

Approbation of the developed technique of superelement simulation of dynamics for system “Basis – Foundations structures and stands – Structures of the roof” for stadiums for the 2018 FIFA World Cup in Russia

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Abstract. The article presents approbation of the developed technique of numerical (superelement) simulation of dynamics of the three-dimensional systems "ground base - reinforced concrete foundation structures and stands - metal structures of the roof" of stadiums for the 2018 World Cup in Russia with basic and special combinations of loads.

1. Introduction

Numerical simulation of the stress-strain state, dynamics and stability of such unique responsible objects as football stadiums of large capacity, has a number of specific features. One of the key is that the development and design optimization of related subsystems, such as the basis, the reinforced concrete structures of the stadium stands, the metal structures of the roof, the facade structures, etc. various design and survey organizations are largely independent of each other. It is often not possible to build the design model of the complete system “foundation - reinforced concrete structures of the stadium bowl - metal roof structures” by their forces. The obstacles to this are various factors: the large computational dimension of such models, the use of various software systems and, as a result, the possible incompatibility of files, the introduction of changes to the project in the course of its development, trade secrets, etc. To solve this problem, the author proposed a technique that implements super element approaches, widely used in the aerospace industry and in engineering, but practically not represented in civil engineering. Detailed description and verification of the developed technique are given in [1].

With the application of the developed technique, for the first time, the problem was solved in such a high level of responsibility, complexity, and dimensionality – computational investigation of the stress-strain state, dynamics, and strength were carried out bearing structures of football stadiums of large capacity (from 35 000 to 68 000 spectators) in St. Petersburg, Samara, Volgograd, Nizhny Novgorod, Rostov-on-Don and Yekaterinburg, with the main and special combinations loads and impacts. [2]. This article presents the application of the developed superelement technique on the



example of the real system “foundation - reinforced concrete structures of foundations and stands – metal structures of the roof” of a football stadium in Rostov-on-Don with the action of various combinations of loads and impacts.

2. Description of the designs of the football stadium in Rostov-on-Don

The Rostov-on-Don Football Stadium (“Rostov-Arena”), with a capacity of 45 000 spectators in FIFA mode (37 868 spectators in the “Heritage” mode), is located on the left bank of the Don River. The system of bearing structures of the stadium includes the following groups of elements: reinforced concrete structures of the foundation and the stands, metal structures of the roof, structures of the bypass gallery with exit ramps. Figure 1 shows the initial architectural design of the stadium and the general views of the developed FE model.

