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Features of the structural safety analysis (strain-stress state, dynamics, strength and stability) of stadiums for the 2018 FIFA World Cup in Russia

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Abstract. The article presents special features of numerical simulation and main results of structural safety analysis of the three-dimensional long-span systems "ground base - reinforced concrete foundation structures and stands - metal structures of the coating and facades" of football stadiums for the 2018 World Cup in Russia with basic and special combinations of loads and key procedures of scientific support during examination. A brief description is given of the component mode synthesis as applied to the calculation of structures of this type

1. Introduction

Modern design and construction of unique buildings and structures is unthinkable without a calculated justification and in-depth comprehensive studies of the load-bearing structures behavior under the various kinds of influences. The most grandiose and responsible objects of construction are unique large-span structure such as stadiums, sports palaces and water parks, shopping and entertainment complexes, pedestrian, automobile and railway bridges of various design solutions. This yearб the World Football Cup took place in the period from June 14 to July 15 in Russia. Preparation for this event required significant costs and, first of all, the design and construction of new very capacious stadiums that meet modern security requirements and FIFA criteria. 12 football stadiums were built and reconstructed for the championship: “Luzhniki” and “Otkritie Arena” in Moscow, “Saint Petersburg Stadium” (“Zenit”), in Saint Petersburg, “Kazan Arena” in Kazan, “Nizhny Novgorod Arena” in Nizhny Novgorod, “Volgograd Arena” in Volgograd, “Rostov Arena” in Rostov-on-Don, "Ekaterinburg Arena" in Ekaterinburg, "Samara Arena" in Samara, "Mordovia Arena" in Saransk, "Kaliningrad Stadium" in Kaliningrad, "Fisht Stadium" in Sochi.

2. Special features and main results

Bearing structures of the football stadium are a spatial large-span system consisting of the following main fragments: a ground or pile foundation, reinforced concrete constructions of foundations and stands, metal structures of a cover and a facade. The calculated rationale for mechanical / structural safety (stress-strain state, dynamics, strength and stability) of combined systems has a number of characteristics [1, 2]. Below are the most significant of them:

- "Extreme" computational dimension of problems, with known consequences. The obvious difficulty lies in the analysis and processing of a design significant amount, regulatory documentation and the construction in exact accordance with them of a detailed geometric and then finite element model of the system "foundation - reinforced concrete structures of foundations and stands - metal structures of the cover and facades" with basic and special combinations of loads and effects. Models include an impressive (several hundred thousand) number of types of sections, stiffnesses, construction materials. Figure 1 shows the computational dimensions of the FE models of stadiums developed by the team of authors

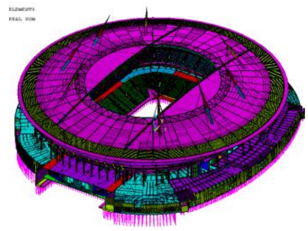
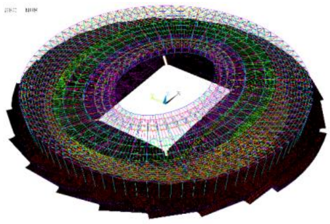
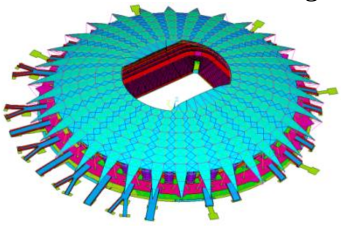
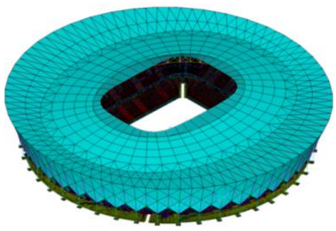
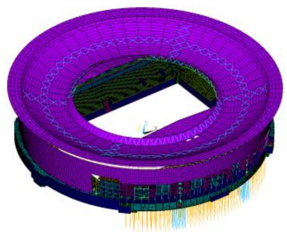
Complete stadium FE model	Computational dimension	Complete stadium FE model	Computational dimension
	1 038 614 nodes 1 489 043 elements		680 127 nodes 811 522 elements
Saint Petersburg Stadium		Nizhny Novgorod Arena	
	1 994 450 nodes 2 399 271 elements		480 109 nodes 704 013 elements
Samara Arena		Rostov Arena	
	540 76 nodes 583 783 elements		312 636 nodes 350 382 elements
Volgograd Arena		Ekaterinburg Arena	

Figure 1. General views of the three-dimensional shell-beam FE football stadiums (ANSYS Mechanical) models developed, with an indication of their computational dimensions.

