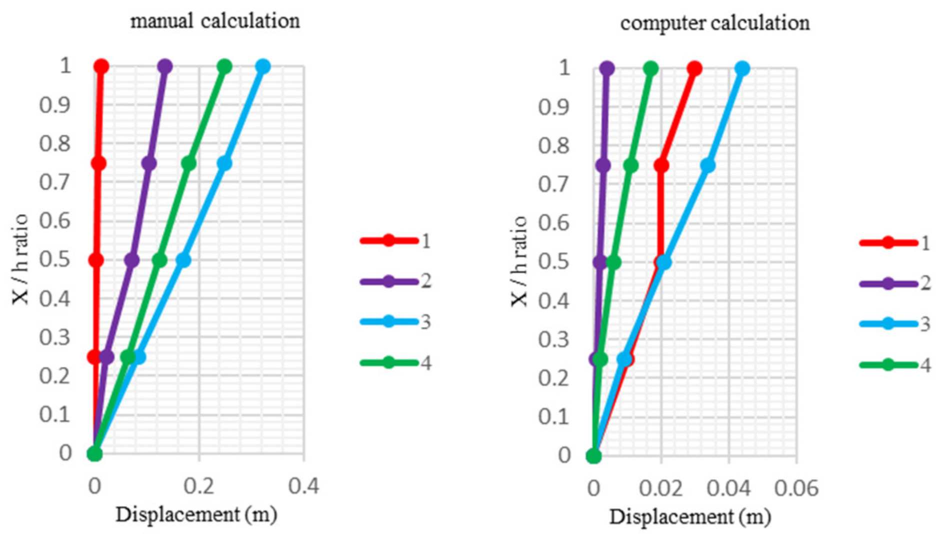

Figure 10: Comparison of the graphs of deflections of floor slabs

When comparing the deflections, the vertical axes of buildings at the level of floors in manual and computer calculations of displacement differ, according to some schemes, up to 6 times (Fig. 10). In this case, computer models were built according to traditional methods - without finite, variable connections, stiffness between floors and vertical structures. In the theory of P.F. Drozdova laid down a decrease in the rigidity of the bonds during operation. In any case, the deformations depend on the ratio of the rigidity of the vertical and horizontal elements of the frame. A computer calculation also shows several extremes along the height of the building when the slope of the tangent to the bend line changes. According to the results of computer simulation, it has been determined that the deformation line of a building vertically is non-linear, which corresponds to the general theory of calculating high-rise buildings with a bond-type frame.

This is in good agreement with the general theory the bond of frameworks with the core of rigidity. With this stiffness ratio of the vertical and horizontal frame elements, the characteristic fracture points are located through ¼ of the building height, with extreme stiffness ratios (stiffer overlaps), these points may shift slightly lower.

A number of papers [7] to [9] discuss the required number of sensors and the principle of their installation in high-rise buildings [10] to [12]. In many buildings [13], [14], inclinometers were installed according to the “on each floor” principle [33], [40]. In an article devoted to the three-spline mathematical processing of the results of measurements of tilt angles to derive the function of the deformation line of the vertical of a building, the reduction in the number of sensors twice is analyzed [7]. It is noted that after the mathematical processing of the function remains unchanged. In the variant of inclinometers proposed by us, the principle of differentiation of the vertical strain line by extremes is used, which leads to the same principle of continuity. Consequently, the number of sensor groups can be reduced to the number of extremum points.

Most authors pay attention to the placement of sensors vertically, but does not always pay attention to the deformation of buildings around the vertical axis and the control of stiffness on the shear of floors.In [40], correlation relations between the angles of inclination of columns between floors and within one floor are considered. The article [8] describes the measurement of the inclination of sensors on inclinometers installed only on the top floor of a building in Istanbul. Describes the method of processing the signal from the sensors in time with the exception of random noise. Articles [9] and [10] speak about the need for an integral approach to monitoring the position of points of a building in space. GPS sensor readings should be adjusted by inclinometers and readings of anemometers for wind load should be taken into account. However, the number of inclinometers in the article is out of the question.

Interesting is the article [11], which explores alternative ways of measuring the deformations of buildings using video cameras and algorithms for processing a shifting image.

On some sites, an unreasonable number of sensors, accelerometers on each floor or often located and inclinometers only on the foundation plate and at the top of the building are sold [12], [13].

The paper [36] presents a method for evaluating the design with accelerometers using the example of a high-rise building in Dalian, which states that the distribution of accelerometers should be based on the vibration characteristics of the structure and analysis of the theoretical model.

The article [14] speaks about the need to study the deformations of buildings, including flexural and torsional.

High-rise buildings are constantly in motion. Buildings experience inevitable oscillatory movements under the influence of wind and seismic loads, which are dynamic.

Operational control of the technical condition of the building is carried out at its own frequency of oscillation and acceleration of control points from dynamic loads determined during normal operation of the object in the entire controlled frequency range, including higher frequencies. Accelerometers are placed evenly along the height of the building. In the case of the use of computer systems based on the finite element method to determine the oscillation frequencies of the bearing systems of buildings should take the natural frequency corresponding to the form of vibrations closest to the form of displacement of the building from the static load (maximum amplitude deviations). Operational control of the state is carried out by the frequency of natural oscillations of several higher forms.

Additional information on the state of a high-rise building is provided by strain gauge, which is based on the determination of stresses and strains. Strain gauge allows you to trace the process of redistribution of effort in the vertical bearing elements as a result of uneven precipitation of the building, bending from the wind.

The most useful information about the deformations of buildings can be obtained using inclinometers. They provide information about the deformations of a high-rise building in space.

In all the objects under consideration, the principle of placing inclinometers in terms of the building "center - building corners" is implemented. In this case, the correlation of the angles of inclination of the columns with the maximum values is well traced. The inclination of all columns can occur in one direction, which means the total roll of the building, in two directions - deformations in space, and twisting around the axis of the building. It is necessary to compare the deformations of the extreme columns with the deformations of the center of the building (stiffening core). In the future, this comparison should be implemented programmatically in the SMIC system.

In the process of preparing the monitoring, it should be borne in mind that the bulk of the strain is due to the weight of the structures, and the strain sensors:inclinometers and strain gauges are installed after this exposure. The prehistory of the deformations can be determined theoretically, with the need to estimate the level of stresses in the vertical elements relative to the limiting to account for the proportion of nonlinear deformations.

