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ESTIMATING THE STRESSED-STRAINED STATE OF THE VERTICAL MOUNTING JOINT OF THE CYLINDRICAL TANK WALL TAKING INTO CONSIDERATION IMPERFECTIONS

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Based on the use of a multi-level mathematical model, this paper estimates the stressed-strained state of a cylindrical reservoir in the mounting joint and considers the concentration of stresses in the joint zone.

The correctness of the selected mathematical model was verified to show that for an engineering assessment of the stressed-strained state of the wall of a cylindrical tank with variable thickness, it is possible to use the ratios for a cylindrical shell with a constant wall thickness. The spread of values is no more than 1 %, which indicates the proper selection of the mathematical model.

A numerical assessment of the stressed-strained state in the zone of the mounting joint proved the assumption of significant stress concentrations in the zone and indicated the determining effect exerted on the concentration of stresses by its geometric dimensions.

The concentration of stresses in the joint zone of the tank wall was investigated at various sizes in the ANSYS programming environment. The result of calculating the stressed-strained state of the reservoir for various values of the dent parameters f/t and $a/\sqrt{Rt}$ ***is the constructed polynomials that approximate the stress concentration coefficient*** K_σ.

As a result of the calculations, an interpolation polynomial and an approximating stress concentration coefficient were derived, which could be used to assess the strength, durability, residual life of the tank and to normalize the limiting dimensions of the imperfection of the joint.

This paper reports comparative results of the calculations of the stress concentration coefficient depending on the geometric dimensions of the imperfection of the mounting joint in the ANSYS software package, as well as using an interpolation polynomial.

The results could be used to assess the strength and residual life of such structures

Keywords: steel tank, stress concentration, mounting joint, joint parameters, numerical method

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1. Introduction

Production, transportation, and refining of oil are currently one of the main areas characterizing the level of competitiveness of the state economy and the degree of industrial efficiency. This predetermines an increase in capacities for the transportation, processing, and storage of oil and petroleum products, and, consequently, an increase in the need for specialized storage facilities for large volumes. With the continuous growth of production and refining of oil and petroleum products, the need for large storage facilities requires intensive construction of steel tanks of large volumes [1, 2]. Tanks for the storage of oil and petroleum products are categorized as objects of increased danger since they operate in a complex stressed-strained state. Such a phenomenon is caused by the simultaneous effect of the hydrostatic pressure of the stored product, a significant temperature difference, wind and snow loads, uneven precipitation, and seismic phenomena [3–5].

Therefore, the construction and operation of tanks should be based on reasonable scientific, technically possible, fundamentally new structural and economically justified solutions. This leads to the need to intensify study into the development of new approaches to assessing the strength, durability, and stability of vertical cylindrical tanks, taking into consideration actual operating conditions, and improving the regulatory framework for their design and operation.

It is known that the most common causes of accidents and emergencies on all types of tanks (steel, concrete, reinforced concrete, vertical, horizontal, etc.) are stress concentrators in combination with adverse operational influences; [6–11] considered various variants of tank structures: steel, concrete, horizontal, and vertical. The design of the tanks took into consideration the characteristics of the material, as well as ways to increase the strength properties of the materials. This led to the need to consider the technical task of devising new approaches to assessing strength, and durability, identifying reserves and improving the design standards for steel vertical cylindrical tanks, taking into consideration the concentration of stresses.

The destruction of tanks can lead to serious economic and environmental consequences and can be caused by a number of reasons, among which are stress concentrators that occur in areas of imperfections and defects in shapes. Stress concentrators can emerge both during operation and when installing the tank.

The analysis [12] of the consequences of the destruction of reservoir structures suggests that one of the main factors responsible for initiating the destruction are defects in the welded joints and seams made during the installation.

The rolling technique, used since the 1940s, has passed the test of time and is now widely used in various countries. This technique has a number of advantages in comparison with the sheet-by-sheet method [13].

However, during the construction of large-sized tanks, significant disadvantages were identified in the rolling technique, along with the advantages. One of the main disadvantages is that the vertical mounting joint that closes the cylindrical body of the tank often has geometric angular imperfections due to stresses at welding, damage and deformation of the edges during installation and transportation [14, 15].

