

A multi-level mathematical model was used to estimate the stressed-strained state of a cylindrical reservoir with a defect in the wall shape in the form of a dent; the concentration of stresses in the defect zone was studied.

The proper choice of the mathematical model was verified; it has been shown that the engineering assessment of the stressed-strained state of the wall of a cylindrical tank with the variable thickness could employ ratios for a cylindrical shell with a constant wall thickness. The spread of values is 2–10 %. This indicates the proper choice of the mathematical model, as well as the fact that it is possible, for an engineering assessment of the stressed-strained state of the wall of a cylindrical tank with variable thickness, to use the ratios for a cylindrical shell with a constant wall thickness.

The stressed-strained state of the dent zone in the tank wall was numerically estimated, which proved the assumption of significant stress concentrations in the dent zone and indicated the determining effect on the concentration of stresses in the dent zone exerted by its geometric dimensions and its depth in particular.

The concentration of stresses in the zone of dents in the tank wall was investigated in the ANSYS programming environment at different sizes of dents on the tank wall, for which two dimensionless parameters were introduced: the dimensionless radius of the dent and the dimensionless depth of the dent.

Based on the results of a numerical study into the stressed-strained state of the dent zone in the tank wall, graphic dependences were derived of the stress concentration coefficient on the dimensionless depth of the dent for various values of the dimensionless radius of dents, which does not exceed 2 % of the indicator.

Based on fitting the stress concentration curves on the dimensions of the dent and tank, a formula was derived for calculating the stress concentration coefficient as a function of the dimensionless radius  $\xi$  and the dimensionless depth  $\zeta$  of the dent. The resulting formula makes it possible, with known dimensionless parameters of the depth and radius of the dent, to determine the coefficients of stress concentration in the dented zone of the tank wall

**Keywords:** steel tank, stress concentration, defects in the form of dents, dimensionless parameters of dents, numerical method, modeling

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# ESTIMATION OF THE STRENGTH OF VERTICAL CYLINDRICAL LIQUID STORAGE TANKS WITH DENTS IN THE WALL

**Ianbator Suleimenov**

Doctor of Technical Sciences, Professor  
Department of Architecture\*\*\*

**Nurlan Zhanabay**

Corresponding Author

PhD, Associate Professor\*

E-mail: Nurlan.zhanabay777@mail.ru

**Akmaral Utelbayeva**

Doctor of Chemical Sciences, Associate Professor  
Department of Chemistry\*\*\*

**Masrah Azrifan Azmi Murad**

PhD Doctor, Professor, Deputy Dean (Research and Graduate Studies)  
Universiti Putra Malaysia

UPM Serdang, Selangor Darul Ehsan, Malaysia, 43400

**Aibarsha Dosmakanbetova**

PhD, Associate Professor

Department of Mechanics and Mechanical Engineering

Mukhtar Auezov South Kazakhstan University

Tauke Khan ave., 5, Shymkent, Republic of Kazakhstan, 160012

**Khasse Abshenov**

PhD, Associate Professor\*\*

**Svetlana Buganova**

PhD, Associate Professor

Department of Building Technologies, Infrastructure and Management

International Education Corporation

Ryskulbekova str., 28, Almaty, Republic of Kazakhstan, 050043

**Arman Moldagaliyev**

PhD, Associate Professor\*\*

**Kuanysh Imanaliyev**

PhD, Associate Professor

Department of Architecture\*\*\*

**Bolat Duissenbekov**

PhD\*

\*Department of Construction and Construction Materials\*\*\*

\*\*Department of Mechanics and Mechanical Engineering\*\*\*

\*\*\*Mukhtar Auezov South Kazakhstan University

Tauke Khan ave., 5, Shymkent, Republic of Kazakhstan, 160012

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## 1. Introduction

The main link of the facilities for storing oil and petroleum products is vertical steel cylindrical tanks, the inten-

sification of whose construction and whose maintenance in working condition will continue [1–3]. At the same time, vertical cylindrical tanks are categorized as particularly responsible structures, the destruction of which could lead

to environmental disasters, significant material costs, and human casualties. The construction and operation of tanks should be based on reasonable scientific, technically feasible, fundamentally new structural, and economically justified solutions. That leads to the need to intensify the study on the development of a scientific basis for assessing the strength, stability, and durability of vertical cylindrical tanks, taking into consideration real operating conditions [4–9].

Despite the constant improvement of the technology of manufacturing, installation of vertical cylindrical tanks, full accounting in the calculations of operational loads, there are still geometric imperfections in their shapes. These imperfections have a significant impact on the stressed-strained state of the tank structure and lead to the concentration of stresses.

The experience of operation of vertical cylindrical tanks indicates that the most likely places of origin and development of destruction are stress concentrators such as shape defects, welds and joints, tie-ins and openings, mechanical damage, geometric imperfections [10–13]. One of the most dangerous, unpredictable, and poorly studied zones, in terms of stress concentration, for vertical cylindrical tanks are dented zones.

In this regard, it is a relevant task to study the features of the stressed-strained state of the dented zone in the walls of cylindrical tanks, as well as assess the concentration of stresses taking into consideration this defect.

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## 2. Literature review and problem statement

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Despite the constant improvement of the technology for the manufacture and installation of cylindrical tanks, the calculations of the stressed-strained state of the tank wall do not fully consider operational loads and the influence of dents of various shapes. Thus, in [14], only the issue of repairing dents through carbon fiber reinforcement was considered, in order to restore the bearing capacity. To this end, tank models have been developed to demonstrate how repairing dents using a polymer affects the tank's recovery processes. A given technology requires significant additional funds and does not guarantee the service life since there is no analysis regarding the geometric dimensions of the dent and durability, taking into consideration the residual life of the tanks. Study [14] did not assess the strength of the wall of the tank with a dent, taking into consideration the concentration of stresses in the defect zone, which could significantly save additional reinforcement costs.

In [15], scientists considered the issue of linear steel structures in the form of underground gas and oil pipelines with defects such as corrosion, dents, and cracks that violate the integrity of the linear structure. This circumstance could lead to irreversible processes in the form of an environmental catastrophe. However, the cited study addressed the issue of linear shell structures only, while the issue of durability of vertical steel shell structures was not considered. It should be noted that the consideration and forecasting of vertical structures cannot be considered by similar procedures used in linear structures, even if they relate to shell steel structures. It should be noted that a study in the field of assessing the strength of the wall of vertical shells with a dent, taking into consideration the concentration of stresses in the defect zone, could generally supplement the section of shell metal structures.

Paper [16] reports a procedure for determining elastic deformations in the wall of a steel vertical tank in the form of a dent. The procedure takes into consideration the effect

exerted on the stress amplitude by four parameters such as deflection boom, the height and relative width of the dent, the minimum thickness of the tank wall in the dent zone. The authors substantiate the chosen calculation methodology, based on selecting the calculation scheme for determining the stressed-deformed state and an elliptical dent, based on which analytical dependences were derived. The cited study provides minimal information about the parameters of the dent and the shape of the dent since the dents considered are only in the form of an ellipse, that is, proper dents. However, if the geometry of the dent has a complex shape, it is advisable, when making calculations, to use a spherical scheme for idealizing the shape of the dent. Thus, considering irregularly shaped dents, such as spherical, could favorably complement research.

The imposed restrictions on the defect of the "Dent" type in steel tanks in accordance with regulatory documents on the design and operation of steel tanks in different countries are given in work [17]. In addition, the results of modern studies into the formation and influence of that defect on the stressed-strained state of the tank are reported. However, the question of durability and the absence of a mathematical dependence of the stress concentration coefficient in the dent zone on their geometric dimensions of complex dents in an extensive form, taking into consideration the continuous and variable wall thickness of the steel vertical tank, was not considered. In this regard, a study of this kind could positively complement the research conducted earlier.

Work [18] addresses the issue of the durability of the structure against a corrosion process of the shell of vertical steel tanks, which is due to the thinning of the wall thickness. The study under consideration could be positively supplemented when considering corrosion processes, taking into consideration the complex dents formed on the wall of the structure.

The task to assess the safe service life of steel vertical cylindrical tanks requires full coverage and indicates an integrated approach to estimating the residual life of the structure, taking into consideration various defects. Study [19] highlights the issue of increasing corrosion rate over time, as well as analyzes the calculation of residual service life. Despite extensive research, the cited work ignored the issues of an alternating wall and its effect on the residual resource while the indicator of the stress concentration coefficient was not considered. At the same time, the dent was considered only in the lower layers of the tank. Taking into consideration [19], the current study could fully complement the previously reported results.

A procedure for predicting the durability of shell structures, taking into consideration the geometric dimensions and parameters of defects, could positively complement study [20] on the seismic resistance of linear structures in the form of a large-diameter pipeline. In it, pre-stress is used as a solution to increase the strength of dynamic influences. Thus, for example, prestressing in the pipeline is carried out by winding a high-strength profile on the pipeline body. However, the cited study does not take into consideration the defects formed on the shell itself, which is an important indicator of the durability of the steel structure itself and cost savings in general.

