Prof. Alexandr Belostotskiy, Assoc. Prof. Sergey Dubinsky,
PhD student Sergey Petryashev, PhD student Nicolay Petryashev

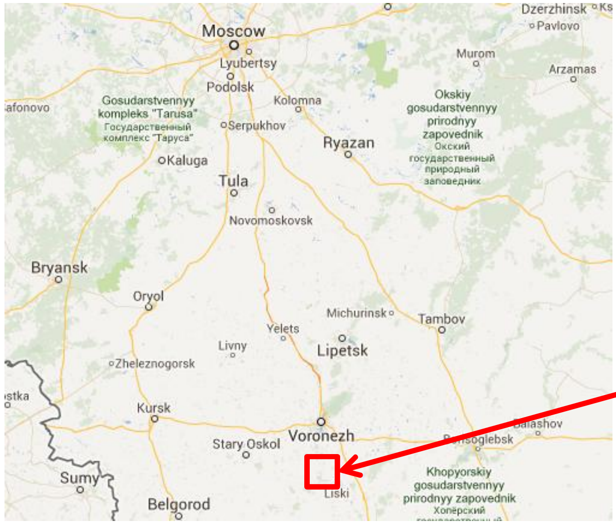
Computational Analysis of Stress-strain State, Dynamics, Strength and Stability of Load-bearing Concrete Structures of NPP Evaporative Cooling Towers

*National Research University **M**oscow **S**tate **U**niversity of **C**ivil **E**ngineering (**MGSU**)*

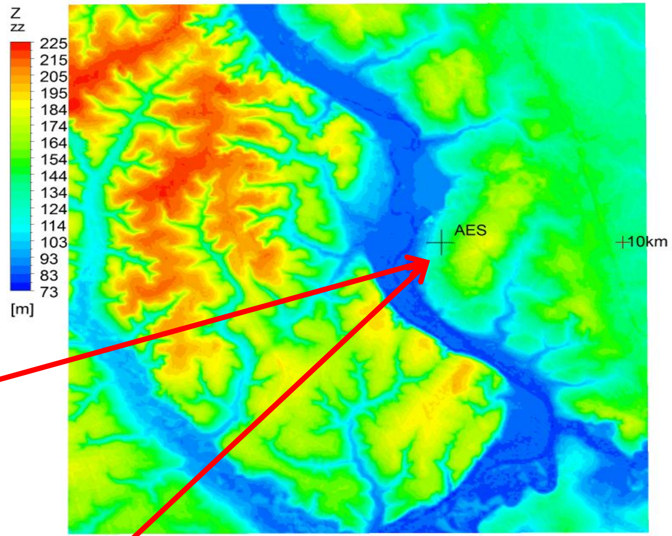
Stages of computational research

- Processing and compilation of the source data
- Realization and verification methodology for calculating the basic and specific (extreme) wind loads and effects based on CFD (special report)
- Development of numerical CFD models. The boundary conditions (wind profiles , etc.) , the choice of turbulence models and parameters calculation.
- Steady and unsteady calculations
  - Evaluation of equivalent roughness cooling tower shell
  - Determination of wind loads , with the standard wind
  - Determination of wind loads in hurricane wind
  - Determination of wind loads when impact to a tornado (four scenarios)
- Transfer pressure (average and pulsation components) for the basic and specific (extreme) wind loads in ANSYS Mechanical
- The spatial shell and solid finite element models of the combined system "soil foundation – RC structures of evaporative cooling towers“ were developed
- Using the developed finite element models to verify the ANSYS Mechanical settings are defined stress - strain state of load-bearing structures (displacement, stress) at the design combinations of loads and impacts
- Selection of the required reinforcement and strength assessment («OM SNiP RC») .
- Determination of the dynamic characteristics of the ANSYS Mechanical
- Determination of critical loads / buckling in the ANSYS Mechanical

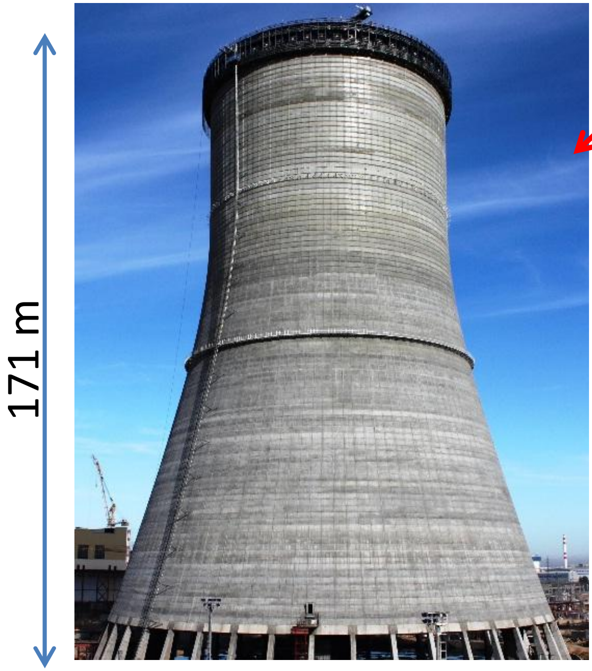
Design description



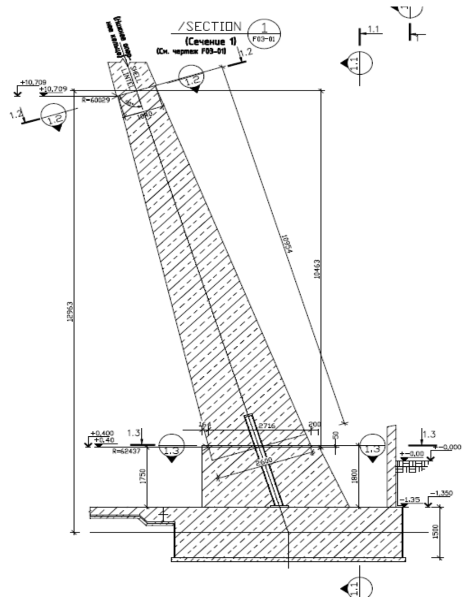
Location NV NPP-2



Height map is presented in the vicinity of NV NPP-2 satellite sensing data SRTM3



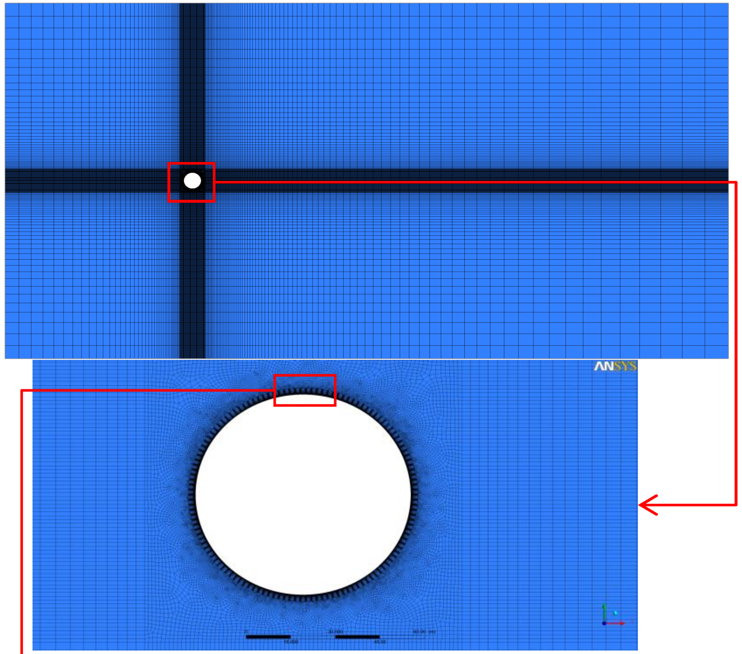
September 2013



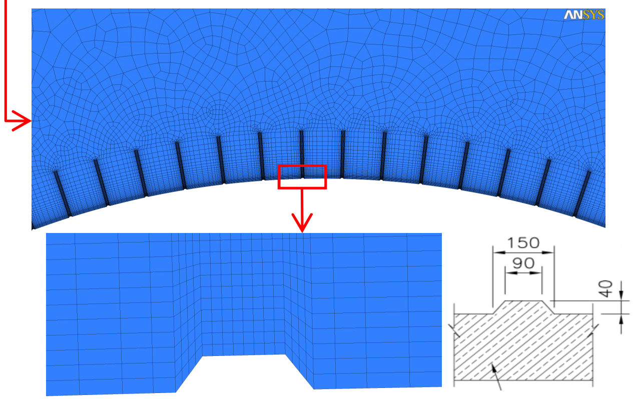
Design support colonnade

The wind aerodynamics. Selection of an equivalent surface roughness cooling towers.

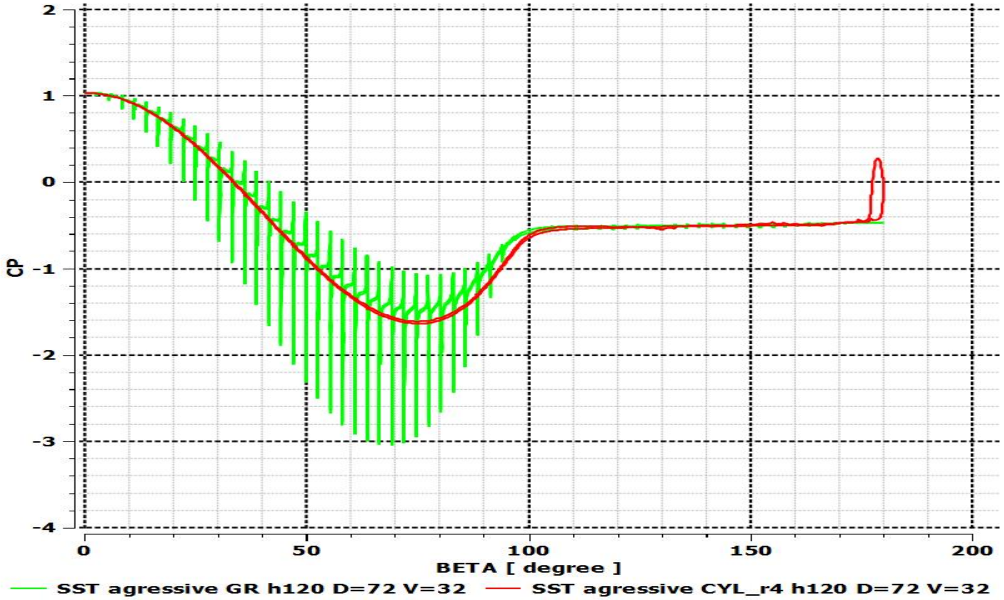
ANSYS CFD



The computational mesh (400 thousand cells). A general view



Cylinder ribs (rib height 0.04 m). The computational mesh in the prismatic boundary layer. Size of the first element$1.8 \cdot 10^{-3}$ m



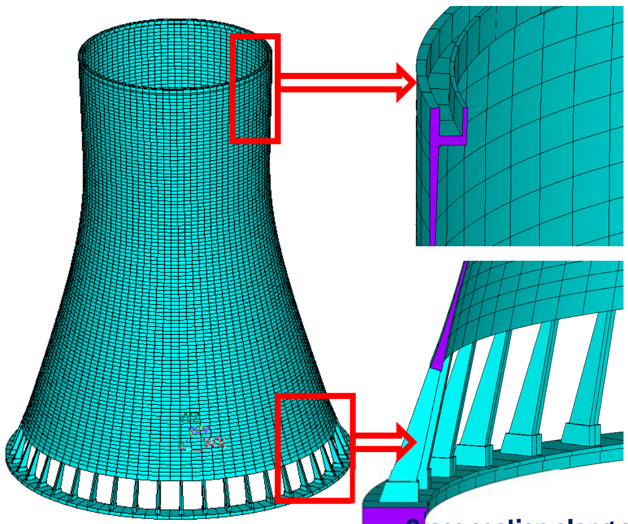
Average Cp on the angular coordinates for the model:
with a specified roughness - the red line,
modeled ribs - the green line.

The calculations were carried out for three models:

a) smooth cylinder,
b) cylinder with a specified roughness on the outer surface,
c) section of the cooling tower with direct modeling ribs.

