Justification of the estimation technique for the technical condition of the tank with inadmissible imperfections in the wall shape

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Abstract. The paper has its focus on the problem of estimating the stress-strain state of the vertical steel tanks with the inadmissible geometric imperfections in the wall shape. In the paper, the authors refer to an actual tank to demonstrate that the use of certain design schemes can lead to the raw errors and, accordingly, to the unreliable results. Obviously, these design schemes cannot be based on when choosing the real repair technologies. For that reason, authors performed the calculations of the tank removed out of service for the repair, basing on the developed finite-element model of the VST-5000 tank with a conical roof. The proposed approach was developed for the analysis of the SSS (stress-strain state) of a tank having geometric imperfections of the wall shape. Based on the work results, the following was proposed: to amend the Annex A methodology "Method for calculating the stress-strain state of the tank wall during repair by lifting the tank and replacing the wall metal structures" by inserting the requirement to compulsory consider the actual stiffness of the VST entire structure and its roof when calculating the structure stress-strain state.

1. Introduction

Uninterrupted midstream operations (pipeline transportation) are largely owed to the reliable functioning of the tank farms. Currently, there is a large number of tank farms with vertical steel tanks (VST), operation of which should be stopped according to the geodetic surveys results. However, the experience of operating tanks with similar defects [1, 2] shows that they can function safely far beyond the normative operating life. Due to the scale of the infrastructure of the production system and the midstream operations as well as the large number of operating tank farms, it is impossible to completely ban the operation of tanks with inadmissible imperfections – for both technical and economic reasons. Existing regulatory documents allow to perform additional calculations to justify the possible further operation of tanks with inadmissible wall imperfections. RD-08-95-95 [3] is one of the first national regulatory documents that indicates the need for additional strength calculations to determine the remaining operation life of the tank with geometric imperfections in the elements shape. In the years since, the feasibility of this standard approaches was confirmed in actual practice resulting in advent of new regulations, in particular, the RD-23.020.00-KTN-283-09 [4] of the Transneft oil company. Due to the lack of sufficient practical experience, the most interesting method for discussion is the "Method for calculating the stress-strain state of the tank wall during repair by lifting the tank and replacing the wall metal structures" (based on the FEM-finite element method) presented in the normative Annex A of this standard. The main advantage of this technique is that it allows to calculate the SSS of the tank wall with account of the real geometric imperfections: dents, bulges and welding joints angularities. Also, one can perform the calculation for different operating conditions of the tank: when replacing the metal structures of the wall and stiffening ring (taking into account the reinforcing rib), when repairing the VST base by lifting.

However, the numerical modelling of a tank is a time- and resource-consuming process that can lead to unreliable results of the finite calculations if there are any errors. The choice of boundary conditions in the VST design model is the most important issue. Thus, in the methodology of [4], the description of the boundary conditions for the wall upper edge is simply absent. Based on the design models description, one can conclude that the edge of the wall upper ring has no restrictions in the degrees of freedom, and the roof geometry is not considered at all. Herein, it is not clear whether additional fixing of the wall upper edge is used. In other works, the authors took the rigid fixing of the wall upper edge to account for the roof stiffness. Thus, the studies [5, 6] say that the approaches associated with simplifying the geometry of the upper junction and restrictions to the displacements of the wall upper edge are feasible when solving problems in an axisymmetric formulation. On the other hand, when the asymmetric loading factors (uneven settlement, geometric imperfections in the wall shape, the section absence in the wall, roof or the stiffening ring) are present in the design scheme, the discrepancies in the results can reach 600% if compared with models that consider the roof and the stiffening ring structure.

