

This paper reports a study into the effect of the winding type on the stressed-strained state of the wall of a steel cylindrical tank filled with oil to the predefined level. The shapes of free oscillations of oil in the tank and the effect of the winding type on the natural frequencies of the structure were analyzed. Stress in the tank wall was estimated on the basis of finite-element simulation of the deformation of a three-dimensional structural model under the influence of distributed oil pressure on the inner surface of the wall and stresses on the outer surface of the wall. The stresses were induced by the winding of various types, taking into consideration the level of oil loading, the winding step of the winding, and the mechanical characteristics of the thread.

The stressed-strained state of a cylindrical tank with winding was investigated at its full filling with oil, half-filling with oil, and without oil. Three winding options were simulated: single, double, and triple intervals. Two types of winding were considered: made from high-strength steel wire and made from composite thread. It was established that when winding the tank wall with steel wire at a triple interval, the stress in the structure does not exceed 34.2 % of the yield strength. At the same time, the height of oil loading does not significantly affect its strength. Applying a composite thread leads to an increase in the stress of up to 47.2 % of the yield strength but makes it possible to reduce the mass of the tank with winding. When winding with a composite thread at a triple interval, the mass of the structure increases by only 3.6 %. The results reported here make it possible to effectively use pre-stress in order to improve the strength and dynamic characteristics of the studied structures, taking into consideration their windings made of different materials

Keywords: steel tank, pre-stress, tank oscillations, operational loads, winding step

UDC 69.07

DOI: 10.15587/1729-4061.2022.254218

STRENGTH ANALYSIS OF PRESTRESSED VERTICAL CYLINDRICAL STEEL OIL TANKS UNDER OPERATIONAL AND DYNAMIC LOADS

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Received date 11.02.2022

How to Cite: Tursunkululy, T., Zhanabay, N., Avramov, K., Chernobryvko, M., Suleimenov, U., Utelbayeva, A., Duissenbekov, B., Aiko-

Accepted date 25.03.2022 zov, Y., Dautbek, B., Abdimanat, Z. (2022). Strength analysis of prestressed vertical cylindrical steel oil tanks under operational and dynam-

Published date 28.04.2022 ic loads. Eastern-European Journal of Enterprise Technologies, 2 (7 (116)), 14–21. doi: <https://doi.org/10.15587/1729-4061.2022.254218>

1. Introduction

When designing tanks for the storage of crude oil or petroleum products, special attention is paid to ensuring industrial safety requirements. In order to prevent environmental pollution during the destruction of the structure, an analysis of the strength of the tanks under operating loads is carried out. The operation of steel vertical cylindrical tanks in areas with high seismic activity requires the implemen-

tation of additional measures to ensure and improve their safety. This leads to the need to implement new technical solutions aimed at enhancing the strength of the structure as a whole.

Structural failure of the tank can occur for a number of reasons [1]. Many of them lead to the formation of zones of localization of stresses in the structure. Such zones in the tank wall are especially dangerous [2]. To reduce the likelihood of tank failure [3], it is proposed to strengthen the

wall with a winding of high-strength steel wire or smooth composite thread [4]. At the same time, there is a need in the research to consider the strength and dynamics of a tank reinforced by winding, which is completely or partially filled with oil or oil products.

At the stage of the general design of such steel structures, it is necessary to conduct studies into the effect of the winding type on the stressed state of the structure wall. The correct choice of winding material and the distance between the turns makes it possible to reduce the stress in the wall of the tank filled with oil products, thereby, prolonging its service life and ensuring the reliability of the structure during operation. Experimental studies on this issue are extremely expensive due to a large number of possible winding options and different levels of filling the tank with oil. In this regard, it is advisable to conduct such studies by numerical modeling based on the use of modern finite-element software systems.

Therefore, research into designing a prestressed structure of a steel vertical cylindrical tank in terms of the strength and dynamic resistance of the structure, with the use of a composite material as a winding, is a relevant task.

