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STRESS CONCENTRATION IN VERTICAL TANK WELD SEAMS

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The article describes a new method for analyzing and predicting the stress concentration coefficient in a rolled vertical tank weld seam under hydrostatic loading. Vertical tanks are widely used for storing petroleum products. The use of roll-to-roll assembly technology is advisable for a quick and inexpensive installation of oil tanks. However, the use of this technology in the installation of large-capacity tanks leads to the need to use thick rolled steel. This leads to the appearance of significant angularities of the weld seams used to fasten steel sheets in a roll. Such angularities are mechanical stress concentrators and can damage the tank. Therefore, the problem of modeling the dependence of stress concentration factors on the geometrical parameters of angularity is relevant and important to ensure both the economic and environmental efficiency of operation of the oil tanks assembled by the roll-to-roll method. The approach described in this article is based on a combination of a numerical experiment and an approximation approach. The stress concentration factor depends on two dimensionless parameters of the dent. Thus, a method of approximation of a two-dimensional problem is described. This method is applied to the data collected by numerous computational experiments using the finite element approach to construct an approximate model of the stress concentration factor. Such a model can be used to predict stress values, as well as tank strength and durability. The change in material properties in the weld seam is not taken into account. Thus, the estimated stress is higher than the real one and represents a majorant estimate. An approximating model of the stress concentration factor was constructed in the area of angularity of the weld seam of a 3,000 m^3 complex structure oil tank under hydrostatic loading. The tank consists of four belts made of steel of various thickness. The density of the tank contents is close to that of water. It has been found that stress concentration increases as the distance to the tank bottom becomes smaller. Therefore, when building an approximating model, the results in the most strained region are considered.

Keywords*: vertical tank, hydrostatic loading, stress concentrator, weld, roll-to-roll assembly, dent.*

Introduction

The roll-to-roll method of manufacturing tanks for storing petroleum products is most profitable in terms of labor intensity, time and material costs. It allows one to carry out the main stages of installing and welding the elements of metal structures under factory conditions. At a construction site, only the tank wall and tank bottom are welded together and the welding of the wall field joint is carried out.

When using the roll-to-roll method of manufacturing large-capacity tanks, angularities occur in the construction weld seam area, associated with the formation of angular deformations during sheet welding. Such defects are characterized by a pointed shape, located along the entire tank height and are mechanical stress concentrators in the tank walls.

It is assumed that the stress-strain state (SSS) of a tank is described by the Kirchhoff hypotheses in the shell theory [1, 2]. The displacements of the middle surface of a shell are small, resulting in the connection between the middle surface deformations and displacements being assumed to be linear. The shell material is in the area of elasticity. Therefore, the relationship between stresses and strains satisfies Hooke's law. We emphasize that the shell SSS in the angularity area is also described by the shell theory mentioned above.

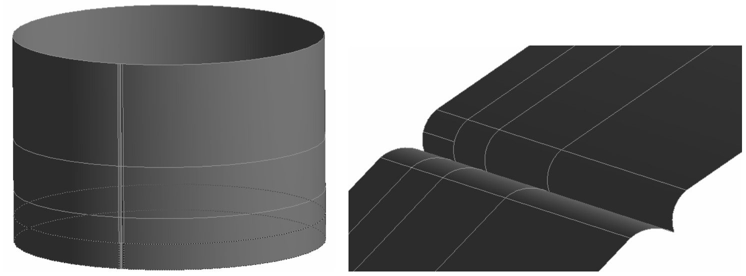
The geometry of the structure near the angularity is quite complicated. Therefore, the SSS analysis can be effectively carried out by the finite element method. The results of the finite element analysis are used to construct an approximating model of stress concentration in the tank wall, which can be used to predict the values of equivalent stresses by dent parameters. In [3, 4], it was shown that the stress concentration factor depends on two parameters: dimensionless depth and dimensionless width of a dent. We emphasize that these parameters are easy to measure.

This paper outlines a method for constructing an approximating model of stress concentration in the weld seam area on the wall of the tank assembled by the roll-to-roll method. When calculating the strength of tanks, methods of finite element analysis are often used, whose effectiveness directly depends on the three-dimensional model complexity. Using an approximate method of calculating the stress concentration in the weld seam area can significantly simplify the calculation of tank strength by simplifying its three-dimensional model and focus the calculation on other structural elements (nozzles, hatches, dents).

