Computational analysis of the stress-strain state, strength and stability of tallest skyscraper of the Moscow international business center with allowance for static and wind loads and hypothetical local damage

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Abstract. The paper is devoted to the stress-strain state computational analysis, strength and the load-bearing structures stability of a multifunctional high-rise residential building with an underground parking lot, developed by the architect Sergey Skuratov. This object is the tallest skyscraper, located on the territory of the Moscow International Business Center also known as Moscow-City. Static loads, wind loads and hypothetical local damage are taken into account. Brief information about the problems formulations, methodology of structural analysis and corresponding software systems, the building finite element models (including verification issues) and the analysis results are presented. The computational studies results analysis performed with the use of software package ANSYS Mechanical showed a consistent displacements and forces distribution (forces and moments) in the building foundation and frame with allowance for vertical static and wind loads, significant natural frequencies and mode shapes of building.

1. Introduction
In constructive terms, the designed object is a complex multi-functional high-rise residential building consisting of an underground part (size in axes 186.9 x 37.2 m) with 4 underground floors, a stylobate part (size in axes 166.95 x 30.7 m) with a number of floors equal to 12, and the high part (height 403.9 m above the absolute elevation 129.30, dimensions in axes 113.4 x 27m) with a number of floors equal to 92 (refer with Figure 1). The high-level part constructive scheme is a monolithic reinforced concrete frame with a rigidity core and supporting columns. The spatial rigidity and the
building monolithic frame immutability are provided by the horizontal disks joint operation of floors and vertical supporting walls of the core, columns and frame pylons.

When conducting the computational studies, the following types of floor slab loads were taken into account:

dead loads, live loads (short duration loads, long duration loads) from domestic premises, offices, engineering stories, elevator halls, halls, stairways, accessible roof area, commercial premises, loading/unloading areas, parking areas, entrance ramps, fitness facilities, swimming pool, locker rooms, bathrooms, technical areas, preschool, catering facilities and facade structures.

The geological stratum structure in the area of the construction site studied to a depth of 80.0 meters includes sediments of the modern part of the Quaternary system, as well as upper Carboniferous and Middle Carboniferous deposits.

The piles rigidity values in the longitudinal (vertical) and transverse directions were taken according to the data from previous studies. The total number of piles is equal to 685.

Wind loads were taken in accordance with previously completed studies. These studies were based on the methods of aero-physical (experimental) and computer simulation of non-stationary three-dimensional flow around an object in a shear air flow simulating the structure of irregularity of the design wind in the surface boundary layer, taking into account aerodynamic interference with aerodynamically significant objects of surrounding buildings. Comprehensive modeling of the airflow around a mock-up of the complex was carried out using the specialized wind tunnel A-6 of the Research Institute of Mechanics of Lomonosov Moscow State University and corresponding design codes. Due to the study, the maximum integral forces and moments of the wind load applied to the frames and foundations of the complex were determined. The most dangerous are the wind loads with

\[ \text{Figure 1. Considering high-rise building: a) general view (rendering); b) finite element model.} \]
a wind attack angle of 30˚ (when the widest facade of the building is windward and the laying wind is perpendicular to this facade) and 210˚ (opposite facade) (refer with Figure 2).

Generally the following problems were formulated and solved: analysis and synthesis of project documentation and survey data; formulation of computational research problems; development and verification of the computational spatial shell-rod finite element models of considering residential building; parameters determination of the stress-strain state (displacements, efforts) and design reinforcement of load-bearing reinforced concrete structures with normatively regulated combinations of vertical and wind loads; progressive collapse analysis.

2. Methodology of analysis and corresponding software systems

As is known, the finite element method (FEM) is the universal and powerful modern numerical method of mechanics.

It is used for spatial discretization and solving the corresponding boundary problems of solid mechanics. We have the following geometrically linear system (small displacements and deformations) motion matrix equation in the displacement method form:

\[
[M][\ddot{u}(t)] + [C][\dot{u}(t)] + ([K] + [K_G])[u(t)] = \{F(t)\} + \{R(u,\dot{u})\},
\]

where \([M],[C],[K],[K_G]\) are correspondently symmetrical, block, rarely filled global matrixes of mass, damping, linear (initial) and geometrical rigidity of the finite element (FE) model; \(t\) is the time; «point» means differentiation in time; \(\{F(t)\}\) is the given vector of static and dynamic loads; \(\{R(u,\dot{u})\}\) is so-called pseudo-loads vector, describing physical nonlinear effects; \(\{u(t)\}\) is the unknown vector of generalized dynamic displacements of the FE model.

It should be noted that kinematic boundary conditions are taken into account in equation (2.1). Besides, this equation is defined by the initial conditions based on results of corresponding static analysis at \(t = t_0\).

The given general dynamic formulation naturally reduces to important particular problems (static analysis, eigenvalue analysis (natural frequencies and vibration modes, loss of initial stability) and
dynamic analysis (within spectral formulations of dynamic problems)) with appropriate loads and solutions by zeroing out insignificant matrices.