Since, according to the authors of [21], corrosion tends to deepen at the sites of the defect, a study in the field of predicting the durability of the shell structure in question, taking into consideration complex local defects, could positively complement the cited works. In particular, we are

talking about studies that tackle the durability of the structure, taking into consideration the corrosion process. This would also help solve a series of tasks in the field of corrosion with the difference in the thickness of the shell wall and the influence of corrosion.

The results of the reviewed works [14–21] demonstrate general issues of forecasting the durability of steel shell structures, which significantly affect further operation. However, this does not make it possible to accurately assess the effect of various types of defects in the form of complex dents on the service life, taking into account the stress concentration in the dent zone.

There are not enough studies to predict the durability of shell structures in a vertical steel cylindrical tank, taking into consideration the formations on the wall of the structure in the form of dents. Practically, standards [22–24] lack studies into the methodology for calculating the strength and durability of tanks with dents in the wall, there is no procedure for assessing the resource and geometric dimensions of dents. The results of such studies could be applied to assess the risk of such defects in horizontal and vertical reservoirs, tanks, gas tanks, pressure vessels, apparatuses, and main pipelines.

Our review of studies of steel cylindrical tanks reveals that the existing regulatory documents for the design of vertical cylindrical tanks for petroleum products do not contain methods for taking into consideration the features of the stressed-strained state in the dented zone. This circumstance requires their development and implementation as soon as possible.

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### 3. The aim and objectives of the study

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The purpose of this study is to numerically assess the stressed-strained state of the dent zone in the wall of a cylindrical tank and to identify the dependence of the stress concentration on the geometric parameters of the dent and the size of the tank. This will make it possible to predict the service life of vertical steel tanks, taking into consideration defects; the resulting dependences could be used in the design of such structures.

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

- to devise a procedure and verify the results of numerical simulation of the stressed-strained state of tanks with dents in the wall in the ANSYS programming environment;
- to examine the stressed-strained state of the wall of cylindrical tanks with a dent in the wall;
- to investigate the concentration of stresses in the area of dents in a tank wall in the ANSYS programming environment;
- to establish the dependence of the stress concentration coefficient on the parameters of the dent and the size of the tank.

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### 4. The study materials and methods

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When performing this study, we used the methods of shell theory, a finite-element method, the methods of computer modeling in the ANSYS programming environment, numerical modeling of the stressed-strained state of tank structures with a dent in the wall.

The methodology of scientific research is based on theoretical studies. At the first stage, we built a mathematical

model and idealized the shape of a dent. At the second stage, we simulated the stressed-strained state of a tank wall without geometric imperfections of the shape and with a dent in the wall. At the final stage of our study, the dependence of stress concentration on the geometric dimensions of dents was established.

This paper examines the static stressed-strained state of vertical cylindrical tanks filled with fuel oil with stress concentrators in the wall in the form of dents. The shape and size of the dent in the tank wall, which affect the stress concentration in the defect zone, is subjected to numerical analysis.

It is assumed that the shell is made of isotropic material, which is in the region of elasticity. Stresses and deformations obey Hooke's law. Displacements and deformations are assumed to be small. Therefore, Cauchy's linear formulas are valid.

To solve this task, the most effective is to apply a finite-element method, which is implemented using the ANSYS software package.

A numerical study of the stressed-strained state of tank structures, like any other structure, requires the replacement of actual structures with its mathematical model. The chosen mathematical model should possess the basic properties of the estimated full-scale structure and, at the same time, should be simple enough and suitable for engineering calculations.

The choice of a design scheme for numerical simulation of the stressed-strained state of the wall of a vertical cylindrical tank with a dent with a known topography of the defect when using finite-element packages of the ANSYS software is not a difficult task. The programming environment allows an engineer to build and calculate models of any complexity, to construct an optimal design scheme, by moving from a more complex and maximally real structure to a simpler computational scheme.

It should be noted that the tank design standards, according to which vertical cylindrical steel tanks for oil and petroleum products are diagnosed, do not require detailed measurements of the topography and geometry of local defects in the form of dents. Technical reports and survey reports provide minimal information about the parameters of the dent, often the depth, height, and location of the dent.

This circumstance and the need to derive simple empirical estimation formulas for assessing the stressed-strained state require the idealization of the shape of the dent and the development of a model for several basic parameters that determine the peculiarity of the stressed-strained state of the dent zone.

Typically, when idealizing the shape of a dent in the wall of a cylindrical shell, models of spherical and round dents are considered [25]. Comparison of the stress calculation results for these two models of dent shape idealization in the finite-element analysis of cylindrical shells with the results of experiments was carried out by the author of [25]. It is shown that the concentration coefficient of the maximum principal stresses differs little from the values obtained experimentally. However, the maximum stresses and their corresponding stress concentration coefficients for spherical dents were greater than for round dents. It is concluded that the spherical schematization of dents produces results that determine the margin of safety.

Comparison of maximum equivalent stresses for elliptical dents located at an angle, according to Fig. 1, with stresses in the round and spherical idealized dents showed

a satisfactory match with the results reported in [25]. The margin of safety when using spherical idealization of the shape of the dent in comparison with the ellipsoidal could be 12–30 %. Calculations have shown that this pattern persists for dents of various shapes.

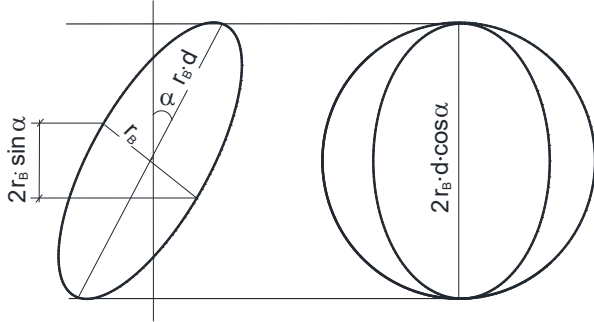


Fig. 1. Idealization of the shape of an ellipsoidal inclined dent into a spherical one

It could be concluded that in the case when the geometry of a dent is unknown except for the basic dimensions, or when the shape of a dent is complex, it is advisable, in calculations, to use a spherical scheme for idealizing the shape of the dent.

## 5. Results of studying the stressed-strained state of the dented zone in a tank wall

### 5.1. Procedure and verification of the results of numerical simulation of the stressed-strained state of tanks with dents in their walls

The study of the stressed-strained state of the defect zone in the form of dents in the wall of cylindrical shells is a difficult task.

Given this, multi-level mathematical models were used in the modeling methodology. At the first level, the stressed-strained state of the cylindrical shell operating under internal pressure was considered. At the next stage, a cylindrical tank with a wall of constant thickness was considered; and then a vertical cylindrical tank with a wall of variable thickness of a typical structure. At the final stage, a defect in the form of a dent in a tank wall was simulated and the stressed-strained state of the dented zone was investigated. The use of a multi-level model and the gradual complication of the model would make it possible to choose correct estimation parameters, ensure the convergence of calculations, and make it possible to avoid errors in calculations.

The initial model considered in the first task is a cylindrical shell loaded with an internal pressure that rests on a basis.

The shell is under constant internal pressure  $p_0$ . The shell thickness is  $h$ , the radius of the base of the shell is  $R$ , the modulus of elasticity of the shell material is  $E$ , the Poisson coefficient is  $\nu$ . The stressed-strained state of such a shell is axisymmetric. Therefore, it depends only on the longitudinal coordinate  $x$  and does not depend on the angular coordinate  $\theta$ . The axisymmetric deformation of the shell is described by one ordinary differential equation with respect to the radial deflection  $w$  [26, 27]:

$$\frac{d^4 w}{dx^4} + 4\beta^4 w = \frac{p_0}{D}, \quad (1)$$

where  $D = \frac{Eh^3}{12(1-\nu^2)}$  is the cylindrical stiffness;  $\beta^4 = \frac{Eh}{4R^2 D}$ .

According to work [26], for a wide range of cylindrical shells, the solution to equation (1) could be represented as follows:

$$w(x) = \exp(-\beta x)(C_1 \cos \beta x + C_2 \sin \beta x) + \frac{p_0}{4\beta^4 D}, \quad (2)$$

where  $C_1, C_2$  are the constants of integration, which, for a console shell, take the form:

$$C_1 = C_2 = -\frac{p_0}{4\beta^4 D}. \quad (3)$$

The solution to (2) consists of two components. The first term describes the boundary effect in the shell. It is of great importance near pinching and quickly fades with increasing coordinate  $x$ . The second term describes the stressed state that prevails over most of the shell. It is this component that is the subject of research in the theory of shells.

