

Numerical simulation of loads and impacts, stress-strain state, strength and stability of unique structures, buildings and facilities. Experience of StaDyO research & engineering centre

A M Belostosky^{1,2,3,4,5}, P A Akimov^{1,3,4,6}, T B Kaytukov⁶, A S Pavlov¹, A A Aul¹,
I N Afanasyeva¹, V V Vershinin^{1,7}, D S Dmitriev¹, Yu N Dyadchenko¹,
A I Nagibovich^{1,7}, K I Ostrovsky¹, S O Petryashev^{1,8}, N O Petryashev^{1,8},
S V Scherbina^{1,7}, A S Chauskin^{1,9}, O S Goryachevsky² and O A Negrozov^{6,7}

¹ Research & Development Centre StaDyO, office 810, 18, 3ya Ulitsa Yamskogo Polya, Moscow, 125040, Russia

² Department of Structures, Buildings and Facilities, Russian University of Transport (RUT – MIIT), 9b9, Obrazcova Street, Moscow, 127994, Russia

³ Tomsk State University of Architecture and Building, 2, Solyanaya sq., Tomsk, 634003, Russia

⁴ Department of Architecture and Civil Engineering, Peoples' Friendship University of Russia, 6, Miklukho-Maklaya str., Moscow, 117198, Russia

⁵ Department of Building Constructions and Computational Mechanics, Perm National Research Polytechnic University, 29, Komsomolsky prospekt, Perm, 614990, Russia

⁶ Russian Academy of Architecture and Construction Sciences, 24, ul. Bolshaya Dmitrovka, Moscow, 107031, Russia

⁷ Department of Applied Mathematics, National Research Moscow State University of Civil Engineering, 26, Yaroslavskoe Shosse, Moscow, 129337, Russia

⁸ Research Institute of Building Constructions (TSNIISK) named after V. A. Koucherenko, JSC Research Center of Construction, 6, 2nd Institutskaya st., Moscow, 109428, Russia

⁹ School of Engineering, Far Eastern Federal University, 8 Sukhanova St., Vladivostok, 690090, Russia

amb@stadyo.ru

Abstract: The paper contains analytical overview of the most important unique/critical objects and the computational analysis problems of the mechanical safety, carried out by the team of Research & Development Centre StaDyO (StaDyO R&D Centre) researchers for the last two years (2016-2018). Corresponding complex coupled problems of continuum mechanics were solved with the use of contemporary methods and models of numerical modeling (nonlinear models, coupled problems, substructures, submodeling, etc.), implemented in verified software complexes. Some of these results are briefly considered and analyzed. Conclusions about the main directions of further research and development are presented as well.



1. Introduction

This paper, in accordance with the Symposium “Actual Problems of Computational Simulation in Civil Engineering” (APCSCE) tradition, contains an analytical overview of the most important unique/critical objects and computational analysis problems of the mechanical safety, carried out by the team of StaDyO R&D Centre researches [1, 2] for the last two years (2016-2018). Corresponding complex coupled problems of continuum mechanics were solved with the use of contemporary methods and numerical modelling models (nonlinear models, coupled problems, substructures, submodeling, etc.), implemented in verified software complexes. Some of these results are considered in more detail in other papers of the APCSCE 2018.

2. Computational fluid dynamics (CFD). Determination of wind loads on bearing and facade (enclosing) structures, pedestrian comfort parameters and other tasks

Numerical analysis of wind loads on bearing and facade / enclosing structures, as well as analysis of pedestrian comfort parameters are performed, based on three-dimensional stationary solving and non-stationary problems of aerodynamics (Navier-Stokes equations with the selected turbulence models (ANSYS CFD)) for:

- several multi-storey residential complexes (Moscow), taking into account the surrounding buildings and terrain;
- stopping complex Kutuzovo, Moscow ring railway;
- wind power plant with capacity of 14x2.5 MW in Ulyanovsk region (with fixed blades, in case of hurricane and tornado); responsible surface mining facilities (Ural Potassium, Norilsk Nickel)
- others objects (Figure 1).