The relevance of the problem under consideration is also due to a sharp decrease in the volume of new construction, which led to a noticeable «aging» of the tank fleet. At the same time, that has led to an increase in the proportion of tanks, the technical condition of which is close to the limit and requires taking any measures to ensure their trouble-free operation.

2. Literature review and problem statement

The few studies carried out on deviations in the shape of the tank wall in the area of the mounting joint can be conditionally divided into two groups depending on the criterion by which the permissible deviations are determined.

Such criteria are:

1) ensuring the stability of the wall, which has deviations from the design shape;

2) ensuring the strength of the wall, which has deviations from the design shape.

The most interesting are the issues related to the influence of geometric imperfections of shape in the dented zone on the stability and stressed-strained state of the tank wall.

Paper [16] reports the results of modeling the operation of steel cylindrical tanks filled with liquid. Study [17] describes the procedure of numerical analysis of the composite structure under the operational loads associated with the transportation of tanks. Work [18] deals with a cylindrical tank for storing petrochemical products. It is noted that a typical tank design has a wall that is modeled with a thin shell. Paper [19] discusses the features of deformation processes of cylindrical steel tanks with defects in the form of concavity of the seam. The longitudinal bend of the tank wall at constant external pressure was studied. It is shown that the presence of initial defects in the structure significantly reduces the strength of the tanks. Study [20] deals with the repair of dents by carbon fiber reinforcement in order to restore the lost bearing capacity. In [21, 22], only an assessment of the strength of the wall of cylindrical shells with a dent is given, taking into consideration the concentration of stresses in the defect zone. However, the issue of stress concentrations in the defect was not addressed, nor were the shape and geometric dimensions of the defects in the form of dents taken into consideration.

Paper [23] addresses only the problem of assessing the technical condition of steel tanks with a defect in the form of a dent without taking into consideration the weld. Study [24] mainly considered the issue of the durability of the structure depending on the corrosion process of the shell of vertical steel tanks, which is caused by the thinning of the wall thickness, as well as the appearance of defects in the welded joint. The cited paper can be positively supplemented in the case of consideration of corrosion processes in the mounting joints of steel tanks.

Estimating the duration of safe operation of steel cylindrical tanks requires full coverage of such a problem and indicates an integrated approach to assessing the residual life of the structure, taking into consideration various defects, including in the mounting joints. Study [25] highlights the issue of increasing corrosion rate over time and analyzes the calculation of residual life. Despite extensive research, in the cited study the issues of the variable wall and its effect on the residual resource and the indicator of the stress concentration coefficient are not illuminated taking into consideration the mounting joint.

Based on the analysis of the results of the review of cylindrical shells with an initial curvature of the wall, it is concluded that there are currently no tolerances for the amount of initial curvature of the tank wall. At the same time, there is no method of calculation to be effectively used in studies of the features of the stressed-strained state of the walls of tanks with local curvature in the zones of mounting joints. In the cited works [16–25], the presence of stress concentration in the zone of the vertical welded mounting joint was directly or indirectly revealed. However, none of the procedures gives a clear definition of the presence of stress concentration, there is no list of parameters affecting the concentration of stresses. The calculation procedures under consideration are built without taking into consideration the concentration of stress in the area of the mounting joint, which prevents a reliable assessment of the actual operation of the tank.

3. The aim and objectives of the study

The purpose of this study is a numerical assessment of the stressed-strained state of the imperfection zone of the mounting joint in the tank body, taking into consideration establishing the dependences of the stress concentration on the geometric dimensions of the imperfection of the joint. This will make it possible to subsequently assess the strength, durability, and residual life of the tanks, taking into consideration the concentration of stresses in the area of the mounting joint.

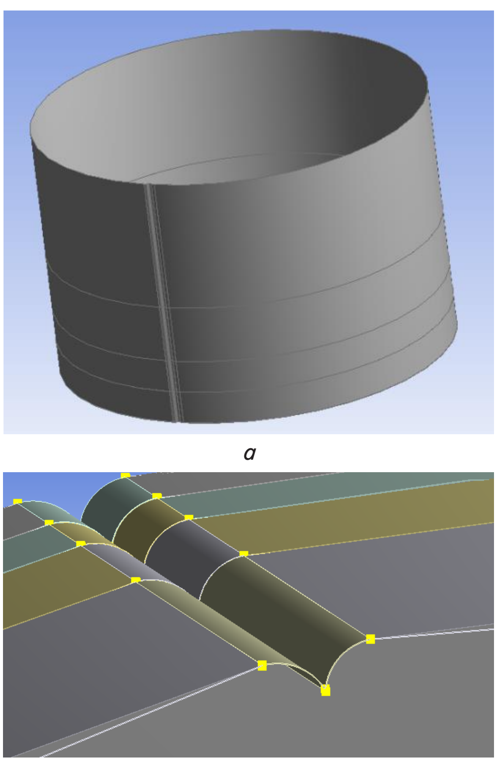
To achieve the set aim, the following tasks have been solved:

– to perform a numerical simulation of the stressed-strained state of the imperfection zone of the joint of cylindrical tanks;

– to establish the dependence of the stress concentration coefficient on the geometric dimensions of the imperfection of the mounting joint.

4. The study materials and methods

Our problem deals with the structure of a typical vertical cylindrical tank with a volume of 3000 m^3 [26], filled with a liquid with a zone of imperfection of the mounting weld joint along the entire height of the tank, in accordance with Fig. 1, *a*. A diagram of the mounting connection with the imperfection of the joint is shown in accordance with Fig. 1, *b*. The basic geometric parameters of the mounting joint used in the calculations are represented in accordance with Fig. 2. The static stressed-strained state (SAS) of the structure is considered.



a, *b*

Fig. 1. General view of the tank, taking into consideration the mounting joint: *a* – scheme of a vertical cylindrical tank with a volume of 3000 m^3; *b* – diagram of the mounting joint

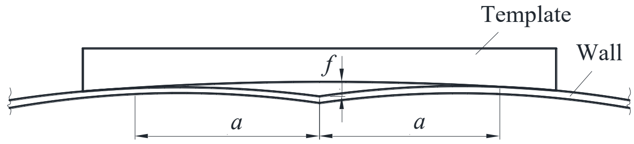


Fig. 2. Diagrams of imperfections of the geometric shape of the wall in the zone of the mounting joint of the tank

The effect of the stored product on the tank wall is described by static pressure. Consider the static stressed-strained state of the tank structure. The calculation took into consideration the areas of plasticity of the material using the model of elastic-plastic medium with linear hardening. Since the shell has large displacements, geometrically nonlinear deformation of the structure was also taken into consideration.

For numerical simulation of the stressed-strained state of the reservoir caused by the action of internal pressure, the ANSYS software package was used. The perturbations of the stressed-strained state in the junction zone are described by the stress concentration coefficient K_σ.

The experience of the operation of tanks has shown that the stressed-strained state of the tank wall in the area of the mounting joint depends on the geometric imperfection of the joint itself. Such imperfections include the angularity under the action of a uniformly distributed pressure determined by the deflection of the joint f, the width of the angularity a, the radius R, and the wall thickness t of the reservoir.

Based on the hypothesis described in works [27, 28], the stress concentration coefficient K_σ^T is represented as dependent on two dimensionless parameters f/t and $a/\sqrt{Rt}$, where t is the thickness of the shell; f is the depth of bending of the joint; R, t – radius and thickness of the tank.

The resulting expression for the stress concentration coefficient K_σ^T is obtained as:

$$K_\sigma^T \approx \alpha\left(f/t; a/\sqrt{Rt}\right), \qquad (1)$$

As a result of calculations of the stressed-strained state of the reservoir for various values of the dent parameters f/t and $a/\sqrt{Rt}$, polynomials have been constructed that approximate the stress concentration coefficient K_σ.

Such approximating polynomials for the coefficient K_σ are extremely effective for estimating the stressed-strained state of the tank body with arbitrary geometry and with arbitrary geometric dimensions of the imperfection of the mounting joint.

The structure of a typical vertical cylindrical tank with a volume of 3000 m^3 and the stressed-strained state of the tank wall of variable thickness in accordance with [29] are considered.

The modulus of elasticity and the Poisson coefficient of the tank material are as follows: $E=2.1\cdot10^{11}$ Pa; $\upsilon=0.3$. Assume that the tank is completely filled ($h=11.92$ m) with a liquid with a volumetric weight of $\gamma=1000$ kg/m^3.

In our problem, the pressure acting on the tank wall is taken to satisfy the equation given in [29].