- As a rule, the development and design optimization of the associated major subsystems, such as the base, reinforced concrete constructions of foundations and stands, metal coating structures, facade structures, etc. independently of each other, different design organizations.

Often, it is not possible for these companies to construct a design model of a complete system "base - reinforced concrete constructions of foundations and stands - metal structures of the cover and facades". Obstacles to this are various factors, from the large computational dimension of such models to the incompatibility of computational models file formats in various software complexes and commercial secrets.

In such a situation, a rational decision would be to switch to the stress-strain state study, the spatial system strength stability and dynamics of the bearing reinforced concrete and metal structures of the football stadium as separate models, which allows solving organizational problems in the process of unique structures designing and the computational dimension of the task reducing.

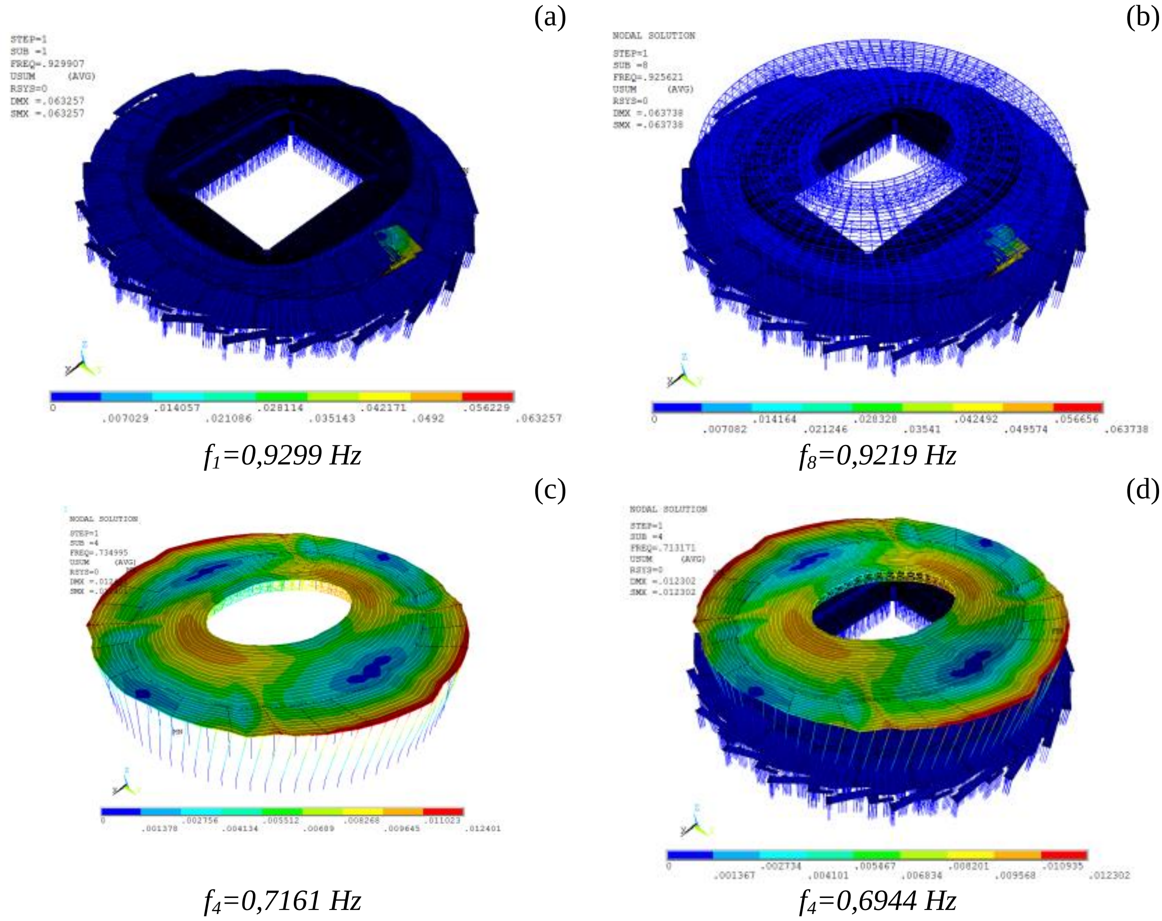


Figure 2. Comparison of natural frequencies and vibration modes of the complete FE model «base - reinforced concrete constructions of foundations and stands - metal structures of the stadium cover and facades» ((b) and (d)) in Nizhny Novgorod and subsystem FE-models ((a) and (c)) (ANSYS Mechanical).