The minimum number of sensors is taken at critical monitoring points from the principle of measuring deformations at the extremes of the deflection line of a building, which characterizes the shape of the vertical axis of the building depending on the ratio of the stiffnesses of the system elements and their changes during operation.

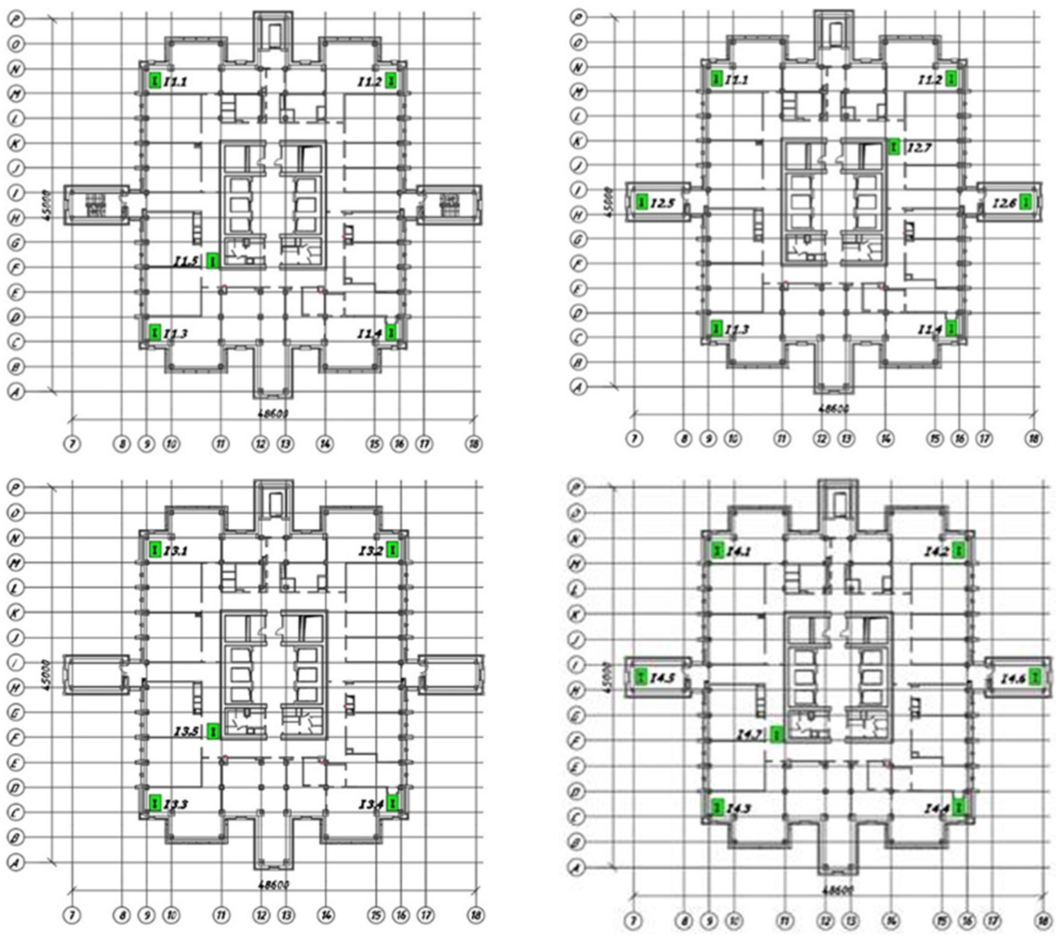

Figure 11: Location of inclinometers for frame-bond frame with monolithic reinforced concrete core on 7, 13, 20, 26 floors

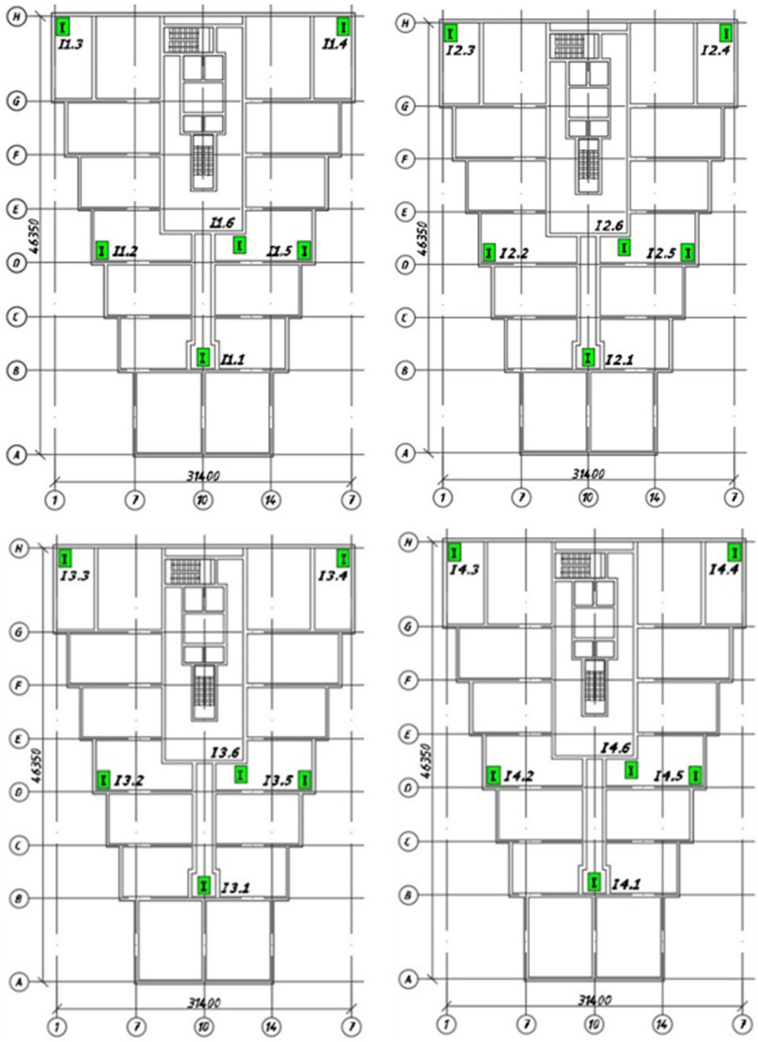

Figure 12: Location of inclinometers for the cross-wall structural system on 11, 22, 33, 44 floors