The stressed state in such shells is characterized by radial stress  $\sigma_r$ , circumferential stress  $\sigma_\theta$ , longitudinal stress  $\sigma_x$ , and tangential stress  $\tau_{r\theta}$ . Based on the theory of cylindrical shells [26, 27], the predominant stresses are the circumferential stresses  $\sigma_\theta$ . With this deformation of the structure, all other components are negligible. In tanks, the circumferential stresses  $\sigma_\theta$  would also be the predominant component of the stressed-strained state of the structures. Based on shell theory, the circumferential integrated force factors  $N$  are determined from the following expression:

$$N_\theta = -\frac{Eh w}{R}. \quad (4)$$

Once a constant component for the cylindrical shell (2) is used in ratio (4), it could be determined that the circumferential stresses in the structure are in the following form:

$$\sigma_\theta = \frac{p_0 R}{t}. \quad (5)$$

We emphasize that ratio (5) is used to calculate the circumferential stresses in tanks of constant thickness [26, 27].

A cantilevered cylindrical shell of constant thickness, which is fixed in the base, assuming that it is filled with liquid inside, was considered. The height to which the liquid is poured is  $h$ . Then the pressure acting from the inside on the shell is calculated from the following expression:

$$P_0 = -\gamma(x-h), \quad (6)$$

where  $\gamma = pg$  is the specific gravity of the liquid;  $p$  is the density of the liquid filling the tank.

After introducing an expression for determining pressure (6) into equation (1), the general solution of this equation is represented as:

$$w(x) = \exp(-\beta x) \left( \begin{matrix} C_1 \cos \beta x + \\ + C_2 \sin \beta x \end{matrix} \right) - \frac{\gamma(h-x)R^2}{Et}, \quad (7)$$

where  $C_3, C_4$  are the integration constants.

Since at a distance from the pinched edge of the shell the first component in (7) quickly fades, the movement in the shell at some distance from the pinching is described by the following expression:



$$w = -\frac{\gamma(h-x)R^2}{Et} \tag{8}$$

Then, using (4) and (5), the circumferential stresses  $\sigma_\theta$  in the shell could be described by the following relation:

$$\sigma_\theta = -\frac{\gamma(h-x)R}{t} \tag{9}$$

Ratio (9) coincides with ratio (5) once one introduces expression (6) to determine the pressure into ratio (5).

The calculation of the shell presented above in the ANSYS programming environment involved the following parameter values:

$$E=2.1 \cdot 10^{11} \text{ Pa}; \nu=0.3; R=0.5 \text{ m};$$

$$h=0.5 \cdot 10^{-2} \text{ m}; p_0=1 \cdot 10^5 \text{ Pa}; L=5 \text{ m}.$$

For these parameter values, the magnitude of the circumferential stresses  $\sigma_\theta$  is constant except for the area exposed to the boundary effect, that is, near the sealed part of the shell. The circumferential stresses were determined from formula (5):

$$\sigma_\theta=1 \cdot 10^7 \text{ Pa}.$$

Calculations were carried out in ANSYS R15.0. Shell 281 with 8 nodes was chosen as a finite element. To study convergence, our calculations involved 40 and 100 finite elements in the circumferential direction.

Fig. 2 shows the results of calculations in the ANSYS software package in the form of equivalent stresses on the deformable shell when sampling with 40 and 100 finite elements in the circumferential direction.

It is noted that the stressed-strained state of each point of the shell body, the circumferential stresses  $\sigma_\theta$  predominate while all the other components of the stress tensor are negligible. Therefore, the chosen equivalent stresses are the circumferential stresses  $\sigma_\theta$ ; we take into consideration that significant changes in equivalent stresses are observed in the pinching node of the shell to the base, which is due to the edge effect in the pinching zone. In this regard, the results from our finite-element calculations could be considered correct.

At the second stage of modeling, the stressed-strained state of a typical vertical cylindrical tank with a volume of 3,000 m<sup>3</sup> was considered [28].

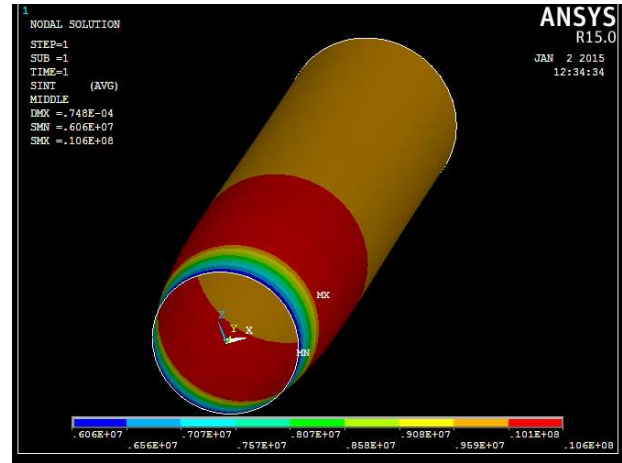
The shell of the tank is cylindrical, made of steel. The wall thickness is assumed to be constant for height.

The calculation was performed for the following data:

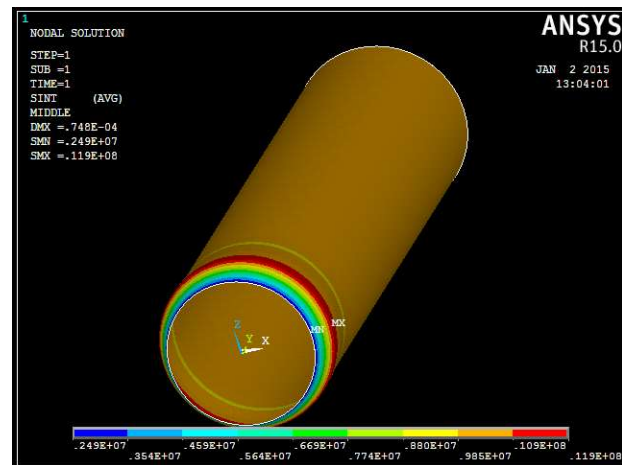
$$E=2.1 \cdot 10^{11} \text{ Pa}; \nu=0.3; R=21.22 \text{ m};$$

$$t=0.5 \cdot 10^{-2} \text{ m}; p_0=1 \cdot 10^5 \text{ Pa}; h=10.728 \text{ m}.$$

Our analysis of the results from calculating the equivalent stresses shown in Fig. 3 shows that the bottom of the tank is not loaded. The most loaded structure is the tank housing. There is a significant contribution of the circumferential stresses  $\sigma_\theta$  to the general stressed-strained state of the tank body. The values of radial and longitudinal stresses are extremely small. The circumferential stresses  $\sigma_\theta$  in the circumferential and longitudinal directions are constant.



a



b

Fig. 2. Equivalent stresses on the deformable shell: a – shell at sampling 40; b – shell at sampling 100

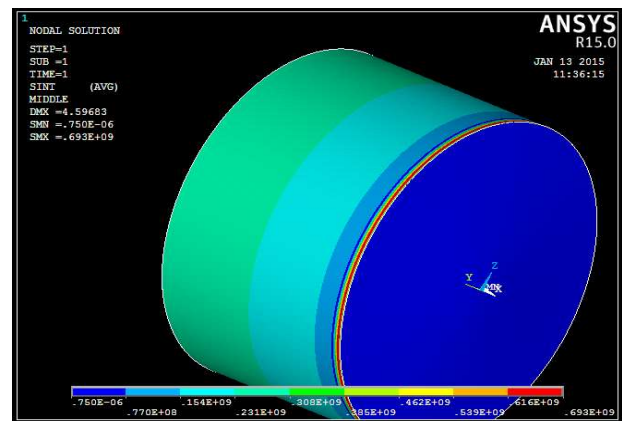


Fig. 3. Results of the calculation of equivalent stresses of the median surface of the tank with a constant wall thickness

Table 1 gives the results of a comparison of equivalent  $\sigma_i$  and circumferential  $\sigma_\theta$  stresses of the median surface of the shells as a function of the longitudinal  $x$  coordinate.

Note that the values of the circumferential stresses  $\sigma_\theta$  were calculated from (9) and compared with the results obtained from a calculation using the ANSYS software package.

At the next stage of the numerical study, we considered the stressed-strained state of the tank wall of variable thickness in accordance with Fig. 4 [28].