2. Literature review and problem statement

Vertical cylindrical tanks have long been widely used for the storage of liquids. There is a large body of research into the static and dynamic strength of such structures. The need to operate oil storage tanks in seismically hazardous areas, as well as several accidents caused by earthquakes, demonstrated the need for additional studies into the strength of tanks and the implementation of new engineering solutions. Thus, paper [5] reports the results of experimental studies confirming the effectiveness of hardening pipes by winding steel wire. It is shown that winding the wire on a pipeline can be used as a technique of seismic protection of the structure. However, the cited paper shows the method of evaluation and the protection technique only for linear structures using pre-stress.

Expanding the capabilities of modern computational systems based on finite-element research models makes it possible to replace a number of full-scale experiments with numerical analysis. Such a replacement is especially relevant for predicting the behavior of the structure under operating loads. Computer simulation can significantly reduce the time for research, compared with full-scale experiments. Article [6] reports the results of modeling the operation of metal tanks filled with water. Study [7] describes a procedure of numerical analysis of the composite structure under the operational loads associated with transportation. In paper [8], a simulation of the dynamic strength of the tank during transportation on a railway ferry was carried out. Study [9] considers 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. The dynamic response of the structure to the external explosive load is investigated. The structure is reinforced with anti-explosion strips. The simulation was carried out at various parameters of the anti-explosion strips during an external explosion. Article [10] investigates the features of deformation processes of cylindrical steel tanks with defects. 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.

When designing tanks, it is also necessary to understand the nature of the splashing of liquid in the tank. Monograph [11] addresses a number of issues related to the effect of liquid on the tank. Partially filled tanks have been shown to be exposed to particularly strong claps when the liquid is splashed. The powerful movement of the liquid induces high pressure on the walls of the tank. In [12], the free oscillations of the liquid in the elastic shells of rotation are investigated. The oscillations of the shell in combination with the splashing of the liquid under the influence of gravitational forces are considered. Analysis of nonlinear oscillations of cylindrical panels with a complex base is given in work [13]. Study [14] considered the movement of a viscous incompressible liquid in an elastic cylindrical shell. In this case, it is established that at low frequencies of oscillations of the reservoir with a liquid, only the liquid oscillates.

Our review of the scientific literature [5–14] has revealed that there are almost no studies on the use of winding to increase the strength of vertical cylindrical steel tanks for oil.

3. The aim and objectives of the study

The purpose of this work is to devise a methodology for numerical analysis and determine the features of the stressed-strained state and the process of oscillations of a pre-stressed vertical cylindrical steel tank with oil. This will make it possible to predict the impact of the design parameters of the preliminary stress on the strength of the tank under operating loads. The results would make it possible to assess the strength of the reinforced wall of a vertical cylindrical steel tank for oil with different types of winding.

To accomplish the aim, the following tasks have been set:

- to analyze the strength of the wall of a steel vertical cylindrical tank, reinforced with a winding of steel wire or composite filament, subject to the maximum filling with oil, half-filling with oil, and without it;
- to investigate the shapes of free vibrations of the liquid in the tank at the maximum and half level of oil filling, to determine the natural frequencies of oscillations of the tank with different types of winding made from the high-strength steel wire and made from the smooth composite filament.

4. The study materials and methods

Typical tanks are quite complex structures. Studying their stressed-strained state, taking into consideration the level of liquid filling, is associated with a number of difficulties, which are caused by the extremely small thickness of the cylindrical wall compared to the internal radius of the structure. This feature is exacerbated when it is necessary to take into consideration the change of 1–2 mm in the wall thickness for the height of the tank. For such studies, it is most effective to apply a finite-element method and to solve the problem in a three-dimensional statement [15, 16]. Therefore, it is proposed to use three-dimensional geometric models that make it possible to accurately take into consideration these design features. The current development of computer hardware and ANSYS software makes it possible to conduct research into thin structures using three-dimensional geometric models. Calculations are proposed to be carried out in the finite-element analysis software system

ANSYS Workbench. To build a uniform grid of three-dimensional finite elements, one must select Sweep Method with the Automatic Thin parameter and set a limit on the size of the finite element.