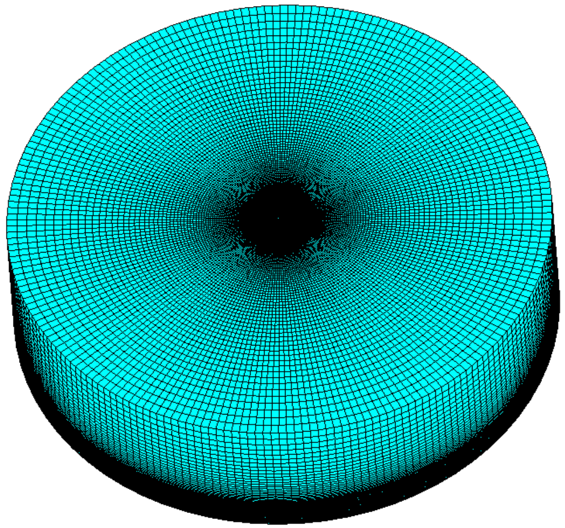
If the specified equivalent roughness equal to 0.04 m (case b)), then the results for this case with the practical accuracy consistent with the results for the case c). Mismatching of results does not exceed 10%

The wind aerodynamics. Development of the calculation model. *ANSYS CFD*

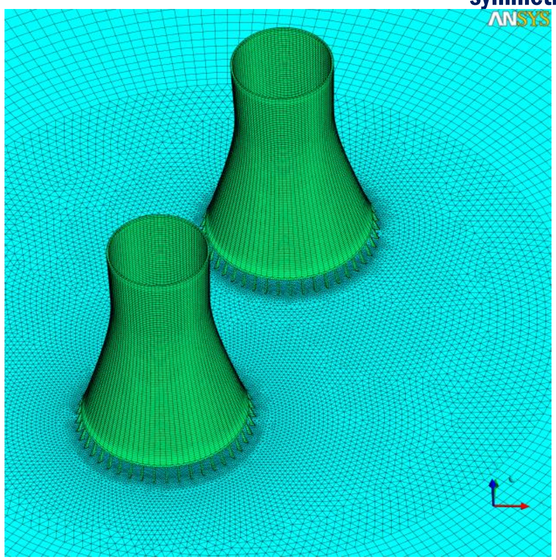


Geometric model

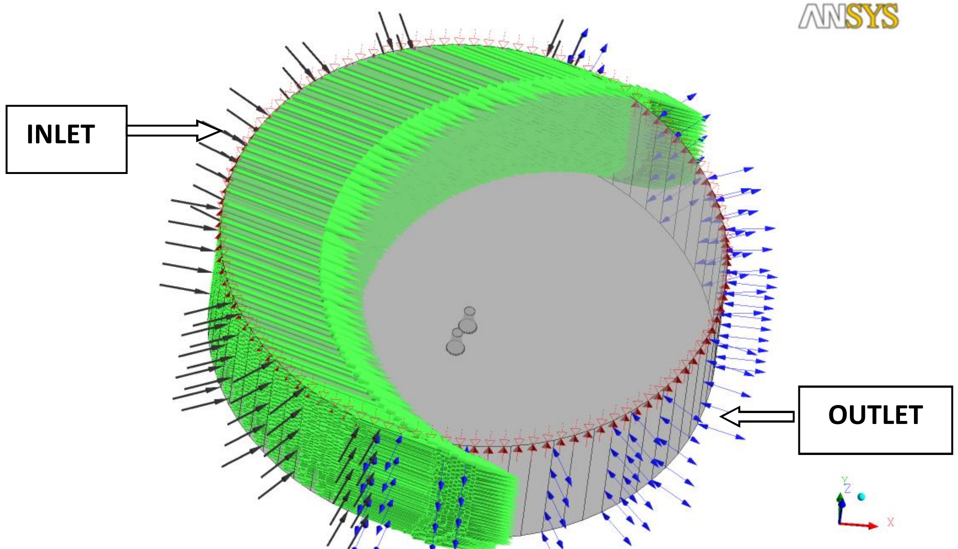
Cross section along a symmetry axis



The computational domain (model with 5.28 million cells)

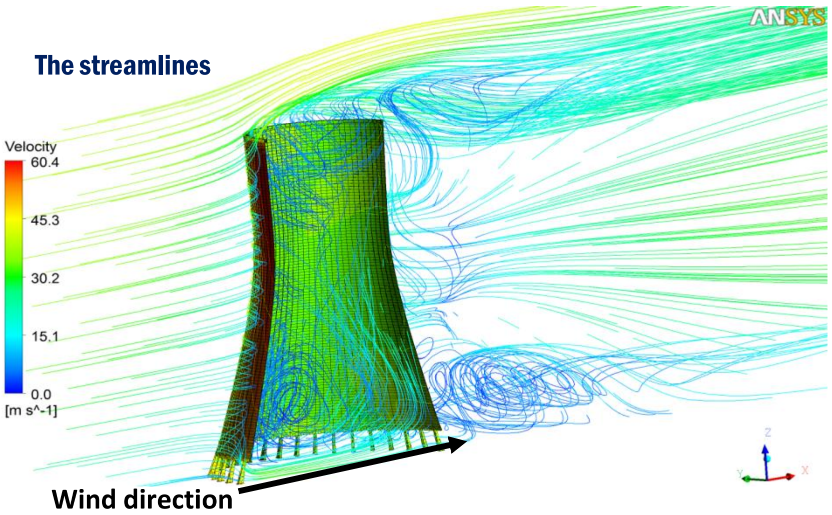


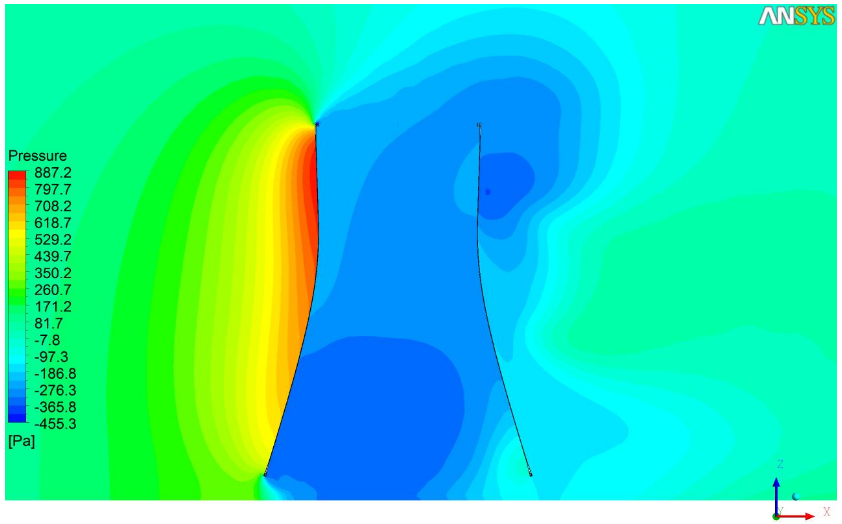
The surface mesh for cooling towers (model with 5.28 million cells)



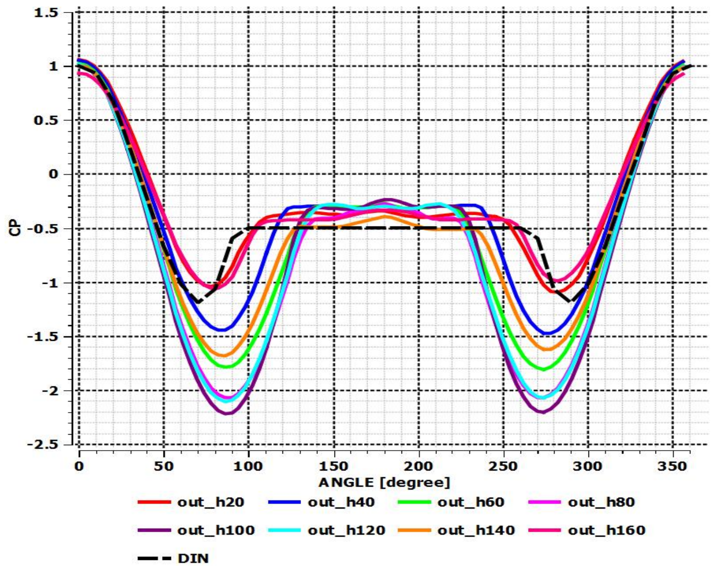
The computational domain with defined boundary conditions.
The angle of attack of the wind 0°

The wind aerodynamics. The results of numerical steady calculations . *ANSYS CFD*

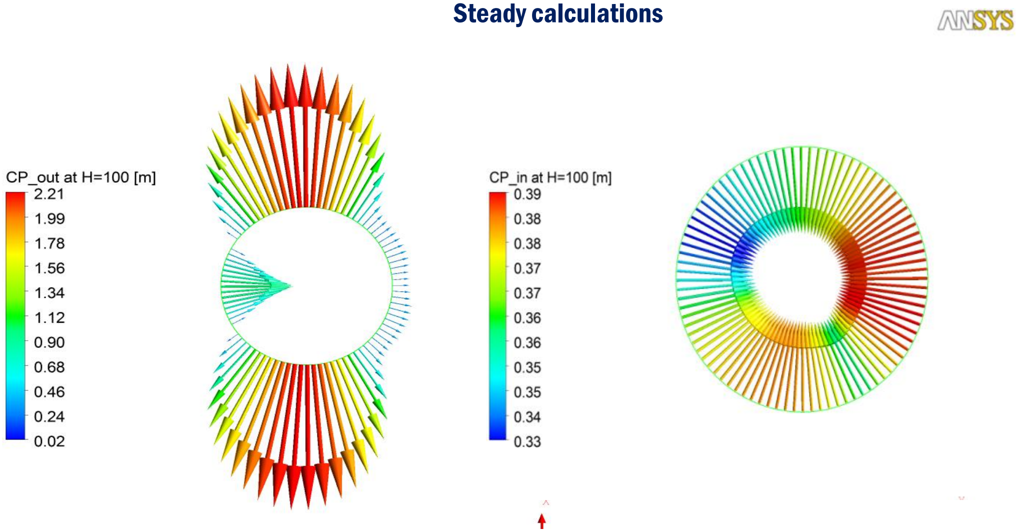




The average wind pressure in the plane of symmetry XZ, from -455 Pa to 887 Pa. Steady calculations

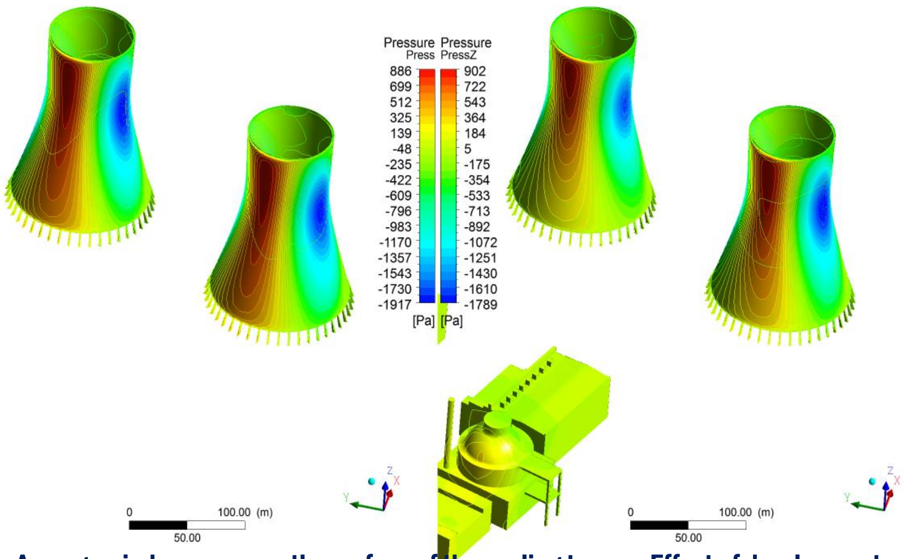


Aerodynamic pressure coefficient Cp at the outer of the tower at various heights (from 20 m to 160 m). The vertical axis - the value of Cp, the horizontal axis - the angular coordinate α.