Table 1

Comparing the results of equivalent  $\sigma_i$  and circumferential stresses  $\sigma_\theta$  of the median surface of the shell

Coordinate of the estimated point $x$ , m	Equivalent stresses, $\sigma_i$ , Pa	Circumferential stresses, $\sigma_\theta$ , Pa
1.0728	0.14251E+09	0.118E+08
1.2516	0.13859E+09	0.118E+08
2.2052	0.15865E+09	0.158E+08
2.5032	0.15800E+09	0.158E+08
3.2184	0.19150E+09	0.19E+08
3.4568	0.19107E+09	0.19E+08
3.8144	0.19007E+09	0.19E+08
4.4104	0.18994E+09	0.19E+08
4.7680	0.18997E+09	0.19E+08
5.1256	0.19005E+09	0.19E+08
5.3640	0.18952E+09	0.19E+08
6.1984	0.24439E+09	0.238E+08
6.4368	0.23993E+09	0.238E+08
6.6752	0.23778E+09	0.238E+08
8.8208	0.23745E+09	0.238E+08
10.728	0.23745E+09	0.238E+08

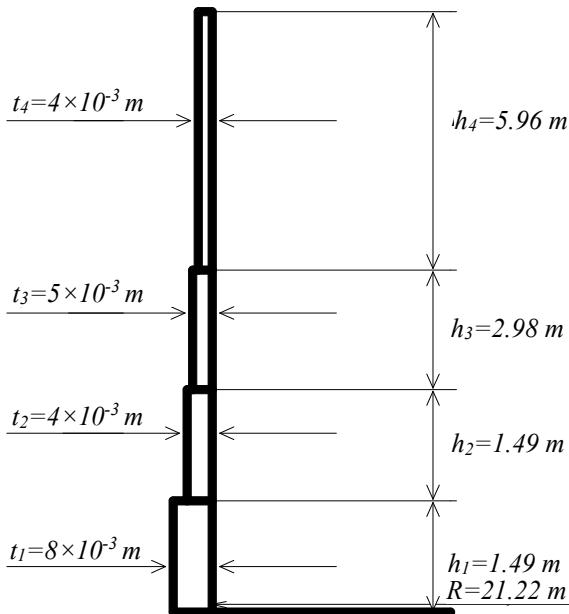


Fig. 4. Cross-section of a vertical cylindrical tank

Assume that the tank is completely filled ( $h=11.92$  m) with a liquid whose volumetric weight is  $\gamma=8,820$  kg/m<sup>2</sup>s<sup>2</sup>.

In the problem, the pressure acting on the tank wall is taken to satisfy equation (6).

The results of the calculation in the ANSYS software package of the tank design under consideration are shown in Fig. 5 and given in Table 2.

Our analysis of the calculation results reveals that the magnitude of the equivalent stresses  $\sigma_i$  coincide with the circumferential stresses  $\sigma_\theta$ . The circumferential stresses are constant in the circumferential direction, but, due to the fact that the cross-section of the shell wall is variable in the longitudinal direction, the values of the circumferential stresses change in this direction.

The values for the circumferential stresses  $\sigma_\theta$  were derived by an analytical solution, using ratio (9) for each section of the shell with a changed thickness.

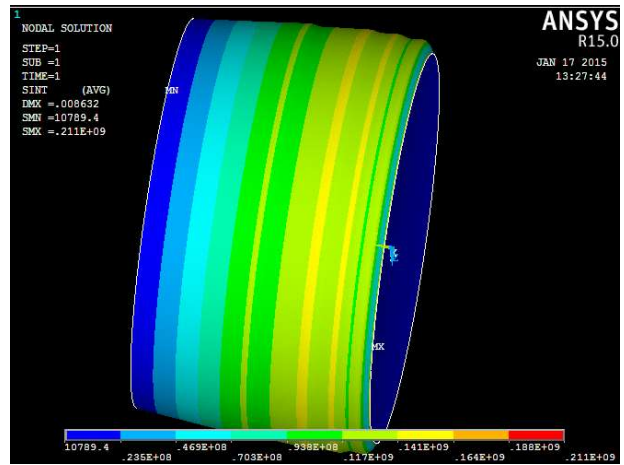


Fig. 5. Results of the calculation of equivalent stresses of the median surface of a tank with variable wall thickness

Table 2

Results of comparing the calculated values of equivalent stresses  $\sigma_i$  and circumferential stresses  $\sigma_\theta$  in the tank wall

Coordinate of estimated point, $x$ , m	Equivalent stresses, $\sigma_i$ , Pa	Circumferential stresses $\sigma_\theta$ , Pa
1.3112	0.12294E+09	1.11113E+08
1.7880	0.14321E+09	1.41493E+08
2.5032	0.13125E+09	1.31505E+08
3.2184	0.14962E+09	1.45821E+08
4.0528	0.13178E+09	1.31838E+08
5.1256	0.11389E+09	1.13860E+08
6.1984	0.12359E+09	1.19853E+08
7.1520	0.99855E+08	9.98776E+07
8.3440	0.74893E+08	7.49082E+07
8.8208	0.64907E+08	6.49204E+07
9.5360	0.49928E+08	4.99388E+07

Table 2 demonstrates that the results of circumferential stress calculations obtained using the ANSYS software package and the analytical solution using ratio (9) are close. This indicates that the ratios for a cylindrical shell with a constant wall thickness could be used to assess the stressed-strained state of the wall of a cylindrical tank with variable thickness.

### 5. 2. The stressed-strained state of the wall of cylindrical tanks with a dent in the wall

The geometric shapes of dents in the tank wall are diverse (spherical, diamond-shaped, elliptical, etc.). Given that dents of various geometric shapes could be idealized into a spherical shape, consider dents of spherical shape with a radius  $r_b$  and a depth  $f$ .

Numerical studies were conducted using the ANSYS software package. A typical vertical cylindrical tank with a volume of 3,000 m<sup>3</sup> was considered [28]. The cross-section of the wall of the estimated tank is shown in Fig. 6.

The following numerical parameters were used in the calculation: modulus of elasticity of the tank structure material  $E=2.1*10^{11}$  Pa, Poisson coefficient  $\nu=0.3$ , internal pressure in the tank  $p_0=1*10^5$  Pa.

A simulation of a dent in the upper belt of the wall with a thickness of  $t=4*10^{-3}$  was performed. Dents of various geometric sizes were considered. The parameters describing the

dent are the depth of the dent  $f$  and the radius of the dent  $r_b$ . To describe the dent, we shall introduce its dimensionless parameters:

– dimensionless radius

$$\xi = \frac{r_b}{\sqrt{R^*t}}; \tag{10}$$

– dimensionless depth

$$\zeta = \frac{f}{t}, \tag{11}$$

where  $R^*$  is the radius of the tank,  $t$  is the thickness of the belt of the tank wall at the dent site.

Assume that the radius of the spherical dent  $R_b$  is related to the radius of the dent  $r_b$  and the depth of the dent  $f$  by the following expression:

$$R_b = \frac{r_b^2}{2f}. \tag{12}$$

The coordinates of the center of the spherical dent are taken as follows:  $(x, y, z) = (21,22; 7,16; 0)$  m.

To simulate the stressed-strained state of the tank structures, a finite-element grid was built in accordance with Fig. 6.

To simulate the stressed-strained state of the defect zone, a finite-element grid was built with a thickening of the grid in the dented zone in accordance with Fig. 7.

The calculation of the fields of equivalent stresses was performed for different values of the dimensionless parameters of the dent  $\xi$  and  $\zeta$ . The results of the calculations of the fields of equivalent stresses in the dent zone for different values of the dimensionless parameters of the dent  $\xi$  and  $\zeta$  are shown in Fig. 8–13.

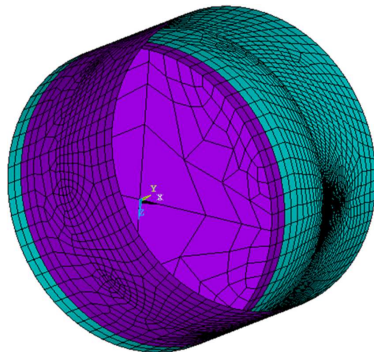


Fig. 6. A finite-element grid of the tank structure

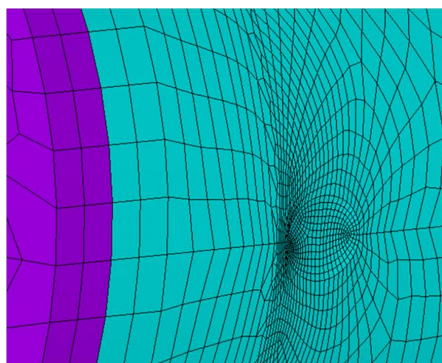


Fig. 7. Fragment of the finite-element grid in the tank wall area

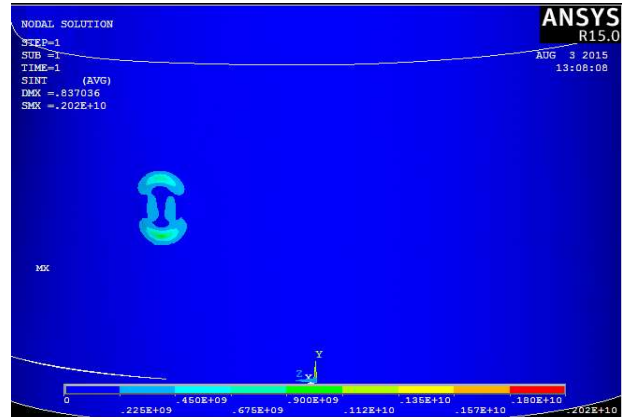


Fig. 8. Fields of equivalent stresses of tank structures with a dent in the wall at dimensionless parameters  $\xi=5$  and  $\zeta=10$