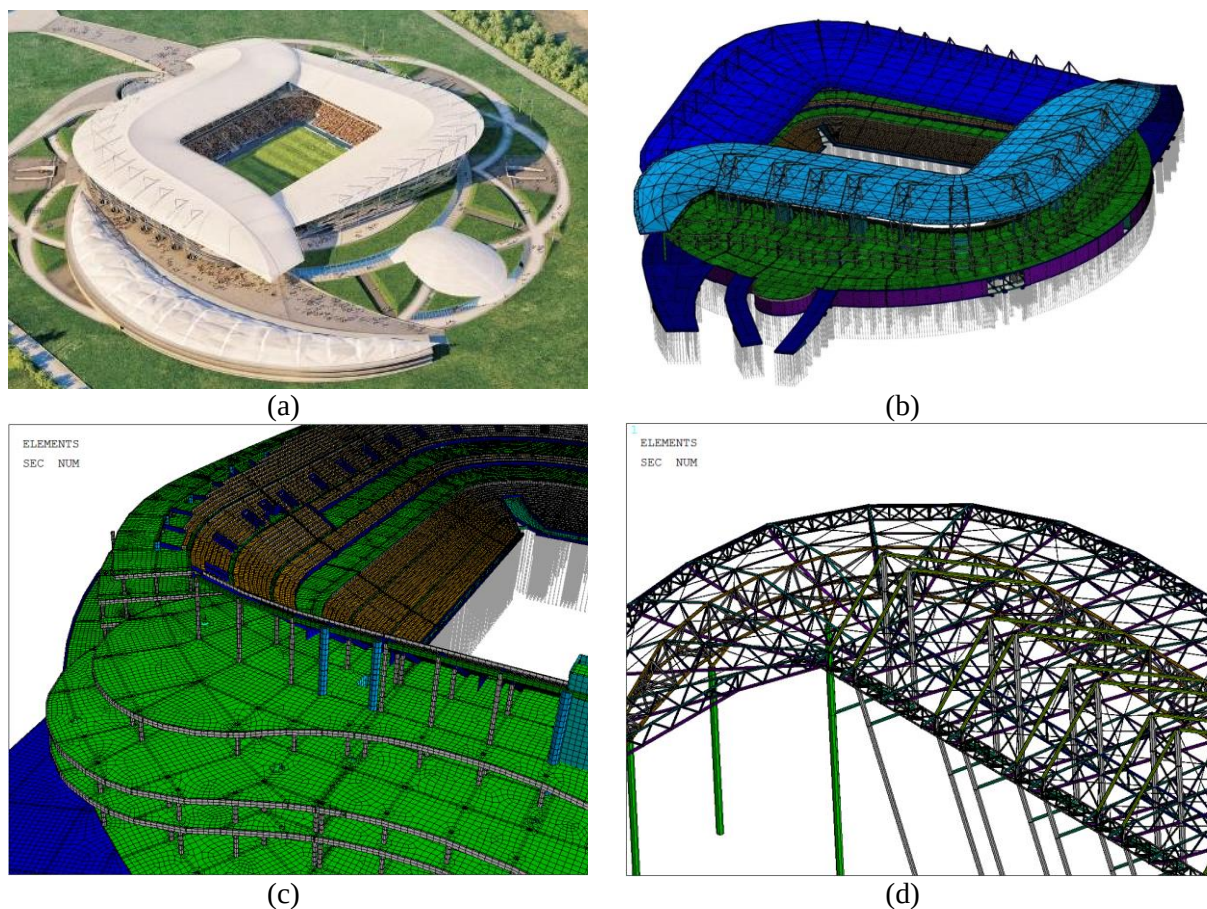


Figure 1. Stadium in Rostov-on-Don. Initial architectural project (a). Complete FE model (b). Enlarged views of fragments of the complete FE model (c) and (d).

The main bearing structures of the stands of a football stadium are a system of monolithic reinforced concrete elements consisting of columns, pylons, walls, floor slabs, beams. The foundations are pile and pile-slabs. The total number of piles is 11 091. The roof of the football stadium in Rostov-on-Don consists of two wings with the dimensions of the sides $147 \times 108 \times 80$ m each, located above the north-east and south-west stands. The main bearing elements of the stadium cover are 34 consoles, which are flat construction of variable height, consisting of a flat trellised truss with a departure of 51.7 m to the field and a section height of 7 m at the place of fastening of the delay above the stands, vertical stands.

3. The FE-models of a football stadium in Rostov-on-Don

The following spatial shell-beam finite element models of the supporting structures of the stadium in Rostov-on-Don were built and verified in the ANSYS Mechanical software package. Table 1 provides descriptions of the models and submodels of the system, with an indication of the computational dimension and the types of finite elements used. Figure 2 shows the images of the FE models of the system and subsystems

Table 1. FE models of system/subsystems of stadium in Rostov-on-Don (ANSYS Mechanical).

№ model	FE-models system/subsystem description	Number of nodes	Number of elements	Used FE types
1	“basis – reinforced concrete constructions of foundations and stands – metal structures of the roof”	621 048	604 358	SHELL181, BEAM188, MPC184, SURF154, LINK180, COMBIN14
2	“basis – reinforced concrete constructions of foundations and stands”	599 417	589 387	SHELL181, BEAM188, MPC184, SURF154, COMBIN14
3	“metal structures of the northeast wing”	9 185	6 304	BEAM188, LINK180, SURF154
4	“southwest wing metal structures”	12 446	8 667	BEAM188, LINK180, SURF154
5	“basis – reinforced concrete constructions of foundations and stands” + SE metal structures of the roof	599 417	589 388	SHELL181, BEAM188, MPC184, SURF154, COMBIN14, MATRIX50
6	“metal structures of the roof” + SE reinforced concrete constructions of foundations and stands	21 651	14 972	BEAM188, LINK180, SURF154, MATRIX50