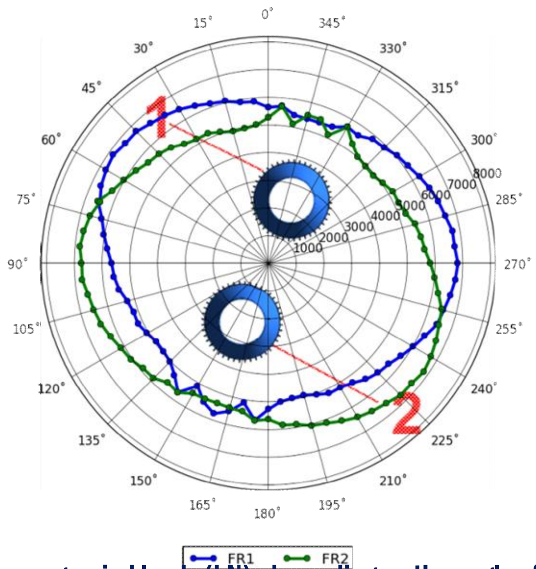


Aerodynamic pressure coefficient Cp at the outer (left) and the inner (right) of the tower at heights of 100 m

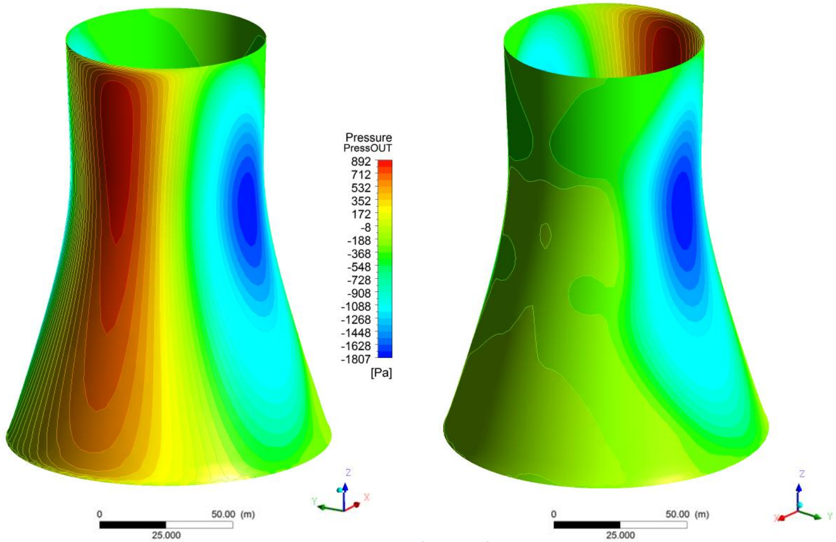
The wind aerodynamics. The results of numerical steady calculations . *ANSYS CFD*



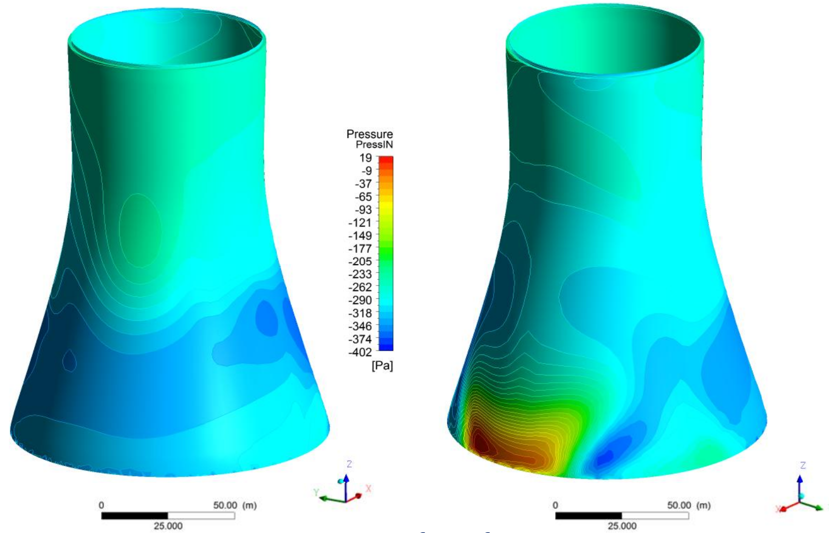
Average wind pressure on the surface of the cooling towers. Effect of development
Calculation with “development" (right) - from -1789 Pa to 902 Pa,
calculation without “development" (left) - from -1917 Pa to 886 Pa



Resultants average wind loads (kN), depending on the angle of the wind direction (degrees) for the cooling tower. Steady calculations. The blue line (FR1) - on the tower number 1, the green line (FR2) - on the tower number 2



Average pressure on the outer surface of the insulated cooling tower



Average pressure on the inner surface of the insulated cooling tower

Insulated cooling tower. The calculation at the tornado. *ANSYS CFD*

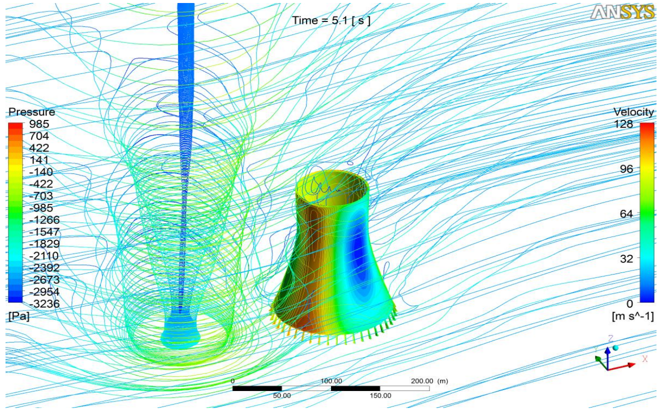
The tornado class 3.16 by Fujita scale according to the preliminary specifications

Tangential velocity

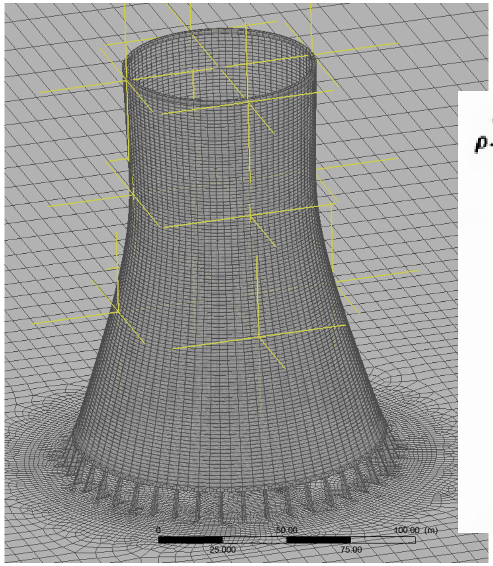
$$V_\tau = \begin{cases} \dfrac{r}{R_m} V_m, & 0 \le r \le R_m \\ \dfrac{R_m}{r} V_m, & R_m \le r < \infty \end{cases}$$

Vacuum-gauge pressure

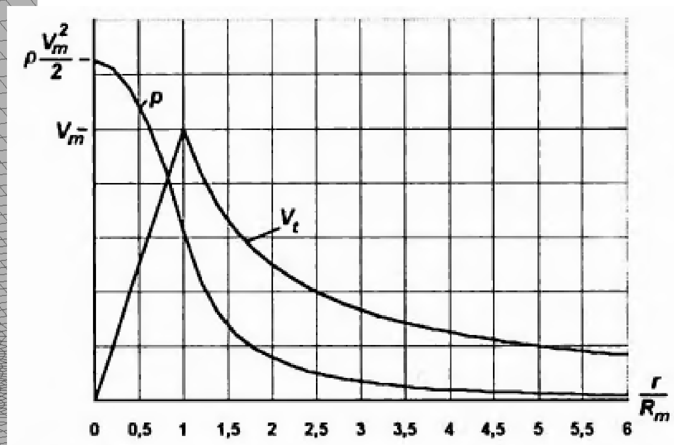
$$p = \begin{cases} \rho \dfrac{V_m^2}{2}\left(2 - \dfrac{r^2}{R_m^2}\right) & (0 \le r \le R_m) \\ \rho \dfrac{V_m^2}{2} \dfrac{R_m^2}{r^2} & (R_m \le r \le \infty) \end{cases}$$



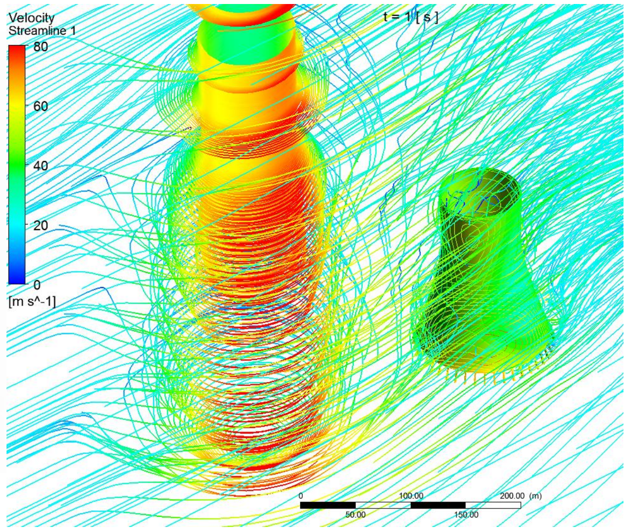
The streamlines of the wind speed in the vicinity of the cooling tower at time T = 5.1 c



Monitoring points

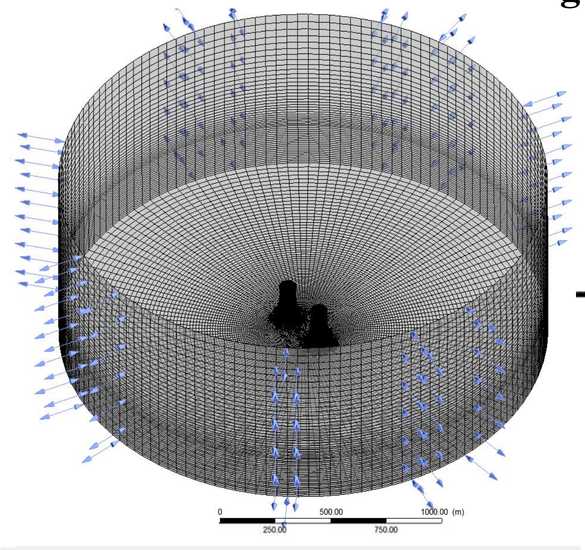


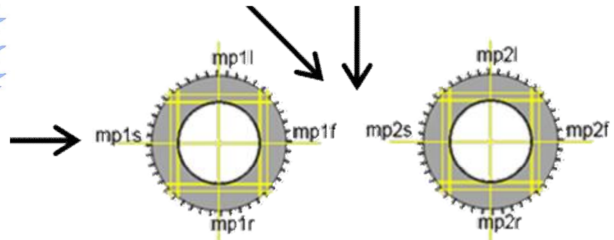
Changing the tangential velocity and pressure for the Rankine vortex



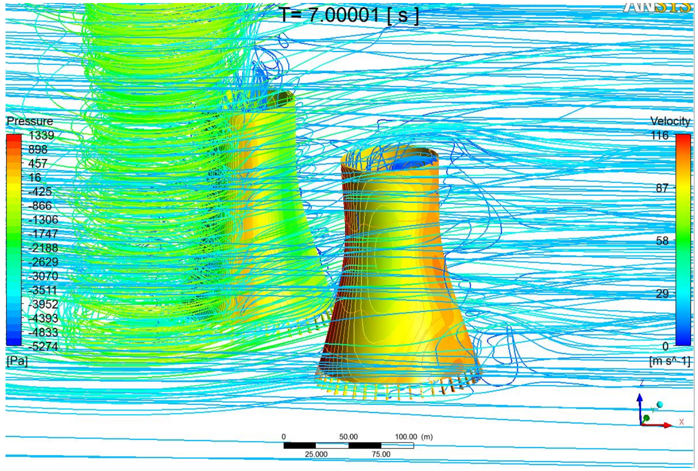
The streamlines of the wind speed in the vicinity of the cooling tower at time T = 1 c (the distance from the "wall" of the tornado to the wall tower approximately 180 meters)

