Analysis of stress-strain state of RVS-20000 tank under non-axisymmetric wind load action

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Abstract. In modern reference documentation, it is customary to set the wind load as uniformly distributed pressure over the area and wall of the tank. Experimental studies in the wind tunnel for various designs of the VST carried out under the guidance of professors V.E. Shutov and V.I. Berezin showed that when wind acts on the shell, there occur rarefaction zones, which must be taken into account during strain analysis of tanks. A finite-element model of the RVS-20000 tank was developed to calculate the wind load in a non-axisymmetric setting, taking into account the array of differentiated values of the aerodynamic coefficient. The distribution of stresses and strains of RVS-20000 metal structures under the effect of unevenly distributed wind pressure with a normal value of \( Q_n = 600 \text{ Pa} \) is obtained. It is established that the greatest strains and stresses occur at the interface of the wall and the fixed floor.

1. Introduction

Currently in Russia, a branched network of main oil pipelines connects regions with different physical and geographical characteristics. The infrastructure of the main oil transportation extends from the polar regions of raw materials extraction to the southern regions where loading to sea transport is carried out. Integral structures in the technological chain are large-sized steel tanks (vertical steel tanks - VST), which have been extensively used. During operation, tanks experience a complex combination of operating loads: hydrostatic (from the weight of the product); own body and cover weight; vacuum and overpressure (cooling/heating or draining/pouring the product, accordingly); snow and wind loads - to the greatest extent due to the natural climatic factor.

Many years of experience in the design of tanks has shown that taking into account the wind load, which is a random field of aerodynamic pressures that is not non-axisymmetrically distributed over the surface of the structure, it has a number of nuances. Since a VST is a combination of various metal structures with different curvatures, which also have geometric imperfections, for each tank the distribution of the aerodynamic coefficient of wind flow over the surface of the shell and roof is unique despite the uniformity of tank structures: the height to diameter ratio H/D, the type of cover (fixed, floating, etc.), the installed technological equipment on the wall and roof (hatches, branch pipes, pipes), the relief of the site and the adjacent territory (and a nearby facilities) - all these factors are essential for the distribution of the wind flow over the surface of a tank. Therefore, the authors have set the task to estimate the tank’s stress-stain state (SSS) when exposed to wind load, taking into
account the uneven distribution of the aerodynamic coefficient, and also to determine the effective stresses and strains of the shell and fixed roof of the common RVS-20000 tank constructed according to the standard project 704-1-60.

In [1], a hypothesis is proposed for representing a turbulent wind flow, consisting in the fact that some generally steady-state air flow velocity is superimposed by gust velocities, i.e. the steady-state pressure, which is almost constant, is superimposed by a pulsation of pressure, which is of an accidental nature. The pulsations of velocity pressure caused by wind gusts exert a dynamic effect on the structure, which is taken into account by multiplying the velocity pressure by factor \( \beta \):

\[
Q_v = \beta \cdot Q_v \cdot K
\]  

where \( \beta \) – coefficient of increase in the velocity pressure depending on the wind flow pulsation and the dynamic characteristics of the structure;

\( Q_v \) – estimated velocity pressure, Pa.

The coefficient of increase in the velocity pressure is determined by the formula:

\[
\beta = \varepsilon \cdot m + 1
\]

where \( \varepsilon \) – dynamic amplification factor which depends on the period of natural oscillations of the structure \( T \) and the logarithmic decrement of the oscillations attenuation of the structure;

\( m \) – high-velocity wind flow ripple coefficient.

Since determination of the aerodynamic coefficient over the entire surface of the tank is a complex experimental task, to calculate the SSS of the structure we used the results of [1-3] obtained by experiments on a reduced geometrically similar model of RVS-20000 (scale 1:100) in a wind tunnel of the Central Aerohydrodynamic Institute named after N.E. Zhukovsky (TsAGI). The value of the aerodynamic coefficient \( K \) is the ratio of excess pressure \( p \) on the surface of the tank to the normal velocity pressure \( Q_n \), taken according to SP 20.13330.2011 [4]:

\[
K = \frac{p}{Q_n}
\]

The aerodynamic coefficient \( K \) for RVS-20000 with a fixed roof is shown in Table 1.

| Coordinates of points along the generator of the RVS-20000 wall, m | 0  | 2.8 | 5.6 | 7   | 8.4 | 9.8 | 10.5 | 11.25 | 11.95 |
|---------------------------------------------------------------|----|-----|-----|-----|-----|-----|------|--------|-------|
| K                                                             | 1  | 0.97| 0.9 | 0.82| 0.65| 0.5 | 0.185| -0.2   | -1.56 |

2. Materials and Methods

To determine the stresses and strains of RVS-20000 metal structures, the authors proposed a design scheme shown in Figure 1 [5-7].

The geometric model takes into account RVS-20000 structures according to technical design TP-704-1-60:

- reinforced concrete foundation ring with a thickness of 0.3 m and a width of 1.5 m;
- 8 belts of the wall with a thickness of 13 to 11 mm, aligned along the inner edge;
- roof, consisting of 24 segments connected by sheets with a thickness of 6 mm and beams;
- stiffening ring.

The geometric model of the tank was used in calculating the RVS-20000 design SSS for uneven ground subsidence in [8, 9] and underwent verification.
Figure 1. Design scheme: R – tank radius; \( H_w \) – wall height; \( V_w \) – direction of wind flow; \( K_1 \) – air rarefaction on the roof surface; \( K_2 \) – excess pressure on the surface of the front wall; \( K_3 \) – air rarefaction on the wall surface in the boundary zone; \( H_1 \) – distribution of \( K \) in the plane of the corner weld joint; \( H_2 \) – distribution of \( K \) at a height of 7.5 m; \( H_3 \) – distribution of \( K \) in the plane of the upper edge of the wall.