The stressed-strained state of the tank was studied at different geometric dimensions of the imperfection of the mounting joint. The bending depth f of the mounting joint varied from 1 to 10 cm, and its width a from 0.15 to 0.5 m.

The adequacy of the results was assessed by comparing the values of the stress concentration coefficient obtained from the calculation in ANSYS and the values obtained from the polynomial, taking into consideration the imperfections of the mounting joint of the cylindrical tank wall.

5. Results of the numerical assessment of the stressed-strained state of the imperfection zone of the mounting joint in the tank body

5. 1. Numerical simulation of the stressed-strained state of the zone of imperfection of the joint of cylindrical tanks

The tank body was divided into shell finite elements with a variable grid. In the dented area, the size of the grids decreased. The grid of finite elements of the lower belt of the tank is represented in accordance with Fig. 3.

The convergence of the calculations of the stressed-strained state with a decrease in the size of the finite-element grid was investigated. To this end, we calculated the stressed-strained state of the tank wall at different sizes of finite-element grids, and, according to the results of the comparison, the desired finite-element grid was selected.

The results of the calculations of equivalent stresses on the outer surface of the tank for different values of bending and width of imperfection of the mounting joint of the tank wall are given in accordance with Fig. 4–7.

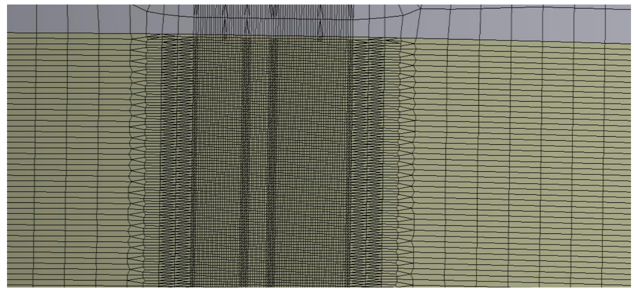


Fig. 3. A finite-element grid of the lower belt of the estimated tank

Fig. 4–7 show the results of calculations of equivalent stresses at the following values of the parameters of imperfections of the mounting joints:

$$(a,f)=(50;1);\ (a,f)=(50;15);$$

$$(a,f)=(50;10);\ (a,f)=(15;10). \qquad (2)$$

Our calculations have shown that the highest concentration of stresses occurs at the base of the tank in the junction of the bottom with the tank wall near the mounting joint zone.

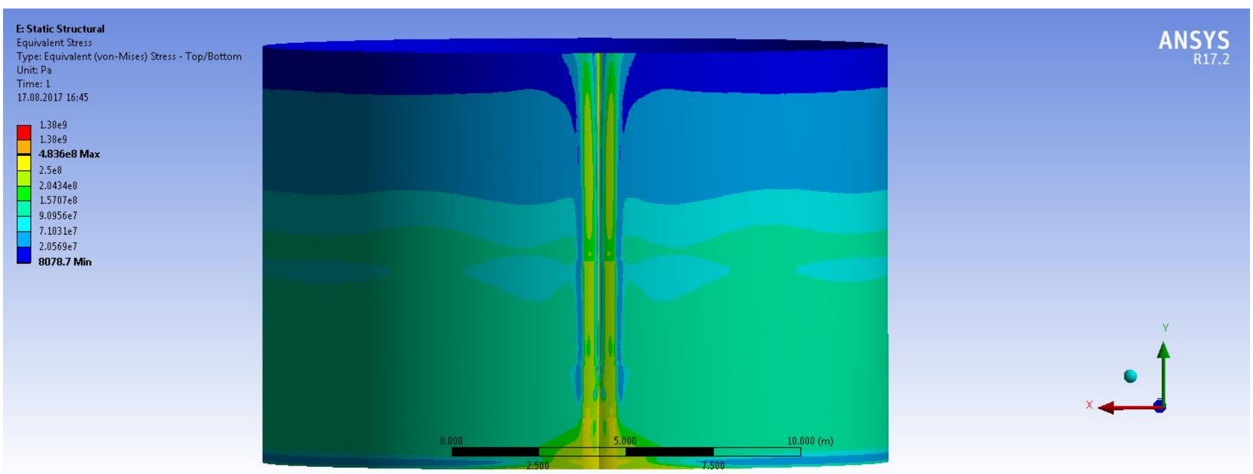


Fig. 4. Distribution of equivalent stresses in the area of the mounting connection with imperfection of the joint at $a=50$ cm, $f=1$ cm