Two cooling tower. The calculation at the tornado. *ANSYS CFD*



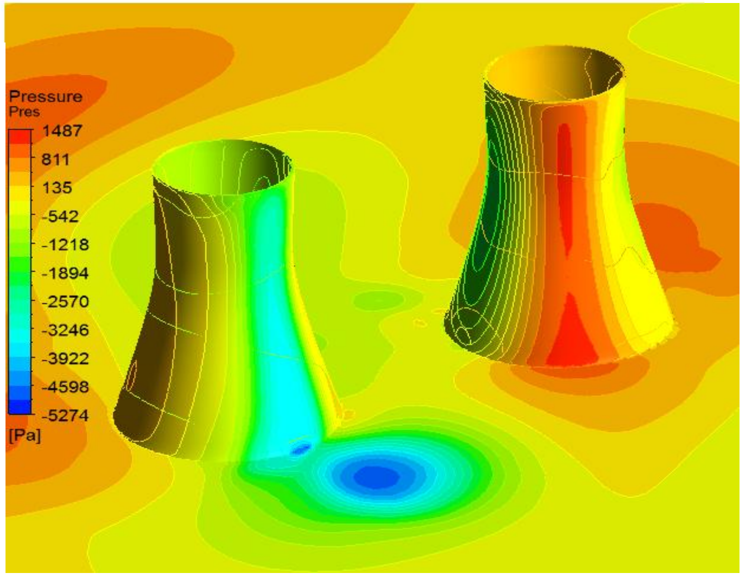


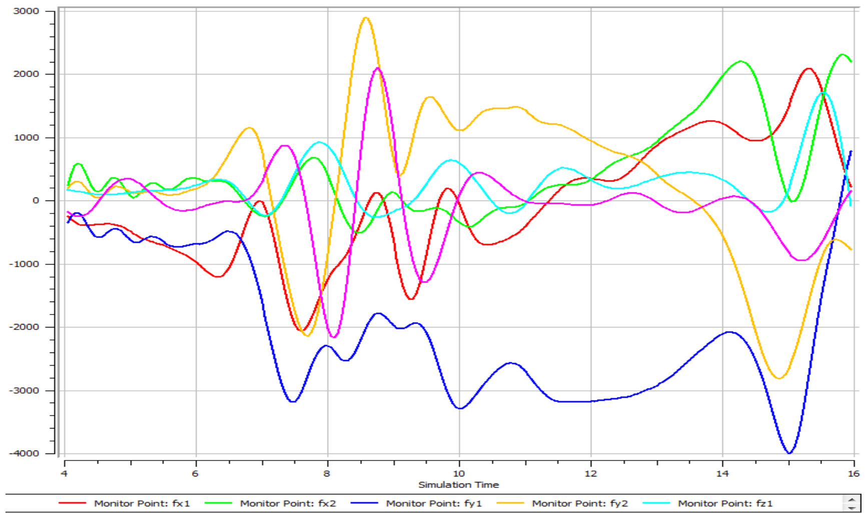
Simulation cases



The computational domain (model with 1.8 million cells)

Pressure (Pa) on the surface of the cooling tower and the streamlines. Physical time T=7 s



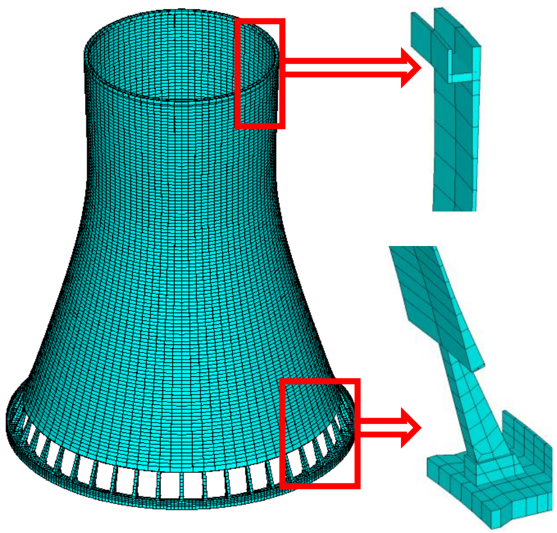


Pressure (Pa) on the surface of towers and in a plane z=10 m. Physical time T=7 s

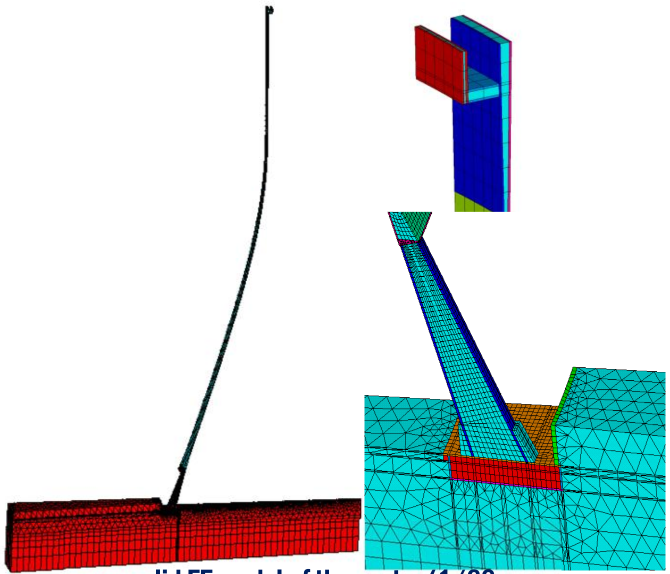
Summary load (tnf) FX and FY for 1 and 2 cooling tower of a tornado in time (sec)

Calculation models for determining the strain-stress state, the strength and stability.

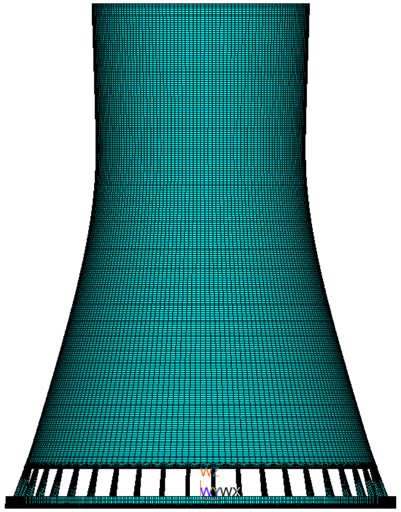
ANSYS Mechanical



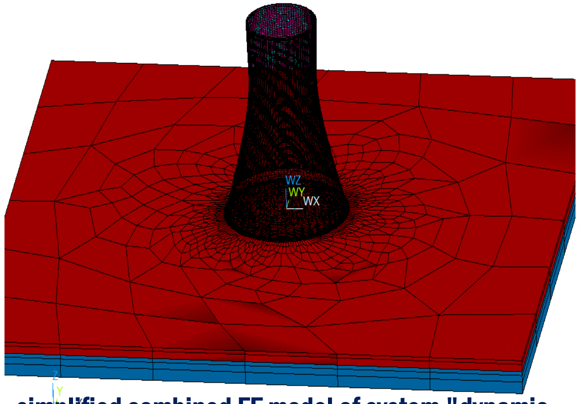
shell FE model
14 thousand nodes



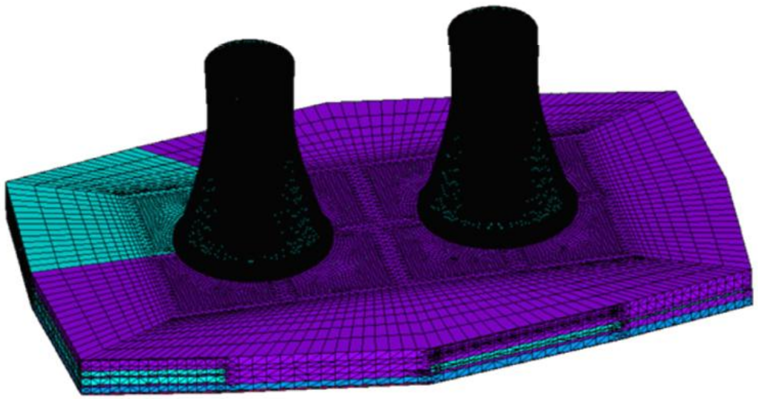
solid FE model of the sector (1/88 part) "soil foundation – RC evaporative cooling towers"
36 thousand nodes



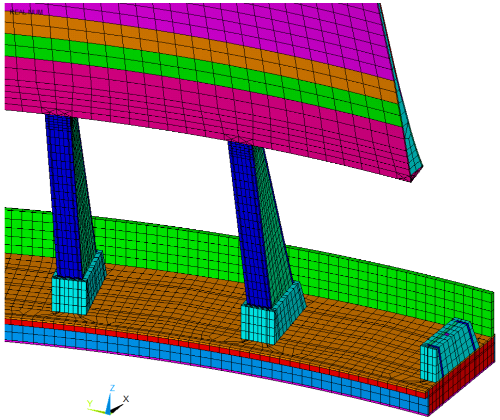
solid FE model
724 thousand nodes



simplified combined FE model of system "dynamic foundation soil - RC evaporative cooling towers" in the formulation of the contact
35 thousand nodes

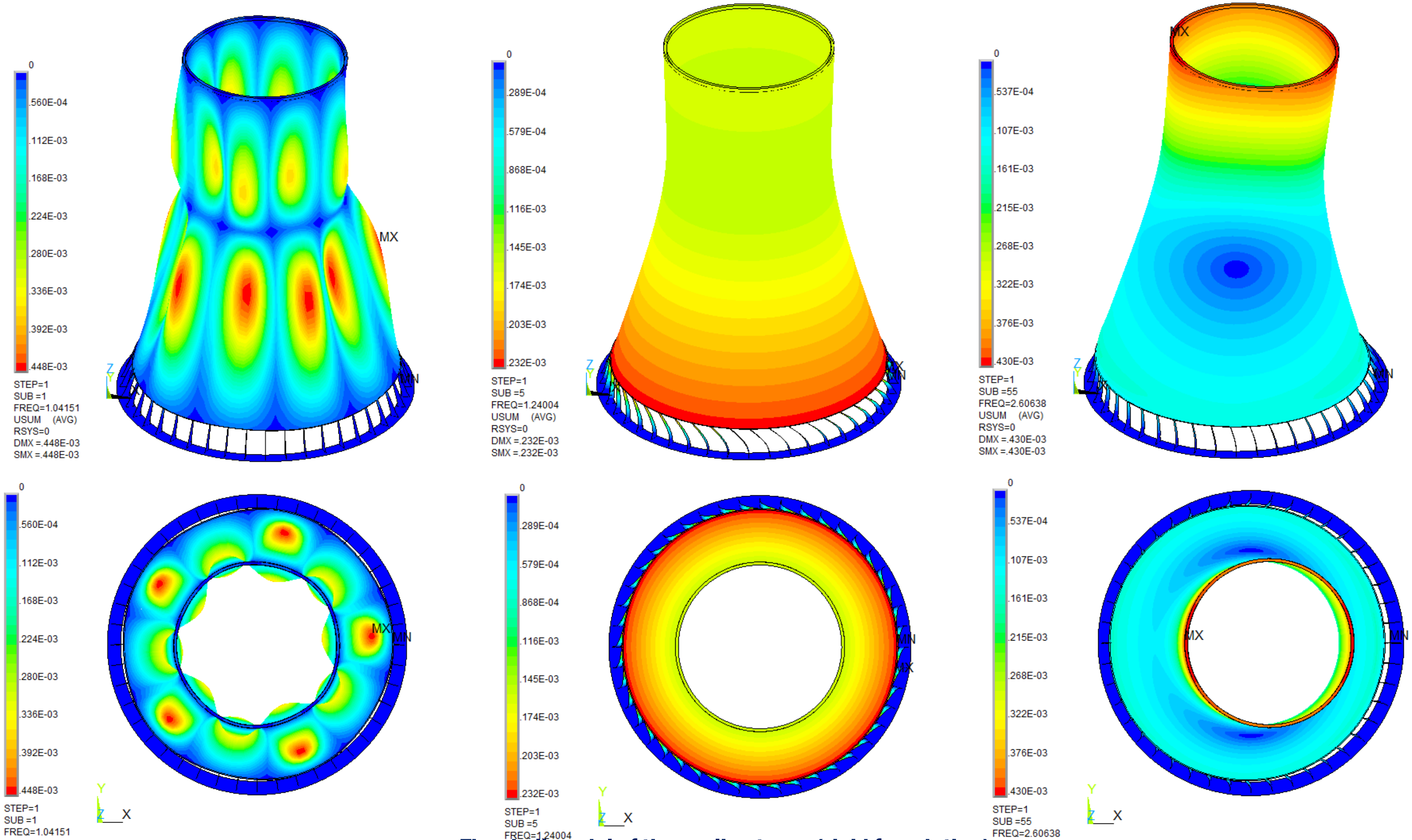


solid FE model of system "soil foundation – RC evaporative cooling towers"
1310 thousand nodes



solid FE model for the calculation of an emergency situation
49 thousand nodes

The results of the modal analysis. *ANSYS Mechanical*



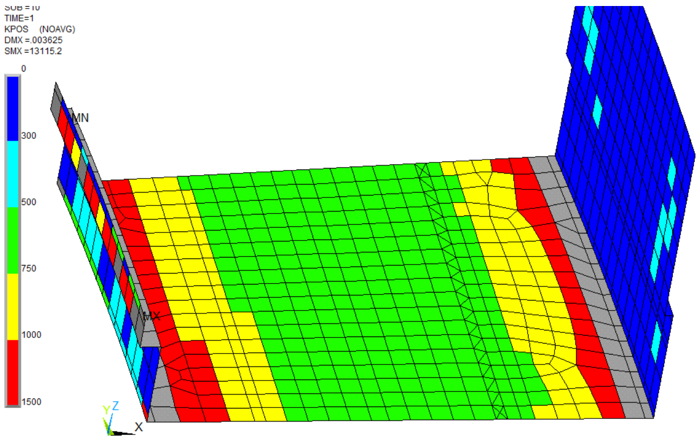
The shell model of the cooling tower (rigid foundation)

1-st eigenmode(5 waves in a circle), f = 1.0415 Hz.