To justify such a transition, it is required to carry out a comparative analysis of the natural frequencies and modes of the complete FE model stadium structures vibrations (the system “base - reinforced concrete constructions of foundations and stands - metal structures of the cover and facades”) (Figure 2 (b) and (d)) and FE models of subsystems and assess how great the compliance effect of the support subsystem “base - reinforced concrete structures foundations and tribunes” (Figure 2 (a)) on the static state, dynamics and stability of the subsystem “metal structures of the coating and facades”(Figure 2 (c)). With weak influence, i.e. in the absence of joint forms and a slight discrepancy between the vibration frequencies values for related forms, it can be concluded the possibility to study stress-strain state within the framework of separate models.

An alternative approach that can be applied even when the comparative analysis of natural frequencies and vibration modes of the stadium designs complete model and subsystem models does not give a satisfactory answer (the possibility of decomposition) is the superelement method or the method of dynamic synthesis of substructures (component mode synthesis).

Component mode synthesis (CMS) is an option used in substructure analysis when degrees of freedom (DOF) are structural. It reduces the system matrices to a smaller set of interface DOFs between substructures (components) and truncated sets of normal mode generalized coordinates [3].

For a damped system, each CMS substructure is defined by a stiffness matrix, a mass matrix, and a damping matrix. The matrix equation of motion (1) is:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\} \quad (1)$$

Partitioning the matrix equation into interface and interior DOFs (2):

$$\{u\}=\begin{Bmatrix}\{u_m\}\\ \{u_s\}\end{Bmatrix},\ [M]=\begin{bmatrix}[M_{mm}] & [M_{ms}]\\ [M_{sm}] & [M_{ss}]\end{bmatrix},\ [C]=\begin{bmatrix}[C_{mm}] & [C_{ms}]\\ [C_{sm}] & [C_{ss}]\end{bmatrix},\ [K]=\begin{bmatrix}[K_{mm}] & [K_{ms}]\\ [K_{sm}] & [K_{ss}]\end{bmatrix},\ \{F\}=\begin{Bmatrix}\{F_m\}\\ \{F_s\}\end{Bmatrix} \quad (2)$$

where subscripts m is are master DOFs defined only on interface nodes and s is are all DOFs that are not master DOFs.

The nodal displacement vector, $\{u\}$, may be represented in terms of master DOFs completed by component generalized coordinates [3] as (3):

$$\{u\}=\begin{Bmatrix}\{u_m\}\\ \{u_s\}\end{Bmatrix}=[T]\begin{Bmatrix}\{u_m\}\\ \{y_\delta\}\end{Bmatrix} \quad (3)$$

where $\{y_\delta\}$ – truncated set of generalized modal coordinates.

For the fixed-interface method, also commonly referred to as the Craig-Bampton method [4], the transformation matrix has the form (4):

$$[T]=\begin{bmatrix}[I] & [0]\\ [G_{sm}] & [\Phi_s]\end{bmatrix} \quad (4)$$

where $[\Phi_s]$ – fixed-interface normal modes (eigenvectors obtained with interface nodes fixed).

For the free-interface method, also commonly referred to as the Herting method [5], Herting [6]), the transformation matrix has the form (5):

$$[T]=\begin{bmatrix}[I] & [0] & [0]\\ [G_{sm}] & [\Phi_{sr}] & [\hat{\Phi}_s]\end{bmatrix} \quad (5)$$

where $[\hat{\Phi}_s]=[\Phi_s]-[G_{sm}][\Phi_m]$, $[\Phi_m]$ – matrix of the master DOF partition of the free-interface normal modes (eigenvectors obtained with interface DOFs free), $[\Phi_s]$ – matrix of the slave DOF partition of the free-interface normal modes, $[\Phi_{sr}]$ is included only if rigid body modes are present. Any rigid body modes present are not included in $[\hat{\Phi}_s]$.

The problem arises of modeling an inhomogeneous ground base and a pile field containing about ten thousand piles in the process of pile or pile-foundation bases of football stadiums installing. The process of modeling such a number of piles requires the use of macros - written on the built-in software (or third-party) programming language of scripts or macro routines, which allows efficient and automated and in a short time to specify and iteratively adjust the rigidity and process the output for such an array of piles.

Dynamic influences caused by the coordinated movements of a large number of people on the stands of sports facilities cause variations in the structures, which in its turn can reduce the comfort of people staying in such structures. It is necessary to exclude the possibility of their resonant excitation, from the synchronous movement of people, in the process of the sports stands structures facilities designing. The limiting deflections of the stands structures should be determined on the basis of physiological requirements ("fluctuations") in accordance with the current regulatory documents. In addition, the frequency of the stands natural oscillations should be in the vertical direction above 5 Hz, and in the horizontal direction - more than 3 Hz (these criteria may vary slightly and are determined by special technical conditions). The calculation for dynamic comfort is inextricably linked with the multi-iteration process of supplementing and correcting the position of the stadium bearing structures on the basis of the static and dynamic calculations results to meet the criteria of dynamic comfort (in other words, fluctuation) in the design of the stands [7].

