Proceedings of the IASS 2022 Symposium affiliated with APCS 2022 conference
Innovation·Sustainability·Legacy
19 – 22 September 2022, Beijing, China

The new egyptian army stadium in Cairo: a cable suspended roof structure

Massimo MAJOWIECKI*[a], Stefano PINARDI[b], Giovanni BERTI[b], Elisa SAMMARCO[b], Giuliano ALOISIO[b], Monica MINGOZZI[b]

* DICAM, University of Bologna
MJW Structures via Tizzano 46/2, Casalecchio di Reno (Bologna, Italy) CAP 40033
info@mjwstructures.com

[b] MJW Structures

Abstract

The New Egyptian Army Stadium is now under construction in the Egypt International Olympic City in Cairo, Egypt. Stadium capacity is of 93,000 covered seats with a roof surface of 45’000 m^2. The building design fulfil the requirements necessary to host a FIFA World Championship final phase and there is also an athletics track meeting the IAAF standards for international competitions. The basic architectural concept is to create an iconic element that can characterize the skyline of the place that is a significant part of the overall development of this sports area. The structural solution has been reached with a tension circular ring supported by 32 pylons that hang the wave shaped roof composed by 64 lattice girders. That static scheme allows to merge efficiency with aesthetic value required by the client in agreement with the previous design experiences of the MJW Structures team. Each radial tension structure is composed by one main column, two outer stays, one inner bearing cable and one inner stabilizing cable connected with the inner tension ring. The radial lattice girders are supported by the columns at the external side and by the tension structure in the inner side. The structural concept has considered erection procedure since earlier phases; erection procedure has been performed with a big lift operation of the inner cable ring with 32 flying jacks and the aerodynamic behaviour of the roof and cables tested in RWDI wind tunnel in Milton Keynes (UK).

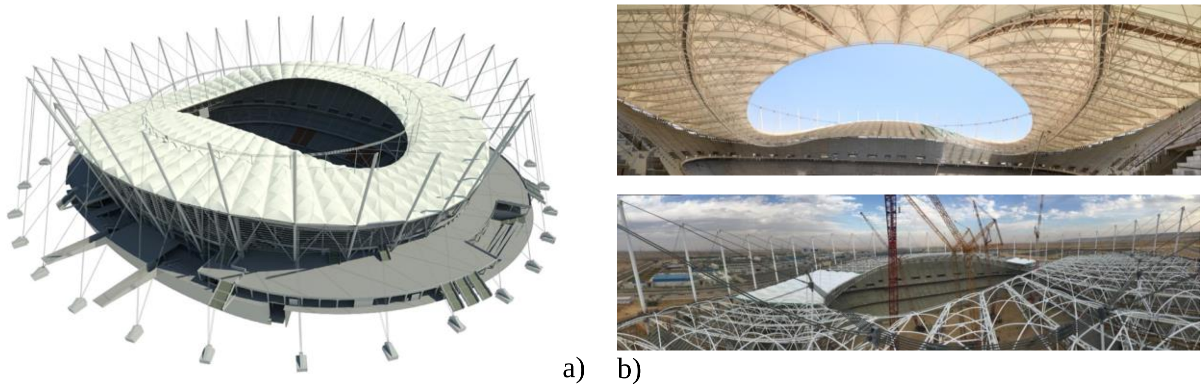
Keywords: stadium roof, wide span structure, cable tension structure, form finding, membrane structures.

1. Introduction

The new Capital Sport City complex project is located in the south-west part of the city of Cairo, along the east-west axis of the Ain El Sokhna road, crossing the Regional Ring Road. The area of intervention, still further developing, was chosen for the realization of the sport’s village for the new capital City.

The project is part of a broader ongoing development plan, which includes the realisation of various sport venues to be built inside the compound of the new sport city, rounded by a main road network, and linked to the city and the future railway network. The proposed project is integrated in the general masterplan, which is being previously designed, benefiting from choices already made and plotting the future shape of this area focussed on the versatility of the stadium and its various related activities.

Copyright © 2022 by <substitute here the name(s) of the author(s) or individual(s) claiming copyright>
Published by the International Association for Shell and Spatial Structures (IASS) and Asian-Pacific Conference on Shell and Spatial Structures (APCS) with permission.



a) b)

Figure 1: a) Rendered isometric view of the stadium structure; b) Roof view from the construction site

The general development plan for the sport city complex defines the location of a series of sport's structures and leisure-social activities, which are part of a unique system related to amateur and professional training, with the core football and athletics stadium for 93,000 spectators.

2. Structural system

The structural system, adopted for the roof of the new Olympic Stadium in Cairo, belongs to the so-called lightweight structural typologies conceptual design especially suited in designing wide enclosures and long span structures, as it is the case. In fact, a Stadium of a capacity of 90.000 spectators usually requires a roof covering, with transversal and longitudinal dimensions, of the order of 300m or more. The roof surface is 45700[m^2] and the lateral cladding is 19700[m^2].

Figure 2: Section view of the stadium structure

According the architectural design, the roof structural system is mainly formed by:

- A 3D principal supporting tensile structure made of:
  - an inner tension ring;
  - 32 inner-outer radial oriented carrying stay steel cables;
  - 32 inner-outer radial oriented stabilizing steel cables;
  - 32 CHS masts of variable high;
  - 32 tension-compression flying masts.