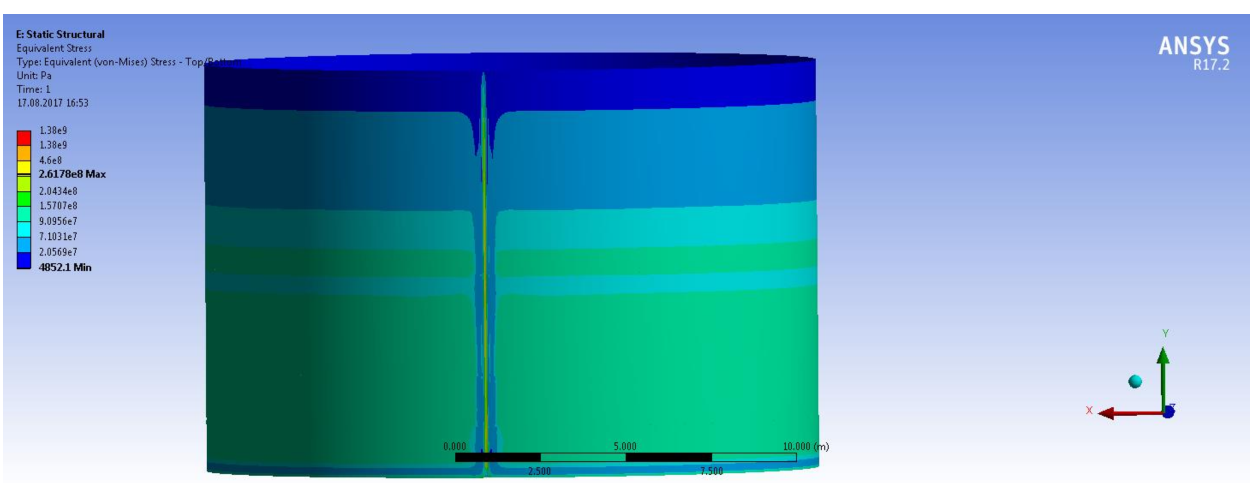


Fig. 5. Distribution of equivalent stresses in the area of the mounting connection with imperfection of the joint at $a=50$ cm, $f=15$ cm

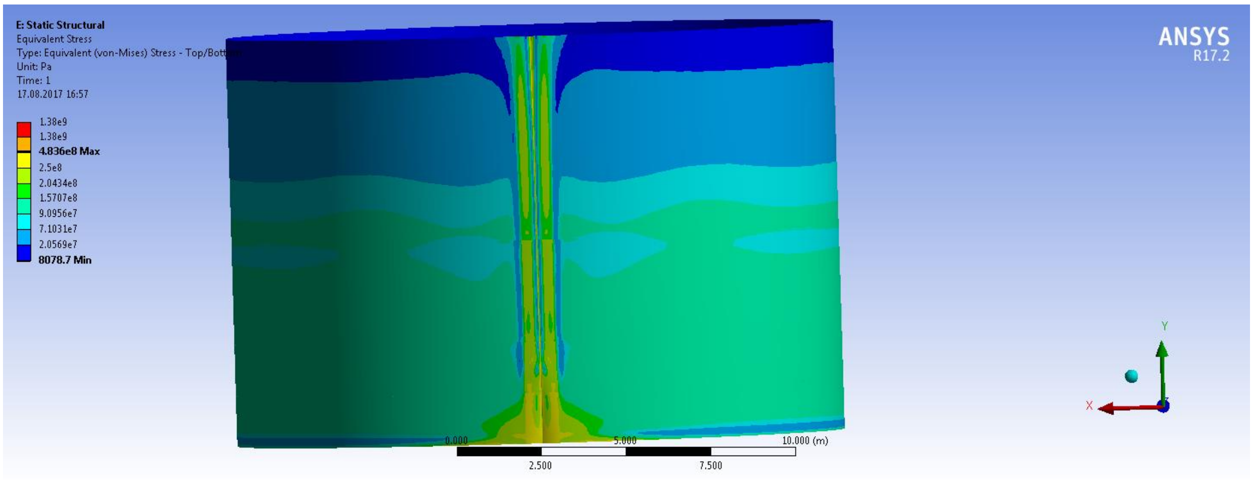


Fig. 6. Distribution of equivalent stresses in the area of the mounting connection with imperfection of the joint at $a=50$ cm, $f=10$ cm