The mechanical characteristics of the materials of the tank and winding are such that the relationship between stresses and deformations follows Hooke's law. The appearance of zones of plastic flow of the material is considered unacceptable, therefore it is proposed to solve the problem in an elastic statement.

The variable internal pressure on the walls of the tank from the liquid poured to an arbitrary height is determined as follows. The global coordinate system is arranged in such a way that the bottom of the tank is in the xOy plane, and the height of the tank wall and the height of the liquid filling are determined by only one coordinate along the z -axis. Then the internal pressure on the tank wall ρ_0 is determined according to the following dependence [17]:

$$\rho_0 = -\gamma(z-d), \tag{1}$$

where $\gamma = pg$ is the specific gravity of the liquid; p is the density of the liquid filling the tank; g is the acceleration of free fall; d is the height to which the liquid is poured. Our study considers crude oil with a density of 850 kg/m^3 . The acceleration of gravity was assumed to average 9.81 m/s^2 .

Preliminary stresses in the tank wall are due to the tension force of the winding N (Fig. 1). Their value is influenced by both the tension force itself and the winding step of the wire thread. The force N is used to determine the force of pressure between the tank wall and the wire, P . The equilibrium equation is considered on the basis of the momentless theory of shells:

$$N \sin \theta = \lim_{\phi \rightarrow 0} \left(P \cdot \int_0^\phi \cos \phi d\phi \right). \tag{2}$$

The integration and transformation of expression (2) result in an equality of $P=N$. Thus, the contact pressure of the winding on the tank p_c is determined from the following dependence:

$$\rho_c = \frac{N}{b \cdot 2\pi R}, \tag{3}$$

where b is the width of the contact zone between the tank wall and the winding; R is the radius of the outer surface of the tank wall.

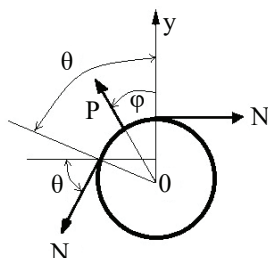


Fig. 1. Diagram of the action of forces in the creation of preliminary stresses

The winding step of the wire thread is used to determine the value for b in formula (3). Three variants of winding were considered. For the first option, the winding was applied with one interval between the turns along the tank

wall, for the second – with a double interval, and for the third – with a triple interval. The size of the interval corresponded to the size of the diameter of the wire. When modeling the preliminary stresses on the outer surface of the tank, it is proposed to determine the width of the contact zone b as the sum of the contact zone of each individual turn of the winding b_i : $b = \sum_{i=1}^K b_i$, where K is the total number of turns. It is assumed that the pressure exerted by one turn is distributed over the outer surface of the tank wall by the width of the wire diameter and the distance between the turns.

5. Results of estimating the strength and dynamics of prestressed vertical cylindrical steel tanks

5.1. The stressed-strained state of a cylindrical tank reinforced with a winding of steel wire or composite filament

The stressed-strained state of the tank wall model with the following geometric parameters is investigated: the inner diameter takes a value of 18.38 m, the height is 11.92 m. The height of the tank wall consists of four belts. The lower first belt has a thickness of 8 mm and a height of 1.49 m, the second belt is 6 mm thick and 1.49 m high, the third belt is 5 mm thick and 2.98 m high; the upper fourth belt has a thickness of 4 mm and a height of 5.96 m.

The material of the structures is the steel C245: the modulus of elasticity, $E=2,1 \cdot 10^{11} \text{ Pa}$; the Poisson coefficient, $\nu=0.3$; the density of the material, $\rho=7850 \text{ kg/m}^3$; the yield strength, $\sigma_{0,2}=245 \text{ MPa}$.