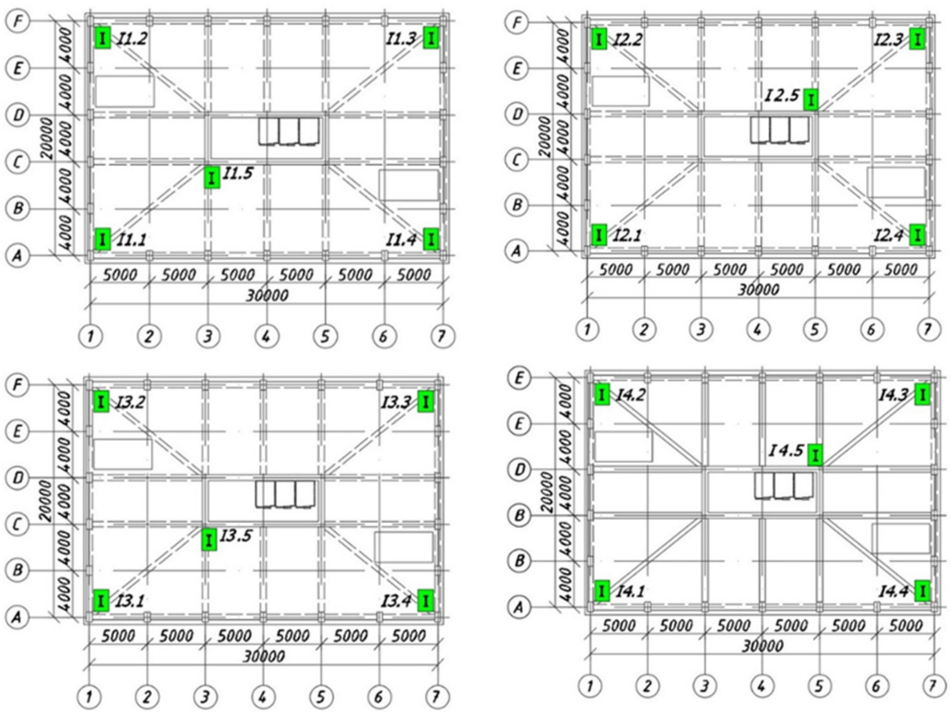

Figure 13: Location of inclinometers for a box-stem structural system with outrigger floors on 6,12, 18, 23 floors

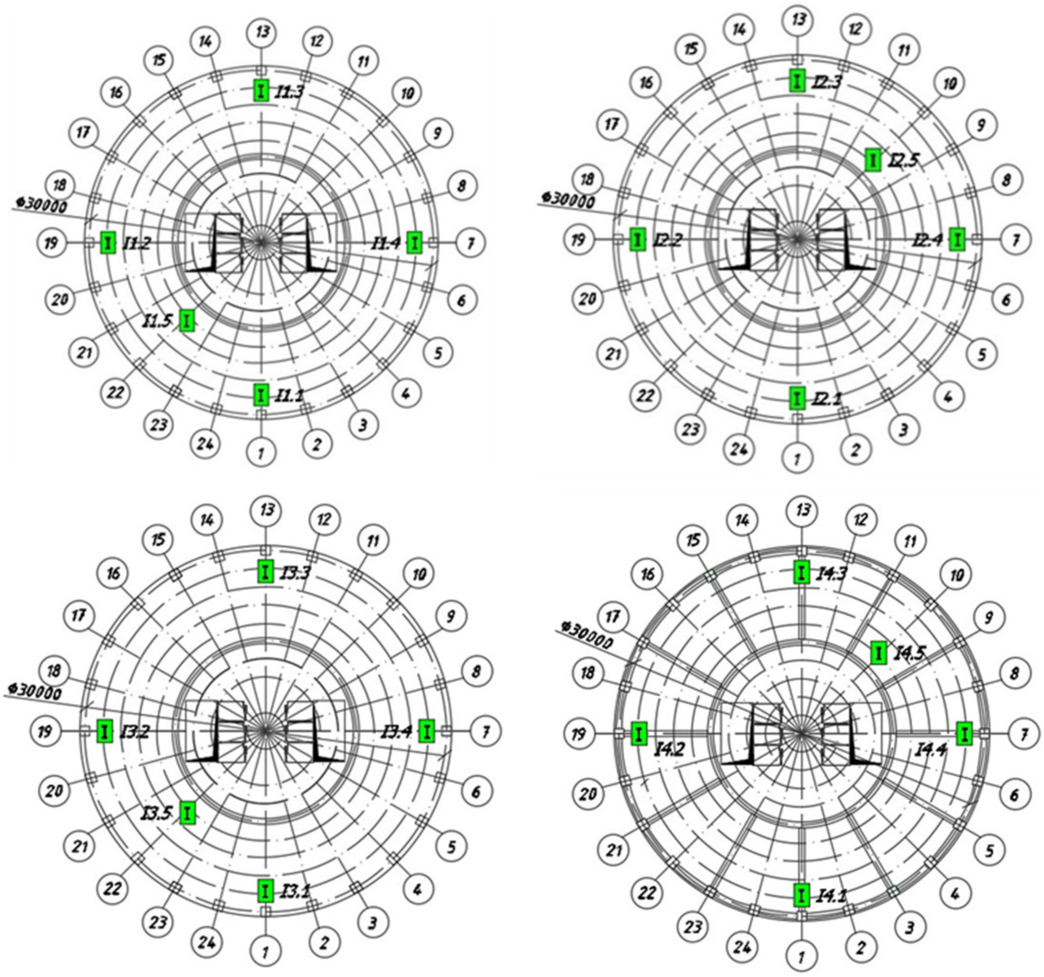

Figure 14: Location of inclinometers for the shell structural system with outrigger floors on 6.12, 18, 25 floors

According to the calculations, the maximum tilt of the temporary load was 379”. Maximum roll angle for high-rise building 412”by Russian Construction Rules/Norms SP 20.13330.2016. Similarly, according to EN 1990 with the maximum possible deviation of the building from the vertical L/500.

Based on this, inclinometers with a measuring range of ± 720 "(angular seconds) - two-coordinate were taken. The location of inclinometers is shown in fig. 11 – 14.