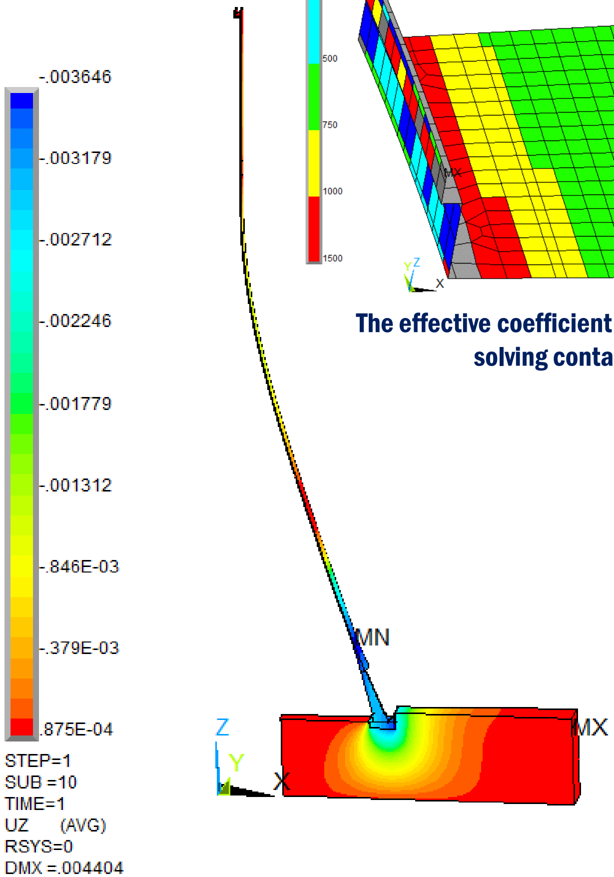
5-th eigenmode (rotation shell on the columns), f = 1.2400 Hz.

Seismically significant multiples of 54-th and 55-th eigenmodes, f = 2.6064 Hz.

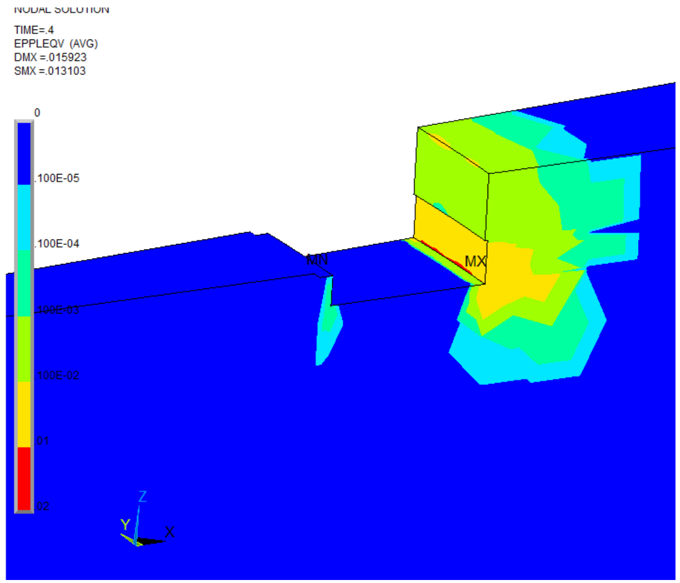
Determination the effective coefficient of soil reaction. *ANSYS Mechanical*

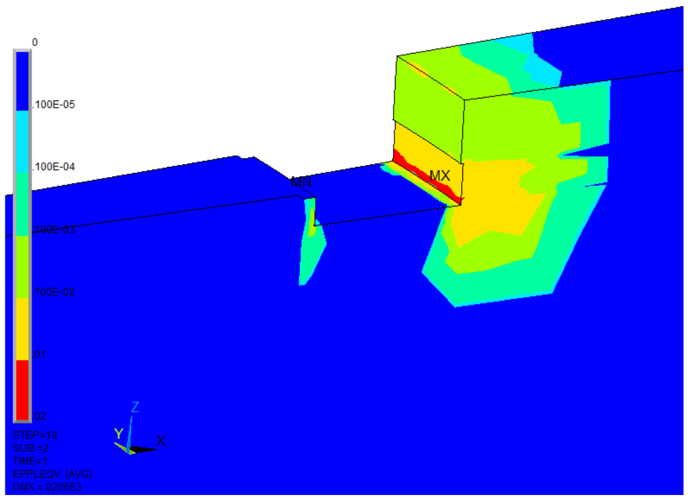


The effective coefficient of soil reaction (tnf/m^3) a result of solving contact problem. Own weight.



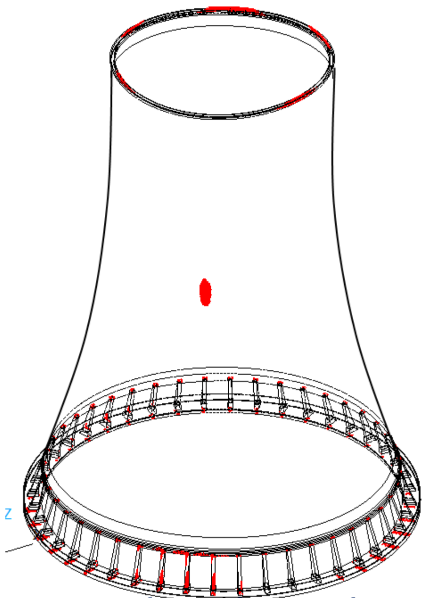
Vertical (m) the movement in the model. The maximum value of $0.875 \cdot 10^{-4}$ m, the minimum value –0.003646 m . Own weight.



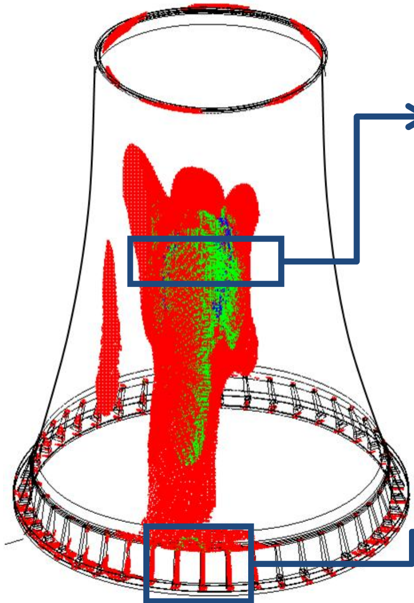


Plastic deformation in soil at 40% (top) and 100% (below) the construction, the clutch 1 kPa. Own weight.

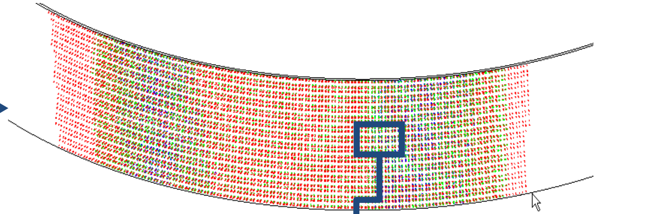
Non-linear analysis on the impacts of tornado loads. *ANSYS Mechanical*

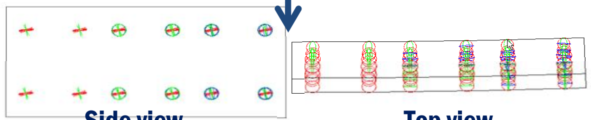


The scheme of cracks formation(first crack).
the impacts 60% of tornado loads

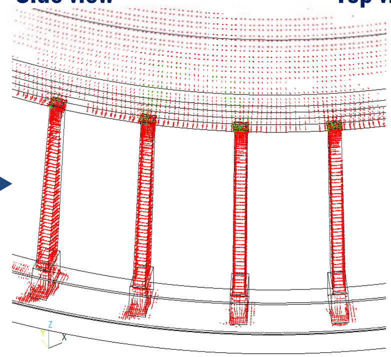


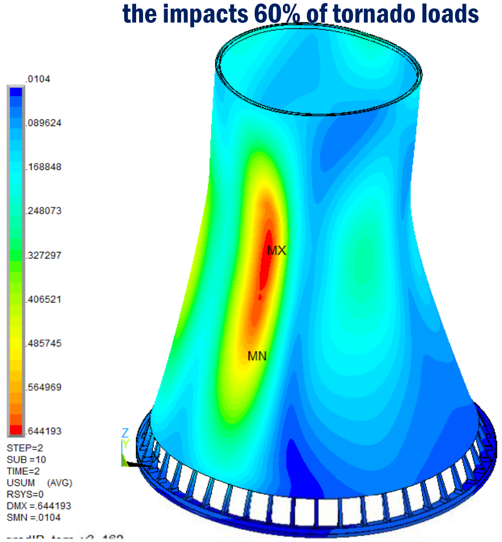
The scheme of cracks formation.
the impacts 100% of tornado loads



