[1] **S. N. Buganova**,

[2] **K. V. Avramov**, Doctor of Technical Sciences

[1] Kazakh Academy of Architecture and Civil Engineering, Almaty, Kazakhstan

[2] A. Podgorny Institute of Mechanical Engineering Problems of NASU, Kharkiv, Ukraine,

e-mail: kvavramov@gmail.com

UDC 624.953; 622.519.6

NUMERICAL ANALYSIS OF STRESS-STRAIN STATE OF VERTICAL CYLINDRICAL OIL TANKS WITH DENTS

Розглядаються результати скінченно-елементного аналізу напружено-деформованого стану циліндричного резервуару зі сферичними вм'ятинами. Отримано наближені залежності для коефіцієнтів концентрації напружень, які можуть бути використані при розрахунках циліндричних резервуарів зі сферичними вм'ятинами. Детально аналізується напружено-деформований стан резервуарів зі сферичними вм'ятинами.

Introduction

The destruction of vertical cylindrical tanks results in both human and economic losses. Despite constant improvement of the manufacturing technology of cylindrical tanks, a complete analysis of the influence of various dents on stress-strain states was not performed [1, 2]. Dents are the most dangerous, unpredictable zones that are studied a little [3]. It should be specially emphasized that there is no system to assess the stress concentrations in the dent zone, and the regulatory documents for the construction and operation of oil tanks do not take into account the stress-strain state in the dent [4, 5, 6].

The paper presents the results of a finite element analysis of the stress-strain states of the cylindrical tanks with spherical dents. On the basis of the finite element analysis, approximate relationships are derived for stress concentration coefficients that can be used to calculate various sized cylindrical tanks with different dents.

Problem formulation and calculation of stress-strain states

A cylindrical tank with a spherical dent is investigated. The reasons for dent formation are not considered. It is assumed that there are no residual stresses in the dent area. Such models of stress-strain state in the dent area are studied in papers [1, 3]. Photos of the dents in the tanks are shown in Fig. 1. The walls of the tanks are considered as thin cylindrical shells. Therefore, we neglect a shear. It is assumed that the shell is made of an isotropic material. Stresses and strains satisfy Hooke's law. Displacements and strains are assumed to be small. Therefore, linear Cauchy relations are true.
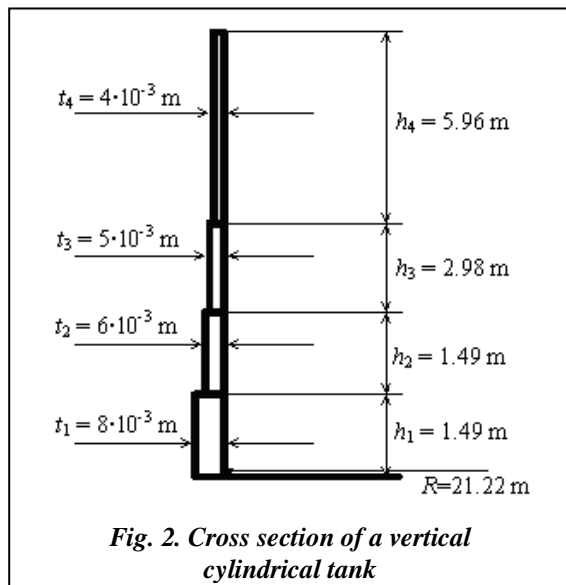

a)   b)