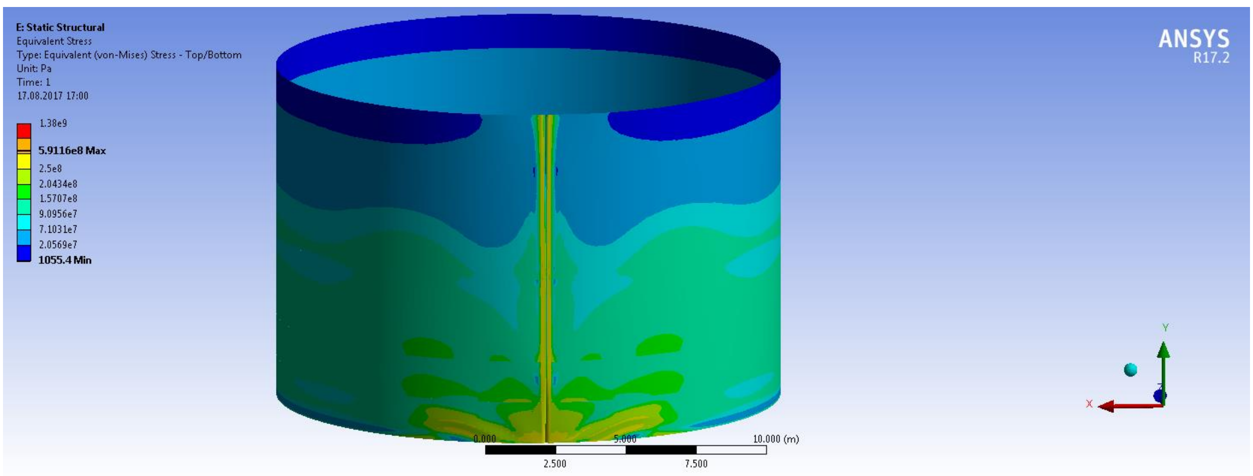


Fig. 7. Distribution of equivalent stresses in the area of the mounting connection with imperfection of the joint at $a=15$ cm, $f=10$ cm

When calculating the stress concentration coefficient at the initial stage, we found a node with the highest value of equivalent stresses σ_{max}, as well as the rated equivalent stresses in the defect-free zone of the tank wall σ_θ. In this case, the stress concentration coefficient was determined from the following expression:

$$K_\sigma = \frac{\sigma_{max}}{\sigma_\theta}. \quad (3)$$

The results of calculations of stress concentration coefficients using the ANSYS software package at various values of dimensionless parameters of the imperfection of the joint are given in Table 1.

The results of the calculation of the stress concentration coefficient according to Table 1 demonstrate that with increasing dimensionless parameters $\varsigma = f/t$ and $\xi = r_b/\sqrt{R \cdot t}$, the K_σ values increase.

Table 1

Results of the calculation of the coefficient of concentration of stresses K_σ in the zone of imperfection of the mounting joint of the wall of the cylindrical tank

Dimensionless parameter $\xi = \frac{r_b}{\sqrt{R \cdot t}}$	Dimensionless joint deflection values, $\varsigma = \frac{f}{t}$									
	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50
1.87	1.487	1.761	1.775	1.818	1.859	1.889	1.917	1.946	1.977	2.009
1.68	1.495	1.763	1.783	1.836	1.873	1.905	1.937	1.971	2.002	2.037
1.49	1.502	1.765	1.796	1.851	1.885	1.920	1.956	1.994	2.030	2.066
1.31	1.550	1.769	1.815	1.865	1.903	1.945	1.987	2.030	2.071	2.108
1.12	1.661	1.775	1.836	1.883	1.928	1.973	2.016	2.059	2.116	2.172
0.93	1.753	1.784	1.855	1.904	1.954	2.014	2.066	2.128	2.201	2.273
0.75	1.761	1.800	1.872	1.933	1.995	2.061	2.146	2.234	2.311	2.384
0.56	1.762	1.820	1.899	1.974	2.062	2.176	2.284	2.380	2.468	2.546