For the design of the Moscow soccer stadium “Torpedo” with a flexible membrane coating problems were solved in the related aeroelastic formulation (fluid-structure interaction, FSI) analysis of the instabilities effects (galloping, buffeting, flutter and divergence). Based on the results of FSI computations analysis, several measures to eliminate the identified effects of aeroelastic instability were recommended and implemented in the project.

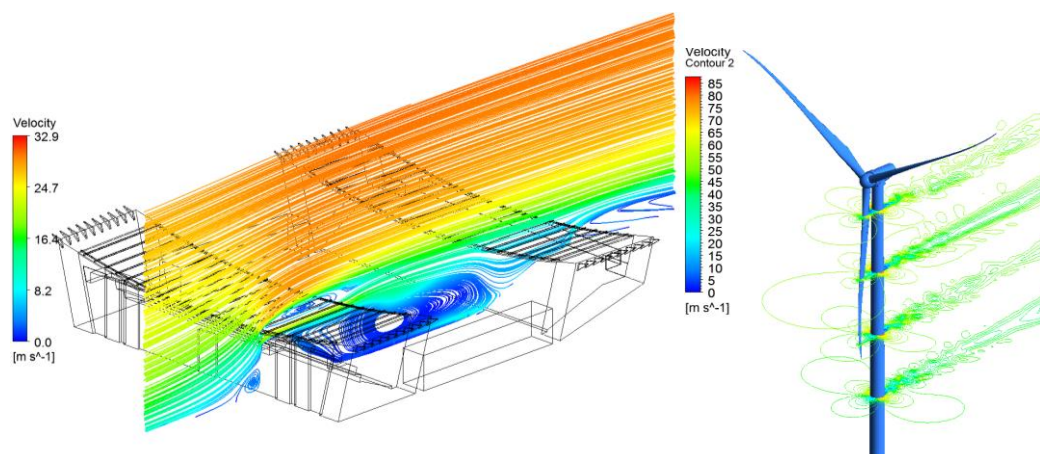


Figure 1. Samples of computational fluid dynamics' problems.

3. Heterogeneous numerical models of the system "foundation-structure" as a base of health monitoring systems

Development, verification and integration of adaptive three-dimensional finite element models of the main facilities (the 1st and 2nd stage) of Zagorskaya hydro-accumulate power station (HAPS) into the existing structural health monitoring system (Figures 2, 3, 4) were under consideration. For the first

time, a “heterogeneous” mathematical model consisting of an independently number developed and interrelated models in software systems, the most adequate to the problems to be solved, was implemented: models of filtering in non-uniform soil (*Modflow*); nonlinear geomechanics models for soil (*Midas GTS*); models of three-dimensional stress-strain states (SSS) of the main concrete, steel-concrete and ground structures of the HAPS (more than 20 models were used in *ANSYS Mechanical*).