To check the convergence of the calculation results, the stressed-strained state of the tank was examined at a pressure of 100 kPa evenly distributed over the entire inner surface. On the lower edge of the cylindrical tank, at the point of fixation of the tank wall with the bottom, the Fixed Support boundary condition was set. Verification of the degree of reliability of the results was carried out using a number of test calculations. Similar values were obtained in calculations with a maximum size of the finite element of 0.1 m and 0.05 m. Fig. 1 shows the results of these calculations. The relative error of the results for stress is 0.4 %. At the same time, the number of elements when broken down by a finite-element grid with a step of 0.05 m increases nine times compared to the breakdown with a step of 0.1 m. Therefore, all the studies below were carried out on a finite-element grid with a maximum finite-element size of 0.1 m.

Table 1

Results of checking the convergence of problem solutions

The number of elements, pcs.	The number of nodes, pcs.	Maximal displacements, m	Maximal equivalent strains	Maximal equivalent stresses, MPa
69,019	485,973	0.0105	0.0011	232.41
626,098	2,823,216	0.0105	0.0011	231.49

The internal pressure (1) in the tank filled with crude oil increases linearly from zero, on the free surface, to 92.4 kPa, at the junction of the tank wall with the bottom. Obviously, reducing the height of the liquid filling by half would lead to a decrease in the maximum pressure to 46.2 kPa. In this case, the upper boundary of the liquid would be on the third belt.

The strength of the vertical steel tank was investigated without taking into consideration the winding of the body.

The calculation was carried out for cases of maximal and half-filling with oil, as well as without oil. Table 2 gives the maximum values of displacements, equivalent deformations, and equivalent Mises stresses for these cases.

Table 2

Maximum values of the parameters of the stressed-strained state of the tank without winding under operating loads

Load condition	Maximal displacements, m	Maximal equivalent strains	Maximal equivalent stresses, MPa
The tank is filled to the maximum with oil	0.0052	0.0005	119.5
The tank is half full of oil	0.0021	0.0002	49.1
The tank without oil	0.00002	0.000004	0.63

It was established that for all estimated cases, the maximum values of equivalent Mises stresses are less than the yield strength at stress $\sigma_{0,2}=245$ MPa. Thus, the applied operating load causes elastic deformations that lead to stresses in the allowable range. However, in the zones of connection of belts of different thicknesses, the wave nature of the increase in stress is observed. These stress concentration zones pose a hazard in the event of additional loads during seismic impacts. Therefore, it is proposed to strengthen them with a winding.

Fig. 2 shows the results of the calculation of equivalent Mises stresses at the maximum level of oil filling of the tank. The thickening of the tank wall to the bottom significantly affects the distribution of stresses. The maximally stressed circumferential belt of the cylindrical wall is located near the junction of the third belt of the tank wall with a thickness of 5 mm with the second belt with a thickness of 6 mm. There is a characteristic decrease in equivalent stresses on the lower fixed edge of the tank.

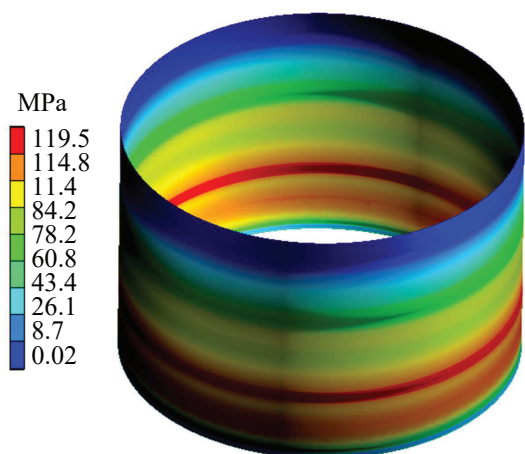


Fig. 2. Equivalent Mises stresses at the maximum level of tank filling with oil

Studies into the stressed-strained state of a steel vertical cylindrical tank with winding at the full filling with oil, half-filling with oil, and without oil were carried out. Three winding options were simulated. For the first variant, the winding was applied at one interval (1:1), for the second – at a double interval (1:2), and for the third – at a triple interval (1:3). The results of the numerical analysis of the

maximum equivalent stresses for a tank with a winding of high-strength steel wire are given in Table 3. It was assumed that the steel wire is made of the steel 65T. Yield strength, $\sigma_{0,2}=785$ MPa. The diameter of the wire, $d=0.004$ m. The value of the tension force of the thread was taken to be equal to $N=0.75\sigma_{ult}\cdot 0.25\pi d^2 H$.