The values of the limiting relative deformations with a prolonged load of Russian Construction Rules/Norms SP 63.13330.2018 with a relative humidity of ambient air of 40-75% under compression for heavy concrete is 0.0034. According to EN 1992 (Eurocode 2) under similar conditions - 0.0035. Under the action of design loads, the relative deformations in the lower tiers of the columns amounted to 1 for the building - 0.00227, in the stiffening core - 0.0003. For all buildings, these values did not exceed the limit. Based on this, strain gauges with a maximum measurement range of up to 3000 microstrain (µm/m) were adopted. The location of strain gauges is shown in Fig. 15.

According to the results of computer simulation, the maximum natural vibration frequencies of all forms for all buildings were: 1.38; 1.17; 1.25; 1.67 Hz. All of them are within the limits of the first form of oscillations according to Russian Construction Rules/Norms SP 20.13330.2016 for different wind regions. Taking into account additional harmonics from oscillations of local elements, accelerometers with a low level of the range, from 0.1 to 40 Hz, were taken. The location of accelerometers is shown in Fig. 16 - 19.

Particular attention when installing inclinometers should be paid to the base plate. The plate receives part of the deformations from the action of a constant load of the own weight of the core of rigidity, which can lead to its “concavity”, however, the sensors are installed after this situation, the initial state must be taken into account when determining the rotation angles from the temporary load. If only the wind load is considered, the base plate can “break away” from the base, then an adjustment should be made to the inclinometer readings. In a physically existing building of this size, there is no separation of the foundation from the base, since at the same time the own weight of the building. However, it is necessary to consider a one-sided change in the angle of rotation of the base plate under the action of wind load.

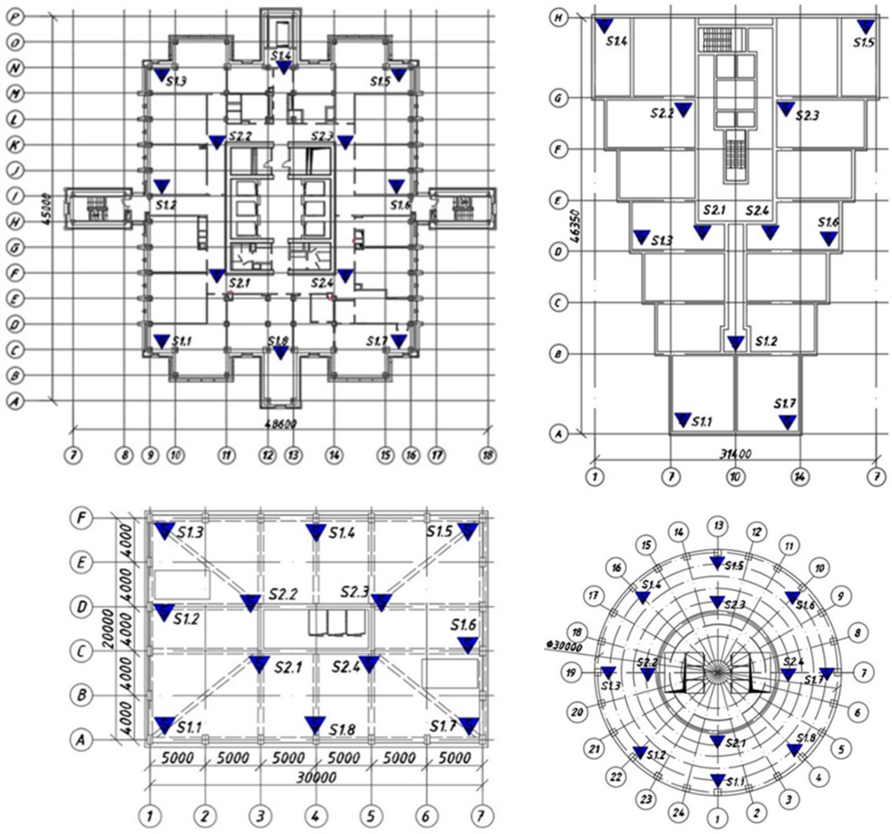

Figure 15: Location of strain gauges for different structural systems of high-rise buildings on the 1st floor

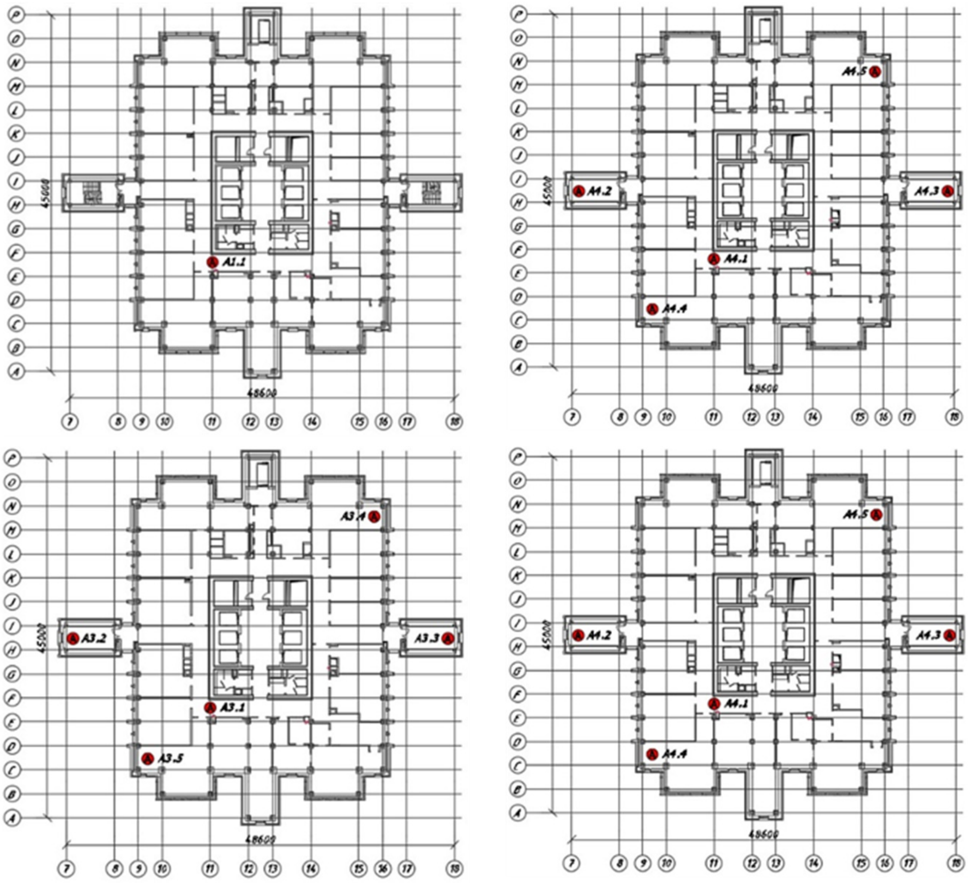

Figure 16: Location of accelerometers for the frame-bond frame with a monolithic reinforced concrete core stiffness 7,13, 20, 26 floors