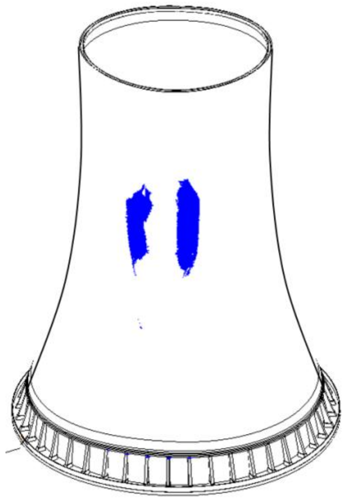


Side view **Top view**

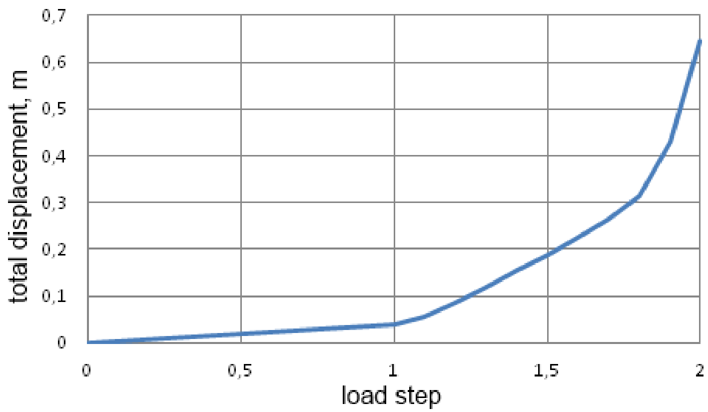




The total displacement
the maximum value 0.64 m

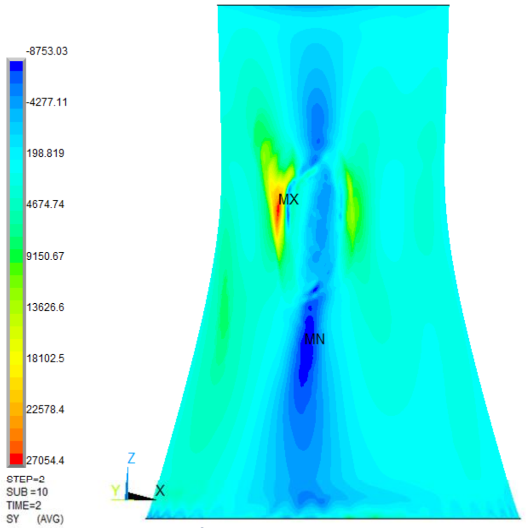


The scheme of destruction
the impacts 100% of tornado loads

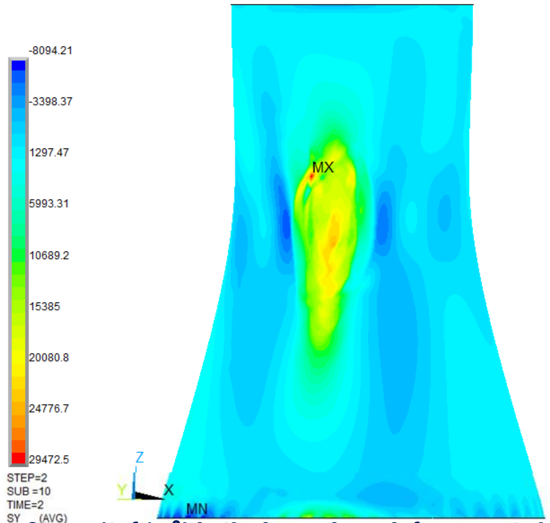


Graph of the maximum displacement of the load

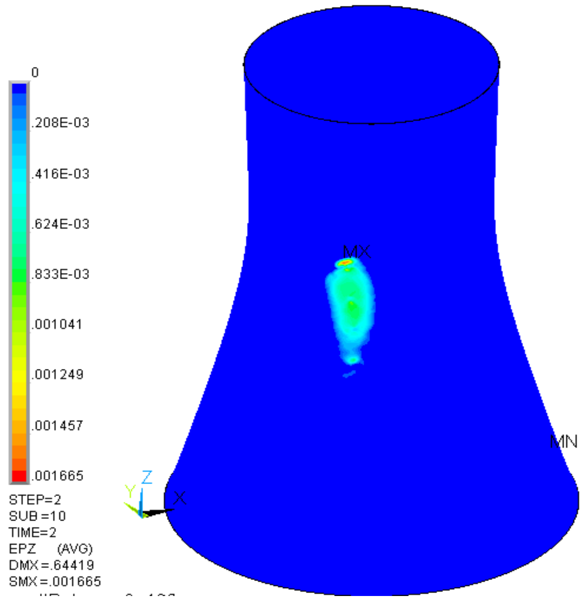
Non-linear analysis on the impacts of tornado loads. *ANSYS Mechanical*



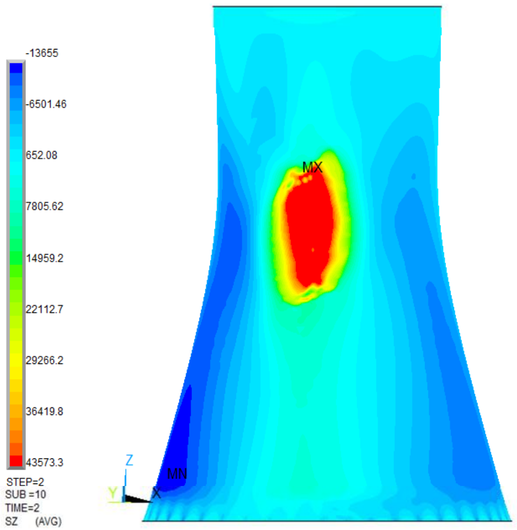
Stress (tnf/m^2) in the external ring reinforcement shell. From -8753 tnf/m^2 to 27054 tnf/m^2



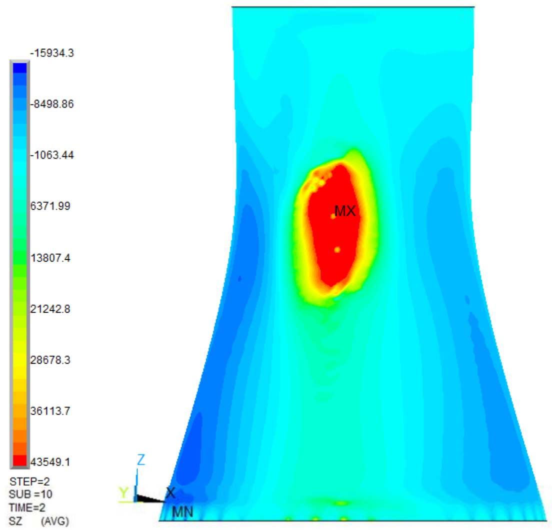
Stress (tnf/m^2) in the inner ring reinforcement shell. From -8094 tnf/m^2 to 29473 tnf/m^2



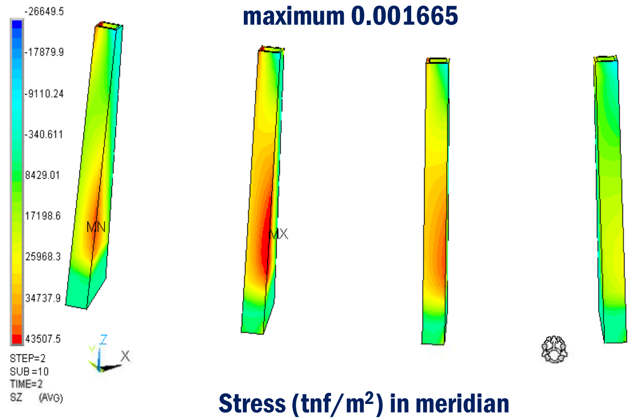
Zone of plastic deformation in the meridian reinforcement shell maximum 0.001665



Stress (tnf/m^2) in the external meridian reinforcement shell. From -13655 tnf/m^2 to 43573 tnf/m^2

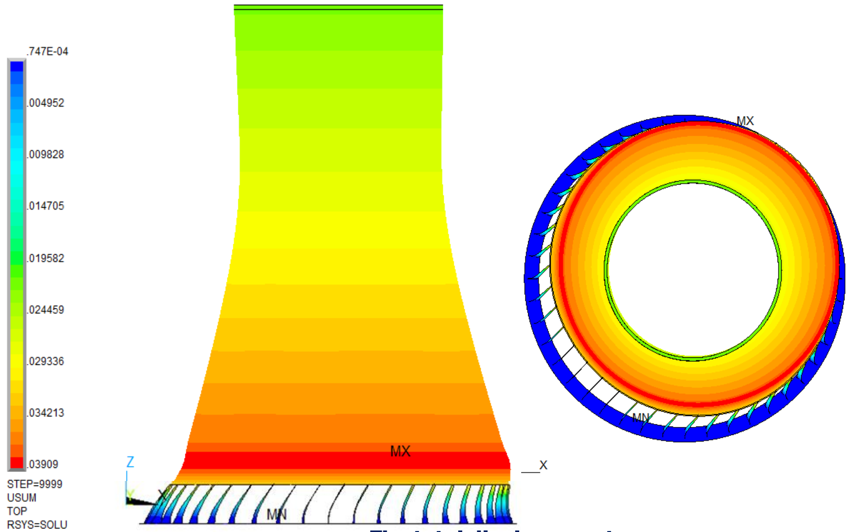


Stress (tnf/m^2) in the inner meridian reinforcement shell. From -15934 tnf/m^2 to 43549 tnf/m^2

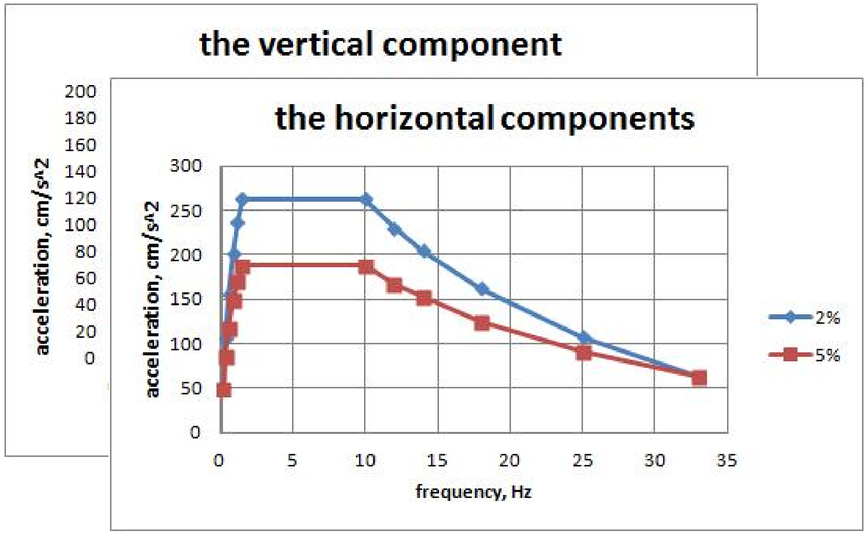


Stress (tnf/m^2) in meridian reinforcement columns. From -26650 tnf/m^2 to 43507 tnf/m^2

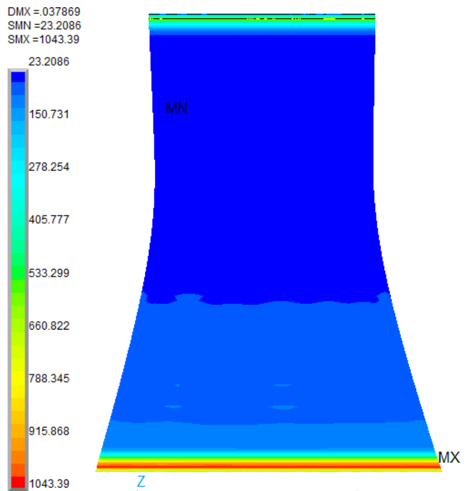
Calculation of seismic impact on linear spectral method. *ANSYS Mechanical*



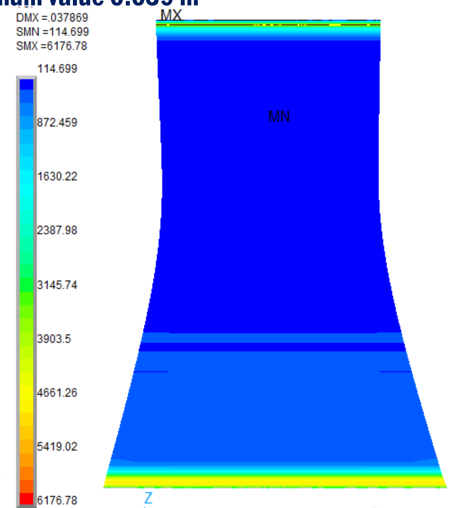
The total displacement
the maximum value 0.039 m



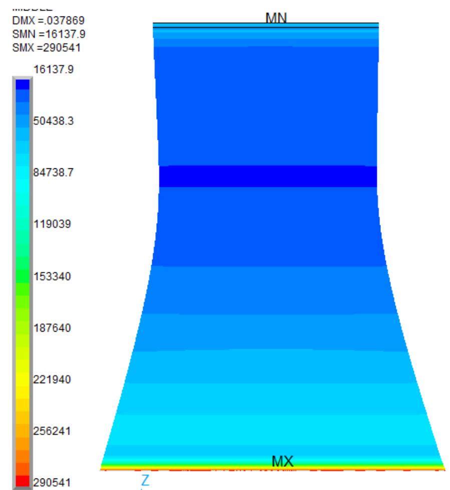
Response spectra (sm/c²) for the base project of the NPP-2006, 6 intensity on the MSK-64 scale.



