Scientific and technical support features of the high-rise buildings design

D S Dmitriev1*, A M Belostosky1,2, A I Nagibovich1,3
1 Scientific and Research Center Stage, 18, 3rd Yamskogo Polya street, Moscow, 125040, Russian Federation
2 Moscow State University of Railway Engineering (MIIT), 9 bldg. 9 Obraztsova street, Moscow, 127994, Russian Federation
3 National Research Moscow State University of Civil Engineering, 26, Yaroslavskoe highway, Moscow, 129337, Russian Federation

E-mail: dmitriev.d.s@yandex.ru

Abstract. Article reflects the main aspects of the scientific and technical support of the design stage of high-rise buildings. As well as the peculiarities of creating design models for substantiating the mechanical safety of three-dimensional systems “foundation - high-rise building structures”.

Introduction
In Russia, construction objects with a height of more than 100 meters belong to the class of high-rise buildings and have the increased responsibility class in accordance with national standards and regulatory documents. [1, 2]. According to these regulatory documents, at the design stage of such facilities and during the passage of mandatory state expertise, scientific and technical support of project documentation should be carried out. Scientific and technical support should be carried out by an independent, specialized organization with high scientific potential and extensive experience in this field.

Such scientific and technical support is based on mathematical modeling of a high-rise building, on which basis calculated substantiation of the mechanical safety (stress-strain state, dynamics, strength and stability) of large-sized spatial systems “foundation-high-rise building” is made.

Scientific and Research Center Stage has extensive experience in scientific and technical support of high-rise buildings and structures, among which there are skyscrapers in the Moscow International Business Center "Moscow-City" (refer with Figure 1). Using the example of the already built Evolution tower and the tallest skyscraper under construction in Moscow (404 meters), the article will show some features of the scientific and technical support of high-rise buildings.

The main features of the design justification for high-rise buildings in the framework of scientific and technical support design
In the process of scientific and technical support of a number of unique high-rise buildings, the team of the Scientific and Research Center Stage identified a number of characteristic development features of Calculation models and substantiation of the stress-strain state, strength and stability of the supporting structures of high-rise buildings with basic and special combinations of loads and impacts.
Most significant features are presented below:

1. Considerable computational problems dimension with known consequences. The obvious difficulty lies in the analysis and processing of a significant amount of the design and regulatory documentation and the construction of a detailed geometric and finally a finite element model of the “foundaion - high-rise building” system in accordance with them (refer with Figure 2). The large dimension of the computational model requires significant computational resources, which places special demands on the technical equipment of the organization that carries out scientific and technical support. The computational dimension of the computational model of the Evolution tower is $1 \times 856 \times 983$ unknowns and the dimension of Sergey Skuratov’s skyscraper is $3 \times 682 \times 434$ unknowns.

Figure 1. Finite element models of high-rise buildings in the Moscow International Business Center "Moscow-City".

a) 404 meters tall skyscraper. Sergey Skuratov is an architect. Under construction.

b) Evolution tower height of 246 meters. Built.

c) Fragment of the outrigger floor in Sergey Skuratov’s tower; d) Fragment of a typical floor in the Evolution tower.

Figure 2. Fragments of the calculated finite element models.

c) Fragment of the outrigger floor in Sergey Skuratov’s tower; d) Fragment of a typical floor in the Evolution tower.
2. Simulation of a heterogeneous soil base and a pile field containing several hundred piles. In the work performed pile fields were modeled, where the stiffness for each pile was set separately, for which macros written in the APDL language — embedded in the ANSYS Mechanical software package — were widely used. Piles were modeled with COMBIN14 finite elements with a given stiffness. Assessment of the pile strength is a mandatory criterion in assessing the mechanical safety of a high-rise building. The maximum calculated longitudinal force in the piles of a skyscraper with a height of 404 meters is 5 200 tons in the Evolution tower the maximum calculated longitudinal force in the piles is 2 644 tons.