Following ratio (1), interpolation polynomials for approximating the stress concentration coefficient are considered as a dependence on two independent variables: $K_\sigma = \alpha(\zeta, \xi)$. Then the interpolation polynomials are represented in the following form:

$$K_\sigma^T = \sum_{i=0}^{4} B_i(\zeta)\xi^i \alpha; \quad (4)$$

where

$$B_i(\varsigma) = \Sigma_{i=0}^{8} b_i \varsigma^i; \ \xi = \frac{r_b}{\sqrt{R \cdot t}}; \ \varsigma = \frac{f}{t}.$$

To construct this dependence, a two-stage application of the method of least squares was carried out. First, a polynomial approximation of the dependence $K_\sigma(\xi)$ was performed at each of the specified values of the parameter σ, then an approximate polynomial dependence of the obtained coefficients of the approximating polynomials on ξ was constructed.

To build an interpolation polynomial, the data from Table 1 were used.

$$K_\sigma = \begin{pmatrix} 9 \quad 34.820\varsigma + 51.233\varsigma^2 + 4.828\varsigma^3 - \\ -92.993\varsigma^4 + 110.249\varsigma^5 - 60.477\varsigma^6 + \\ +16.520\varsigma^7 - 1.818\varsigma^8 \end{pmatrix} +$$

$$+\begin{pmatrix} 9 - 68.83\varsigma + 224.56\varsigma^2 - 408.82\varsigma^3 + \\ +454.87\varsigma^4 - 317.13\varsigma^5 + 135.45\varsigma^6 - \\ -32.44\varsigma^7 + 3.339\varsigma^8 \end{pmatrix}\xi +$$

$$+\begin{pmatrix} 9 - 73.80\varsigma + 257.28\varsigma^2 - 496.76\varsigma^3 + \\ +581.33\varsigma^4 - 422.87\varsigma^5 + 187.123\varsigma^6 - \\ -46.156\varsigma^7 + 4.86\varsigma^8 \end{pmatrix}\xi^2 +$$

$$+\begin{pmatrix} 9 - 67.80\varsigma + 217.80\varsigma^2 - 390.58\varsigma^3 + \\ +428.48\varsigma^4 - 294.90\varsigma^5 + 124.51\varsigma^6 - \\ -29.514\varsigma^7 + 3.009\varsigma^8 \end{pmatrix}\xi^3 +$$

$$+\begin{pmatrix} 9 - 68.87\varsigma + 224.86\varsigma^2 - 409.63\varsigma^3 + \\ +456.04\varsigma^4 - 318.12\varsigma^5 + 135.94\varsigma^6 - \\ -32.57\varsigma^7 + 3.353\varsigma^8 \end{pmatrix}\xi^4. \quad (5)$$

Thus, an interpolation polynomial was derived, taking into consideration the imperfections of the mounting joint of the cylindrical tank wall.

5. 2. Analyzing the stress concentration of the mounting joint of the tank while taking into consideration the geometric dimensions of the imperfection

Our calculations of the stress concentration coefficient depending on the geometric dimensions of the imperfection of the mounting joint were performed using the ANSYS software package and applying polynomial (5). The results of the comparison are given in Table 2.

Table 2 demonstrates that the relative error of the results is not more than 1 %, that is, it is within acceptable limits.

The resulting dependences of the stress concentration coefficient K_σ on the dimensionless bend depth of the junction σ and the dimensionless width of the imperfection of the joint ξ confirmed the determining effect exerted on the concentration of stresses in the junction zone by its depth *f*. At the same time, the obtained dependences of the stress concentration coefficient on the parameters of the imperfection of the joint are important from the point of view of deriving an engineering empirical calculation formula.