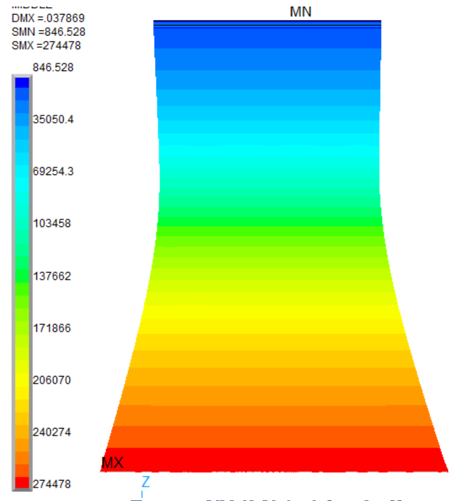
Moments MX (kN·m/m) in shell
From 0.023 to 1.043 (kN·m/m)



Moments MY (kN·m/m) in shell
From 0.115 to 6.177 (kN·m/m)

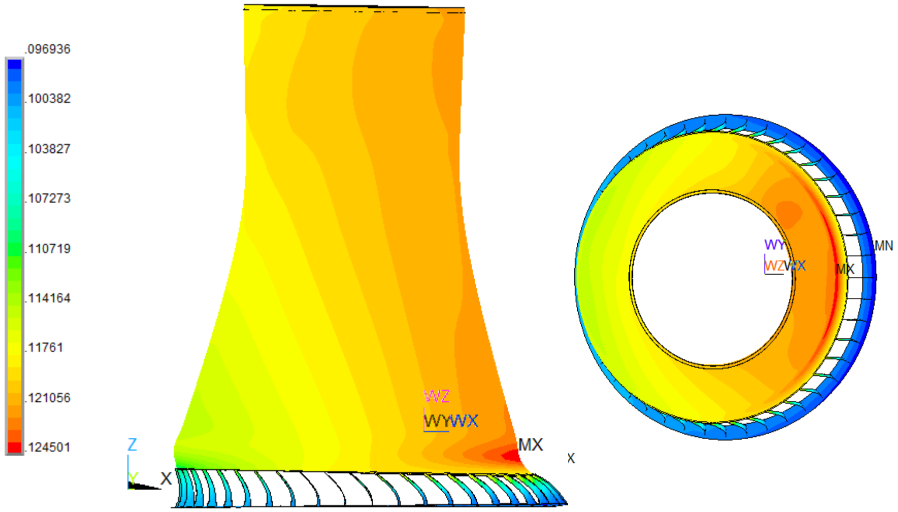


Forces NX (kN/m) in shell
From 16.138 to 290.5 (kN/m)

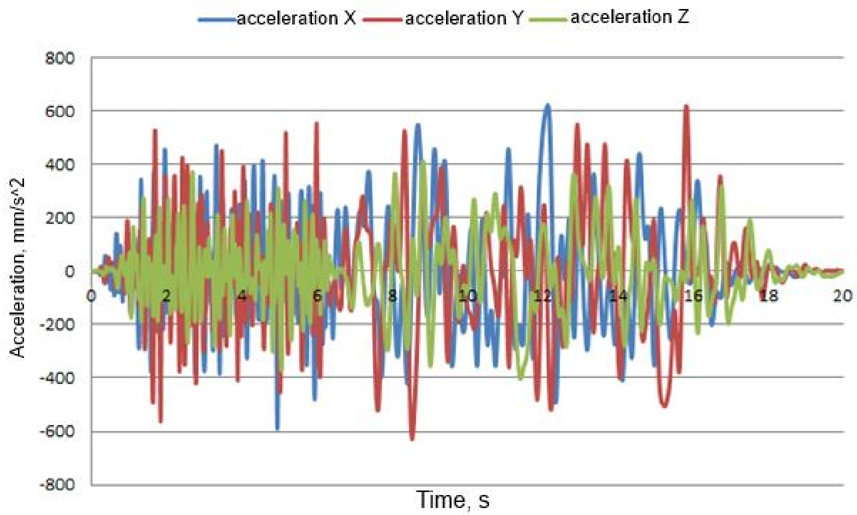


Forces NY (kN/m) in shell
From 0.846 to 274.5 (kN/m)

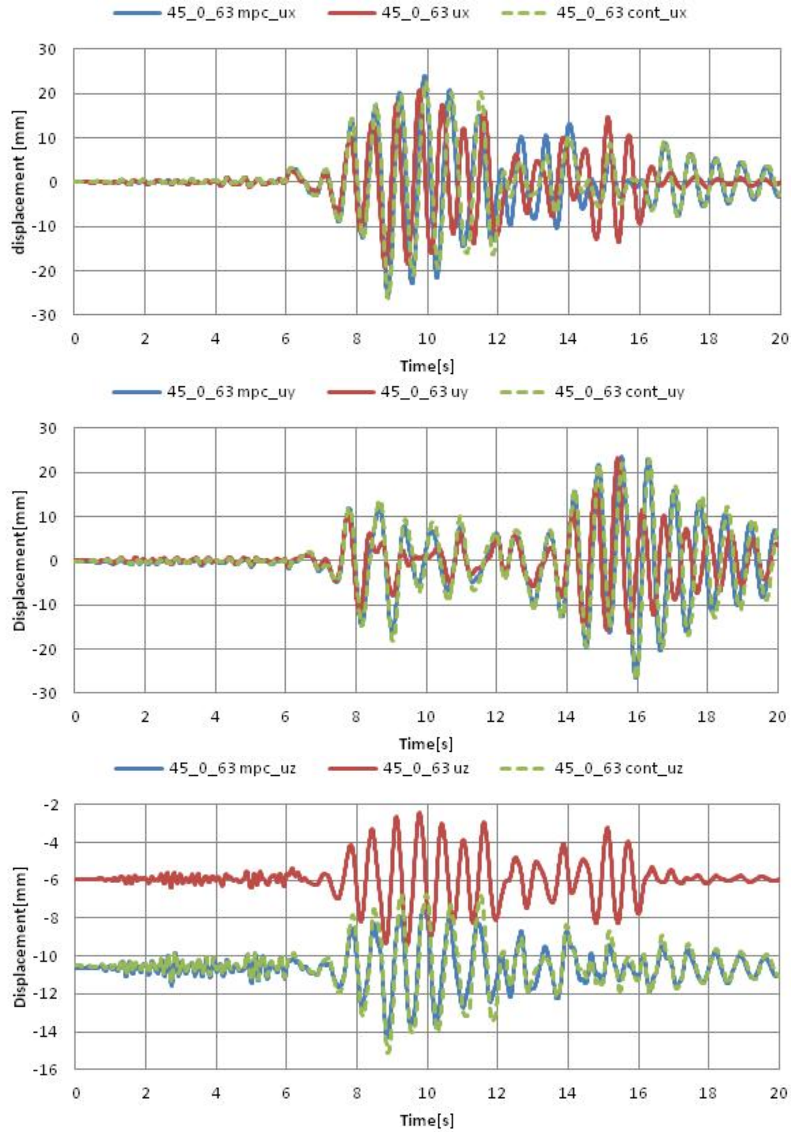
Calculation of seismic impact on the direct dynamic method. *ANSYS Mechanical*



The total displacement (m) at time t = 8,85 s. The results with the displacements the base. The maximum value 0.125 (m), the minimum value 0.097 (m)

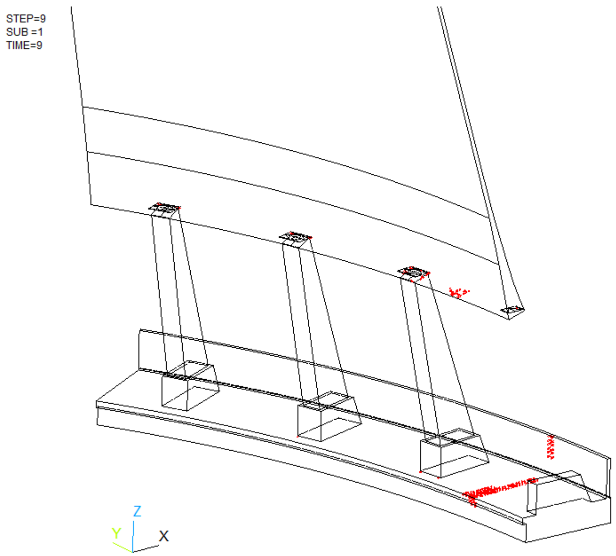


Standardized accelerograms (mm/s^2) for the base project of the NPP-2006, 6 intensity on the MSK-64 scale.

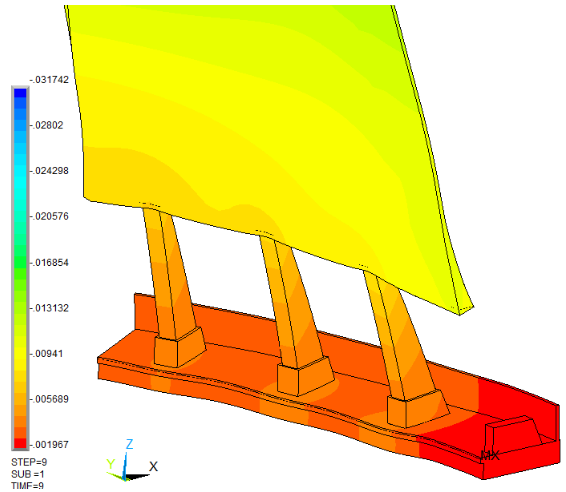


Displacement UX, UY, UZ (mm) for nodes at a height of 63 m relative to the foundation for three cases. Blue line – «indissociable" MPC contact, the red line - on a rigid foundation, the green dotted line - a standard contact.

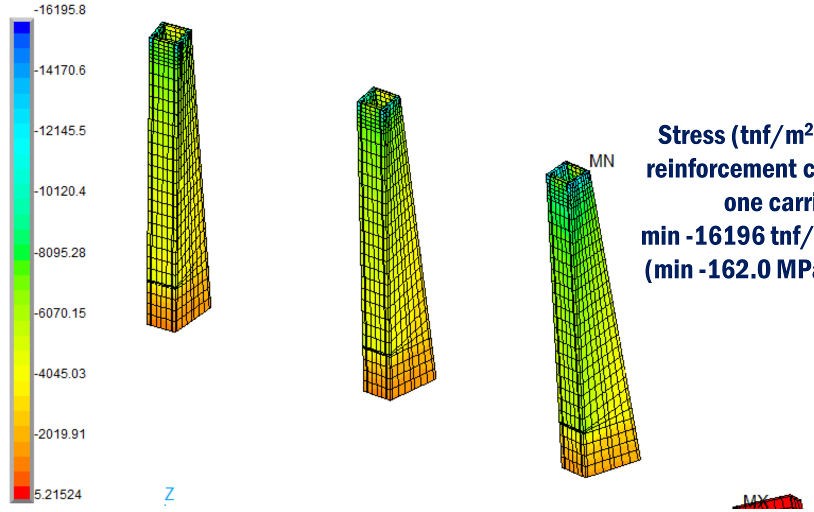
The calculation of an emergency situation. *ANSYS Mechanical*



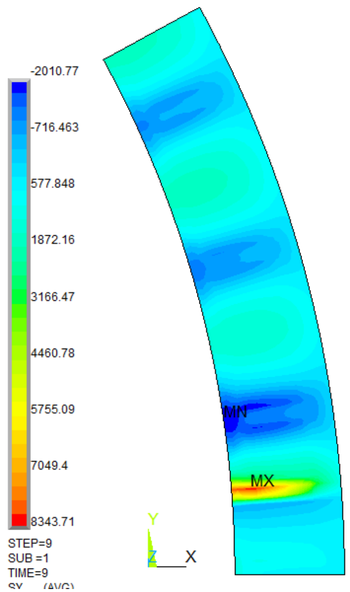
The scheme of cracks formation after the removal of the column



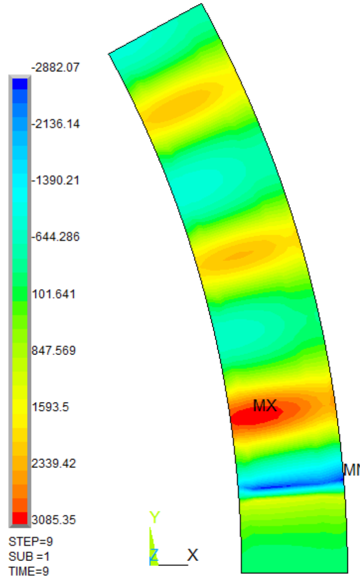
Displacement UZ (m) after the removal of the column.
Min -0.002 m, Max -0.0317 m



Stress (tnf/m^2) in the meridian reinforcement columns. Removed one carrier column
min -16196 tnf/m^2, max -5 tnf/m^2
(min -162.0 MPa , max -0.05 MPa
)