1. Problem Statement

SSS of a cylindrical tank with a defect in the form of weld seam angularity along its entire height is investigated (Fig. 1). The container is filled to the brim with a liquid whose density is 1000 kg/m^3. The tank radius is 8.95 m; it consists of four steel belts with a thickness of 8, 6, 5, 4 mm and a height of 1.49, 1.49, 2.98, 5.96 m, respectively. The total height of the tank is 11.92 m. The bottom edge of the tank is clamped. The angularity is characterized by two parameters: f (depth) and a (width) (Fig. 2). The parameter a varies from 0.15 to 0.5 m, and that of f – from 1 to 10 cm. Young's modulus and Poisson's ratio of the tank material are as follows: $2.11 \cdot 10^{11}$ Pa and ν=0.3.

A significant stress concentration occurs in the dent area. It is necessary to establish the dependence of the stress concentration factor K_σ^T on the angularity size: $K_\sigma^T \approx \alpha(f/t, a/\sqrt{Rt})$, where t, R are the wall thickness and radius of a tank; α is the desired function.



a b

Fig. 1. Tank model with angularity in the weld area:
a – tank sketch; b – weld angularity type

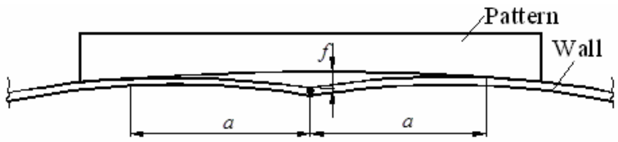


Fig. 2. Weld angularity geometry

2. Modeling in the Finite Element Analysis Environment

The geometry of the structure is shown in Fig. 1. To obtain the finite element mesh, a uniform mesh with an element size of 6 cm was first used over the entire surface of the tank, except for the defect area where the mesh had been refined. The calculations showed that the greatest stress concentration is observed at the sealing of the tank near the angularity of the weld seam. In this case, the angularity itself is a special area due to the presence of an arrow-like ridge. This is evidenced by a significant increase in von Mises equivalent stresses on its ridge during the mesh refinement; however, this increase is not accompanied by an increase in the displacements of tank points. Such behavior is characteristic of singularities in mathematical models, which is why the values of stresses on an angularity ridge found by a computational method cannot be considered reliable. To increase the reliability of the results, stress at a certain distance from the ridge was used as the maximum value of the stresses in the defect area. In addition, since the maximum stresses are observed at the base of the tank, it was decided to enlarge the finite element mesh in the region far from the weld seam, as well as in the angularity area far from the sealing. The area of particular interest for the study has undergone a finer partition. The adequacy of such a finite element mesh is confirmed by the fact that the maximum displacements of tank points practically do not change as the finite element mesh decreases.

The distribution of equivalent stresses on the tank surface varies depending on the defect depth and width. In Figs. 3 and 4 is shown the distribution of equivalent stresses in the weld seam area. Away from it, the tank SSS is analogous to that of the tank without the defect. The figures show that SSS perturbation occurs in the area near the angularity.

In order to build a model of stress concentration in the tank, a series of 80 numerical experiments was carried out, uniformly covering the range of changes in the angularity parameters $a\in[0.15; 0.50]$ m; $f\in[0.01; 0.1]$ m.

Values of maximum equivalent stresses were obtained by the method described above and a tabular dependence of the equivalent stress concentration factor (SCF) on the dimensionless angularity parameters $\xi=a/\sqrt{Rt}$; $\zeta=f/t$.

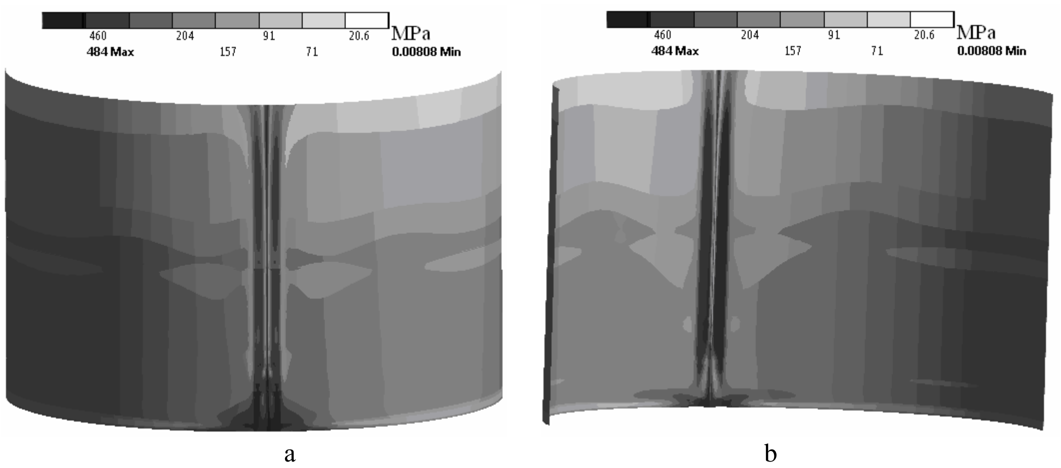


Fig. 3. Distribution of equivalent stresses in the tank with a=50 cm, f=10 cm:
a – external surface; b – inner surface