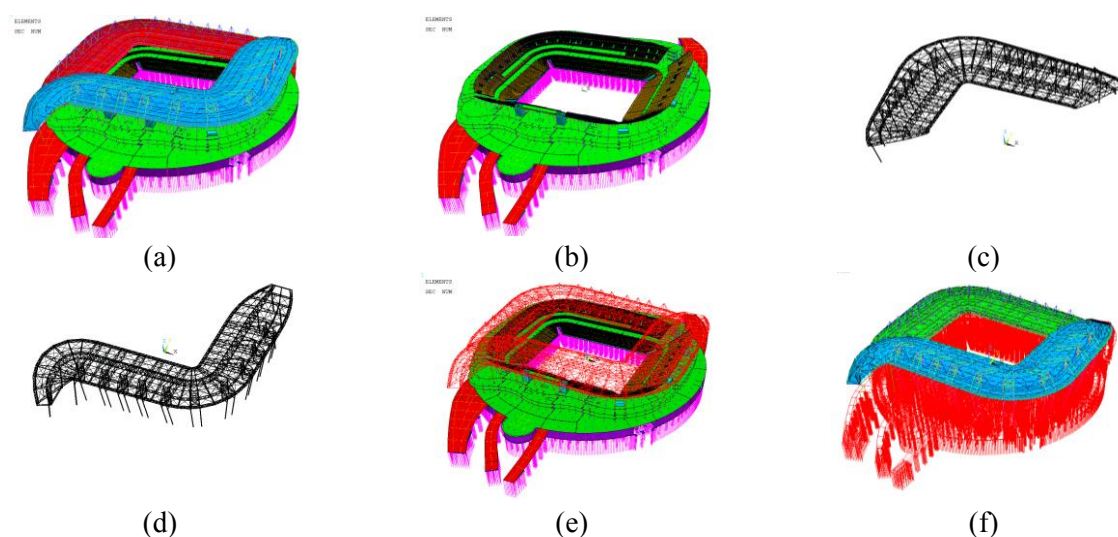


Figure 2. FE models of system/subsystems of stadium in Rostov-on-Don studied in ANSYS Mechanical. Model 1 (a), Model 2 (b), Model 3 (c), Model 4 (d), Model 5 (e) and Model 6 (f).

Finite elements SHELL181, implementing the theory of Mindlin-Reissner, are used for modeling the foundation, walls, floor slabs, stair and elevator shafts, a ridge of stands, beams under the ridge of stands. BEAM188 are the finite elements based on Timoshenko beam theory, used for modeling beams and columns. LINK180 are a spatial core elements working in tension or compression. Piles are modeled by special finite elements COMBIN14. MPC184 – finite elements of kinematic restrictions. SURF154 are surface effect finite elements, used to set the loads on the roof, as well as on inclined flights of stairs. MATRIX50 (super element / substructure) is a group of pre-assembled finite elements that is considered as a separate element and is represented by reduced matrices (stiffness, masses, loads).

4. Comparative analysis of the results of dynamic calculations of the models of the complete system “foundation - reinforced concrete structures of foundations and stands - metal structures of the coating” and models of its constituent subsystems

For all six models of systems and subsystems, 150 lower natural frequencies and modes were calculated. To obtain the dynamic characteristics of models with superelements (Model 5 and 6), the fixed-interface component mode approach (Craig-Bampton method [3, 4]) is used. This method has proven to be the most effective and highly accurate. It is also possible to take into account the internal modes for the free-interface of the substructure [5], however, the accuracy of this approach is somewhat lower than in the case of fix-interface. Recommendations on the number of modes retained in modal expansions are given in [6]. In the present investigation, the calculation of the substructures took into account from 50 to 100 internal modes of the substructure.