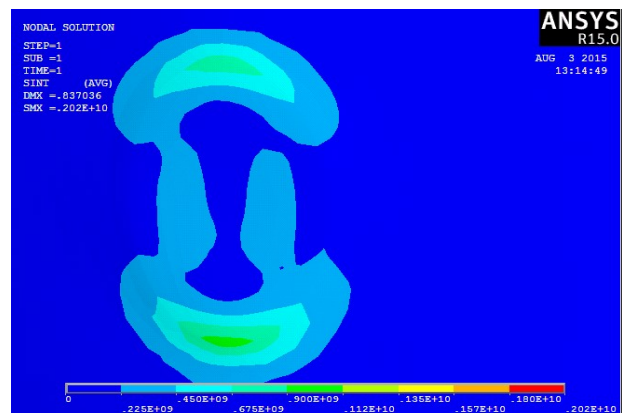


Fig. 9. Fields of equivalent stresses in the dent zone at dimensionless parameters  $\xi=5$  and  $\zeta=10$

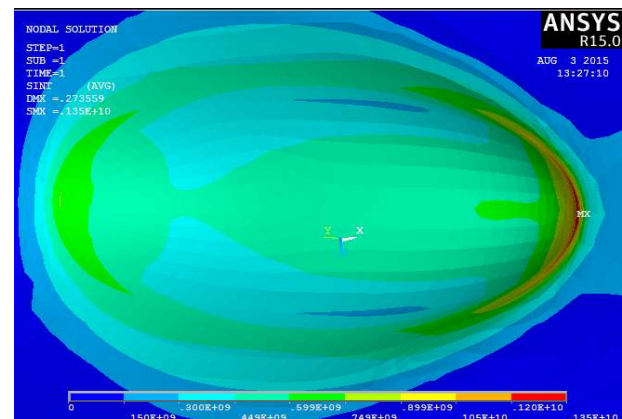


Fig. 10. Fields of equivalent stresses in the dent zone at dimensionless parameters  $\xi=9$  and  $\zeta=10$

The figure shows a significant increase in the values of equivalent stresses in the dent area. Note that the maximum values of equivalent stresses are observed in the lower part of the dent where the hydrostatic pressure of the liquid is greater. Fig. 9 shows an enlarged region of the stress field in the dent zone.

The results of our analysis of the stress field reveal that at high values of the relative depth of the dent  $\zeta$ , the maximum stresses are observed only at the lower boundary of the dent. With small values of the relative depth of the dent  $\zeta$ , the region of maximum stresses shifts up the dent. As an example, the fields of equivalent stresses at high values of the relative



depth of the dent  $\zeta$  are shown in Figs. 10, 12,  $a$ , and the fields of equivalent stresses at small values of the relative depth of the dent  $\zeta$  are demonstrated in Figs. 11, 13.

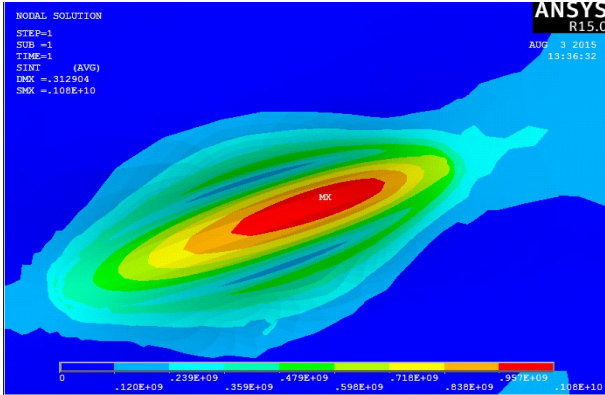


Fig. 11. Fields of equivalent stresses in the dent zone at dimensionless parameters  $\xi=9$  and  $\zeta=4$

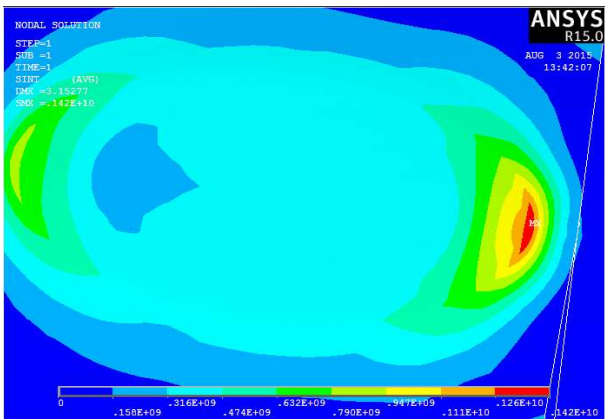


Fig. 12. Fields of equivalent stresses in the dent zone at dimensionless parameters  $\xi=7$  and  $\zeta=18$

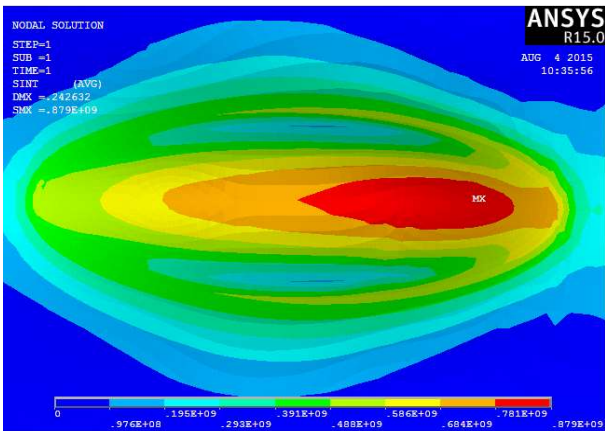


Fig. 13. Fields of equivalent stresses in the dent zone at dimensionless parameters  $\xi=7$  and  $\zeta=4$

It is shown that away from the stress concentrator (dent), to calculate the stressed-strained state, you could use formula (9). For this purpose, the results of the calculation of the circumferential stresses  $\sigma_\theta$ , away from the dent, given in Table 3, were used.

The first column of Table 3 gives the values of the longitudinal coordinate of the estimated points of the tank. The second column shows the values of the circumferential

stresses  $\sigma_\theta$  calculated in Pa, and the third column shows the results of the calculation of circumferential stresses using (9). The results of calculating the circumferential stresses  $\sigma_\theta$ , when applying (9) and when using the ANSYS software package, are close, which proves the possibility of using (9) to calculate equivalent stresses away from the dent.

Table 3

Results of calculating the circumferential stresses,  $\sigma_\theta$ , in the tank wall using the ANSYS software package and applying (9)

Coordinate of estimated point $x$ , m	Circumferential stresses $\sigma_\theta$ , Pa, using ANSYS	Circumferential stresses $\sigma_\theta$ , Pa, using (9)
4.6098	$0.116 \cdot 10^9$	$0.122 \cdot 10^9$
5.2721	$0.166 \cdot 10^9$	$0.114 \cdot 10^9$
5.1933	$0.138 \cdot 10^9$	$0.112 \cdot 10^9$
5.6411	$0.121 \cdot 10^9$	$0.105 \cdot 10^9$
7.1527	$0.9825 \cdot 10^8$	$0.9986 \cdot 10^8$
8.5363	$0.697 \cdot 10^8$	$0.709 \cdot 10^8$

### 5.3. Numerical studies of stress concentration in the dented zone of the tank wall

Experimental and numerical evaluation of the stressed-strained state of the dent zone in the tank wall proved the assumption of significant stress concentrations in the dent zone. There is a decisive influence on the concentration of stresses in the dent zone of its geometric dimensions and especially its depth.

In this regard, at this stage of our study, numerical studies of vertical cylindrical tanks with dents in the wall were carried out in order to establish the dependence of the concentration of stresses in the dented zone on the parameters of the dent and tank.

When calculating the stress concentration coefficient at the initial stage, we searched for a node with the highest value of equivalent stresses  $\sigma_{max}$ , as well as the rated equivalent stresses in the defect-free zone of the tank wall  $\sigma_\theta$ .

In this case, the coefficient of concentration of stresses was determined from the following expression:

$$K_\sigma = \frac{\sigma_{max}}{\sigma_\theta}. \tag{13}$$

In assessing the danger of defects in the form of dents, the main difficulty is due to the fact that the stressed-strained state of the dent is greatly influenced by the topography of the dented surface, which could be very diverse [29].