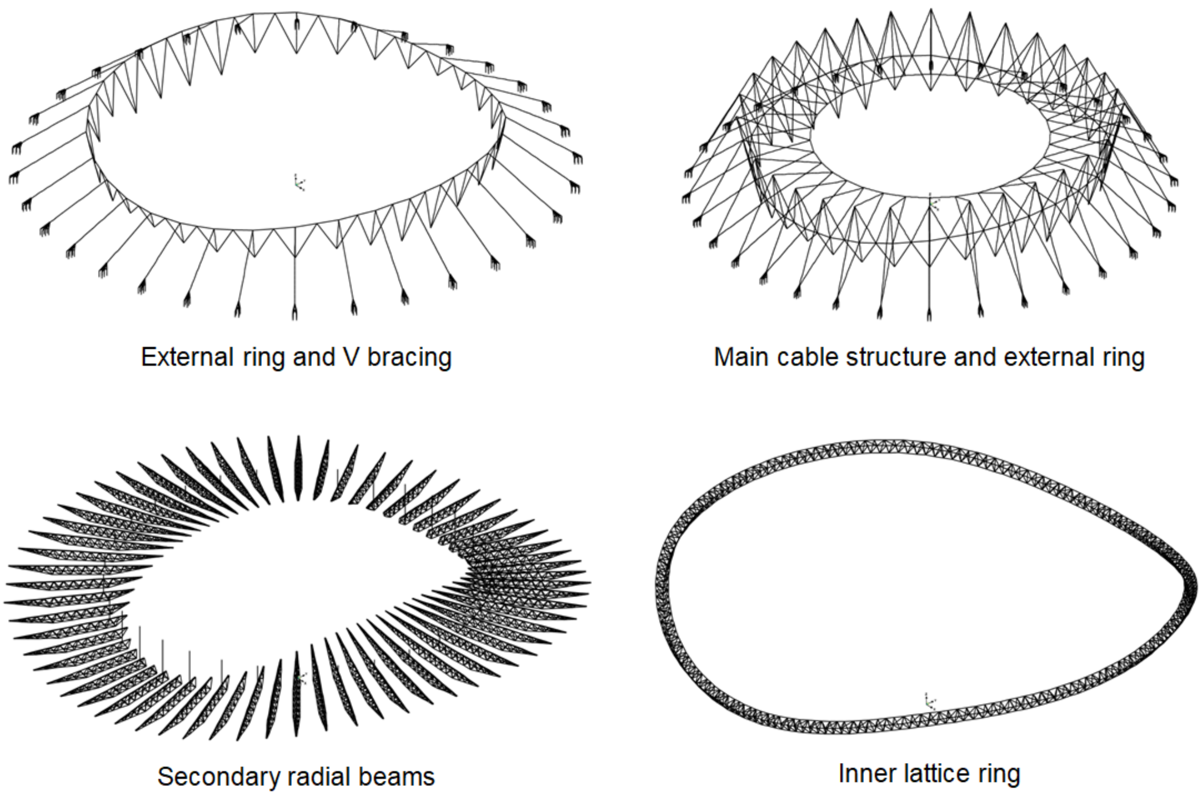


Figure 3: Roof structural system

- A secondary structural system made of:
  - 64 radial oriented simple supported space lattice girders, following the wave shape of the roof surface, interconnected by a stiffening ring;
  - 64 membrane panels.

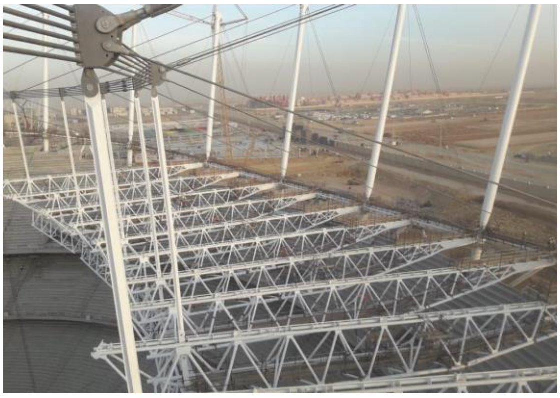
The separation, between primary and secondary structural system, increases the reliability of the structural response and, the double effect response system against downward and upward directed loading actions (see wind effect), gives a higher degree of robustness against accidental loading actions and permits easier erection methodology.

The columns, supporting the roof, have a tangential separation of around 24m along the perimeter of the reference circle identifying the geometry of the column's support points; furthermore, the carrying masts have different high and the beams have different spans following the wave shape of the roof surface.

The 64 beams support the translucent doubly curved 3D prestressed roof membrane panels made by polyester fabric coated, both sides, by translucent PVDF.

Each radial tension structure is composed by one main column, two outer stays, one inner bearing cable and one inner stabilizing cable connected with the inner tension ring. Each couple of radial tension structures are mutually braced by posts and bracing diagonals. The radial lattice girders are supported by the columns at the external side and by the tension structure in the inner side by a connection with a CHS flying mast.

Lattice girder typical static scheme is a simply supported beam with a cantilever. It be useful to distinguish radial girder in main ones and secondary ones. Main radial girders are hanged directly by flying masts (Figure 4 a)), secondary girders are supported by annular lattice ring.


a)

b)

Figure 4: a) Main radial girders; b) annular lattice ring

An inner annular lattice girder is suspended to main girders at inner stays joints (Figure 4 b)). Annular ring supports secondary girders and connects rigidly radial girders system in transversal and vertical directions.