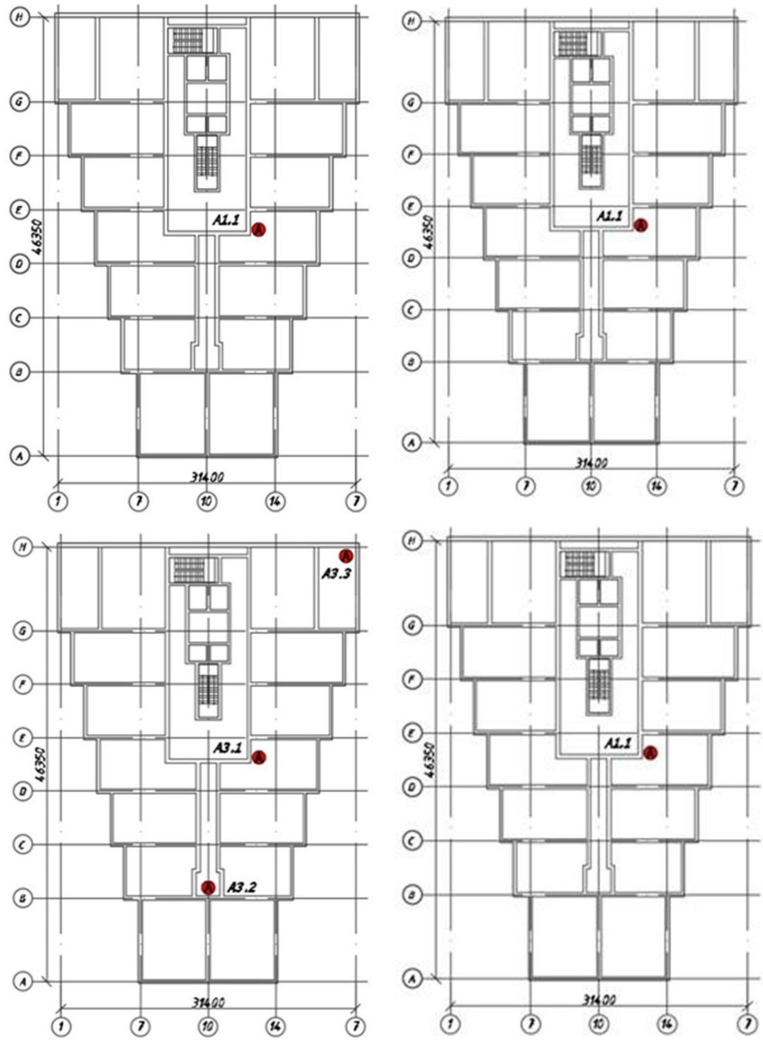

Figure 17: Location of accelerometers for the cross-wall structural system on 11, 22, 33, 44 floors

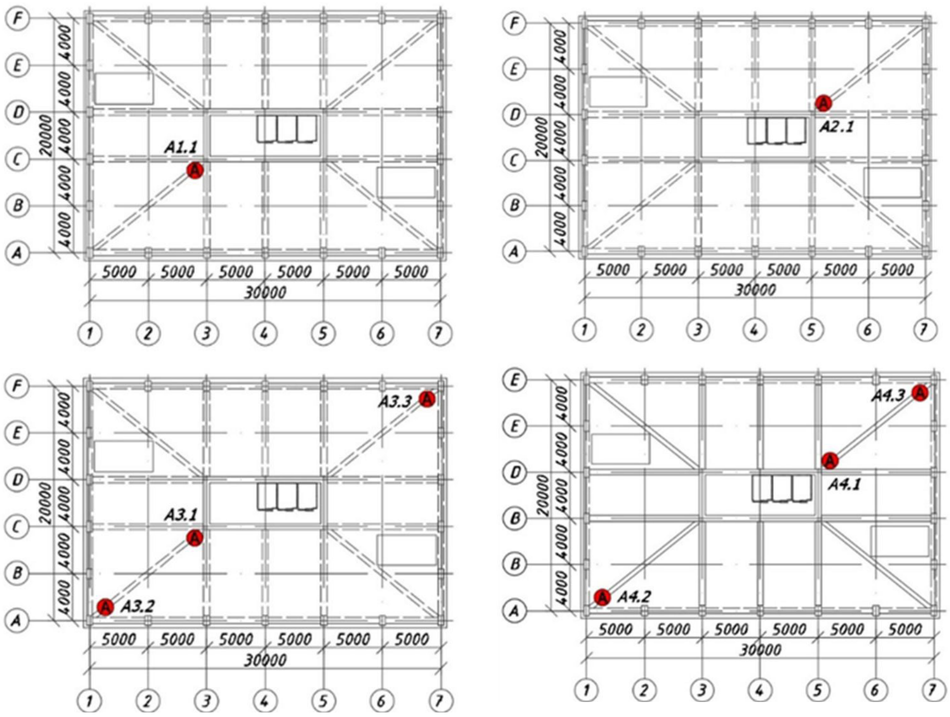

Figure 18: Location of inclinometers for a box-stem structural system with outrigger floors on 6,12, 18, 23 floors