Table 2 shows the natural frequency and modes of the studied models. Green background indicates the natural frequencies of the complete model and the submodels at which the modes match. The orange background indicates those natural frequencies of “non-superelement” models 2, 3 and 4, on which the modes do not correspond to the modes of the full model, or are absent. In Table 2, data are arranged in such a way that natural frequencies in a single line are close in value and have similar or coinciding mode shapes.

Table 2. Comparison of natural frequencies and vibration modes of the complete FE model «basis - reinforced concrete constructions of foundations and stands - metal structures of the roof» (model 1) of stadium in Rostov-on-Don and subsystem FE-models (models 2-6).

Model 1		Model 2		Model 3		Model 4		$\Delta_1, \%$	Model 5		Model 6		$\Delta_2, \%$
Nº	Freq, Hz	Nº	Freq, Hz	Nº	Freq, Hz	Nº	Freq, Hz		Nº	Freq, Hz	Nº	Freq, Hz	
1	1.2304					1	1.3157	6.483	1	1.2307	1	1.2326	0.178
2	1.4093					2	1.4253	1.123	2	1.4094	2	1.4096	0.021
3	1.5981					3	1.7469	8.518	3	1.5997	3	1.5987	0.100
4	1.6012			1	1.7369			7.813	4	1.6020	4	1.6042	0.187
5	1.6498	1	1.6504					0.036	5	1.6503	5	1.6511	0.079
6	1.6658					4	1.8129	8.114	6	1.6665	6	1.6687	0.174
7	1.7059			2	1.8215			6.346	7	1.7064	7	1.7098	0.228
8	1.7275	2	1.7790						8	1.7285	8	1.7350	0.432
9	1.7835	3	1.7833	3	1.8967			5.968	9	1.7837	9	1.7922	0.485
10	1.8206	4	1.8269			5	1.8913	3.738	10	1.8214	10	1.8238	0.175
...	...	...	...	...	...	...	...	...	...	...	...	...	...
22	2.0406	15	2.0404					0.010	22	2.0406	22	2.0494	0.429
23	2.0412	16	2.0508	4	2.0924			2.447	23	2.0455	23	2.0980	2.707
24	2.0946	17	2.0699						24	2.0959	24	2.1025	0.376
25	2.1016	18	2.0979					0.176	25	2.1023	25	2.1343	1.532
26	2.1257								26	2.1278	26	2.1443	0.867
27	2.1340								27	2.1358	27	2.1607	1.236
28	2.1409	19	2.1344						28	2.1451	28	2.1704	1.359
29	2.1561	20	2.1667						29	2.1577	29	2.1796	1.078
30	2.1812					7	2.1910	0.447	30	2.1815	30	2.1818	0.028
31	2.1861			5	2.1925			0.640	31	2.1863	31	2.1896	0.160
32	2.1924	21	2.1913						32	2.1940	32	2.1946	0.100
33	2.1981								33	2.1987	33	2.1985	0.027
34	2.1992								34	2.1994	34	2.2012	0.091
...	...	...	...	...	...	...	...	...	...	...	...	...	...

At the first stage, the natural frequencies and modes of the complete model (model 1) and models of subsystems without the use of superelements (models 2-4) were compared. At the next step, the natural frequencies and modes of the complete model and models of subsystems with the superelements (models 5-6) were compared. The results of such a comparison are shown in Table 2. Δ_1 is the maximum difference between the natural frequencies of the complete model and models of subsystems without the use of superelements. Δ_2 is the maximum difference between the natural frequencies of the complete model and the models of subsystems with the superelements.

The results of the comparison carried out at the second stage shows that the discrepancy between the values of the calculated natural frequencies for most modes does not exceed 0.5-0.7%, and for individual modes, in the studied range, it was 1.5-2.8%. Figure 3 shows a comparison of the mode shapes of the complete model and submodels with the superelements: first mode shape of the complete model (a); first mode shape of the complete model with the display of roof structures turned off (b), first mode shape of the Model 5 (c), first mode shape of the Model 6 (d), fourth mode shape of the complete model (e), fourth mode shape of the complete model with the display of roof structures turned off (f), fourth mode shape of the model 5 (g), fourth mode shape of the model 6 (h).