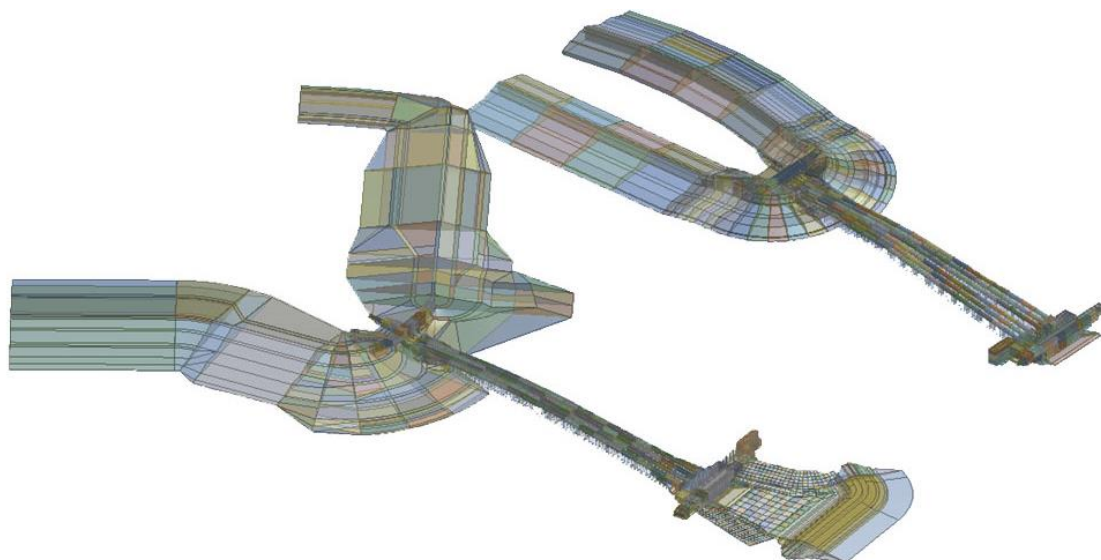


Figure 2. Sample of system “foundation – structure” (Structures of Zagorskaya hydro-accumulate power station). Geometrical model (Fragment).

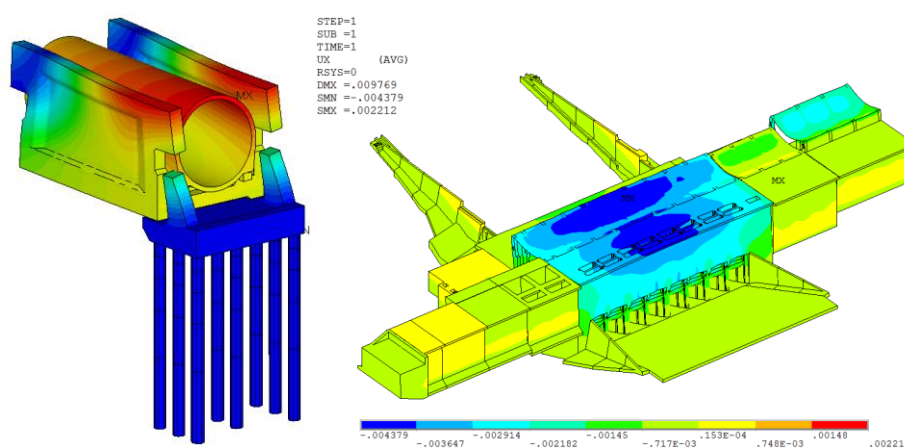


Figure 3. Sample of system “foundation – structure” (Structures of Zagorskaya hydro-accumulate power station). Results of analysis (Fragment).

The relationship of the these three groups’ results of mathematical models and software systems together with the data of the information and diagnostic system BING-2 will allow to safely operate the facilities and determine the optimal operating modes that meet all the requirements of reliability.

The results of the verification and practical significant computations with the use of the developed models showed good compliance of the computed and field data (for the main structures and

scenarios) and the existing restrictions (as a consequence – forced simplifications and agreements) related to the various capabilities of software systems.

4. Analysis of stress-strain state, strength and stability of underground-above-ground object with allowance of main and special (including seismic) loads and impacts

Special technical conditions (so-called “STU”) were developed, the numerical analysis of SSS, strength and stability of the underground – above ground object presented in Figure 5.