Fig. 1. Dents in the walls of tanks:
a) – tank with a volume of 3000 m³; b) – tank with a volume of 2000 m³
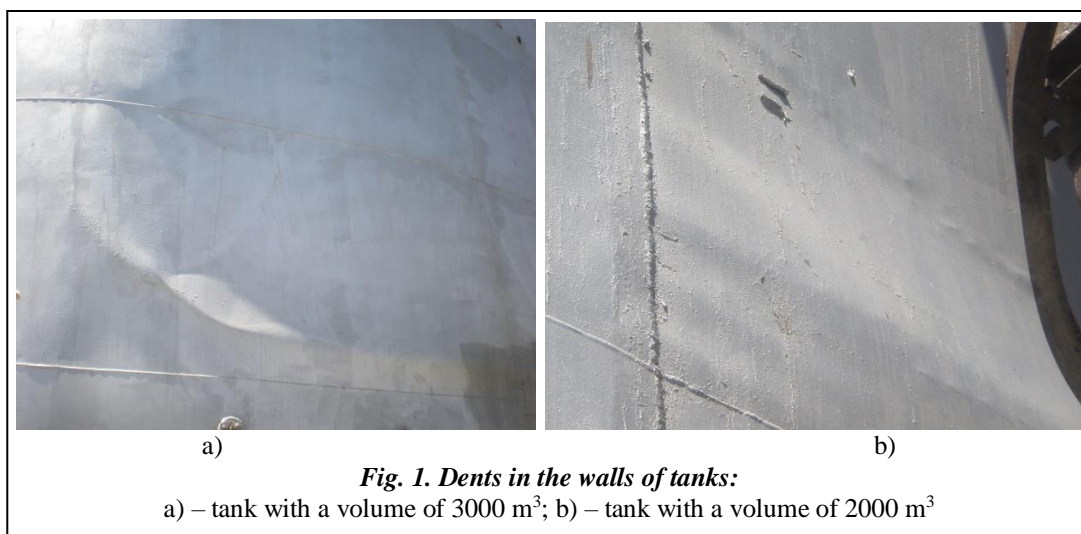
Fig. 2. Cross section of a vertical cylindrical tank

The stress-strain state of a vertical cylindrical tank with volume a of 3000 m^3, was analyzed. The shell cross section is shown in Fig. 2. The radius of such a cylindrical tank is 9.5 m. The tank has a 0.095 m thick bottom in the form of circular plate. As follows from Fig. 2, the tank consists of four belts. Each of the belts is a part of the shell with a constant cross-section. It is assumed that the tank is completely filled with fuel. From a visual inspection, it follows that the dents are observed in the upper part of the tanks. The dent in the bottom of the upper fourth belt of the structure is examined. Following the paper [1], we introduce two dimensionless parameters to describe a spherical dent:

$$\xi = \frac{r_B}{\sqrt{Rt}}; \varsigma = \frac{f}{t},$$

where R – radius of the tank; t – thickness of the tank in the dent area; r_B – radius of the dent; f – depth of the dent. Parameter ξ is a dimensionless radius of the dent, and parameter ζ is dimensionless depth of the dent. These two dimensionless parameters completely determine the geometry of spherical dents.

The ANSYS software package is used for calculations. In the calculations, the tank with a dent is divided into shell finite elements. The elements are the shell 281 elements with 8 nodes.

The results of simulation of the stress-strain state in the tanks are considered. Fig. 3 shows the field of Mises stress in the tank with a dent, which has dimensionless parameters $\xi=5$, $\zeta=10$. This figure shows a significant increase in the Mises stress in the dent area. Thus, the dent is a stress concentrator. The stress field far from the dents has the only predominant circumferential stress. All the other components of this tensor vanish. Despite the variability of the cross-section, it is possible to calculate the circumferential stresses from the formula that is true for tanks with a constant cross-section:

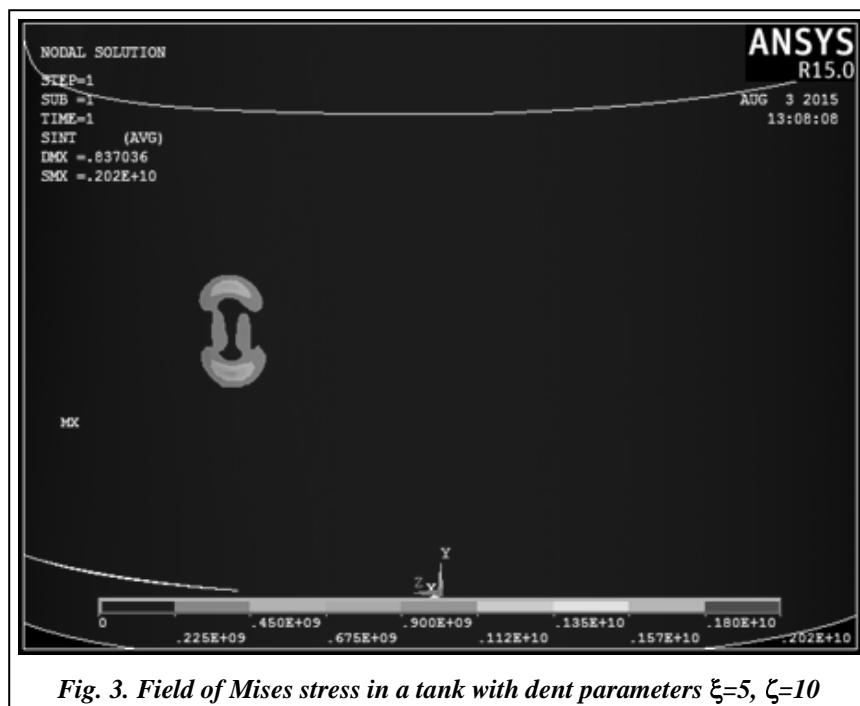$$\sigma_\theta = \frac{\gamma(d-x)R}{t}, \tag{1}$$

where γ – liquid density; d – height of the tank; x – longitudinal coordinate of the tank, which is measured from the bottom. The value of the tank thickness at the considered point of the structure is used to calculate a tank with a variable cross-section in (1).

Fig. 4 shows the Mises stress field in the dent area. As follows from Fig. 4, the greatest stresses are observed in the lower part of the dent. As in the lower part of the dent, the internal pressure of fuel oil is greater. At high values of the relative depth of the dent ζ the maximum stresses are observed only at the lower boundary of the dent.

Fig. 3. Field of Mises stress in a tank with dent parameters $\xi=5$, $\zeta=10$

Numerical analysis of the stress concentration factor

The calculations of the tank stress-strain states have been performed for various spherical dents, which correspond to the various values of the dimensionless parameters ξ and ζ. For each dent, the stress concentration factor K_σ is determined. The results of stress concentration factors calculation are shown in Fig. 5. These graphs show the dependence of K_σ on the dimensionless depth of the dent ζ. We emphasize that the calculations were performed for different values of the dent dimensionless radius ξ. The calculations (Fig. 5) were carried out for the following values of the dent dimensionless radius ξ=2; 3; 4; 5; 6; 7; 8; 9.

Fig. 4. Field of Mises stress in the dent area with parameters $\xi=9$, $\zeta=10$

The curves (Fig. 5) are divided into two groups. The first group of curves corresponds to a small and an average values of the radii of the dents. These curves do not intersect (Fig. 5). They correspond to the following values of the parameter ξ=2; 3; 4; 5; 6. The second group of curves corresponds to large values of the radius of the dent ξ=7; 8; 9. These curves do not intersect.

All the curves, shown in Fig. 5, are approximated by power polynomials. We use the hypothesis [1], that the stress concentration coefficient is determined by two parameters ξ and ζ:

$$K_\sigma = \Phi(\zeta;\xi) . \tag{2}$$

The graphs (Fig. 5) correspond to different values of $\xi=\xi_i$; i=1, 2, …. For each value ξ_i the polynomial approximant of the stress concentration coefficient is obtained in the form:

$$\hat{K}_\sigma^{(i)} = B_0^{(i)} + B_1^{(i)}\varsigma + B_2^{(i)}\varsigma^2 + …. + B_N^{(i)}\varsigma^N .$$

According to the values of coefficients $B_0^{(i)}$, i=1, 2, …, the set of the polynomial approximant of these coefficients $B_j^{(i)}(\xi)$; j=0, 1, … is obtained. The set of the coefficients is approximated as:

$$B_j^{(i)}(\xi) = C_j^{(i,0)} + C_j^{(i,1)}\xi + C_j^{(i,2)}\xi^2 + … + C_j^{(i,M)}\xi^M . \tag{3}$$