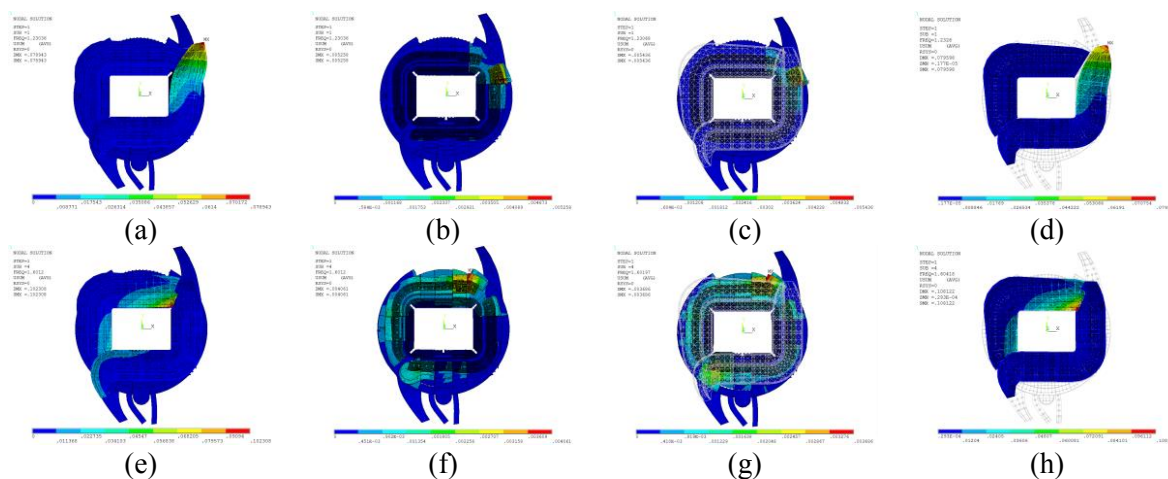


Figure 3. Comparison of natural frequencies and vibration modes of the complete FE model «basis – reinforced concrete constructions of foundations and stands – metal structures of the roof» (Model 1) of stadium in Rostov-on-Don and subsystem FE-models (Models 5 and 6).

5. Conclusion

- With the application of the developed methodology, for the first time in such a formulation, the tasks are solved of a high level of responsibility, complexity and dimension, namely the computational investigation of the stress-strain state, dynamics, and strength of the bearing structures of the football stadiums of large capacity (from 35 000 to 68 000 spectators) in St. Petersburg, Samara, Volgograd, Nizhny Novgorod, Rostov-on-Don and Yekaterinburg, with the main and special combinations loads and impacts.
- An illustrative example of a stadium in Rostov-on-Don presents the results of an analysis of the natural frequencies and modes of the complete system model and subsystem models. Subsystem models were considered without use of a super element (as is customary in practice) and using a super element. Comparison of the results of calculations of superelement submodels and the complete model of the system shows that the discrepancy between the values of the calculated natural frequencies for most modes does not exceed 0.5-0.7%, and for individual modes, in the studied range, it was 1.5-2.8%.
- This has clearly demonstrated the reasonable application of the developed technique with the use of implemented superelement approaches on the actually existing system “foundation -

reinforced concrete foundation structures and stands - metal structures of the roof” under the action of various combinations of loads and impacts.

- The presented results allow us to recommend the superelement technique for a wide use in computational investigation of three-dimensional combined systems “foundation - reinforced concrete structures of foundations and stands - metal structures of the roof” under various combinations of loads and impacts.
- The prospect of further development is the application of the proposed technique for the numerical simulation of the above-mentioned combined systems under the action of dynamic effects. Also a promising direction is their numerical simulation in physically, geometrically, structurally and genetically non-linear modes.

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