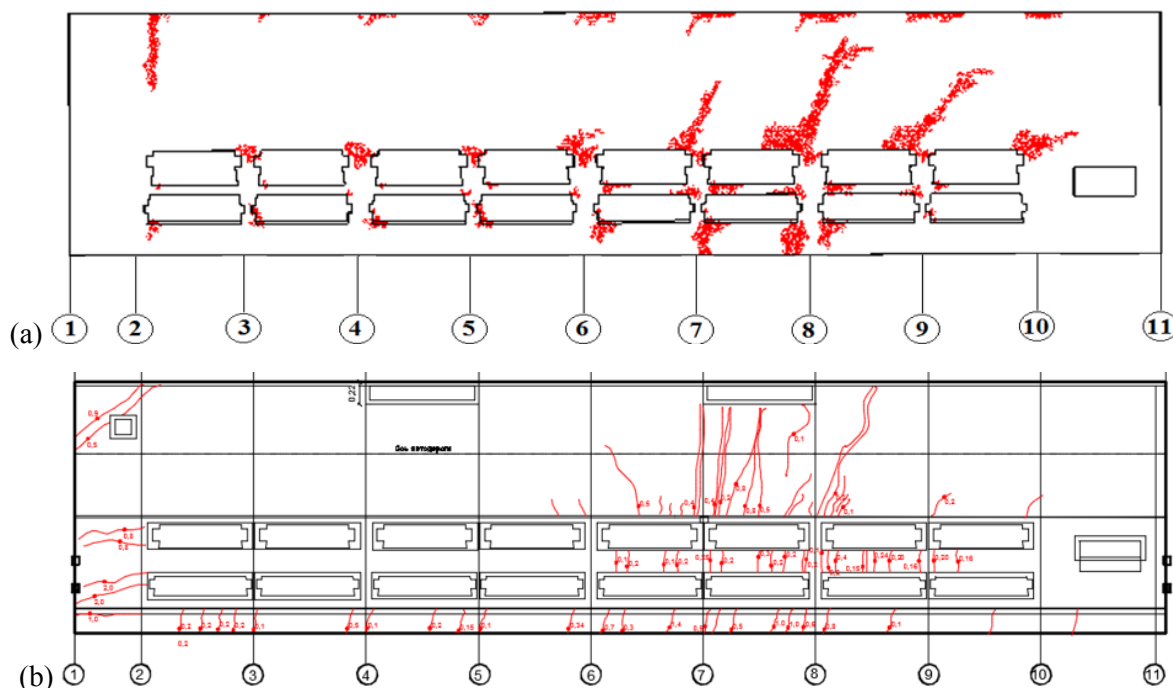


Figure 4. Sample of system “foundation – structure” (Structures of Zagorskaya hydro-accumulate power station). Comparison of computed (in accordance with numerical modelling results) and actual fracture patterns (Fragment): computed fracture pattern (a); actual fracture pattern (b).

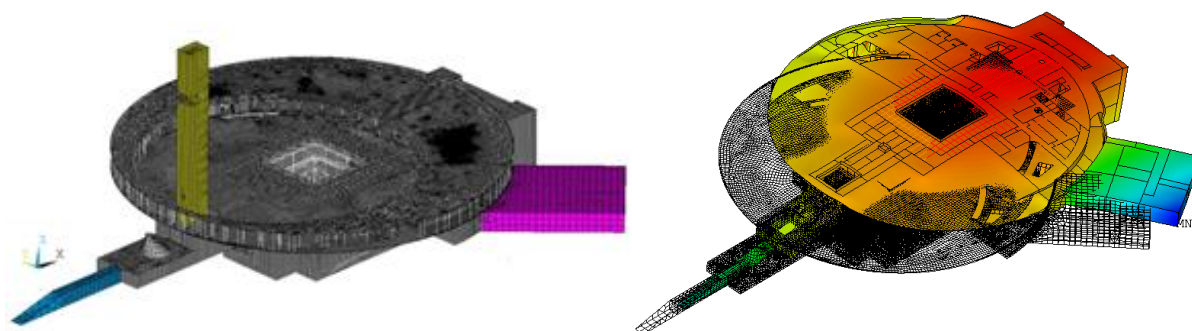


Figure 5. Sample of underground – above ground object. Computer modelling (Fragment).

The leisure and entertainment complex under the main and special (including seismic) loads and impacts (Midas GTS, ANSYS Mechanical) were carried out. The support to the “Main State Expertise of Russia” was successfully completed.

With the use of developed finite element (FE) models, verified in ANSYS Mechanical, the static stress-strain state parameters of supporting structures (displacements, strains) and the estimation of strength for basic design load combinations and effects were considered. Further, the parameters of the

stress-strain state of the bearing structures were determined and the strength was evaluated for special load combinations, including the seismic effect for the levels of design earthquake (by the linear-spectral theory) and maximum estimated earthquake (by the dynamic theory).