The roofing is made by composite fabric panels of Polyester coated both sides by PVDF, tensioned and supported by secondary arches (spacing about 5m) as shown in Figure 5 a). The lateral cladding is composed by polymer panels supported by a lattice steel structure (Figure 5 b)).


a)

b)

Figure 5: a) Membrane and supporting arches; b) Lateral cladding

3. Structural analysis

The structural mathematical analysis has been carried out with the following steps:

- definition of the State 0 configuration of the tension structure roof under the application of the pretension forces and permanent loads;
- non linear geometric elastic analysis of the global structure in order to evaluate the effects of permanent and variable design actions (gravitational live loads, wind action, thermal action);
- Linear elastic dynamic analysis in order to evaluate the dynamic characterization of the structure (natural frequencies and correlated modal shapes) and the effects of design earthquake actions;
- Wind tunnel test on a rigid scale model and evaluation of the equivalent wind load case for the mathematical model;
- Resistance and stability checks of steel structural elements.

3.1. State 0 definition

Considering the boundary conditions (anchorage external points and top coordinates of pylons), together with the design assumption of a circular tension ring able to suspend the wave roof structures, an optimization sequence of form finding ,under a target prestress state, as been run and the state "0" obtained. After that, the identified structural system as starting state has been loaded to find the final state of stress and deformation for all loading combinations.

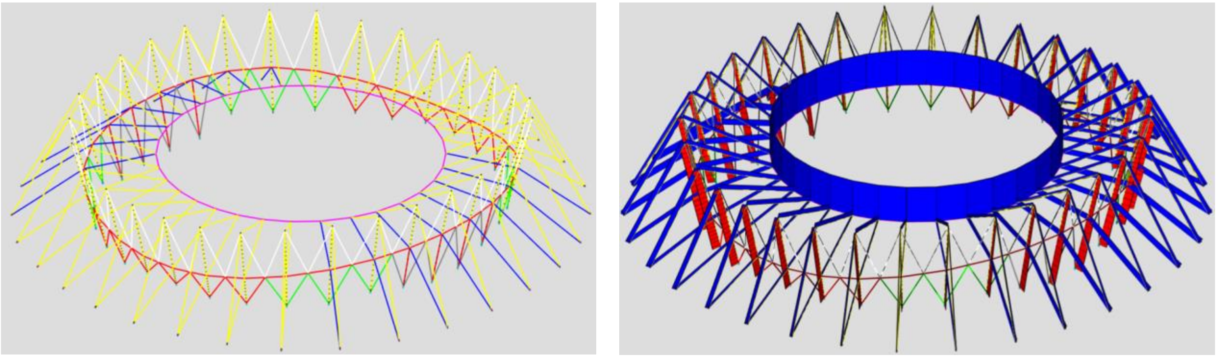


Figure 6: State 0 configuration: global view and axial forces diagram

3.2. Roof structural model non linear static analysis

The non linear static analysis take in account the geometric stiffness of the elements, large displacements and p-delta effects of the axial forces. The values obtained from the mathematical model have been validated with simple calculation using a schematic model of the structure.

Theoric force values in ULS combination (1.2 D + 1.6 L_r + 0.8 W) in agreement with the Egyptian Building Code for the main radial frame:

Vertical force in the hanging profile: F = 3043[kN]

Axial force in the inner bearing cables: $S_{inner,bearing}$ = F/sin(30°) = F / 0.5 = 6086[kN]

Radial component of the force: F_{rad} = $S_{inner,bearing}$ cos(30°) = $S_{inner,bearing}$ 0.866 = 5271[kN]

Axial force in the pylon due to the hanging of the roof: N_{pylon} = 9090[kN]

Axial force in the tension ring: N_{ring} = 0.5*F_{rad}/cos(168.27/2) = 25792[kN]

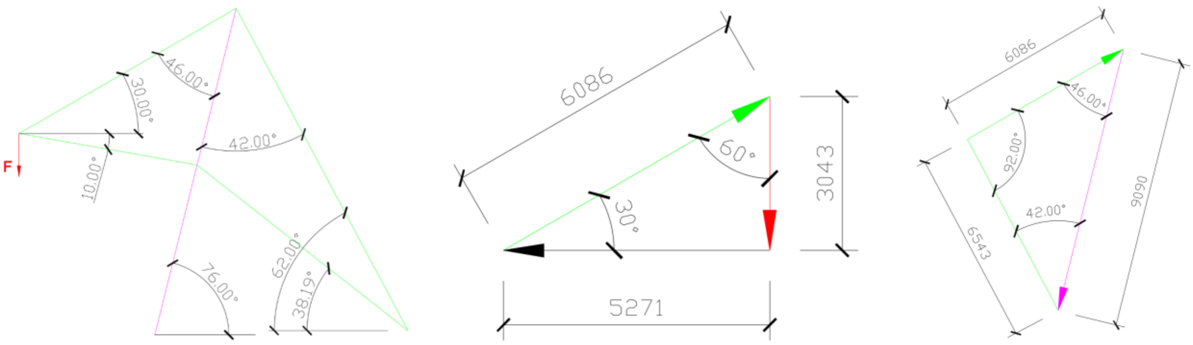


Figure 7: Force components for the mathematical model validation

The values of the forces in the mathematical model have an increment respect the validation model due to a residual pre stress force in the stabilizing cables because the new radial force became F'_{rad} = 5271 + 1257 cos(10) = 6509[kN] and the axial force in the tension ring N'_{ring} = 0.5*F'_{rad}/cos(168.27/2) = 31850[kN], so the mathematical model is validated.