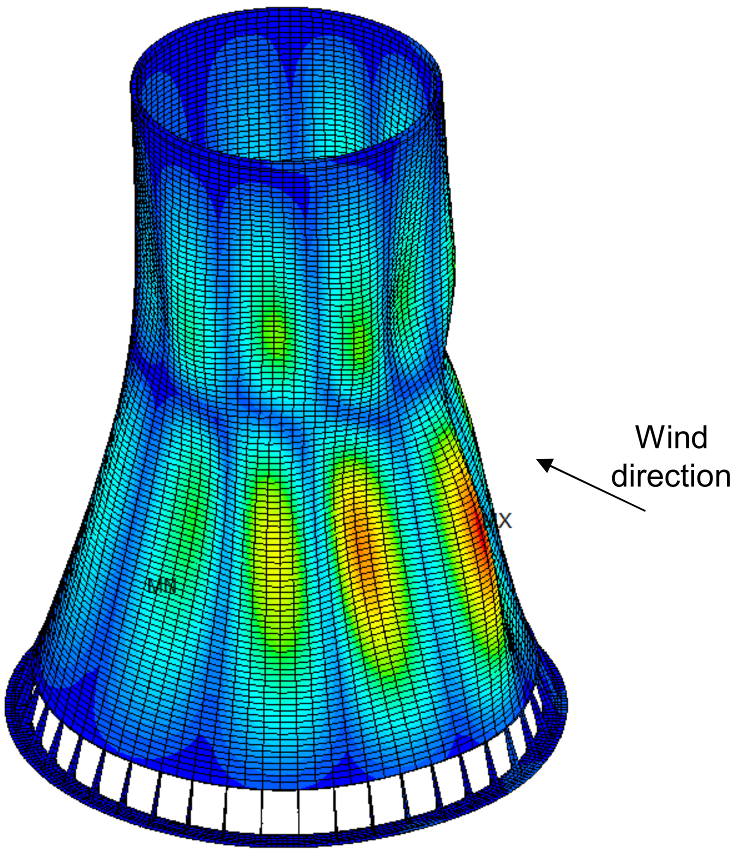


Stress (thf/m^2) in the top ring reinforcement of the foundation plate (from -20.1 MPa to 83.4 MPa)

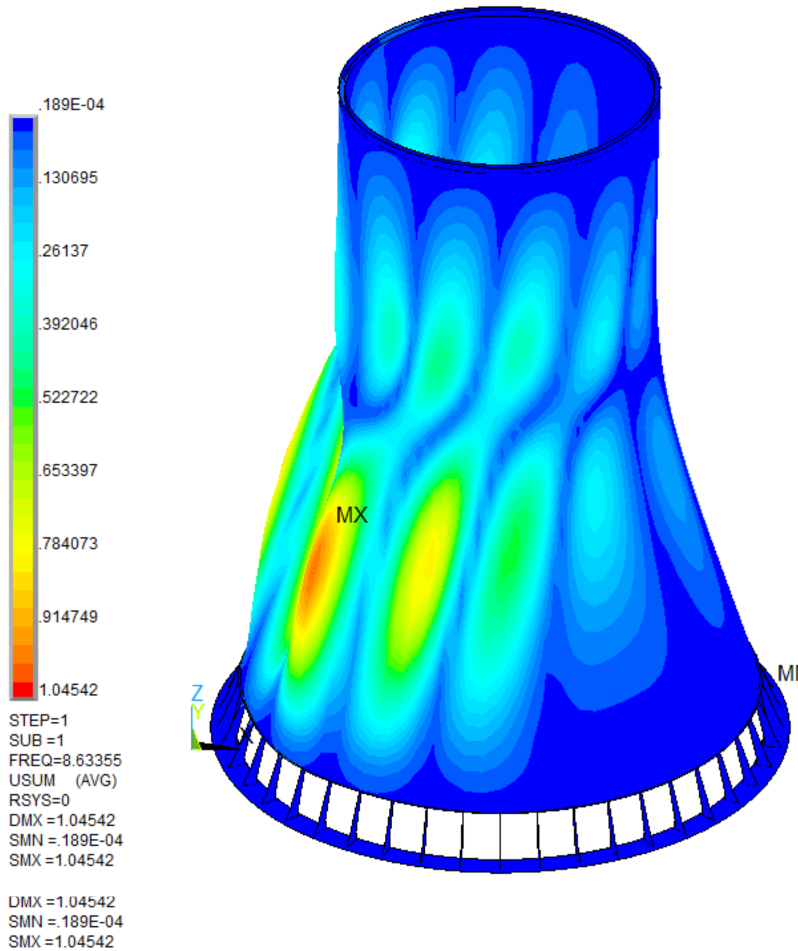


Stress (thf/m^2) in the bottom ring reinforcement of the foundation plate (from -28.8 MPa to 30.85 Mpa)

The calculation of the overall stability "according to Euler". *ANSYS Mechanical*

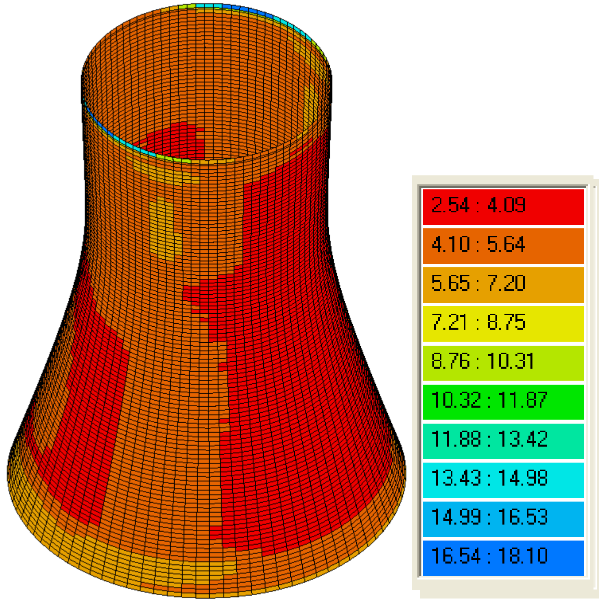


Buckling mode cooling tower from the basic load combination to the project wind.
Estimated reserves for stability 6.63

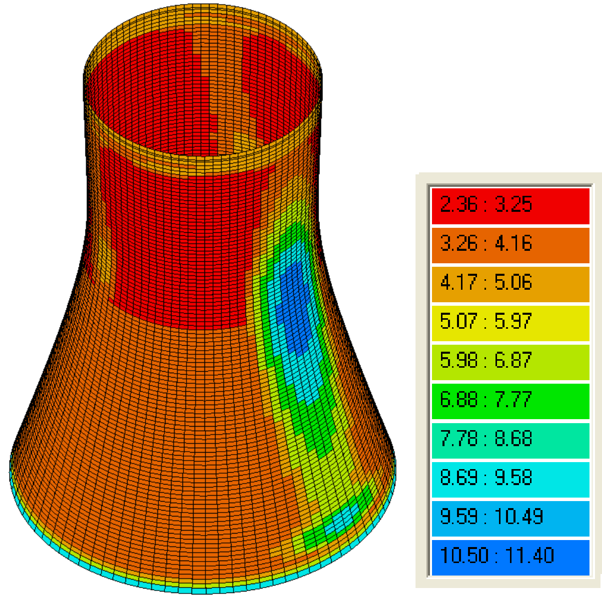


Buckling mode cooling tower from the special load combination to the. Scenario №1
impacts of tornado loads on a group of two towers (tower 2). The time moment t = 9.0 s.
Estimated reserves for stability 8.63

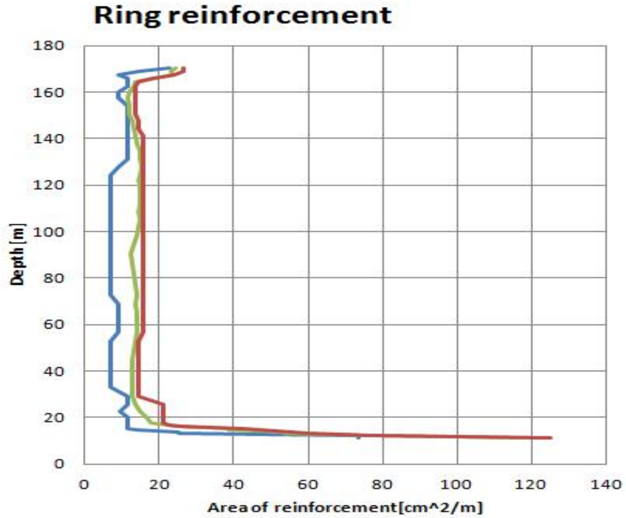
Evaluation of reinforcement. *OM SNiP RC*

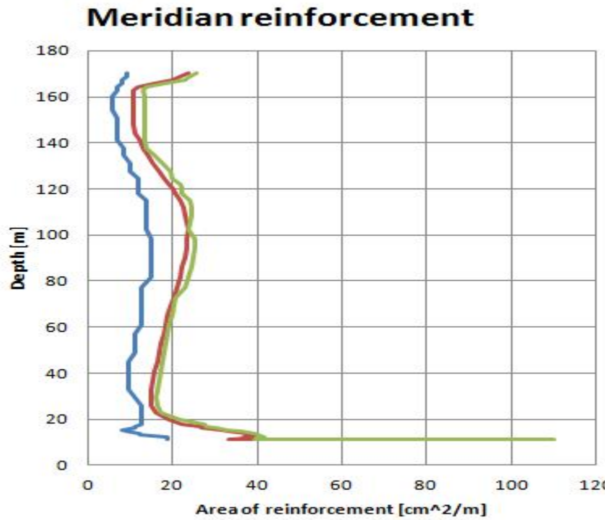


the external ring reinforcement shell (cm^2/m)



the external meridian reinforcement shell (cm^2/m)





The required total ring and meridian reinforcement for the basic load combination and the total project reinforcement. The blue line - a necessary, green-final according to SPX, red - design reinforcement

Settlement definition of stress-strain state, the strength and stability of the structure of cooling towers. Conclusions.

• The absence of significant effects of geometric nonlinearity in the deformation of the cooling tower shell;

•A marked influence compliance support contour (base plate and columns - the “weak link”) on the static state, dynamics and stability of the system;

•Eigenmodes, significant for wind and seismic loads (total offset deformable shell on the columns), are characterized by low frequencies and bend (kink) in the area of the lower support ring.

•Sufficient strength and stability of the shell.

•Bearing capacity of the structure under wind action, the relevant "project" hurricane force winds on the results of physically and geometrically nonlinear analysis is provided with a margin of 1.6.;

•Impact on an isolated tower is the most dangerous variant among scenarios considered tornado moving the intensity of 3.16 on a scale of Fujita. Physically linear analysis and verification of the design of reinforcement ("OM SNiP RC") showed that the required margin of safety provided;

•Additional physical and geometric nonlinear analysis in a quasi-static setting for this scenario tornado demonstrated a significant cracking, plastic deformation of the reinforcement and destruction in the "right" (relative to the direction of motion of a tornado) area of the shell of the positive pressure in the "tightening" of the vortex.

Settlement definition of stress-strain state, the strength and stability of the structure of cooling towers. Conclusions (continued).

•Analysis for 6-magnitude earthquake impact with the using of linear-spectral method for the more than 2,000 natural modes in the frequency range up to 33 Hz showed a maximum total seismic movement of up to 39 mm, which are determined by the dominant forms of frequencies 1,517 Hz and 2,526 Hz;

•Analysis for on 6-magnitude earthquake impact, described by three-component accelerograms and the wave of platform (including the behavior of the soil foundation) schemes show the maximum total displacement of up to 30 knots and 27 mm, respectively;

•Overall stability of the structure according to Euler in the operating loads and effects (weight, temperature, wind, hurricane, tornado, seismic) is provided with sufficient supplies (5.12 and above);

•Analysis for "an emergency situation" in the nonlinear formulation for the considered scenario showed the initiation of local failure to substantiate the stability of the support structure to progressive collapse when you remove one of the columns;

•Analysis of reinforcement in accordance with Russian design codes, performed by a certified program "OM SNiP RC" for the considered combinations of loads showed the following facts:

– The values of the ring and meridian reinforcement shell, don't exceed the design value;

– The values of the radial and ring reinforcement of the foundation plate don't exceed the design values for the key combinations.

– The strength of inclined columns complex variable section at the design reinforcement confirming the performance of non-linear calculations in a three-dimensional finite element formulation

Thank you for your attention!