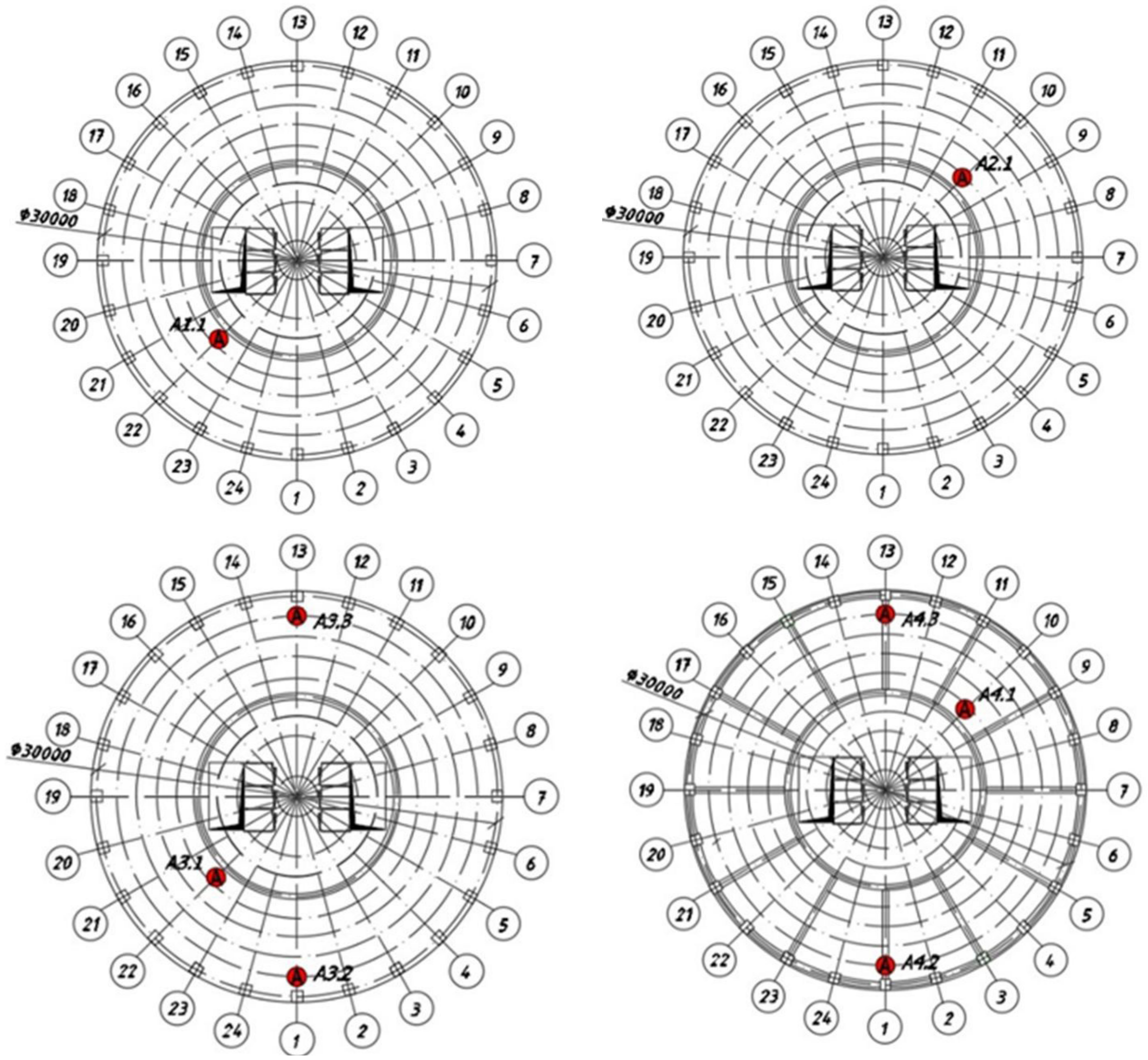

Figure 19: Location of inclinometers for the shell structural system with outrigger floors on 6.12, 18, 25 floors

CONCLUSIONS

1. For automatic (continuous) monitoring of high-rise buildings, an integrated (integrated) method is recommended, which includes the measurement of rotation angles, frequency and amplitude of vibrations, deformations of vertical supporting structures.
2. From the general theory of calculating high-rise buildings and computer design models, it follows that SMIC sensors should be installed uniformly across the building, covering the perimeter of the floors and the entire height.
3. Measurements should be carried out on the contour of floors on the floors every 1/4 of the height of the building, as well as on the core of rigidity to control the integrity of the floors and their connection to the core of rigidity.
4. Accelerometers are recommended to be installed on the same marks as inclinometers, on the core of rigidity, in the center of the building, as a more rigid element that determines the overall rigidity of the building.
5. It is recommended to install strain gauges in the lower tiers of vertical bearing elements, their readings correlate with inclinometers.
6. t is necessary to develop computer programs that trace the correlation between the readings of sensor groups, which will more fully reveal the possibilities of integral monitoring.

REFERENCES

1. Park, H.S., Shin, Y., Choi, S.W., Kim, Y. (2013). An Integrative Structural Health Monitoring System for the Local. Global Responses of a Large-Scale Irregular Building under Construction. Sensors,no. 13, 9085-9103, DOI:10.3390/s130709085.
2. Olenkov, V.D., Popov D.S. (2012). Automation of diagnostics of the technical condition of buildings and structures during their operation. Bulletin of the South Ural State University. Series: Building and Architecture, no. 17(276), 82-85.