Effective loads:
- Calculations were carried out for the emptied tank;
- Distributed load from the fixed roof equipment \( F_r = 100 \) kN;
- Snow load was not taken into account;
- Wind load is taken for the V wind district (Novorossiysk, Primorye) according to SP 20.13330.2011 [4], taking into account the values of the aerodynamic coefficient over the surface of the wall and the roof of the VST given in Figure 1; the normal velocity pressure for this region is \( Q_n = 600 \text{ Pa} \). The V wind district includes oil tank farms and sea terminals on the Black Sea coast and in the Far East, where tank batteries are affected by wind most heavily in the Russian Federation, which is due to the physical and geographic location.

The reinforced concrete foundation ring and the central part of the bottom are rigidly fixed along the lower edge, for which the linear-elastic Winkler model is used. The coefficient of subgrade reaction \( k = 2 \times 10^8 \text{ MN/m}^3 \) is taken for artificially compacted sand-clay soil.

The contact of the edge and the foundation ring takes into account the absolutely rigid connection (bonded contact) without the possibility of disconnection and slippage.

Connections of metal structures of the roof with the foundation ring are permanent, welded - connected by a contact of the bonded type. The roof is not built-in, its real structural rigidity is taken into account.

The wall, sheet roofing, annular plate, bottom, stiffening ring are modeled with the eight-node shell finite element SHELL181 with 6 degrees of freedom for each node (rotation and movement along the X, Y, Z axes) [10].
Beams of the roof frame are modeled using a two-node finite element BEAM188 with 7 degrees of freedom for each node (rotation and movement along the X, Y, Z axes).

Wind load is modeled by an eight-node finite element SURF154, having a zero thickness with a given contact surface pressure (in accordance with the magnitude of the wind load).

A total of 123,906 nodes, 191,307 contact nodes, 102,562 solid elements, 335,248 are the total number of all types of finite elements.

3. Results and Discussion

Using the design scheme proposed by the authors made it possible to obtain the distribution of strains and stresses in the RVS-20000 metal structures taking into account the non-axisymmetric effect of the wind load in accordance with the values of the aerodynamic coefficient experimentally obtained in [1]. Figure 2 shows a diagram of the displacement of the tank wall sheets. The x100 scale factor of deformations is applied for visualization; it can be seen that for the given wind load parameters the maximum radial wall deflections ($\delta_w = 1.19$mm) are located on the 8th belt of the leeward part of the structure. In this case, the tank has a characteristic slope in the direction of the wind.

![Figure 2. Displacements of the RVS-20000 wall when subjected to wind load.](image)

When calculating the SSS of the tank, it turned out that the wind load poses the greatest danger for the roof structure, in particular, for the connecting node of the support ring with the beam and sheet roofing located on the windward part of the VST, where a wind flow break occurs. Due to the peculiarities of the geometric shape of RVS-20000, the entire roofing is under rarefaction. At the junctions of the bearing beams with the stiffening ring, stresses up to 58 MPa occur at a normal wind pressure of 600 Pa. Given that such stresses arise only from the wind action, they contribute greatly to the overall stress-strain state of the tank, since they are added together with stresses from the column of liquid, snow, and vacuum. Even more dangerous are situations when there are deviations in the geometric shape of metal structures from the design values. In this case, unacceptable stresses can be concentrated in the most unpredictable places, especially if strains of structural elements are caused by the development of an uneven subsidence of the RVS foundation [9]. Figure 3 and 4 show the distribution of strains and stresses obtained by the authors in the metal structures of the 8th belt of the wall and the fixed roof of RVS-20000 under the influence of the wind load in accordance with the accepted design scheme shown in Figure 1.
Figure 3. Equivalent stresses in the metal structures of the 8th belt of the wall and the fixed roof of RVS-20000 under the influence of the wind load.

Figure 4. Displacements of the metal structures of the support ring and the roof beams of RVS-20000 under the influence of the wind load.

4. Conclusion

A finite-element model of the RVS-20000 tank was developed to calculate the effect of the wind load on the tank’s SSS, taking into account the array of differentiated values of the aerodynamic coefficient. Distribution of stresses and strains of RVS-20000 metal structures under the effect of the unevenly distributed wind pressure with a normal value of $Q_n = 600$ Pa (for the V wind region) was obtained. It was established that the greatest strains and stresses occur at the interface node of the wall and the fixed roofing. In spite of the fact that the acting stresses in the VST wall do not exceed 122 MPa under the influence of the wind load with normal value $Q_n = 600$ Pa, they add up with the stresses arising from operational and possible non-design loads, which can lead to the RVS-20000 metal structures reaching limiting states.

Calculation results and work experience [8, 9] showed that deviation of the VST geometric shape from the design values leads to a redistribution of the values of the aerodynamic coefficient over the wall and roof surfaces. These values can only be determined experimentally or by simulating in FE packages like ANSYS “Fluent” based on a real 3D model “blown” in a virtual wind tunnel. Given that a large number of existing VSTs are operated with geometric shape deviations, there is a need to develop a universal method and approaches that allow calculating the impact of wind load on tank structures, taking into account imperfections in the geometry of the wall, roof and existing technological equipment. Comparing the results of calculating the SSS of the RVS-20000 tank in cases of a non-axisymmetric and uniformly distributed wind pressure, it was established that when a non-uniform wind action is taken into account, the operating stresses in the connecting node of the roof and the wall are 55 percent higher than in the case of a design scheme with a uniform load.
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