Analysis of the corresponding computations' results showed generally consistent results of the stress-strain state parameters distribution in the bearing structures of the object. After corresponding design works it was found that in compliance with the accepted parameters of the project (geometry, properties of materials and compounds, the magnitude and combination of loads and effects), the load-bearing structures state meets the regulatory criteria of bearing capacity (deformability, strength and stability).

The structural scheme of the object structures, which assumes the absence of deformation and antiseismic joints within the frame, has sufficient rigidity, strength and stability for the loads perception on the main and special combinations of loads. Taking into account the uniqueness of the implemented design solutions, it was recommended to develop and implement a program of structural health monitoring of load-bearing structures for the construction and operation stages, based on both the results of computations and specially developed adaptive predictive mathematical models.

5. Computational studies of the high-rise mechanical safety complex in "Moscow-city»

We made numerical studies of stress-strain state; strength and stability analysis of the load-bearing system "pile foundation – stylobate – 108-storey tower"; comparative analysis of the results obtained by alternative models in various verified/certified software systems (ANSYS Mechanical, SOFiSTiK, SCAD); advanced scientific and technical support of the computational analysis results with the passage of the draft in the Moscow state expertise for the of most high-rise (404 m, the third in Russia-Europe) project and very "slim" residential complex in Moscow-city (Figures 6, 7).

The computed criteria values of the kinematic parameters of the complex (deflections of the foundation slab, floor slabs, coatings, horizontal movements of the top of the building, acceleration of the upper floors) load-bearing structures are in the range of regulatory values. Maximum forces in piles from the computed combination of loads also do not exceed their load-bearing capacity. As a numerous computational studies' result for three scenarios of initiating local destruction of the most loaded bearing structures we found reinforced concrete structures of the building frame are resistant to progressive collapse in compliance with the accepted parameters of the project (geometry, properties of materials and compounds, the magnitude and combination of loads and actions) and the level of reinforcement corresponding to the obtained forces. According to the comparative analysis of numerical analysis' alternative results, it was founded the acceptable compliance of the stress-strain state's significant parameters (displacement, internal forces and moments) and corresponding dynamic parameters (significant natural frequencies and modes, accelerations) of the high-rise complex structures and their normative non-exceedance values in the main combinations of loads and impacts. "In the future" recommendations for a more advanced and sophisticated multi-factor analysis of wind flows in the skyscraper area and the existing system development of engineering structures' (SMIC) health monitoring were developed.

6. Advanced computational simulation of three-dimensional systems "pile foundation – reinforced concrete of stands – metal coating and facades" and the most critical nodes of the projected soccer stadiums for the World Cup 2018

Our research team completed multi-year cycle of stress-strain state's advanced (comprehensive) analysis, strength and stability of the spatial system and the most critical nodes of the projected soccer stadiums for the World Cup 2018 (located in Saint-Petersburg, Samara, Volgograd, Nizhny Novgorod, Rostov-on-Don and Yekaterinburg (Figure 8)) with the main and special load combinations (with allowance for nonlinear dynamic analysis (progressive collapse analysis)) with the use of ANSYS Mechanical, MIDAS Civil, SOFiSTiK, Robot Structure, SCAD, Lira SAPR. Besides, we successfully passed "Main State Expertise of Russia".