Global matrices and vectors $[M],[C],[K],[K_G]$ and vectors $\{F\},\{R\}$ are created basing on the matrixes and vectors of the concentrated factors $[M]^r,[C]^r,[K]^r,[F]^r,[R]^r$ local matrices and vectors element $[m]^r,[c]^r,[k]^r,[k_G]^r,[f]^r,[r]^r$ which composing is in general case realized with the use of quadrature formulae of optimal accuracy. In order to provide approximation accuracy, adequacy and flexibility of geometrical, rigidity, inertial and damping properties, acting static and dynamic loads and the resulting stress-strain state of various space combined systems there was developed, investigated and tested a set of rod, beam, membrane, plate-shell, two-dimensional (flat) and three-dimensional (volume) finite elements, compatible and conformed in one design model and allowing also alternative assembly techniques [1].

The matrices $[M],[C],[K],[K_G]$ and $\{F\},\{R\}$ construction is based on matrices and vectors of concentrated factors $[M]^r,[C]^r,[K]^r,[f]^r,[r]^r$ matrices and vectors of finite elements $[m]^r,[c]^r,[k]^r,[k_G]^r,[f]^r,[r]^r$. Generally, corresponding computations are made with the use of optimal accuracy quadratures. Representative set of bars, membrane, plate-shell, two-dimensional and three-dimensional (solid) finite elements is available for correct, adequate and flexible approximations of geometric parameters, stiffness parameters, inertial and dissipative properties, static and dynamic loads and resultant stress-strain state. These finite elements are compatible in global design model and they allow alternative assembly procedures.

In order to solve the system of linear algebraic equations of static equilibrium

$$[K] \{u\}_1 \ldots \{u\}_l = \{F\}_1 \ldots \{F\}_l$$

(2.2)

with $l$ variants of loads (non-linear, non-stationary and (or) dynamic problems are also reduced to the sequence of such loads $([K] \rightarrow [K^*], \ [H] \rightarrow [H^*])$, effective realization of direct Gauss method can be used for the systems with positive defined, symmetric, block, rarely filled coefficient matrixes (SPARSE-scheme; modified scheme of the square root (of Cholesky)) or iterative realization of conjugate gradient method with preconditioning (PCG).

Partial eigenvalue problem is solved independently or within the spectral dynamic analysis (in particular for the wind load pulsation component analysis):

$$[K][\Phi] = [\Omega^2][M][\Phi], \text{ where } [\Phi] = \{\{\phi\}_1 \ldots \{\phi\}_{N_{ITER}}\}, \ [\Omega^2] = \text{diag}(\omega_1^2 \ldots \omega_{N_{ITER}}^2).$$

(2.3)

The most advanced methods of the generalized partial eigenvalue problems solution (method of subspace iterations and block Lanczos method) were chosen and optimized as the “basic” methods. Numerous computational authors experiments including corresponding samples with ill-conditioned systems and systems with multiple frequencies, confirmed reliability and efficiency of the proposed methods. As shown by the computational practice, block Lanczos method has undeniable advantages for large problems in the speed of computing of given number of natural frequencies and corresponding mode shapes.

The developed computational models adequately reflected the geometric-stiffness and inertial properties and the structures and foundation load characteristics of considering high-rise building. Special quasistatic computational finite element models of the systems “shell-rod structures – non-uniform Winkler sub-foundation” were built and analyzed in order to compute displacements and member forces from the action of permanent and temporary snow and wind loads. Winkler
coefficients were taken according to the static parameters of the soil for constant, temporary, snow and wind loads.

The wind loading dynamic (pulsation) component was computed on the static component basis taking into account the dynamics and pulsation coefficients determined by the corresponding design codes [2].

For the multi-storey buildings with constant height characteristics (to which, with a known “fit”, the considered one can be attributed), the pulsation component can be determined by the formulas

$$W_{dyn}(z) = 1.4z / H \xi W_{stat}(H) \zeta \nu; \quad W_{stat}(H) = P_{stat} k(136) = 1.45 P_{stat},$$

(2.4)

where $z$ is the present height; $H$ is the building height; $P_{stat}$ is the wind pressure from aerodynamic analysis; $\xi$ is the pressure pulsation coefficient, taken in table 7 (terrain type “C” [2]); $\zeta$ is the dynamic coefficient determined according to drawing 2 depending on the parameter $\nu = \sqrt{\gamma_f W_0 / 940 / f_1}$ [2].

With a safety coefficient for load $\gamma_f = 1.4$, standard wind pressure $W_0 = 230$ Pa, natural frequency $f_1 = 0.36$ Hz, taking into account soil compliance, we get $\nu = 0.063$ and, according to the figure $- \zeta = 1.65$ (for reinforced concrete structures with logarithmic decrement $\xi = 0.3$); $\nu$ is the spatial correlation coefficient of wind pressure fluctuations taken from Table 6.9 of corresponding design codes [2]. For sizes $\rho = 69$ m and $\chi = 100$ m we get $\nu = 0.52$.