Table 3

The maximum stress in a tank with the winding made of high-strength steel wire under operating loads

Load condition	Maximal equivalent stresses, MPa			
	winding with a step of 1:1	winding with a step of 1:2	winding with a step of 1:3	no winding
The tank is filled to the maximum with oil	165.58	110.63	83.27	119.5
The tank is half full of oil	167.16	111.45	83.73	49.1
The tank without oil	166.87	111.17	83.43	0.63

Applying the winding to the walls of the tank radically changed the distribution of stresses in the structure. Analysis of the results reveals that in the lower part of the structure for all three options for winding hazardous areas, the concentration of stresses is not observed. The most loaded axial belt for all three cases is the upper loose edge of the tank wall. However, for all three cases, the maximum equivalent Mises stresses are far from the yield strength. Thus, the stressed state in the tank wall caused by the winding of high-strength steel wire compensates for the stresses caused by the pressure of the liquid.

Based on the analysis of the above results, it can be concluded that the lowest maximum equivalent stresses in the structure occur when winding with steel wire in increments of 1:3. At the same time, the height of oil loading does not significantly affect their values, which do not exceed 34.2 % of the yield strength.

The results of the numerical analysis of the maximum equivalent stresses for a tank with a winding of smooth composite filament are given in Table 4. The diameter of the composite filament, $d=0.004$ m. Tensile strength, $\sigma_s=1,100$ MPa. The magnitude of the tension force of the filament was assumed to be equal to

$$N=0.75\sigma_{ult}\cdot 0.25\pi d^2 H.$$

Analysis of the obtained results given in Table 4 showed that the maximum stresses in the tank at half-filling with oil in the case of a winding of composite filament with a step of 1:1 are 95 %. Therefore, the use of a winding of composite filament with a 1:1 step is not recommended.

For a composite filament winding with a step of 1:2 and 1:3, the stressed state at the top of the structure corresponds to elastic deformation. And in the lower part of the structure of the circumferential belts, no concentration of stresses is observed.

Thus, based on the analysis of our results, it is possible to recommend a winding with a step of 1:3. Fig. 3 shows equivalent Mises stresses in the tank wall at the maximum level of oil filling for the cases of winding made from high-strength steel wire (Fig. 3, a) and made from a smooth composite filament (Fig. 3, b).

A comparative analysis of the stress distribution by the height of the structure shows the qualitative similarity of

the deformation process. However, the use of a composite filament leads to an increase in the stresses at the upper edge of the wall, from 34.2 % to 47.2 % of the yield strength of the tank material.

Table 4

Maximum stress values in a tank with the winding made of smooth composite filament under operating loads

Load condition	Maximal equivalent stresses, MPa			
	winding with a step of 1:1	winding with a step of 1:2	winding with a step of 1:3	no winding
The tank is filled to the maximum with oil	231.57	154.55	116.15	119.5
The tank is half full of oil	234.09	155.97	117.04	49.1
The tank without oil	233.76	155.68	116.76	0.63

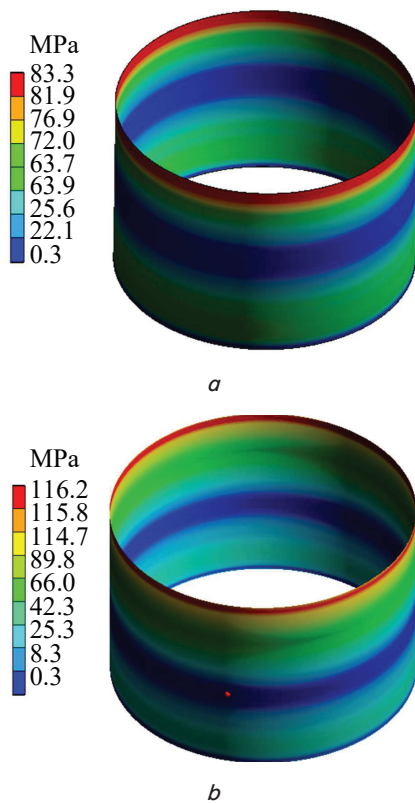


Fig. 3. Equivalent Mises stresses in the tank wall at maximum oil filling level: *a* – winding made of high-strength steel wire; *b* – winding made of smooth composite filament