2. Methods

In this paper, using different calculation schemes, the authors have set the task to compare the results of calculating the SSS of the actual tank removed for the repair obtained by using two methods. The first is the known one [4] and the second was developed by the authors which takes into account the influence of the roof structure stiffness on the overall stress state of the entire structure. It is also proposed to make a comparison with the values of stress arising in a model with a rigid fixing of the wall upper edge. The object of the study was a vertical cylindrical steel cylinder with a volume of 5000 m^3, operated in the main trunk pipeline system. The functional purpose of this tank is the intake, storage, release and emergency discharge of the commercial oil. The operating condition of the facility - removed out of service for the repair. The technical diagnostics results revealed that according to [4] the maximum deviations of the wall from the vertical generatrix exceed the maximum permissible values and equal to 154 mm for the 22nd vertical weld at the level of the 6th ring. The main technical characteristics of the tank are presented in Table-1.

Table-1. Technical characteristics of the VST-5000 tank.

Parameter	Amount	Unit of measure
Diameter	22.78	m
Wall height	11.92	m
The maximum level of the oil filling	9.849	m
Density of the stored product	865	kg/m^3
Thickness of the wall rings:	-	-
Ring 1	10.5	mm
Ring 2	7.6	mm
Ring 3	6.4	mm
Ring 4	5.7	mm
Ring 5	5.6	mm
Ring 6	5.7	mm
Ring 7	5.6	mm
Ring 8	5.6	mm

Let us turn to the design model of the VST-5000 tank, performed with the help of the ANSYS finite element software [7-8]. To simulate the tank wall with imperfections, it was necessary to create a point cloud that was used to construct a closed shell [9-10]. The points coordinates were obtained from the results of the tank tacheometric survey. The results of the tank wall deviations from the vertical generatrix showed that the limits were exceeded at three points according to [4]. Division into the finite elements was carried out using a grid generator MESH. The size of the discretization for the SHELL181 rectangular elements was 200 mm. The problem formulation included three variants of calculation with the following boundary, contact conditions and loading parameters:

Variant I: the upper edge of the wall is not fixed, the lower edge of the wall 1st ring is rigidly fixed along the contour, the hydrostatic load is applied to the inner surface of the wall in accordance with the maximum in age level of 9.849 m, the snow load of 1800 Pa [11] is evenly distributed along the upper edge of the wall, the wind load of 230 Pa [11] is applied evenly over the wall area.

Variant II: similar to variant I, yet the upper edge of the wall is fixed.

Variant III: the real geometry of the roof is considered, the lower edge of the wall 1st ring is rigidly fixed along the contour, the contacts of the roof and the upper ring of the wall are welded, the support column and the roof are welded, the hydrostatic load is applied to the inner surface of the wall in accordance with the maximum in age level of 9.849 m, the snow load of 1800 Pa is evenly distributed over the roof surface, the wind load of 230 Pa is applied evenly over the wall and roof area.

Previous works [7, 8] demonstrated that one model could give completely different results depending on the chosen boundary conditions. In the study of I.V. Slepnev [5], as well as in the current regulation [4], the upper edge of the wall is not fixed. This approach was used in the first variant of our design model. The second approach implying that the upper edge of the wall is fixed was examined in detail in [6] where one can find a detailed description of the VST mathematical model. The third variant of the model proposed by the authors assumes that the real geometrical model of the stationary roof is taken into account. The additional boundary conditions for the wall upper edge are not assigned, but the contact problem of the wall and the conical roof plates sheeting is solved.

3. Results

Let us analyze the model post processing results. In the variant I, where the tank upper edge is not fixed, the radial wall displacements exceed the actual values by a factor of 3 and more. The upper edge has a distinctive undulating distortion with a maximum value of radial displacement W = 316 mm, which contradicts the data of the VST-5000 field surveys. In this case, the maximum stress is in the first ring of the wall and equals to 287.9 MPa. The second variant of the design scheme with a rigid fixing of the wall upper edge also cannot be used to solve practical problems. The simultaneous fixing of the tank from two sides (along the upper and lower edges) leads to the fact that the model acquires much more stiffness than it actually has in reality. Thus, the maximum equivalent stress in the VST-5000 metal structures with geometric imperfections does not exceed 154 MPa, which does not correspond to the data of the majority of studies (including experiments with the full-scale strain gauging).In our opinion, the variant that considers the actual stiffness of the stationary roof is the most acceptable design scheme for analyzing the SSS of the tank with geometric imperfections (figure 1).