The proposed methodology was implemented in the Maple software. The least squares method was used to obtain polynomials. Numerical calculations have shown that for a sufficiently accurate approximation of the stress concentration coefficient in the analysis (2, 3), it is necessary to take a fourth-degree polynomial N=4. For approximation of the coefficients of the polynomial (3) $B_j^{(i)}(\xi)$ it is necessary to take the eight degree polynomials. These polynomials take the following form:

$$A_0(\xi)=-2932.81+4739.78\xi-3088.60\xi^2+1051.44\xi^3-199.96\xi^4+20.49\xi^5-0.88\xi^6-0.10\cdot10^{-1}\xi^7+0.15\cdot10^{-2}\xi^8;$$
$$A_1(\xi)=1547.74-2491.86\xi+1618.96\xi^2-549.19\xi^3+104.06\xi^4-10.63\xi^5+0.45\xi^6+0.52\cdot10^{-2}\xi^7-0.780\cdot10^{-3}\xi^8;$$
$$A_2(\xi)=-274.71+441.57\xi-286.28\xi^2+96.87\xi^3-18.31\xi^4+1.86\xi^5-0.08\xi^6-0.87\cdot10^{-3}\xi^7+0.13\cdot10^{-3}\xi^8;$$
$$A_3(\xi)=19.14-30.75\xi+19.91\xi^2-6.73\xi^3+1.27\xi^4-0.12\xi^5+0.55\cdot10^{-2}\xi^6+0.59\cdot10^{-4}\xi^7-0.92\cdot10^{-5}\xi^8;$$
$$A_4(\xi)=-0.45+0.73\xi-0.47\xi^2+0.15\xi^3-0.30\cdot10^{-1}\xi^4+0.30\cdot10^{-2}\xi^5-0.13\cdot10^{-3}\xi^6-0.13\cdot10^{-5}\xi^7+2.17\cdot10^{-7}\xi^8.$$