At present there is no sound internally inconsistent method for determining the criterial parameter i.e. maximum acceleration of the floor slab of upper floors $a_{max}$, when the wind load pulsation component is applied (should not exceed 0.08 m/s²). Various approximate approaches are used in practice. They are normally reduced to the use of the formula

$$a_{max} = u_{max} \omega^2$$

(2.5)

where $u_{max}$ is the maximum horizontal displacement; $\omega$ is the dominant natural frequency (rad/s).

Determination of the stress-strain state, dynamic analysis and stability analysis of load-bearing structures of considering building were performed using the verified licensed software package ANSYS 15.0, which implements the finite element methods advanced schemes and super-elements for static and dynamic spatial combined systems analysis. Generally, ANSYS 15.0 supports all necessary types of computational analysis.

Besides, “OM SNiP Reinforced concrete” software package was used. It implements all the types of the reinforced concrete structures analysis in accordance with the corresponding design codes.

3. Development and verification of finite element models of the building

The customer transferred AutoCAD files and a set of current drawings and structural diagrams of considering multifunctional high-rise residential complex. Besides, the three-dimensional model of the building in Revit format was transferred to Scientific and Research Center Stage. Based on the analysis and generalization of these materials the spatial shell-rod finite element models of load-bearing structures were developed and verified in the ANSYS software package.

Reinforced concrete foundation slabs, floor slabs, and load-bearing walls were modeled with the use of two-dimensional triangular and quadrilateral (in plan) shell finite elements of constant thickness within the Kirchhoff-Love hypotheses. Reinforced concrete columns and beams were modeled with the use of spatial rod finite elements.

The MPC184 type with the “rigid beam” option rigid parts finite elements were introduced at the junction of floor slabs and foundation slab with columns. Generally, MPC184 comprises a general class of multipoint constraint elements applying kinematic constraints between nodes.
In order to set the Winkler coefficient of sub-foundation, the finite elements of the type SURF154 surface effects applications were “pasted” on the foundation slab.

For static problems, we defined longitudinal stiffness (vertical) of piles in accordance with the data of Gersevanov Research Institute of Bases and Underground Structures (NIIOSP). For dynamic problems, we defined corresponding longitudinal stiffness of piles equal to eight times increased static stiffness.

The computational dimension of the developed ANSYS model was equal to 613739 nodes (3682434 degrees of freedom) and 665350 finite elements.

We especially note that the finite element mesh on the foundation slabs and floor slabs not only had the necessary detail to reproduce displacements, forces and moments, but was also thickened in the zones of columns and pylons.

The computational models geometric-rigid, inertial and load parameters compliance to the design data is checked by the visualization of characteristic fragments and the whole model from different angles. Besides, we issued the volumes, masses and loads of the computational model characteristic fragments, compared them with the design data and computational models in alternative software packages. Moreover, we considered the static and dynamic analysis results in particular for limiting cases having a transparent physical meaning.

Computing of natural frequencies and mode shapes of mechanical systems is one of the most informative verification tasks, integrating many factors and parameters of the computational model and, at the same time, allowing revealing their difference.

4. The analysis results
The results analysis of computational studies performed with the use of verified licensed software package ANSYS Mechanical showed a consistent picture of the displacements and forces (forces and moments) distribution in the foundation and frame of the building with allowance for vertical static and wind loads, significant natural frequencies and shapes of building oscillations.

The criteria values for kinematic parameters of load-bearing structures in the considering building (foundation slab deflections, floor slabs, coverings, horizontal displacements of the building top, upper floors acceleration) are in the range of standard-regulated values: the maximum deflection of the foundation slab is equal to 46.3 mm; the maximum horizontal displacement from the average component of the wind load is equal to 394 mm; the maximum calculated acceleration of floor slab of the upper floors is equal to 0.035 m/s².

Maximum forces in piles (51011 kN) from the design combination of loads did not exceed the load bearing capacity of piles (51200 kN).

Summary
The computational analysis for the most loaded load-bearing structures initiating local destruction different scenarios have established that reinforced concrete structures of the building frame are resistant to progressive collapse with allowance to the adopted design parameters (geometry, properties of materials and structural joints, values and combination of loads and impacts) and the reinforcement corresponding level to the received forces.

The results of mathematical modeling for a multifunctional high-rise residential building (static and wind displacements, natural frequencies and mode shapes) can be used for building foundation and load-bearing structures structural health monitoring program and methodology development during its life cycle (including construction and operation).

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Acknowledgements
The distinctive research work was carried out at the expense of the State program of the Russian Federation “Scientific and technological development of the Russian Federation”, State program of the Russian Federation “Development of science and technology” for 2013-2020 and the Program for Fundamental Research of State Academies of Science for 2013–2020, as part of the Plan for Fundamental Scientific Research of the Ministry of Construction and Housing and Communal Services of the Russian Federation and the Russian Academy of Architecture and Construction Sciences for 2018, within science topic 7.4.2 “Development and numerical implementation of methods for determining the stress-strain state of spatial slab-shell reinforced concrete structures, taking into account physical non-linearity, cracking and acquired anisotropy” and science topic 7.4.17 “Research and development of adaptive mathematical models, numerical and numerical-analytical methods as the basis and component of monitoring systems of bearing structures of unique buildings and constructions”.