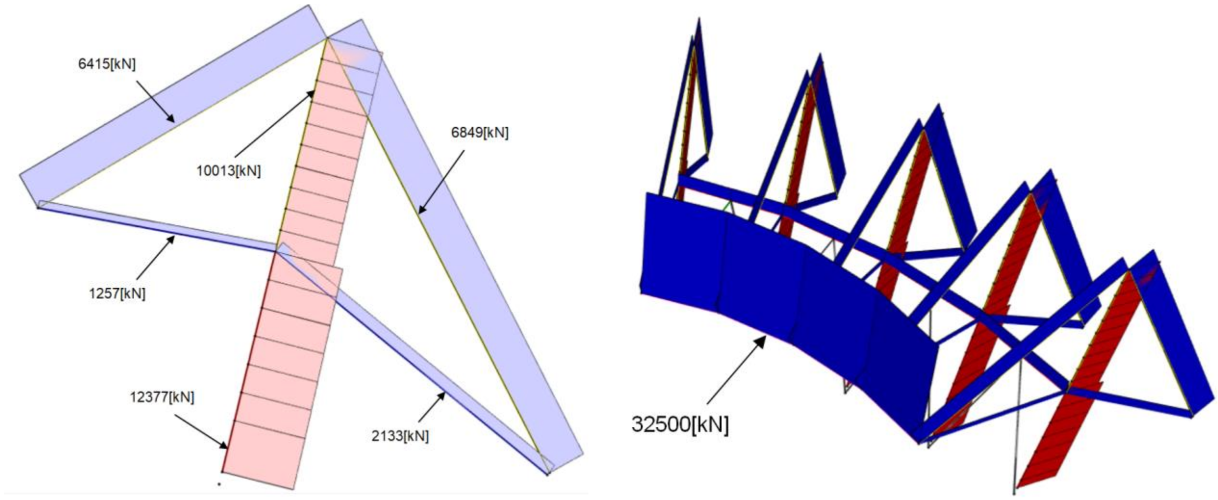


Figure 8: Axial forces in the mathematical model

The structural displacements under permanents and variable loads have been checked in order to ensure that the values respect the code limitations in order to ensure the aesthetic effect and avoid ponding phenomena due to the water accumulation.

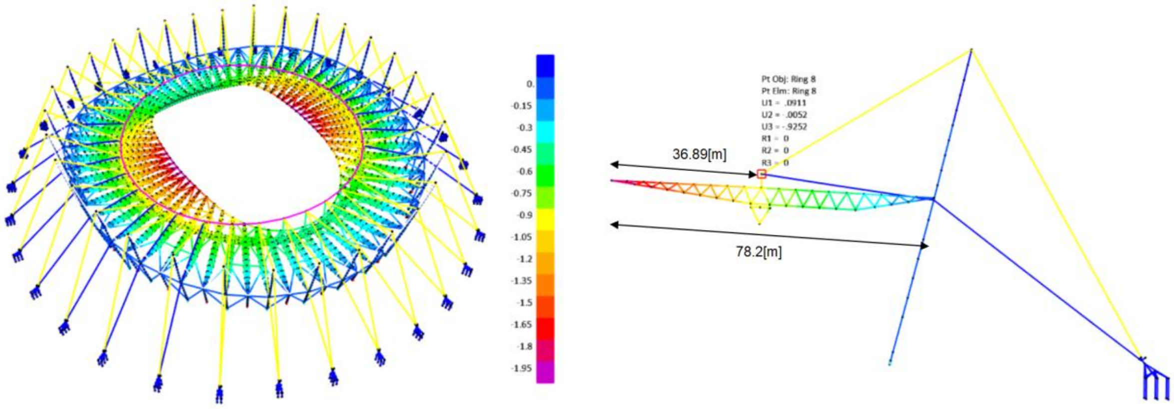


Figure 9: Roof displacements under permanent and variable actions

3.3. Roof structural model modal dynamic analysis

The dynamic properties of the roof structure are determined from a linear dynamic modal analysis on the roof structure model with fixed point at the columns bases. This assumption can be made for the following reasons:

- there is no structural link between the elevation of the roof and the concrete structure except at columns base points (see structural section in Figure 10). At this level the stiffness of the concrete structure is very high respect to the roof and so the contribution to the modal shapes can be neglected;
- the base lower part of the pylon as a double hinge structural scheme and so it's no sensitive to the movement of the concrete basement;
- the main relevant modal shapes of the roof are in vertical direction and so in any case can't be influenced by an horizontal displacement of the concrete base.

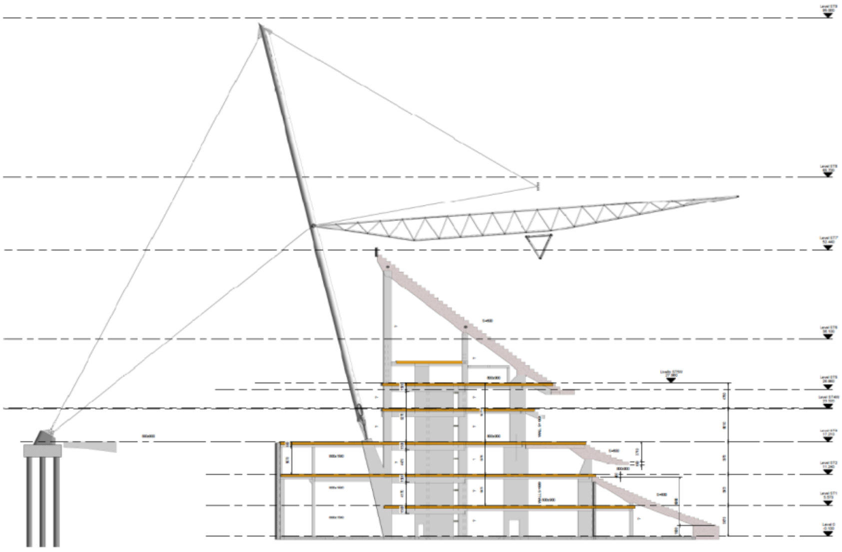


Figure 10: typical roof and granstand section

In any case to confirm these assumptions a global structural model of the concrete and roof elements have been analysed in order to compare the modal periods and shapes with or without the contribution of the grandstands structures. The results of this model give the same dynamic properties of a model with only the roof structure restrained with an hinge at the bottom of the pylons. In Figure 11 the modal shapes of the main global modes obtained from the modal dynamic analysis.