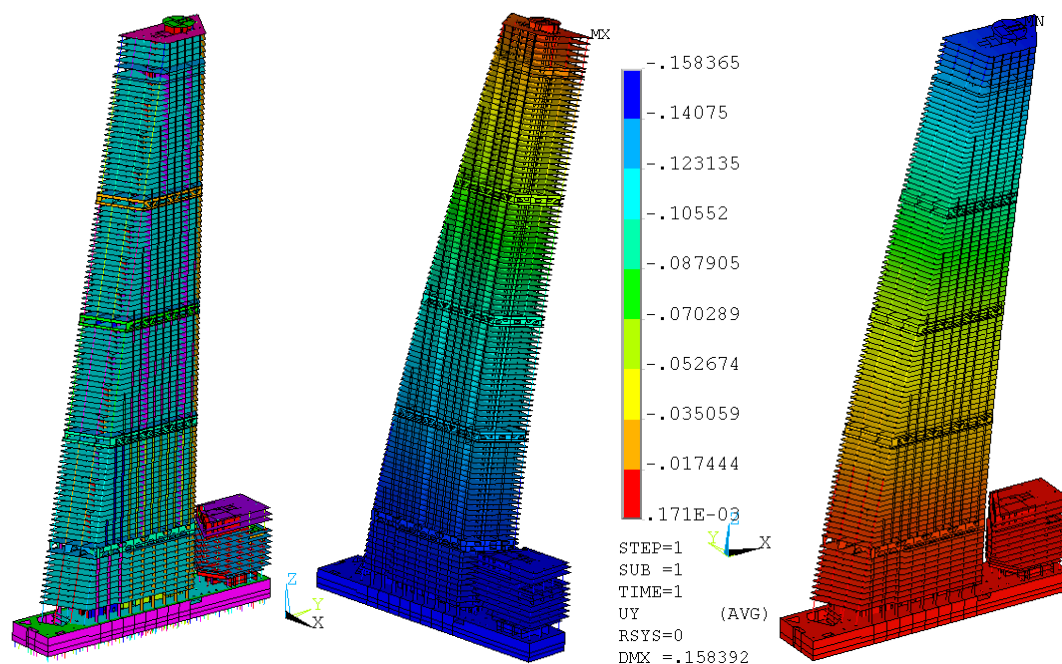


Figure 6. Sample of high-rise residential building. Computer modelling (Fragment).

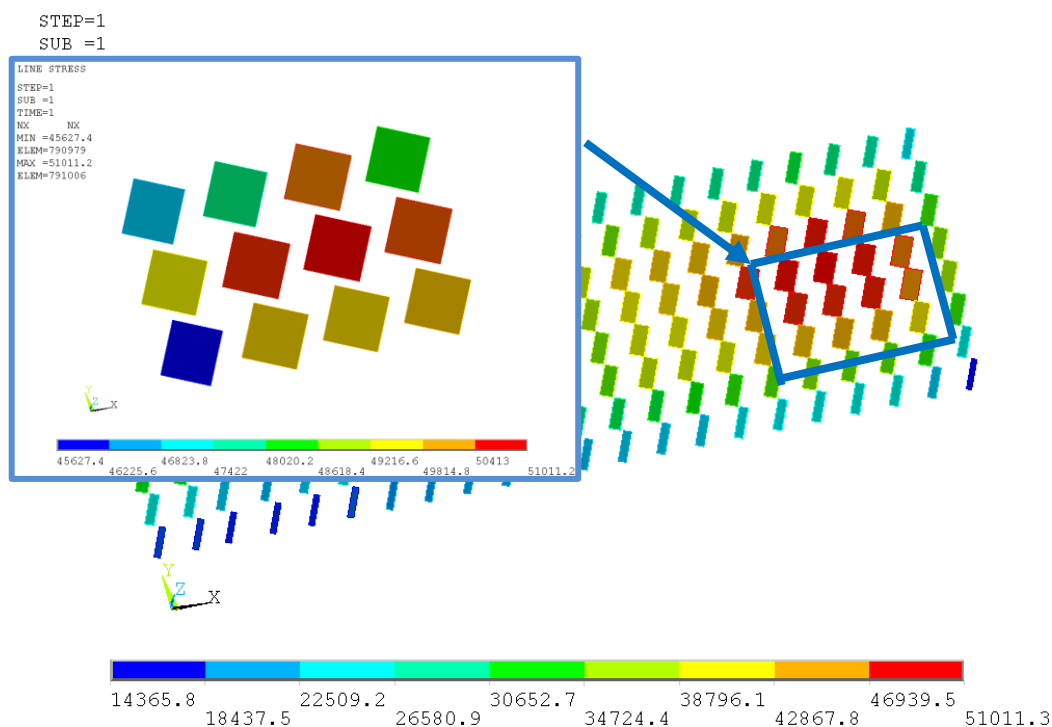


Figure 7. Sample of high-rise residential building. Results of modelling (Fragment). Longitudinal design forces in piles R_z , kN. Visualization of 184 piles of core ($L = 40\text{m}$). The modulus of elasticity for horizontal elements is assumed equal to $0.2E_o$, the modulus of elasticity for vertical elements is assumed equal to $0.6E_o$. Wind load is not taken into account.