3. Iturralde, K., Linner, T., Bock, T. (2020). Matching kit interface for building refurbishment processes with 2D modules. Automation in Construction, vol. 110, 103003, DOI: 10.1016/j.autcon.2019.103003.
4. Pan, M., Linner, T., Pan, W., Cheng, H.-M., Bock, T. (2020). Influencing factors of the future utilisation of construction robots for buildings: A Hong Kong perspective. Journal of Building Engineering, vol. 30, 101220, DOI: 10.1016/j.jobe.2020.101220.
5. Hua, J., Liub, X. (2011). Design and implementation of tailings dam security monitoring system. Procedia Engineering, no. 26, 1914 – 1921, DOI:10.1016/j.preng.2011.11.2384.
6. Li, J., Hao, H. A. (2016). review of recent research advances on structural health monitoring in Western Australia. Structural Monitoring and Maintenance, no. 3(1), 33-49, DOI: 10.12989/smm.2016.3.1.033.
7. Xiong, H.-B., Cao, J.-X., Zhang, F.-L. (2018). Inclinometer-based method to monitor displacement of high-rise buildings. Structural Monitoring and Maintenance, no. 5(1), 111-127, DOI:10.12989/smm.2018.5.1.111.
8. Erol, B. Evaluation of High-Precision Sensors in Structural Monitoring. Sensors, no 10(12), 10803-10827, DOI:10.3390/s101210803.
9. Yigit, C.O., Li, XJ., Inal, C., Ge, L., Yetkin, M. (2010). Preliminary evaluation of precise inclination sensor and GPS for monitoring full-scale dynamic response of a tall reinforced concrete building. Journal of Applied Geodesy, no. 4(2), 103–113, DOI:10.1515/jag.2010.010.
10. Yigit, C.O., Inal, C., Yetkin, M. (2008). Monitoring of tall building's dynamic behaviour using precision inclination sensors. Proceedings of 13th FIG Symposium on Deformation Measurements and Analysis, 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering. Lisbon, 194 p.
11. Lee, J.-J., Ho, H.-N., Lee, J.-H. (2012). A Vision-Based Dynamic Rotational Angle Measurement System for Large Civil Structures. Sensors, no. 12(6), 7326-7336, DOI: 10.3390/s120607326.
12. Sushchev, S.P., Samarin, V.V., Adamenko, I.A., Sotin, V.N.(2019). Monitoring the technical condition of supporting structures of high-rise buildings, from-http://www.pamag.ru/pressa/monitor-tech, date of application16.04.2019.
13. Gurev, V.V., Dorofeev, V.M. (2005). Monitoring the stress-strain state of the supporting structures of high-rise buildings. Stroybezopasnost-2005. Moscow: TSNSTMO. 2005. p.18-21. (rus)
14. Zhang,X.DifferentMonitoringMethodsforBuildingDeformation of Practical Explorationбfromhttps://iopscience.iop.org/article/10.1088/1742-6596/910/1/012029/pdf, date of application16.04.2019, DOI:10.1088/1742-6596/910/1/012029.
15. Linner, T., Pan, W., Hu, R., Zhao, C., Iturralde, K., Taghavi, M., Trummer, J., Schlandt, M., Bock, T. (2020), A technology management system for the development of single-task construction robots, Construction Innovation, vol. 20 no. 1, 96-111, DOI: 10.1108/CI-06-2019-0053.
16. Ferravante, V., Riva, E., Taghavi, M., Braghin, F., Bock, T. (2019). Dynamic analysis of high precision construction cable-driven parallel robots. Mechanism and Machine Theory, vol. 135, 54-64, DOI:10.1016/J.MECHMACHTHEORY.2019.01.023.
17. Mustafin, M. G., Valkov, V. A., Kazantsev, A. I. (2017). Monitoring of deformation processes in buildings and structures in metropolises. Procedia Engineering, no. 189, 729-736, DOI: 10.1016/j.proeng.2017.05.115.
18. Osadchy, G.V., Belyi, A.A., Efanov, D.V., Shestovitskiy, D.A. (2018). Monitoring the technical condition of the sliding roof of the stadium "St. Petersburg Arena". Construction of Unique Buildings and Structures, no. 69(6), 10-24.
19. Vakolyuk A., Glebov N., Otto J., Bulgakov A.G. (2018). Mathematical identification of the mechatronic complex for the construction of mini tunnels in urban conditions. Journal of Applied Engineering Science, vol. 16, no. 1, 111-115, DOI: 10.5937/jaes16-16499.
20. Bulgakov, G. A., & Tokmakov E. G. [2018]. ERP - systems, logistics and mechatronics systems for ensuring the smooth construction process. *Journal of Applied Engineering Science*, 16(1), 1-4.
21. Bulgakov G. A., Vakolyuk A., Glebov, N., & Bienkowski, N. [2017]. A laser system for the control of the complex for the construction of mini. *Journal of Applied Engineering Science*., 15(4), 467-470.
22. Aly A.M. (2013). Pressure integration technique for predicting wind-induced response in high-rise buildings. Alexandria Engineering Journal, no. 52, 717–731, DOI: 10.1016/j.aej.2013.08.006.
23. Semenov, A.A., Porivaev, I.A., Kuznetcov, D.V., Nguen, T.H., Saitgalina, A.S., Tregubova, E.S. (2017).Stress-strain state of high-rise building under wind load and progressive collapse. Construction of Unique Buildings and Structures, no. 8(59), 7-26.
24. Mikhailova, M.K., Dalinchuk, V.S., Bushmanova, A.V., Dobrogorskaya, L.V. (2016). Designing, construction and operation of high-rise buildings taking into account aerodynamic aspects. Construction of Unique Buildings and Structures, no. 10(49), 59-74.
25. Galyamichev, A.V. (2017).Wind load and its effect on facade structures. Construction of Unique Buildings and Structures, no. 9 (60),44-57, DOI: 10.18720/CUBS.60.4.