In a general case, the stressed-strained state of the tank wall in the idealized dent zone under the action of a constant uniformly distributed pressure  $p$  is determined by the depth  $f$  and the radius of the defect  $r=L/2$ , as well as the radius  $R$ , and the thickness  $t$  of the tank wall. Since the stress calculated in the linear setting are proportional to the magnitude of the pressure  $p$ , the coefficient of concentration of stress  $K_\sigma$  does not depend on the operating stresses. In addition, the linear result has the property of similarity: if you multiply all the parameters by the same amount, then all the stresses would change by the same number of times, and the concentration coefficient would not change. The specified multiplier is assumed to be equal to  $1/t$ . Then the coefficient of concentration of stresses is a function of three dimensionless variable ratios  $-f/t, r/t, uR/t$ :

$$K_\sigma = F(f/t, r/t, R/t). \tag{14}$$



Based on the results of research by the authors of [30] and the results reported in [25], the idea was put forward that the determining effect on the concentration of stresses in the dent zone is exerted by the dimensionless depth  $f/t$  (11) and the dimensionless radius  $r/Rt$  (10) of the dent.

The results of calculations of stress concentration coefficients using the ANSYS software package at various values of dimensionless parameters of dents are: dimensionless radius  $\xi$  and dimensionless depth  $\zeta$  of dents are given in Table 4.

Table 4

Results of the calculation of the stress concentration coefficient  $K_\sigma$  in the dent zone in the wall of a cylindrical tank

Dent dimensionless radius $\xi$	Dent dimensionless depth $\zeta$	Dent radius $r_b$ , m	Dent depth $f$ , m	Stress concentration coefficient, $K_\sigma$
1	2	3	4	5
2	4	0.3899	0.016	4.937
2	7	0.3899	0.028	5.3121
2	10	0.3899	0.04	5.406
2	13	0.3899	0.052	5.371
2	15	0.3899	0.06	5.4891
2	18	0.3899	0.072	5.3855
3	4	0.585	0.016	5.672
3	7	0.585	0.028	6.383
3	10	0.585	0.04	6.7322
3	13	0.585	0.052	6.852
3	15	0.585	0.06	6.978
3	18	0.585	0.072	6.906
4	4	0.7797	0.016	6.135
4	7	0.7797	0.028	7.391
4	10	0.7797	0.04	7.405
4	13	0.7797	0.052	7.944
4	15	0.7797	0.06	7.561
4	18	0.7797	0.072	7.714
5	4	0.97	0.016	6.29
5	7	0.97	0.028	8.136
5	10	0.97	0.04	10.02
5	13	0.97	0.052	8.34
5	15	0.97	0.06	8.757
5	18	0.97	0.072	9.0
6	4	1.17	0.016	6.7493
6	7	1.17	0.028	8.4853
6	10	1.17	0.04	10.54
6	13	1.17	0.052	9.204
6	15	1.17	0.06	9.4476
6	18	1.17	0.072	9.598
7	4	1.365	0.016	8.288
7	7	1.365	0.028	8.4469
7	10	1.365	0.04	11.12
7	13	1.365	0.052	10.02
7	15	1.365	0.06	10.09
7	18	1.365	0.072	10.622
8	4	1.5595	0.016	9.6269
8	7	1.5595	0.028	8.4231
8	10	1.5595	0.04	9.849
8	13	1.5595	0.052	10.451
8	15	1.5595	0.06	10.74
8	18	1.5595	0.072	11.013
9	4	1.7544	0.016	10.75
9	7	1.7544	0.028	8.567
9	10	1.7544	0.04	10.30
9	13	1.7544	0.052	11.52
9	15	1.7544	0.06	11.34
9	18	1.7544	0.072	11.799

Based on the results of the numerical study, we built graphical dependences of the stress concentration coefficient  $K_\sigma$  on the dimensionless depth of the dent  $\zeta$  for various values of the dimensionless radius of dents  $\xi$ , which are shown in Fig. 14.

The curves shown in Fig. 14 are divided into two groups. The first group of curves, according to Fig. 15, corresponds

to small and medium dent radii. These curves do not intersect. They correspond to the following values of the dimensionless radius of the dent  $\xi=2;3;4;5;6$ . The second group of curves, according to Fig. 16, corresponds to large values of the dimensionless radius of the dent  $\xi=7;8;9$ . These curves intersect.

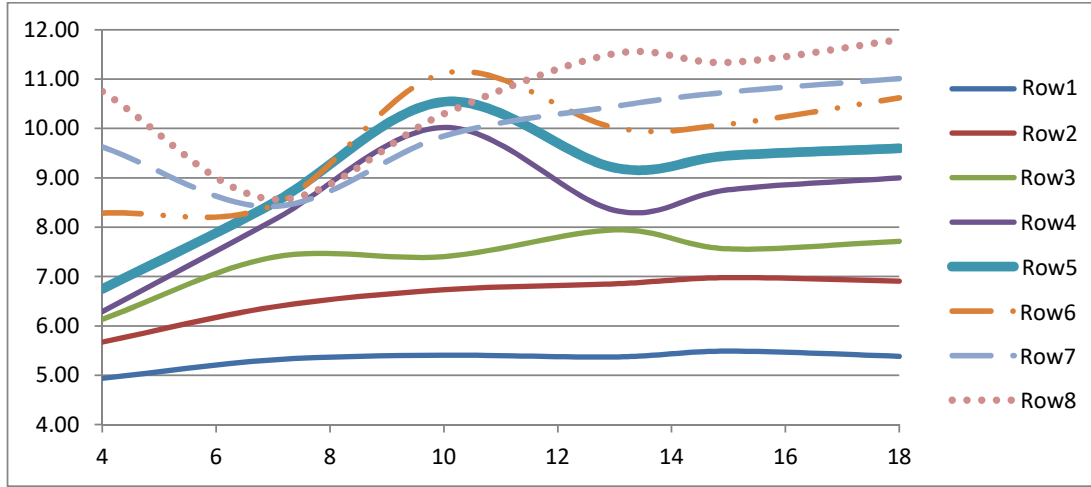


Fig. 14. Dependence of the stress concentration coefficient on the dimensionless depth of the dent  $\zeta$  at the following values of the dimensionless radius of the dent  $\xi=2;3;4;5;6;7;8;9$

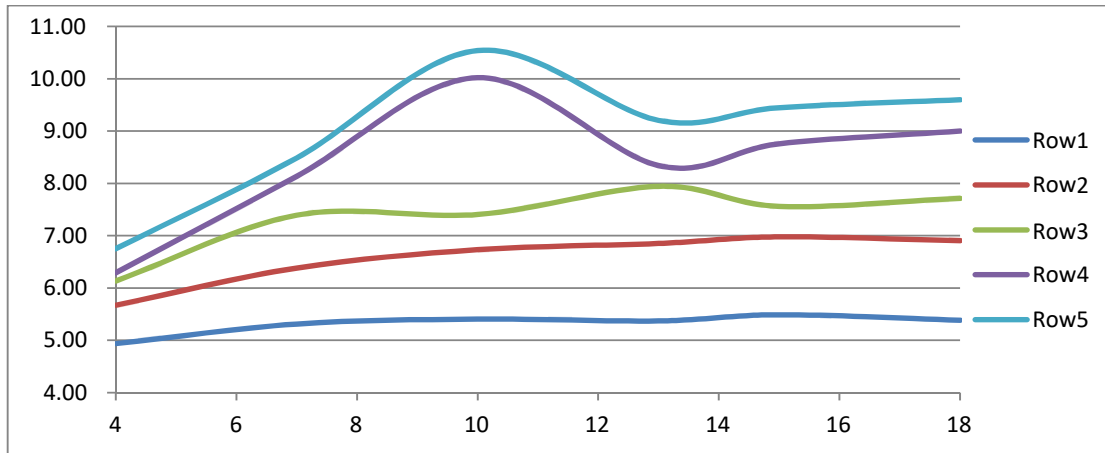


Fig. 15. Dependence of the stress concentration coefficient on the dimensionless depth of dents  $\zeta$  at the following values of the dimensionless radius of dents  $\xi=2;3;4;5;6$

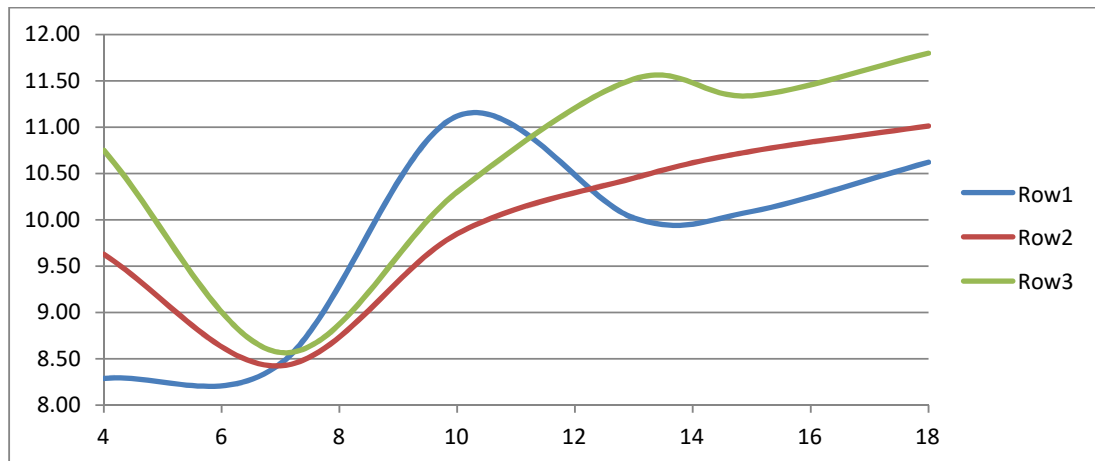


Fig. 16. Dependence of the stress concentration coefficient on the dimensionless depth of dents  $\zeta$  at the following values of the dimensionless radius of dents  $\xi=7;8;9$

The derived dependences of the stress concentration coefficient  $K_\sigma$  on the dimensionless depth of the dent  $\zeta$  and the dimensionless radius of dents  $\xi$  confirmed the determining effect on the concentration of stresses in the dent zone of its depth  $f$ . At the same time, our dependences of the stress concentration coefficient on the parameters of the dent are important from the point of view of deriving an engineering empirical calculation formula.