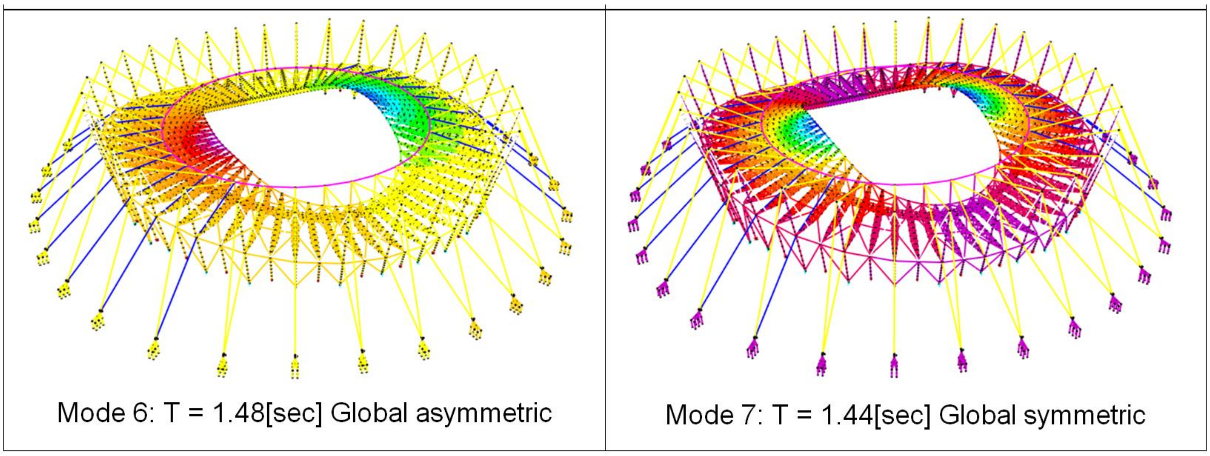
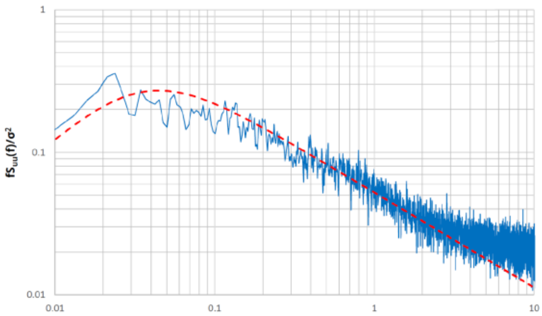


Figure 11: Modal shapes of the main roof global modes

3.4. Wind tunnel test

The wind tunnel test have been carried out in the RWDI boundary-layer wind tunnel facility in Milton Keynes, United Kingdom. The wind load spectra adopted for the wind tunnel tests is shown in Figure 12 a). Velocity fluctuations in the approach flow lead to a spectral peak near 0.03Hz, this peak can be attributed to vertical velocity fluctuations produced by vortices shed from the upstream contribution due to resonance at the natural frequency. The resonant response is far more significant (relative to the total variance) when the upstream section of the roof, but is nevertheless very much smaller than the vortex forced motions when the segment is on the downstream part of the roof. On the basis of the dynamic analysis the lowest natural frequency of the roof is 0.68Hz and sufficiently removed from the peak to avoid excessive resonant response.



a)


b)

Figure 12: a) Wind load spectra; b) Stadium roof rigid model

A rigid wind tunnel model of the roof (scale 1:300) has been instrumented with pressure taps that adequately cover the exterior areas exposed to wind (Figure 12 b)). The mean pressure, the root-mean-square of pressure fluctuations and the peak negative and peak positive pressures have been measured at each tap using a system capable of responding to pressure fluctuations as short as 0.5 to 1 second at full scale. The measured data have been converted into pressure coefficients based on the measured upper level mean dynamic pressure in the wind tunnel. Time series of the simultaneous pressures have been also recorded for post-test processing in order to evaluate the dynamic amplification considering the roof modal data and create equivalent load cases to be applied to the mathematical model (Figure 13).