The complexity of research work does not even allow to consider all the interesting problems, mathematical models and methods of numerical solution. Still, we can highlight some of them:

- the first achieved level of adequacy and, as a consequence, immense computational size (up to 12 000 000 unknowns) and multivariance (we considered hundreds of combinations of main and special loads and impacts) of FE models and corresponding problems;
- comparative analysis of the stress-strain state parameters and dynamic parameters (significant part of the natural frequencies and modes spectrum) of the football stadium structures model and the subsystems “metal structures models of covering” and “base – reinforced concrete structures of the stands”, which allowed to justify the possibility of subsystems considering in the framework of separate models prepared by different teams of designers;
- modelling of heterogeneous soil base and pile field containing up to eleven thousand piles;
- refined three-dimensional physically nonlinear (elastic-plastic) FE analysis of stress-strain state and strength of the most stressed structural units of metal coatings with allowance for the real deformation diagram;
- stability analysis of metal structures of coatings and facade with allowance for physical and geometric nonlinearities and initial imperfections;
- geometrically nonlinear modeling of prestressed cable-stayed elements in the structure of the coating structures, including the progressive collapse analysis;
- dynamic analysis of the system “foundation – reinforced concrete structures of foundations and stands – metal coating and facades” with allowance for levels’ seismic effects of the so-called “design” earthquake (by the linear-spectral method on the three-component spectra of accelerations) and the so-called “maximum estimated earthquake” (by direct integration of the equations of motion on the three-component accelerograms);
- comparison of the alternative computations’ results performed in verified/certified software systems (for models of subsystems “metal coating construction” we used ANSYS, MIDAS Civil, Robot Structural and SOFiSTiK; for models of subsystem “base – reinforced concrete construction” we used ANSYS, SCAD, LIRA SAPR and SOFiSTiK).

As a result of this complex scientific research we archived a new high precision solution level of socially significant problem and received important information about mechanical safety a unique composite construction objects (three-dimensional systems “pile foundation – reinforced concrete of foundations and stands – metal coating and facades”). We designed to host world Cup 2018 (FIFA) and for further use ("Heritage") with modern architectural forms and structural solutions

For this cycle of research work the author's team of StaDyO R&D Centre was awarded by the Gold medal of the Russian Academy of Architecture and Construction Sciences (RAACS) in the field of construction Sciences in 2017.

7. Methodological and expert development and research

A number of methodological, research and expert works were also carried out. Particularly we can highlight among them the expertise of the Russian construction regulations’ projects in the RAACS system (more than 15) and the complicated computational studies expertise of mechanical safety of the multifunctional high-rise complex “Akhmat tower” (Grozny, 435 m), located in the seismic area.

On the basis of the own and advanced world experience we published several monographs – manuals “Computational aerodynamics in construction problems” [3] and "Mathematical and computer modelling based on structural health monitoring of buildings and facilities” [4]. These books are the first of such kind in Russia.