In this case, there is no need to arbitrarily set the boundary conditions for the upper edge of the shell. As the operational loads are applied, the deformations are limited only by the intrinsic stiffness of the structure. To do this, it is necessary to build a model with a high degree of specification of the tank elements and connections

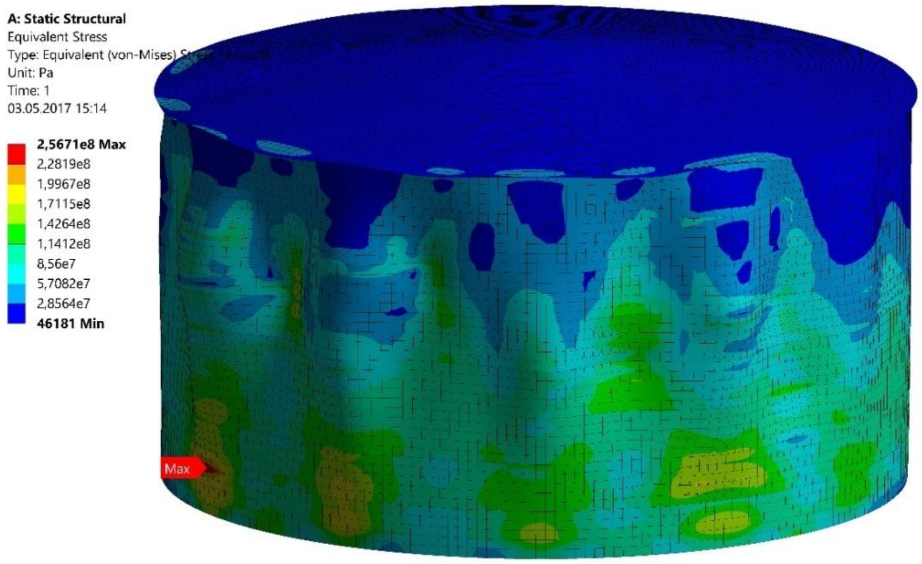

Figure 1. Variant III. Distribution of the actual equivalent stresses in the metal structures of the VST-5000 tank considering the influence of the roof.

. 4. Discussion

Since the support column and the conical roof resting on this column have finite stiffness, as well as the VST shell structure itself, the deformation redistributes to the roof when the operational loads are applied to the tank. In our opinion, this approach is the only one acceptable for solving problems with geometric nonlinearities, since it reflects the actual nature of the VST entire structure deformation. figure-2 displays the dependencies of equivalent stresses in the VST-5000 wall on the height for the model with and without considering the stationary roof (2 variants for assigning the boundary conditions).