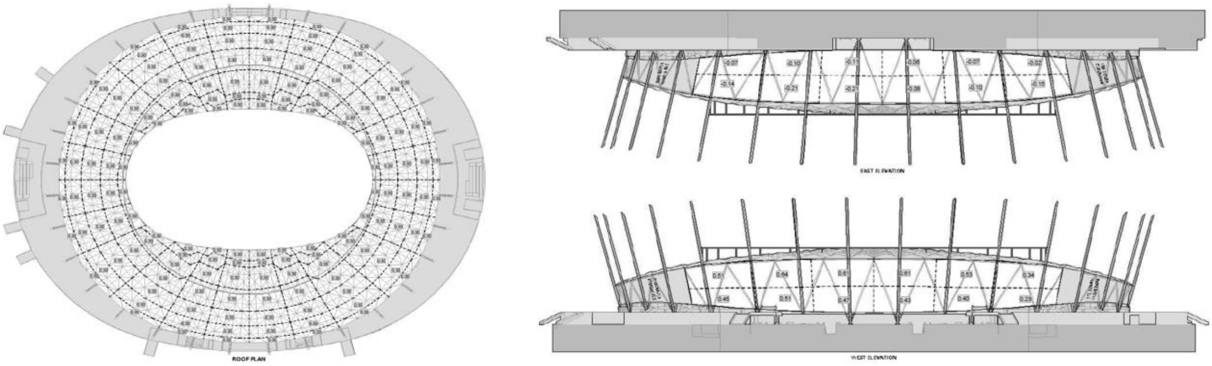


Figure 13: Wind load case applied to the mathematical model

4. Construction process

4.1. Pylons installation

After the installation of the lower part of the pylons and of the connection elements between them a first prestress has been applied to the outer stabilizing cables in order to stabilize the top pylon base point before the installation. In the graph of Figure 14 the differential radial displacements before and after the prestress of outer stabilizing cables: the difference of the values is very small and so it’s a confirmation of the agreement between the forces applied, the geometry and the mechanical properties of the mathematical model and the real structure.

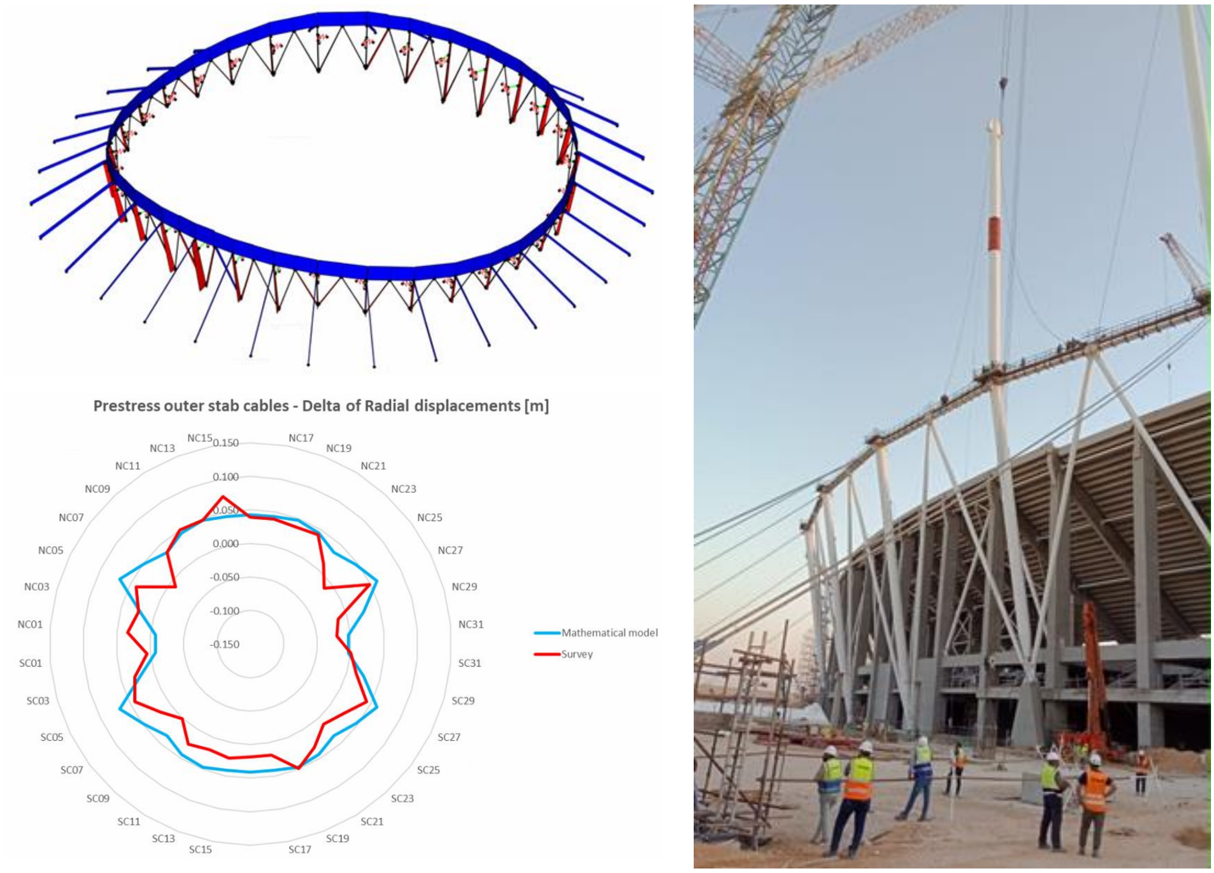


Figure 14: Top pylon installation after an initial prestress of the outer stabilizing cables

4.2. Cable ring big lift

In the initial phase the inner ring connectors are in laydown position on the 32 temporary platforms inside the stadium. The upper pylon is aligned with the lower pylon and is supported by the inner temporary cables and by the outer stay cables. The outer stay cables have an extra length of 1200/1300[mm] in the different alignments in order to allow the pinning of the inner stay cables at the end of the inner ring lift and to avoid too big forces in the inner temporary cables. Inner stay cables are connected with strands to the ring connector.