26. Plotnikov, A.N., Ivanov, M.Yu., Porfiryeva E.N. (2018). Informativeness of monitoring systems for high-rise buildings from the principle of minimizing the number of sensors. New in architecture, building design and reconstruction: materials of the IV International (X All-Russian) conference NACCR-2018. Cheboksary: Izd-vo Chuvash. University. 2018. P. 267 - 277.
27. Ivanov, M.Yu., Porfiryeva, E.N., Plotnikov, A.N. (2018). Necessary zones of control of parameters of high-rise buildings, determined from the nature of the curvature of the elastic line of vertical elements. Collection of scientific works of young scientists and specialists. Cheboksary,Izd-vo Chuvash. University, P. 28-32.
28. Cheilakou, E., Tsopelas, N., Anastasopoulos, A., Kourousis, D., Rychkov, D., Gerhard, R., Frankenstein, B., Amditis, A., Damigos, Y. Bouklas, C. (2018). Strain monitoring system for steel and concrete structures. Procedia Structural Integrity, no. 10, 25–32, DOI: 10.1016/j.prostr.2018.09.005.
29. Park, S.W., Oh, B.K., Park, H.S. (2015). Maximum Stress Estimation Model for Multi-Span WalerBeams with Deflections at the Supports Using Average Strains. Sensors, no. 15, 7728-7741, DOI: 10.3390/s150407728.
30. Ayzenkrayn E. (2015). Continuous monitoring of the movement of meridional cracks that occur in the shells of cooling towers under the influence of external factors. Construction of unique buildings and structures Construction of Unique Buildings and Structures, no. 5(32), 84-94.
31. Park, H.S., Son, S., Choi, S.W., Kim, Y. (2013). Wireless Laser Range Finder System for Vertical Displacement Monitoring of Mega-Trusses during Construction. Sensors, no. 13, 5796-5813, DOI:10.3390/s130505796.
32. Park, H.S., Lee, H.Y., Choi, S.W., Kim, Y. (2013). A Practical Monitoring System for the Structural Safety of Mega-Trusses Using Wireless Vibrating Wire Strain Gauges. Sensors, no. 13, 17346-17361, DOI: 10.3390/s131217346.
33. Castagnetti, C., Bassoli, E., Vincenzi, L., Mancini, F. (2019). Dynamic Assessment of Masonry Towers Based on Terrestrial Radar Interferometer and Accelerometers. Sensors, no. 19, 1280-1319.
34. Tang, Y., Wu, Z. (2016). Distributed Long-Gauge Optical Fiber Sensors Based Self-Sensing FRP Bar for Concrete Structure. Sensors, no. 16, 268-286, DOI:10.3390/s19061319.
35. Ozbey, B., Erturk, V.B., Demir, H.V., Altintas, A., Kurc, O. (2016). A Wireless Passive Sensing System for Displacement. Strain Measurement in Reinforced Concrete Members. Sensors, no. 16, 479-496, DOI: 10.3390/s16040496.
36. Wang, G., Wang, W., Aafshar, K.B., Dojcinovski, D. (2009).Seismic instrumentation of high-rise buildings. Progress in Natural Science, no. 19, 223–227, DOI: 10.1016/j.pnsc.2008.06.011.
37. Almazov, V.O., Klimov, A.N. (2013).Comparison of data from the monitoring system of high-rise buildings with the calculation in the program complex. Modern problems of calculating and designing iron concrete structures of multi-storey buildings: a collection of reports of the International Scientific Conference dedicated to the 100-th anniversary of the birth of P.F Drozdov. Moscow, MGSU, P. 38-44.
38. Tamrazyan, A.G., Mehralizadeh, B.A. (2013). Frequency of free oscillations of multi-storey buildings when calculating the progressive collapse in a nonlinear dynamic formulation, taking into account the time of localized damage. Modern problems of calculating and designing iron concrete structures of multi-storey buildings: a collection of reports of the International Scientific Conference dedicated to the 100-th anniversary of the birth of P.F Drozdov. Moscow, MGSU, P. 235-245.
39. Sanchez Crespo, R., Kaczmarczyk, S., Picton, P., Su, H. (2018). Modelling and simulation of a stationary high-rise elevator system to predict the dynamic interactions between its components. International Journal of Mechanical Sciences, no. 137, 24–45.
40. Kashima, T. (2017). Study on changes in dynamic characteristics of high-rise steelframed buildings based on strong motion data. Procedia Engineering, no. 199, 194–199.
41. Drozdov, P.F. (1977). Design and calculation of load-bearing systems of high-rise buildings and their elements. Moscow, Stroiizdat, 223 p.
42. Drozdov, P.F., Dodonov, M.I. (1986). etc. Design and calculation of multi-storey civil buildings and their elements. Moscow,Stroiizdat, 351 p.
43. Snezhkov, D.Yu. (2016). Monitoring of constructed and operated reinforced concrete structures by non-destructive methods. Minsk, BNTU, 331 p.
44. Nikolaeva, A.G., Yakovleva, O.S. (2016) Analysis of the impact of the loading sequence on the stress-strain state of the elements of high-rise building frames. Managing the assortment, quality and competitiveness in the global economy: Collection of articles of the VIII International Correspondence Scientific and Practical Conference (March 30, 2017). Cheboksary, CHKI RUC, P. 131-134.
45. Ivanova, N.V., Nikolaeva, A.G. (2017). Influence of the percentage of reinforcement on the stress-strain state of the elements frames of multi-storey buildings when calculating with regard to the construction. Modern Issues of Continuum Mechanics 2017: Collection of articles on conference materials (round table) with international participation. Cheboksary, Izd-vo Chuvash. University, P. 38-42.

46. Plotnikov, A.N. (2016). Bearing capacity of reinforced concrete coffered floors, taking into account the plastic deformations of the ribs. Current problems of the calculation of reinforced concrete structures, buildings and structures for emergency effects. Collection of the International Scientific Conference dedicated to the 85th anniversary of the Department of Concrete and Stone Constructions and the 100th anniversary of the birth of N.N. Popov. Moscow, Izd-vo: National Moscow State University of Civil Engineering), P. 348 - 353.

47. Porfiryeva, E.N., Ivanov, M.Yu., Plotnikov, A.N. (2018). Methods of limiting equilibrium and principal stresses for supported along the contour of floors from structural ceramsite concrete floors. Construction - formation of living environment: XXI International Scientific Conference. Collection of materials from the seminar “Youth Innovations” (Moscow, April 25–27, 2018). Ministry of Education and Science of the Russian Federation, National Research Moscow State University of Construction — Moscow,Izd-vo MISI – MGSU, P. 276-282.

48. Ivanov, M.Yu., Porfiryeva, E.N., Plotnikov, A.N. (2017). Marginal equilibrium and main stress methods for floor-supported slabs. Engineering personnel - the future of the innovation economy of Russia: Proceedings of the III All-Russian Student Conference (Yoshkar-Ola, November 21-24, 2017): in 8 parts. Part 5. Innovations in construction, environmental management and technosphere safety. Yoshkar-Ola, Volga State University of Technology, P. 36 - 37.

49. Belostotsky, A.M., Akimov, P.A., Negrozov, O.A., Petryashev, N.O., Petryashev, S.O., Sherbina, S.V., Kalichava, D.K., Kaytukov, T.B. (2018). Adaptive finite-element models in structural health monitoring systems. Magazine of Civil Engineering, no. 2(78), 169–178.

50. Hong, K, Lee J, Choi, SW, Kim, Y, Park, H.S. A strain-based load identification model for beams in building structures. Sensors, no. 13, 9909-9920, DOI: 10.3390/s130809909.

51. Bulgakov, A., Shaykhutdinov, D., Gorbatenko, N., Akhmedov, S. (2015). Application of Full-scale Experiments for Structural Study of High-rise Buildings. Procedia Engineering, no. 123, 94 – 100, DOI: 10.1016/j.proeng.2015.10.063.

52. Grishina, O.S., Savchenko, A.V., Marichev, A.P., Zalata, E.S., Petrochenko, M.V. (2017). Monitoring of the construction site using an information model. Construction of Unique Buildings and Structures, no. 12(63), 7-19, DOI: 10.18720/CUBS.62.1.

Paper submitted: 17.11.2020.
Paper accepted: 04.12.2020.