It is required to calculate stability for metal structures of coatings and facade, taking into account physical and geometric nonlinearities and initial imperfections. It is also necessary to geometrically nonlinear modeling of prestressed cable elements in the structure of the coating (for stadiums, which coatings have corresponding design solutions), including the calculating for progressive collapse.

For the most complex and critical components of metal coatings, it is required to carry out a refined three-dimensional physically non-linear FE-analysis of the stress-stain state and the strength of the most stressed structural units taking into account the actual deformation diagram. As a rule, such a calculation is carried out using a shell-beam finite element model of the coating, where a solid model of the investigated node is built, which has the necessary zones of thickening the finite element grid for more adequate reproduction of the stress-stain state. The models developed in this way are verified by comparing the maximum displacements before and after the node is included in the general model from the design load [8,9].

Some stadiums for the World Cup in Russia are located in seismically active areas (Kaliningrad, Rostov-on-Don, Krasnodar, Sochi). Accordingly, for them it is necessary to carry out dynamic calculations of the systems “base - reinforced concrete constructions of foundations and stands - metal structures of the coating and facades” for seismic actions by linear-spectral method for three-component accelerometer spectra and direct integration of the equations of motion into three-component accelerograms.

In the structure of the stadiums constructed and reconstructed for the World Cup, the seats number increase can be envisaged with the help of temporary assembled demountable stands device. Simulation and calculation of temporary collapsible stands, as a rule, has a multi-iterative character. It is necessary to correct the initial variants of the temporary stands based construction on the results of static and dynamic calculations to meet the strength criteria. As a result of this optimization process, both the strength and stability requirements of structures and the physiological requirements for “fluctuation” or, in other words, for dynamic comfort can be met.

To improve the quality of design justifications for design solutions for modern complex construction projects, in order to avoid miscalculations in design leading to emergency situations during construction and operation, requirements have been developed. The design organizations are encouraged to perform calculations on at least two models independently developed in two verified software packages, carry out a comparative analysis of the results obtained. The basic integral characteristics of structures are compared, such as the structure mass, natural frequencies and vibration modes, the entire structure displacement and individual structural elements, and efforts in the main types of structural components. In order to achieve an acceptable difference in values, in close interaction with colleagues performing an alternative calculation, it is necessary to calibrate the calculation models and eliminate all possible discrepancies in the stiffness characteristics, loads, etc. which in turn makes it possible to reduce the values of the compared design parameters to acceptable values.

Scientific and technical support for the passage in the FAU “Glavgosexpertiza of Russia” regarding the rationale for the stadiums design. The successful completion of the examination is preceded by a large amount of preliminary work, including with the “alternative” subcontractors to achieve acceptable compliance with the main calculations results, the provision of detailed responses to comments and suggestions from established and invited experts who, in some cases, may require serious additional research.

3. Conclusion

- The above-mentioned and a number of other science-intensive problems were successfully solved by the authors of the R&D center StaDyO with the calculation of the stress-strain state, strength and stability of the base and bearing structures of the stadiums in St. Petersburg, Samara, Volgograd, Nizhny Novgorod, Rostov-on-Don and Yekaterinburg, with the main and special combinations loads and impacts. Calculation studies were performed as necessary in complex productions with the use of adequate mathematical models and modern numerical methods of mechanics in software systems verified (in the RAASN system)
- As a result of the completed research and development work on a new level, a socially significant and science-intensive problem of ensuring the mechanical (constructive) safety of unique combined construction objects (three-dimensional systems “ground base - reinforced concrete constructions of foundations and stands - metal structures of the cover and facades”), having modern architectural forms and constructive solutions designed to the 2018 FIFA World Cup (FIFA mode) and for further use after it (“Legacy” mode).
- The mentioned results of computational studies and specially designed, on the basis of the considered design, adaptive predictive mathematical (finite element) models should form the basis of realizable systems for monitoring the bearing structures state of stadiums for all stages of the “life” cycle.
- The main approaches, numerical modeling methods and the computational research results formed the basis for a course of lectures and practical classes for students, undergraduates and number postgraduates of leading Russian universities (NRU MGSU, PNRPU, TSUAB, RUT MIIT, FEFU and etc.), are developed in a number of dissertations, approved at international conferences and symposiums, published in a number of articles and monographs.

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