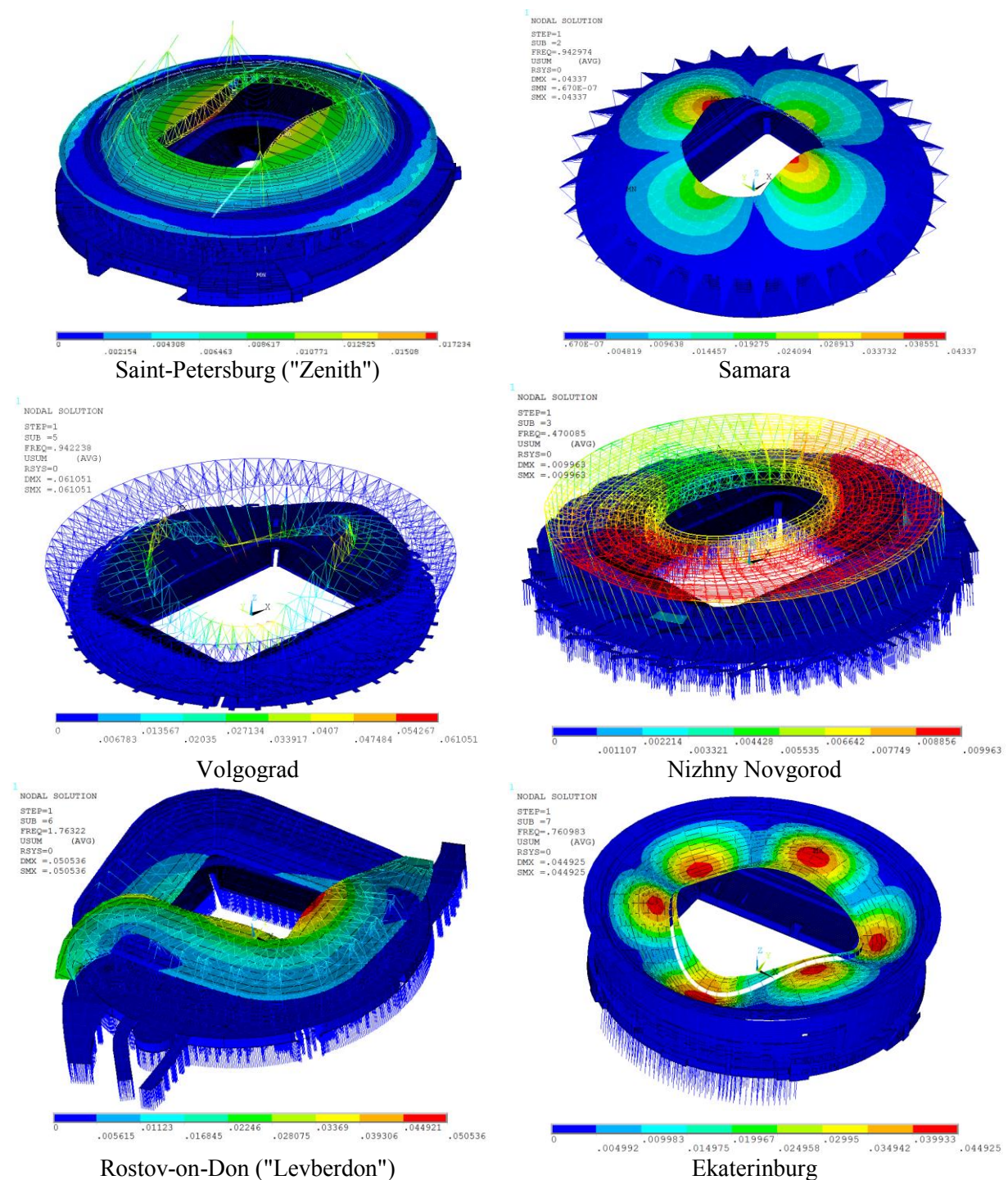


Figure 8. Sample of unique composite construction objects (three-dimensional systems "pile foundation – reinforced concrete of foundations and stands – metal coating and facades, designed for World Cup 2018 (FIFA). Computer modelling (Fragment).

References

- [1] Belostotsky A M and Akimov P A 2016 *Actual Problems of Numerical Modelling of Buildings, Structures and Complexes. The 25th anniversary of StaDyO R&D Center* (Moscow: ASV Press) Vol 1 426 pp
- [2] Belostotsky A M and Akimov P A 2016 *Actual problems of numerical modelling of buildings, structures and complexes. The 25th anniversary of StaDyO R&D Center* (Moscow: ASV Press) Vol 2 594 pp
- [3] Belostotsky A M, Akimov P A and Afanasieva I N 2017 *Computational Aerodynamics in the Construction Problems* (Moscow: ASV Publishing House) p 720
- [4] Belostotsky A M, Akimov P A and Kaytukov T B 2018 *Mathematical and Computer Modelling Based on Structural Health Monitoring of Buildings and Facilities* (Moscow: ASV Press) 712 pp