5. 2. Studying the shape of free oscillations of the liquid in the tank at different levels of filling with oil

Understanding the oscillation process of an oil tank in design is as important as strength analysis. Our study considered the free oscillations of oil in the tank at the maximum and half level of filling, as well as the free oscillations of the tank with a winding of high-strength steel wire and smooth composite filament.

Free oscillation studies for the metal structure-liquid system were conducted using the Modal Acoustics calculation module at ANSYS Workbench. That made it possible to determine the natural frequencies and shapes of oscillation for systems with fundamentally different physical characteristics of the material.

The influence of the level of oil loading on the natural frequencies of the tank oscillations was investigated. A tank without winding was considered. Table 5 gives the results of the calculation of the natural frequencies of a tank filled maximally and filled by half with oil.

Table 5

Natural frequencies (NF) of the tank without winding

NF No.	NF of the maximally filled tank, Hz	NF of the half-filled tank, Hz	Relative difference, %	NF of the empty tank, Hz
1	0.2225	0.2019	9.23	2.3371
2	0.2895	0.2828	2.31	2.3573
3	0.3249	0.3218	0.97	2.4358
4	0.3391	0.3379	0.36	2.5275
5	0.3805	0.3818	0.36	2.6258
6	0.3833	0.3827	0.16	2.8805
7	0.4168	0.4198	0.73	2.8845
8	0.4298	0.4298	0.012	3.1959
9	0.4397	0.4396	0.02	3.4618
10	0.451	0.4541	0.68	3.5488

Analysis of the results given in Table 5 reveals that only the first frequencies have a significant difference, about ten percent. The second ones differ by less than three percent. And the difference between all subsequent frequencies does not exceed one percent. At the same time, the values of the natural frequencies of an empty tank are an order of magnitude greater than those of a tank with a liquid. The first sixty frequencies of the empty tank were analyzed, all of them are paired and are characterized by a large number of nodes in the circumferential direction along the free edge.

Fig. 4–6 show the first three eigenforms of oscillations of a maximally and half-filled tank. There is an identity of the shapes of oscillations at different levels of filling the tank with liquid.

Analysis of the first ten eigenforms of oscillations shows that the main contribution to the process of oscillations of the tank-oil system is made by oil, and the wall of the tank at the lower frequencies of oscillations of the system remains stationary.

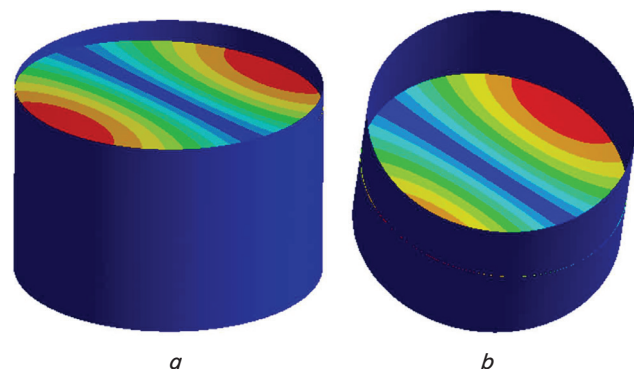


Fig. 4. The first natural shape of oscillations of the oil tank: *a* – filled to the maximum level; *b* – half-filled

The effect of windings made of both high-strength steel wire and smooth composite filament on the natural oscillation frequencies of the reinforced tank was investigated. The first sixty frequencies were considered. Similar to the case of

an empty tank, they are all paired and are characterized by a large number of nodes in the circular direction along the free edge. Table 6 gives the results of the first ten significant frequencies of the tank.