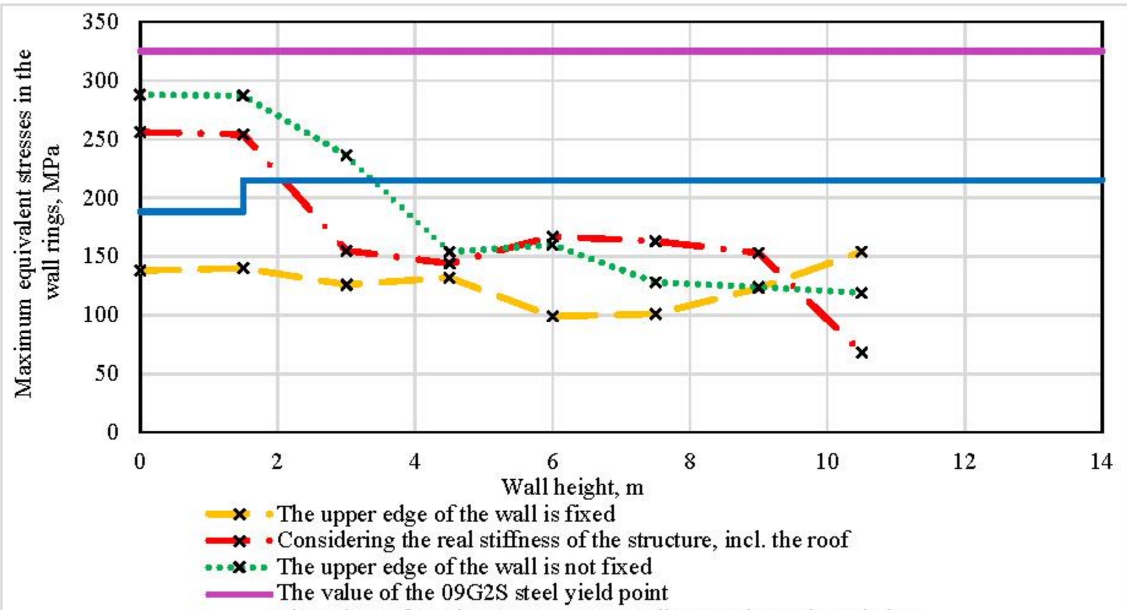

Figure 2.Distribution of equivalent stresses in the VST-5000 wall with height for the model with and without considering the stationary roof.

The graphs demonstrate that the nature of the stresses distribution along the rings is similar for the variants I and III. The differences appear only at the level above the 4th ring of the wall, and this shows how critical the choice of boundary conditions for the upper junction is. In the version with a stationary roof, the stresses in the upper ring die down to 70 MPa, and in the variant with the "released" (not fixed) upper edge the stresses remain at the level of 120 MPa. Figure 2 shows that with rigid fixing of the wall upper edge, the implausibly low stresses arise. It was also found that a sharp increase in stress occurs in the corner weld joint (288 MPa for the variant I of the design scheme, 257 MPa for the variant III of the design scheme). Therefore, when analyzing the SSS of a tank with geometric imperfections on the I and II horizontal wall rings, it is also necessary to consider possible defects in the weld joints, since the total equivalent stresses in the metal can then approach the critical point $\sigma_\tau = 325$ MPa, which is the yield point of 09G2S steel.

Thus, the authors have proposed the approach to the determination of the general design scheme and the construction of the VST FE model. In practice, there is a huge variety of geometric imperfections that can be introduced into the proposed model. Given the imperfections, the calculation for each tank is unique. It should also be noted that properties of the selected finite elements and the parameters of the solver should allow to perform the calculation in a geometrically and physically nonlinear setting of the problem. In the presence of significant wall deformations, it is necessary to perform additional calculation and analysis of the tank shell stability.

5. Conclusions

The authors justified the technique for assessing the technical condition of the tank with inadmissible imperfections in the wall shape. For this purpose, the ANSYS software package was used to develop a finite element model of the VST-5000 tank considering the metal structures of the conical roof and the central support column.

The analysis of the works [5-6, 12-15], long-term experience of tanks operation, diagnostic information and the obtained numerical dependencies show that the approach proposed by the authors is feasible when analyzing the SSS of the tank having geometric imperfections of the wall shape. In this regard, it has been proposed to amend the methodology of Annex A "Method for calculating the stress-strain state of the tank wall during repair by lifting the tank and replacing the wall metal structures" of the current regulation [4] by inserting the requirement to compulsory take into account the VST actual roof structure when calculating the tank SSS in the ANSYS software package.

In accordance with the requirements of [4] (Annex A), the authors obtained the results of the SSS calculations for the actually existing VST-5000 tank, which was put out for repair. The calculations were performed in three variants: I – without fixing the upper edge of the wall ($\sigma_{eqv.max} = 288$ MPa); II – with fixing the upper edge of the wall ($\sigma_{eqv.max} = 154$ MPa); III – the variant proposed by the authors that takes into account the actual stiffness of the roof ($\sigma_{eqv.max} = 257$ MPa). Large discrepancies in the results (up to 100% for the lower wall rings) prove the fact that the choice of the model boundary conditions determines the reliability of the obtained SSS parameters of the entire tank structure. Therefore, it is unacceptable to introduce simplifications and conditionality when modeling the upper junction of the VST.

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