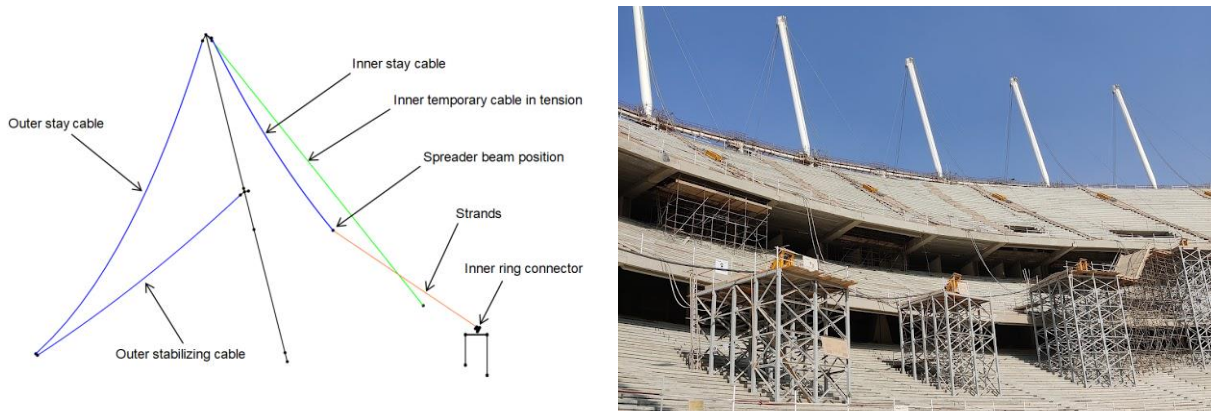


Figure 15: Inner ring in lay down position

In the image below the plan view of the tension ring lay down position on the temporary platforms before the take off and the position at the end of lift. The pull up of the strands start from the north and south alignments in order to overpass the third level grandstands, that's why the lay down plan shape is elliptical, and in the following steps the pulling of the strands in east and west alignments regain the final circular shape.

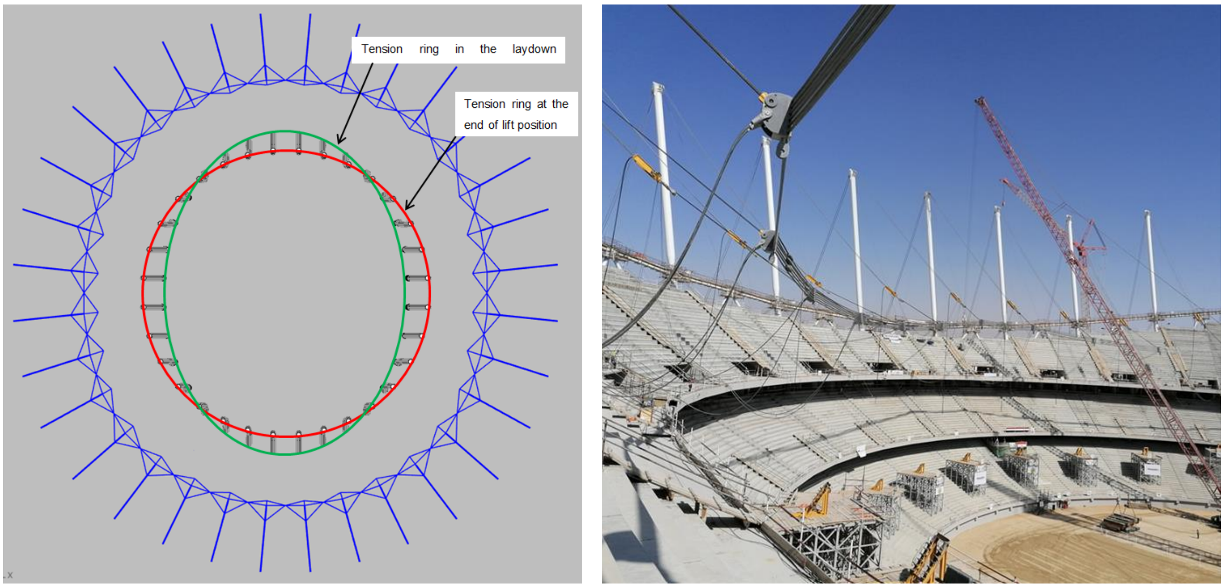


Figure 16: Plan view and photo from the site of the inner cable ring lifting procedure

Stay cables are pinned following a symmetrical sequence acting on four alignments from east and west sector to north and south sector. The pinning forces and force values in the jacks during the big lift procedure are in agreement with the theoretical values from the mathematical model.

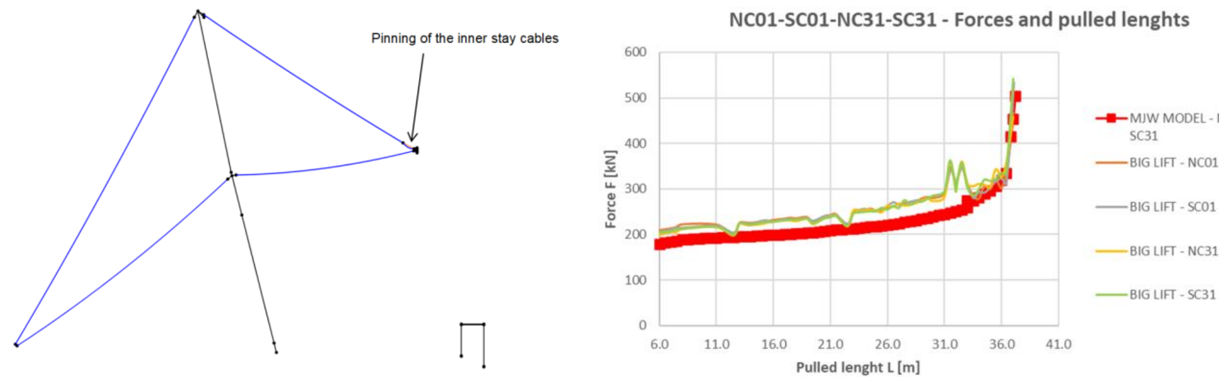


Figure 17: Cable pinning scheme and comparison between theoric and measured values during cables lifting

At the end of cables big lift prestress is applied by pulling the outer stabilizing and stay cables: that action produce an outward movement of the top pylon and a lift of the inner ring connector.