The resulting polynomial (3) can be used for approximate calculations of the stress concentration coefficients of the other tanks with dents.
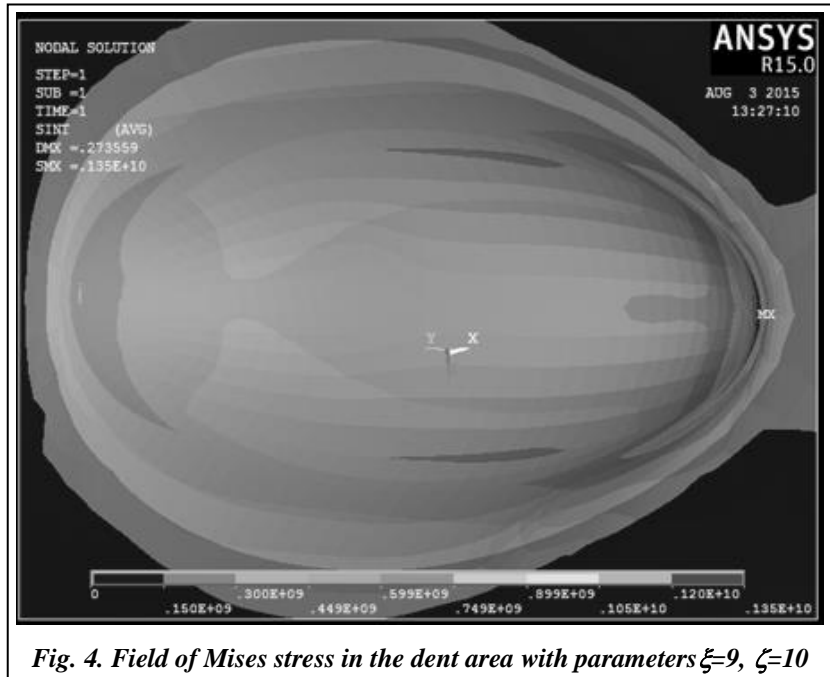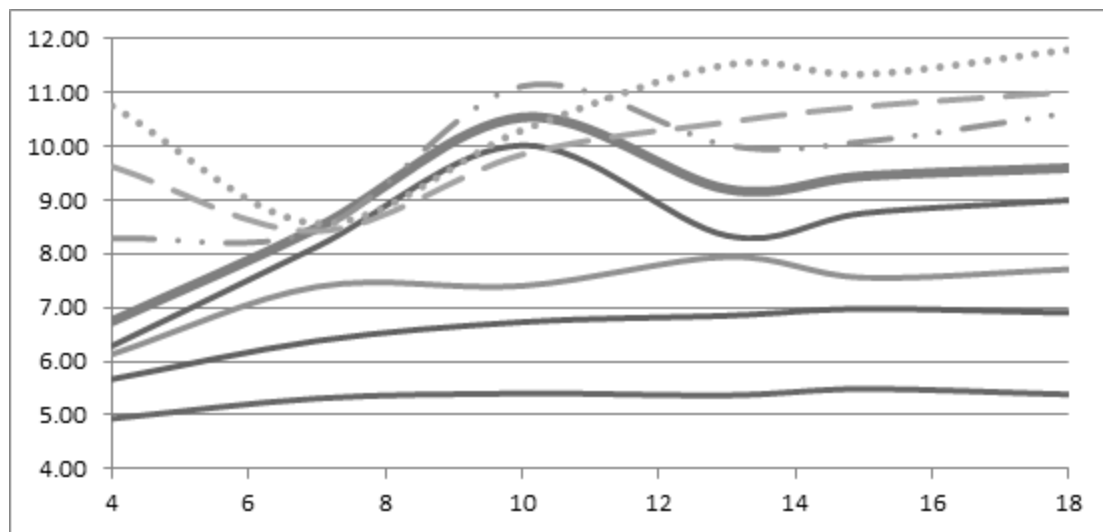
Fig. 5. Dependence of the stress concentration factor on the dimensionless depth of the dent ζ for the following values of the dimensionless radius of the dent ξ=2; 3; 4; 5; 6; 7; 8; 9

Conclusion

The finite element simulations show that a significant increase in equivalent stresses is observed in the dent area. The greatest increase in equivalent stresses is observed in the lower part of the dent. This is because the internal pressure is much greater in this part of the tank. For engineering calculations of equivalent stresses, it is sufficient to know the stress concentration factor in the dent area. It can be determined on the basis of approximating polynomials (3).

References
1. Likhman V. V., Kopysitskaya L. N., Muratov V. M. Concentration of Stresses in Reservoirs with Local Imperfections of Form. *Chemical and Petroleum Eng.* 1992. No 4. P. 22–24.
2. Kuznetsov V. V., Kandakov G. P. Problems of Domestic Reservoir Construction. *Industrial and Civil Construction*, 2005. No 5. P. 17–19.
3. Prokhorov V. A. Assessment of Risk Parameters for Operation of Reservoirs for Storage of Petroleum Products in Conditions of North. Moscow: Nedra, 1999. 144 p.
4. SN RK 3.05-24-2004. The Instruction on Designing, Manufacturing and Installation of Vertical Cylindrical Steel Tanks for Oil and Oil products. Enter. 2005-01-01. Astana, 2004. 78 p.
5. VBN B.2.2-58.2-94. Vertical Steel Tanks for Storage of Oil and Oil Products with Saturated Vapor Pressure not Higher than 93.3 kPa. Kiev: Goskomneftegaz. 1994. 98 p.
6. PB 03-605-03. Rules for Construction of Vertical Cylindrical Steel Tanks for Oil and Oil products. Enter. 2003.06.19. Moscow, Gosgortekhnadzor of Russia. 2002. 83 p.
7. Timoshenko S.P., Voinovsky-Krieger S. Plates and Shells. Trans. With the English. Ed. G.S. Shapiro. Moscow: Fizmatgiz. 1963. 635 p.