3. Accounting for the mounting sequence. Changes in the parameters determining the stress-strain state of main bearing elements of a high-rise building are significantly affected by the mounting sequence. For considered high-rise buildings calculations were made taking into account the mounting sequence, construction stages were coordinated with the construction organization project (section of the project documentation). As expected, the consideration of this factor showed a significant effect on the stress-strain state of the entire system.

4. Assessment of dynamic comfort. According to regulatory requirements [3], the formal criterion of the dynamic comfort for people staying in a high-rise building according to the maximum calculated acceleration of the upper floors overlap $a_{\text{max}}$ when the pulsation component of the wind load is applied should not exceed 0.08 m/s$^2$ and is defined as:

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

where: $u_{\text{max}}$ is the maximum pulsation horizontal movement in the direction of the prevailing own form of oscillations, $\omega$ is the prevailing lower (first) natural frequency of oscillation (rad/s).

5. Comparison of alternative calculations results performed according to the requirements of special technical conditions in verified / certified software systems. To improve the quality of design justification for design solutions of modern complex construction projects, in order to avoid miscalculations in design, leading to emergencies during construction and operation, special requirements have been developed. According to these requirements, design organizations are recommended to carry out calculations of at least two models independently developed in different software packages and conduct a comparative analysis of the results obtained. This procedure is an integral part of the scientific and technical support of high-rise buildings and structures, to which special attention is paid by the exporting authorities. The authors of the Scientific and Research Center Stage developed a “standard” for such comparisons, which formed the recommendations basis of the Federal autonomous institution Glavgosexpertiza for the design documentation.

When comparing the results of alternative calculations, first the main integral characteristics of the structures are compared such as the mass of the structure, natural frequencies and vibration modes, structure displacement as a whole and its individual structural elements, efforts in the main types of structural element. In order to achieve an acceptable difference in the results, in close cooperation with the authors of the alternative calculation, the finite element models are calibrated and all possible discrepancies in stiffness characteristics, loads, etc. are eliminated. Acceptable discrepancies in the results are in the range of 5-10%. For some especially important structures, the design justification is carried out in three independent software complexes, as was the case when designing the 404-meter building in the Moscow International Business Center "Moscow-City". The calculations were carried out in the software packages ANSYS Mechanical, Sofistik and SCAD Office 21.1. (refer with Figure 3). Based on a comparative analysis of alternative calculation results, it was concluded that the relevant parameters of the stress-strain state (displacements, forces) and the dynamic characteristics (significant natural frequencies and modes of oscillation, acceleration) of high-rise complex structures are acceptable and they do not exceed the standard values for the main combinations of loads impacts.
6. Calculation of progressive collapse. Another of the mandatory elements of the design justification of high-rise buildings is the calculation of resistance to progressive collapse. Possible scenarios of local destruction are regulated by regulatory documents or prescribed in special technical conditions. As a rule, the calculation of reinforced concrete structures is carried out by simplified methods due to the complexity of taking into account the nonlinear behavior of concrete and a number of other factors. However, the Scientific and Research Center Stage conducts high-tech calculations for resistance to progressive collapse in a dynamic setting, taking into account various nonlinearities not only of metal structures but also of reinforced concrete structural elements. [4, 5, 6].

Summary
The author team of the Scientific and Research Center Stage with scientific and technical support and design substantiation of the stress-strain state, the base strength and stability and supporting structures of a number of high-rise buildings, including skyscrapers in Moscow International Business Center «Moscow-City» successfully solved number of high-tech features and problems presented in this article. The computational studies have been carried out by necessity in complex productions using adequate mathematical models and modern numerical methods of mechanics in verified / certified software systems.

Despite the absence in the regulatory framework of clear guidance on the composition of scientific and technical support of unique high-rise buildings, the authors consider these features to be mandatory for the design justification of mechanical safety of high-rise buildings.

As a result of a complex of research works at a new level the socially significant and knowledge-intensive problem of ensuring the mechanical safety of unique combined construction objects was solved (three-dimensional systems “foundation - high-rise building structures”).

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