**5. 4. Determining stress concentration coefficients in the dent zone**

The dependence of stress concentrations in the dent zone on the geometric parameters of the dent and tank could be determined by the function of dimensionless variables:

$$K_\sigma = \Phi(\zeta; \xi). \tag{15}$$

An approximation was performed for all the curves shown in Fig. 14. The plots built in the figure correspond to different values  $\xi = \xi_i; i=1,2,\dots$ . For each value  $\xi_i$ , let us construct a separate approximating polynomial of the stress concentration coefficient:

$$\hat{K}_\sigma^{(i)} = B_0^{(i)} + B_1^{(i)}\zeta + B_2^{(i)}\zeta^2 + \dots + B_N^{(i)}\zeta^N. \tag{16}$$

Based on the values of coefficients  $B_0^{(i)}$  at  $\xi_i; i=1,2,\dots$  let us construct an approximating polynomial of these coefficients  $A_0(\xi)$ . Similar approximating polynomials are built for coefficients  $B_1^{(i)}; B_2^{(i)}; \dots$ . As a result, we obtain a set of approximating polynomials  $A_1(\xi); A_2(\xi); \dots$ . Now the stress concentration coefficient  $K_\sigma$  could be approximated as follows:

$$\hat{K}_\sigma = A_0(\xi) + A_1(\xi)\zeta + A_2(\xi)\zeta^2 + A_3(\xi)\zeta^3 + \dots + A_N(\xi)\zeta^N, \tag{17}$$

where

$$A_i(\xi) = C_i^{(0)} + C_i^{(1)}\xi + C_i^{(2)}\xi^2 + \dots + C_i^{(M)}\xi^M. \tag{18}$$

The proposed technique was implemented in the Maple programming environment. The method of least squares was used to construct polynomials. Numerical calculations have shown that for a sufficiently accurate approximation of the coefficients of stress concentration in decomposition (8), it is necessary to take a polynomial of the fourth power ( $N=4$ ). To approximate the coefficients of polynomial (9)  $Ai(\xi)$ , it is necessary to take polynomials of the eighth power.

These polynomials take the following form:

$$A_0(\xi) = -2932.819593 + 4739.787673\xi - 3088.600506\xi^2 + 1051.449043\xi^3 - 199.9660076\xi^4 + 20.49071825\xi^5 - 0.8834190214\xi^6 - 0.1057641244 \cdot 10^{-1}\xi^7 + 0.1534902519 \cdot 10^{-2}\xi^8;$$

$$A_1(\xi) = 1547.740613 - 2491.860794\xi + 1618.964794\xi^2 - 549.1935107\xi^3 + 104.0659131\xi^4 - 10.63271499\xi^5 + 0.4588122494\xi^6 + 0.5210563682 \cdot 10^{-2}\xi^7 - 0.780204147 \cdot 10^{-3}\xi^8,$$

$$A_2(\xi) = -274.7108192 + 441.5732885\xi - 286.2826226\xi^2 + 96.87859904\xi^3 - 18.31070278\xi^4 + 1.867058413\xi^5 - 0.0806446753\xi^6 - 0.875201980 \cdot 10^{-3}\xi^7 + 0.134717180 \cdot 10^{-3}\xi^8;$$

$$A_3(\xi) = 19.14967549 - 30.75832151\xi + 19.91979618\xi^2 - 6.731902434\xi^3 + 1.270493320\xi^4 - 0.129382936\xi^5 + 0.5590475921 \cdot 10^{-2}\xi^6 + 0.591138894 \cdot 10^{-4}\xi^7 - 0.924321462 \cdot 10^{-5}\xi^8;$$

$$A_4(\xi) = -0.4557765815 + 0.73178418\xi - 0.47363243\xi^2 + 0.159937905\xi^3 - 0.301573987 \cdot 10^{-1}\xi^4 + 0.306873918 \cdot 10^{-2}\xi^5 - 0.132635084 \cdot 10^{-3}\xi^6 - 0.137743733 \cdot 10^{-5}\xi^7 + 2.17761112 \cdot 10^{-7}\xi^8.$$

The results of calculations of stress concentration coefficients for different sizes of spherical dents using the dependence built are given in Table 5.

The data in Table 5 show that the estimation values of the stress concentration coefficients determined by numerical calculation using ANSYS and from the analytical expression (17) are quite close and do not exceed 2 % of the indicator, which indicates the correctness of the obtained analytical expression.

The resulting empirical formula (17) could be used for engineering calculations of the stress concentration coefficients of other tanks with different dent sizes.

Based on (17), we built nomograms to determine the concentration of stresses depending on the geometric dimensions of the dent, the radius and thickness of the tank wall in accordance with Fig. 18.

The resulting nomogram makes it possible, with the known geometric dimensions of the dent for a particular tank, to determine the coefficients of stress concentration in the defect zone.

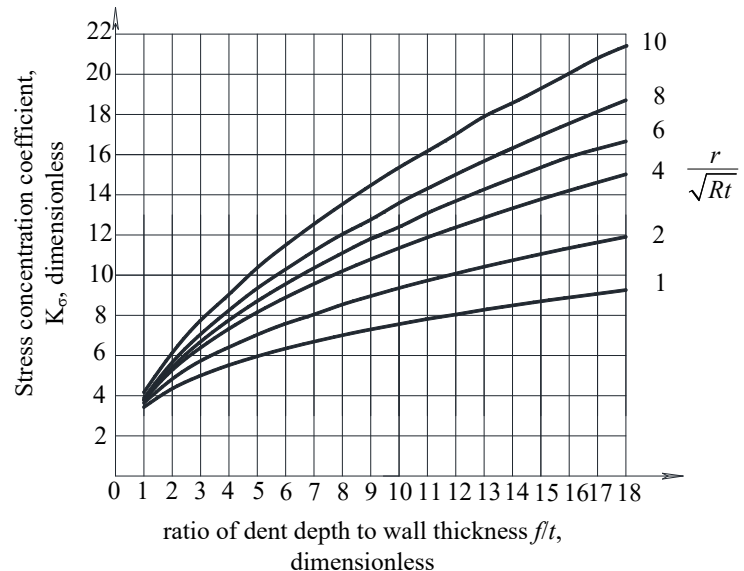


Fig. 17. Nomogram of stress concentration coefficient values for dents

Table 5

Results of comparison of values of stress concentration coefficients calculated by a numerical method and by applying formula (17)

Dimensionless dent radius, $\xi$	Dimensionless dent depth, $\zeta$	Dent radius $r_b$ , m	Dent depth $f$ , m	Coefficient of stress concentration according to numerical calculation, $K_\sigma$	Coefficient of stress concentration calculated from (17), $K_\sigma$
2	4	0.3899	0.016	4.937	4.9341
2	7	0.3899	0.028	5.3121	5.3268
2	10	0.3899	0.04	5.406	5.3736
2	13	0.3899	0.052	5.371	5.4142
2	15	0.3899	0.06	5.4891	5.4625
2	18	0.3899	0.072	5.3855	5.3892
3	4	0.585	0.016	5.672	5.6699
3	7	0.585	0.028	6.383	6.3939
3	10	0.585	0.04	6.7322	6.7083
3	13	0.585	0.052	6.852	6.8840
3	15	0.585	0.06	6.978	6.9584
3	18	0.585	0.072	6.906	6.9088
4	4	0.7797	0.016	6.135	6.1521
4	7	0.7797	0.028	7.391	7.3004
4	10	0.7797	0.04	7.405	7.6036
4	13	0.7797	0.052	7.944	7.6784
4	15	0.7797	0.06	7.561	7.7231
4	18	0.7797	0.072	7.714	7.6898
5	4	0.97	0.016	6.29	6.2459
5	7	0.97	0.028	8.136	8.3655
5	10	0.97	0.04	10.02	9.5133
5	13	0.97	0.052	8.34	9.0134
5	15	0.97	0.06	8.757	8.3414
5	18	0.97	0.072	9.0	9.0566
6	4	1.17	0.016	6.7493	6.7114
6	7	1.17	0.028	8.4853	8.6836
6	10	1.17	0.04	10.54	10.104
6	13	1.17	0.052	9.204	9.7865
6	15	1.17	0.06	9.4476	9.0918
6	18	1.17	0.072	9.598	9.6508
7	4	1.365	0.016	8.288	8.2487
7	7	1.365	0.028	8.4469	8.6508
7	10	1.365	0.04	11.12	10.669
7	13	1.365	0.052	10.02	10.618
7	15	1.365	0.06	10.09	9.7212
7	18	1.365	0.072	10.622	10.672
8	4	1.5595	0.016	9.6269	9.6158
8	7	1.5595	0.028	8.4231	8.4732
8	10	1.5595	0.04	9.849	9.7329
8	13	1.5595	0.052	10.451	10.600
8	15	1.5595	0.06	10.74	10.643
8	18	1.5595	0.072	11.013	11.022
9	4	1.7544	0.016	10.75	10.750
9	7	1.7544	0.028	8.567	8.5492
9	10	1.7544	0.04	10.30	10.332
9	13	1.7544	0.052	11.52	11.475
9	15	1.7544	0.06	11.34	11.369
9	18	1.7544	0.072	11.799	11.799