Table 2

Comparison of the stress concentration coefficient values obtained by the calculation in ANSYS and the results obtained from the polynomial

$\varsigma = \frac{f}{t}$	$\xi = \frac{r_b}{\sqrt{R \cdot t}}$	K_σ		Relative error
		based on ANSYS	polynomial (5)	
12.5	0.654006	2.463818	2.407924	0.022686
12.5	0.840864	2.333172	2.31466	0.007934
12.5	1.5883	2.056622	2.090333	–0.01639
12.5	1.401441	2.085425	2.118964	–0.01608
12.5	1.214582	2.13618	2.156977	–0.00974
12.5	1.027723	2.22376	2.203875	0.008942
12.5	1.775158	2.023336	2.042371	–0.00941
11.875	0.654006	2.424627	2.369812	0.022608
10.625	0.840864	2.22591	2.218303	0.003418
9.375	1.5883	1.963716	1.968443	–0.00241
8.125	1.401441	1.952477	1.939156	0.006823
6.875	1.214582	1.934255	1.923273	0.005677
5.625	1.027723	1.917171	1.911274	0.003076
4.375	1.775158	1.799064	1.747861	0.028461

6. Discussion of results of assessing the stressed-strained state of the mounting joint of the wall of the cylindrical tank

The results of our calculations of equivalent stresses on the outer surface of the tank for different values of bending and width of imperfection of the mounting joint of the tank wall are shown in Fig. 4–7. The above figures substantiate the initial assumption about the change in the stress field and significant concentrations of stresses in the zone of defects in the shape of the mounting joint. It follows from the results of the calculation of the stress concentration coefficient, according to Fig. 4–7 and Table 1, that with an increase in the dimensionless parameters σ and ξ, the values of the stress concentration coefficient K_σ increase.

Numerical analysis of the stressed-strained state of tanks with joint imperfections in the ANSYS programming environment was used to estimate the stressed-strained state of the reservoir for various values of the parameters of the bends of the joint σ and ξ. The dependences of the stress concentration coefficient on the geometric dimensions of the imperfection, radius, and thickness of the tank wall were also obtained.

As a result of our calculations, an interpolation polynomial (5) was built, an approximating coefficient of stress concentration K_σ, which can be used to assess the strength, durability, and residual life of the tank. Additionally, our results can be used to normalize the limit dimensions of the imperfection of the joint and establish the values of the coefficient by taking into consideration the features of the operation of structures at stress concentrations.

The resulting dependences of the stress concentration coefficient K_σ on the dimensionless bend depth of the junction σ and the dimensionless width of the imperfection of the joint ξ confirmed the determining effect exerted on the concentration of stresses in the joint zone by the depth *f* of the defect. At the same time, the obtained dependences of the stress concentration coefficient on the parameters of the imperfection of the joint are important from the point of view of deriving an engineering empirical calculation formula.

Given the limited application of the dependence of the concentration of stresses on the size of the imperfection of the mounting joint, subsequent studies can focus on building a more perfect mathematical model for determining the concentration of stresses in the defect zone. In particular, such a model should take into consideration other operational factors and the shape of imperfection of the joint.

We would like to note that the current paper is part of the research conducted within the study of the actual operation of vertical cylindrical tanks for oil and petroleum products. In the future, there is a need for full-scale studies of the stressed-strained state of tank structures with various geometric imperfections of the mounting joints. At the same time, the results obtained can be used in the tasks of assessing the strength, durability, and residual life of tanks, taking into consideration the concentration of stresses in the area of the mounting joint.

7. Conclusions

1. Comparative results of our calculations of the stress concentration coefficient depending on the geometric dimensions of the imperfection of the mounting joint are presented. The obtained coefficient of stress concentration K_σ depending on the dimensionless bend depth of the junction σ and the dimensionless width of the imperfection of the joint ξ confirmed the determining effect exerted on the concentration of stresses in the junction zone by the depth *f* of the defect. As a result of the calculation of the coefficient of stress concentration K_σ in the zone of imperfection of the mounting joint of the wall of the cylindrical tank, it was revealed that with an increase in the dimensionless parameters σ and ξ, the K_σ values increase to 77 %.

The resulting interpolation polynomial and the approximating stress concentration coefficient can be used to assess the strength, durability, residual life of the tank and to normalize the maximum dimensions of the imperfection of the mounting joint of the tank.

2. A numerical analysis of the stressed-strained state of tanks with joint imperfections in the ANSYS programming environment was used to estimate the stressed-strained state of the tank in the zone of defects in the mounting joint of the vertical cylindrical tank. The dependence of the stress concentration coefficient in the zone of imperfection of the mounting joint of the wall of the cylindrical tank on the geometric dimensions of the defect and the tank has also been established. It was found that the relative error of the calculation results is within the permissible limits, amounting to no more than 1 %.

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