4.3. Roof steel structure installation

The installation of radial trusses have been simulated with the mathematical model following the sequence agreed with the contractor. First have been installed the beams directly connected to the tension ring by the flying mast and then the catwalk beams and the intermediate radial beam.

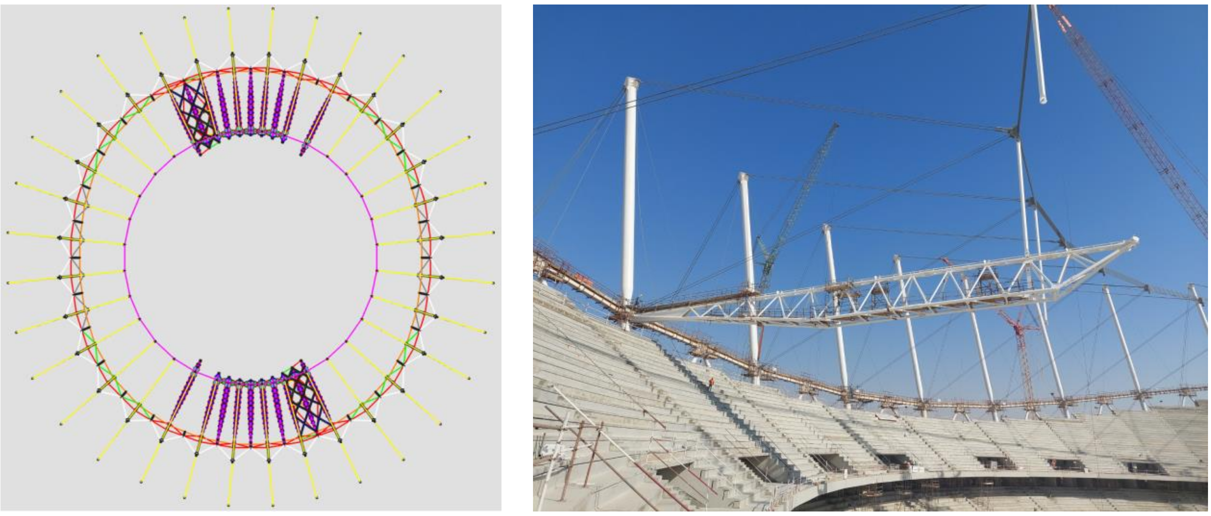


Figure 18: Numerical simulation and photo from the site of the radial beam installation

The last construction step of the roof structure is the installation of the roof membrane supported by pair of crossed arches.

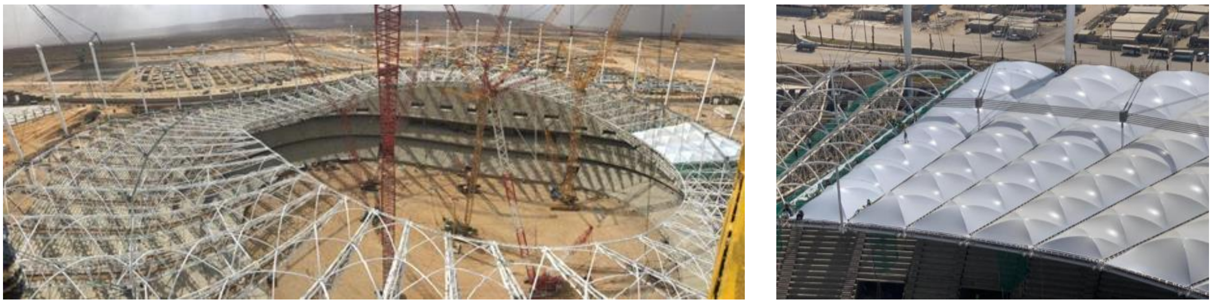


Figure 19: Membrane and arches installation

5. Credits

Owner: Egyptian Army

Main contractor: ORASCOM Construction

General design: SHESA - MJW Structures:

Structural design: MJW Structures

Architectural design: SHESA

Local consultant: COSMOS Engineers & Consultants

Mep consultant: DEERNS

Architectural and Structural Supervision consultant: ACE Arab Consulting Engineers

MEP Supervision Consultant: SHAKER Consultancy Group

Cable supplier: REDAELLI

Membrane supplier: TAIYO KOGYO CORPORATION

5. Conclusions

The Cairo Stadium roof structure has been designed and realized in a short period (about 2 years) with the constant coordination between designers and building company before and during the construction works. The remarkable dimensions of the roof (45’000 m^2) required a design assisted by testing and so the experimental data from the wind tunnel have been post processed in agreement with the mathematical model results. The structural scheme of the roof has been developed till the concept phase in order to allow an efficient and safe installation procedure: the inner tension ring big lift using 32 flying strand jacks that has been performed respecting the time schedule and the theoretical forces values from the mathematical model.

This project can be so considered as a successful example of coordination, from the structural concept phase to the construction, between the designers working in different fields of the structural engineering and the companies working at the building site.