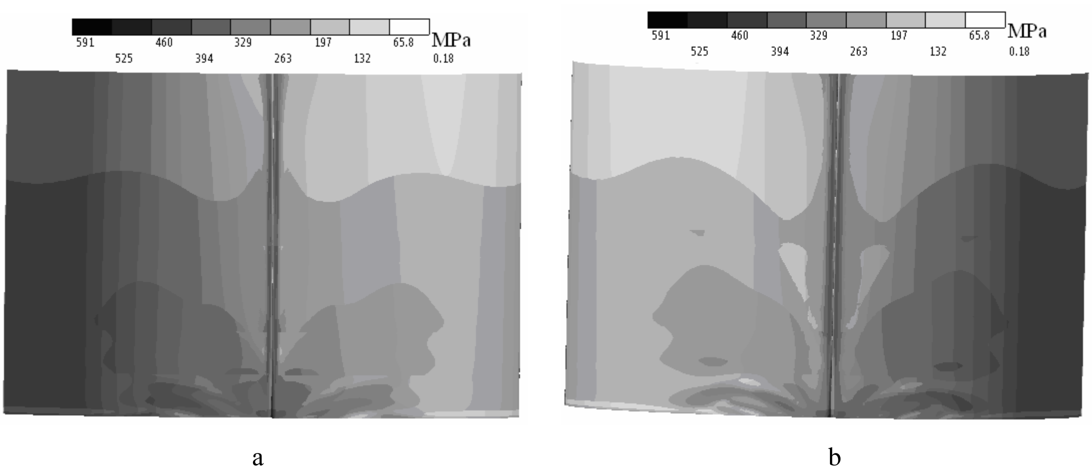


Fig. 4. Distribution of equivalent stresses in the tank with a=15 cm, f=10 cm:
a – external surface; b – inner surface

3. Stress Concentration Factor Model

The dependence of SCF values from the dimensionless parameters of weld seam angularity is given in the Table below. The first column shows the values of ζ, and the first line shows the values of ξ. These table data were used to construct an approximate polynomial dependence.

Results of SCF calculations

ζ	ξ									
	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50
1,87	1.48	1.76	1.775	1.818	1.859	1.889	1.917	1.946	1.977	2.009
1,68	1.49	1.763	1.783	1.836	1.873	1.905	1.937	1.971	2.002	2.037
1,49	1.50	1.765	1.796	1.851	1.885	1.920	1.956	1.994	2.030	2.066
1,31	1.55	1.769	1.815	1.865	1.903	1.945	1.987	2.030	2.071	2.108
1,12	1.66	1.775	1.836	1.883	1.928	1.973	2.016	2.059	2.116	2.172
0,93	1.75	1.784	1.855	1.904	1.954	2.014	2.066	2.128	2.201	2.273
0,75	1.76	1.800	1.872	1.933	1.995	2.061	2.146	2.234	2.311	2.384
0,56	1.76	1.820	1.899	1.974	2.062	2.176	2.284	2.380	2.468	2.546

When constructing the approximate SCF dependence on the dimensionless parameters of the dent, the following approximation was used: $K_\sigma^T=\sum_{i=0}^{4}B_i(\zeta)\xi^i$, where the coefficients of the polynomial $B_i(\zeta)=\sum_{i=0}^{4}b_i\zeta^i$. In order to construct this dependence, a two-step application of the least square method (LSM) was carried out. First, a polynomial approximation of the dependence $K_\sigma^T(\xi)$ was performed for each of the given values of the parameter ζ, then an approximate polynomial dependence of the obtained coefficients of the approximating polynomials on ζ was constructed. As a result of the analysis, the following SCF approximation was obtained:

$$K_\sigma^T = \left(9-34.821\zeta+51.234\zeta^2+4.828\zeta^3-92.993\zeta^4+110.249\zeta^5-60.477\zeta^6+16.521\zeta^7-1.819\zeta^8\right)+$$

$$+\left(9-68.830\zeta+224.563\zeta^2-408.827\zeta^3+454.878\zeta^4-317.139\zeta^5+135.459\zeta^6-32.443\zeta^7+3.339\zeta^8\right)\zeta+$$

$$+\left(9-73.806\zeta+257.286\zeta^2-496.764\zeta^3+581.334\zeta^4-422.876\zeta^5+187.126\zeta^6-46.157\zeta^7+4.869\zeta^8\right)\zeta^2+$$

$$+\left(9-67.802\zeta+217.804\zeta^2-390.588\zeta^3+428.486\zeta^4-294.909\zeta^5+124.513\zeta^6-29.515\zeta^7+3.010\zeta^8\right)\zeta^3+$$

$$+\left(9-68.876\zeta+224.861\zeta^2-409.632\zeta^3+456.044\zeta^4-318.122\zeta^5+135.943\zeta^6-32.572\zeta^7+3.354\zeta^8\right)\zeta^4$$

A graphic view of the SCF dependence on the dimensionless parameters of angularity is shown in Fig. 5.