## 6. Discussion of results of studying the concentration of stresses in the dented zone of the wall of vertical cylindrical tanks

Based on the use of multi-level mathematical models of stress concentration in the dented zone of the wall of a ver-

tical cylindrical tank, the features of stress distribution in the dented zone of various geometric sizes under operating conditions have been investigated.

Our numerical calculations of a cylindrical tank with variable wall thickness showed that the values of the circumferential stresses obtained using the ANSYS software pack-



age and the analytical solution to (9) are close. The range of values is from 2 % to 10 %. This indicates the correctness of the chosen mathematical model, as well as the fact 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 stressed-strained state of the wall of cylindrical tanks with a dent in the wall was investigated. Stress fields show the concentrations of equivalent stresses in the dent area of the tank wall. It is shown that the maximum values of equivalent stresses are observed in the lower part of the dent where the hydrostatic pressure of the liquid is greater. It is demonstrated that at large values of the relative depth of the dent  $\zeta$ , the maximum stresses are observed only at the lower boundary of the dent, and at small values of the relative depth of the dent  $\zeta$ , the region of maximum stresses shifts up the dent, which is shown in Fig. 8–13. In general, it could be noted that the numerical assessment of the stressed-strained state of the dent zone in the tank wall proved the assumption of significant stress concentrations in the dent zone and indicated a determining effect on the concentration of stresses in the dent zone of its geometric dimensions and, especially, its depth.

The concentration of stresses in the dents zone of the tank wall at different sizes of dents on the tank wall was investigated in the ANSYS programming environment. Two dimensionless parameters are introduced to describe the dent: the dimensionless radius of the dent  $\xi$  (10) and the dimensionless depth of the dent  $\zeta$  (11). Based on the results of a numerical study of the stressed-strained state of the dent zone in the tank wall, we derived graphical dependences of the stress concentration coefficient  $K_\sigma$  on the dimensionless depth of dent  $\zeta$  for various values of the dimensionless radius of dents  $\xi$ , which are shown in Figs. 15, 16. It is noted that depending on the location of the dent, its size and operating conditions, the concentration of stresses could reach up to 10–11 times.

An approximation was performed for all curves; the dependence of the stress concentration coefficient on the dimensionless radius  $\xi$  (10) and the dimensionless depth of  $\zeta$  dent (11) was built. The determining effect on the concentration of stresses in the dent zone of the wall of its depth  $f$  was confirmed. The results of comparing the values of the stress concentration coefficients calculated by the numerical method and using the formulas showed that the calculated values of the stress concentration coefficients determined by the numerical calculation using ANSYS and according to the analytical expression do not exceed 2 % of the indicator, which indicates the correctness of the obtained analytical expression (Table 5). The resulting dependence could be used to assess the strength and residual service life of vertical cylindrical steel tanks for oil and petroleum products with dents in the wall, as well as to normalize the limiting of the dimensions of the dents.

The resulting empirical formula (17) could be used for engineering calculations of the stress concentration coefficients of other tanks with different dent sizes.

Based on (17), we constructed nomograms to determine the concentration of stresses depending on the geometric dimensions of the dent, the radius and thickness of the tank wall in accordance with Fig. 17. The resulting nomogram makes it possible, with the known geometric dimensions of the dent for a particular tank, to determine the coefficients of stress concentration in the defect zone.

However, it should be noted that the current study was conducted for an idealized spherical dent in the tank wall. Realizing the limitations of the application of the dependence of the concentration of stresses on the size of the dent within the engineering problem, we shall continue research in searching for a more advanced mathematical model for determining the concentration of stresses in the defect zone.

Depending on the required accuracy of determining the concentration of stresses in the dent zone, it is necessary in the future to proceed to the actual full-scale shapes of the dent.

At the same time, it should be noted that this approach is not acceptable for the problems of the dynamics of tanks with a variable wall at different levels of liquid filling. It is necessary to take into consideration the concentration of stresses in the places of change in the thickness of the tank wall.

The current study is part of the research carried out within the framework of the actual operation of vertical cylindrical tanks for oil and petroleum products. In the future, there is a need for full-scale studies into the stressed-strained state of the tank structures with various geometric imperfections of the shape. At the same time, the issues of normalizing the dimensions of geometric imperfections in the shape of the tank wall and developing methods for eliminating or strengthening them remain important.

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## 7. Conclusions

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1. In our work, with an unknown geometry of the dent or its complex shape but with its known basic dimensions, a spherical scheme for idealizing the shape of the dent has been used. Verification of the calculation results was carried out. Our numerical calculations of a cylindrical tank with variable wall thickness showed that the values of the circumferential stresses obtained using the ANSYS software package and the analytical solution using ratios are close. The range of values is from 2 % to 10 %. This indicates the correctness of the chosen mathematical model, as well as the fact 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.

2. The stressed-strained state of the wall of cylindrical tanks with a dent in the wall has been investigated. Stress fields show the concentrations of equivalent stresses in the dent area of the tank wall. It is shown that the maximum values of equivalent stresses are observed in the lower part of the dent where the hydrostatic pressure of the liquid is greater. It has been shown that at high values of the relative depth of dent  $\zeta$ , the maximum stresses are observed only at the lower boundary of the dent, and at small values of the relative depth of dent  $\zeta$ , the region of maximum stresses shifts up the dent. The different nature of the stress distribution in the dent zone indicates the influence on the concentration of stresses of the structural dimensions of the tank, the size of the dent, and operational factors. The calculation results show the possibility of determining the circumferential stresses  $\sigma_\theta$ , which are far from the stress concentration of the dent in order to calculate the stressed-strained state of the tank wall. In general, it could be noted that the numerical assessment of the stressed-strained state of the dent zone in the tank wall proved the assumption of significant stress concentrations in the dent zone and indicated the determining effect on the concentration of stresses in the dent zone of its geometric dimensions and, especially, its depth.

3. The concentration of stresses in the dents zone of the tank wall at different sizes of dents on the tank wall was investigated in the ANSYS programming environment. The stress concentration coefficient was found as the ratio of the highest values of equivalent stresses  $\sigma_{\max}$  in a node to the rated equivalent stresses in the defect-free zone of the tank wall  $\sigma_0$  in a given node. Two dimensionless parameters are introduced to describe the dent: the dimensionless radius of dent  $\xi$ , and the dimensionless depth of dent  $\zeta$ . Based on the results of a numerical study into the stressed-strained state of the dent zone in the tank wall, we derived graphical dependences of the stress concentration coefficient  $K_\sigma$  on the dimensionless depth of dent  $\zeta$  for various values of the dimensionless radius of dents  $\xi$ . It is noted that, depending on the location of the dent, its size and operating conditions, the stress concentration could reach up to 10–11 times. The greatest influence on the level of concentration of stresses in the dent zone is exerted by the dimensionless depth of dent  $\zeta$ .

4. An approximation was performed for all curves; the dependence was derived of the stress concentration coefficient on the dimensionless radius  $\xi$  and the dimensionless depth of dent  $\zeta$  dent. The determining effect on the

concentration of stresses in the dent zone of the wall of its depth  $f$  was confirmed. The results of a comparison of the values of the stress concentration coefficients calculated by the numerical method and using formulas showed that the calculated values of the stress concentration coefficients determined by the numerical calculation using ANSYS and according to the analytical expression do not exceed 2 % of the indicator, which indicates the correctness of the derived analytical expression. The resulting dependence could be used to assess the strength and residual service life of vertical cylindrical steel tanks for oil and petroleum products with dents in the wall, as well as to normalize the limiting of the dimensions of dents.

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