Conclusions

A method for constructing an approximating model of the equivalent mechanical stress concentration factor in the wall of a vertical cylindrical tank for storing petroleum products designed by the roll-to-roll method is proposed. A specific property of such tanks is the special shape of the weld seam at a large wall thickness, which leads to a significant concentration of mechanical stresses near the weld seam. The stress concentration occurs mainly at the lower area of the weld seam. SCF here can reach values of 2.5, which creates the risk of crack initiation in the lower areas of a tank. The constructed approximating model of SCF near the dent simulating the shape defect of a tank, makes it possible to carry out tank strength calculations based on the easily measurable data on its shape. The proposed approximating model has the property of robustness and makes it possible to analyze stress concentration with the dent parameters significantly different from the experimental points.

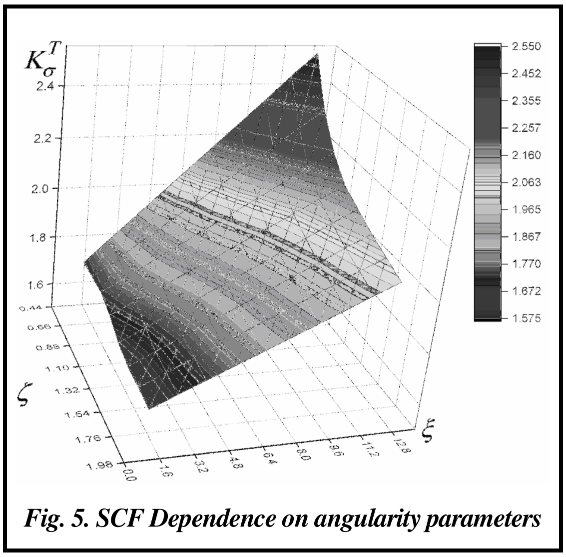


Fig. 5. SCF Dependence on angularity parameters

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У статті описано нову методику аналізу та прогнозування коефіцієнту концентрації напружень в області зварного шва рулонного вертикального резервуару при гідростатичному навантаженні. Вертикальні резервуари широко використовуються для зберігання нафтопродуктів. Використання технології рулонної збірки є розповсюдженим методом швидкого та недорогого монтажу нафтових резервуарів. Однак використання цієї технології при монтажі резервуарів великої ємкості призводить до необхідності використання сталі товстого прокату. В результаті цього виникають суттєві деформації поблизу зварних швів, якими скріплено стальні листи в рулоні. Такі деформації представляють собою концентратори механічних напружень та можуть призвести до пошкодження резервуару. Таким чином, проблема модулювання залежності факторів концентрації напружень від геометричних параметрів дефекту є актуальною та важливою для забезпечення як економічної, так і екологічної ефективності експлуатації нафтових резервуарів, які зібрано рулонним методом. Підхід, який описано в цій статті, базується на поєднанні чисельного експерименту та апроксимаційного підходу. Коефіцієнт концентрації напружень залежить від двох безрозмірних параметрів дефекту, тому описаний метод є методом апроксимації двохвимірної задачі. Цей метод застосовано до даних, які зібрано шляхом чисельного експериментування за допомогою скінченно-елементного підходу, для створення апроксимуючої моделі коефіцієнту концентрації напружень. Таку модель може бути використано для прогнозування значень напружень, а також міцності та довговічності резервуару. Оскільки зміну властивостей матеріалу у зварному шві не взято в розрахунок, оцінюване напруження є вищим за реальне та представляє собою мажорантну оцінку. Побудовано апроксимуючу модель коефіцієнту концентрації напружень у зоні зварного шва вертикального нафтового резервуару об'ємом 3000 куб. м складної конструкції при гідростатичному навантаженні. Бак складається з чотирьох поясів, які розташовані горизонтально та виготовлені зі сталі різної товщини. Питома маса рідини є близькою до питомої маси води. Виявлено, що концентрація напружень збільшується при наближенні до дна резервуару. Тому при побудові апроксимуючої моделі розглядаються результати в найбільш напруженій області.

Ключові слова: *вертикальний резервуар, гідростатичне навантаження, концентратор напружень, зварний шов, рулонна збірка, вм'ятина.*

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