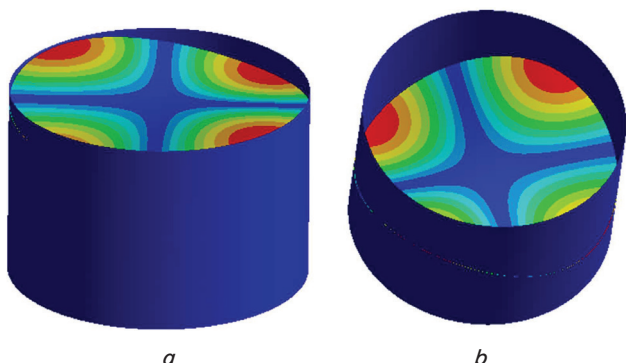


Fig. 5. The second natural shape of oscillations of the oil tank: *a* – filled to the maximum level; *b* – half-filled

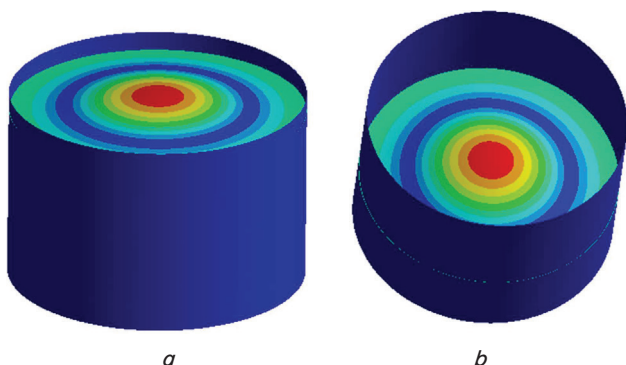


Fig. 6. The third natural shape of oscillations of the oil tank: *a* – filled to the maximum level; *b* – half-filled

Table 6

Natural frequencies of the tank with the winding of different types

Fre- quency No.	Tank without winding	Tank with steel wire winding			Tank with composite thread winding		
		(1:1)	(1:2)	(1:3)	(1:1)	(1:2)	(1:3)
1	2.3371	2.766	2.6265	2.552	2.4211	2.399	2.3873
2	2.3573	2.790	2.667	2.6244	2.4395	2.4045	2.388
3	2.4358	2.953	2.7457	2.6375	2.5561	2.5298	2.506
4	2.5275	2.9757	2.9105	2.8432	2.5778	2.5457	2.5408
5	2.6258	3.2805	2.985	2.8956	2.8067	2.746	2.7157
6	2.8805	3.4028	3.313	3.1383	2.880	2.8794	2.8794
7	2.8845	3.673	3.4053	3.4121	3.1036	3.030	2.9936
8	3.1959	4.133	3.708	3.501	3.4381	3.367	3.324
9	3.4618	4.1865	4.16	3.9156	3.453	3.4452	3.449
10	3.5488	4.647	4.2231	4.2467	3.844	3.7457	3.6964

For all the winding options considered, the lower frequencies of the empty tank are an order of magnitude higher than the lower frequencies of the oil tank oscillations. When designing a structure that is operated in seismically hazardous areas, it is also necessary to take into consideration the

change in the mass of the tank when applying the winding. Table 7 gives the estimated values of the mass of the tank with the winding of different types.

Table 7

Mass of the tank with windings of different types

Mass, t	Tank with no winding	Tank with steel wire winding			Tank with composite thread winding		
		(1:1)	(1:2)	(1:3)	(1:1)	(1:2)	(1:3)
	27.023	37.836	34.214	32.430	28.969	28.321	27.996

Note that the mass of the tank wall without winding is 27,023 kg, and with a winding of steel wire with a step of 1:3, it is 32,430 kg. At winding with a step of 1:1 and 1:2, the mass of the structure increases to 37,836 kg and 34,214 kg, respectively. And the use of composite filament makes it possible to reduce the mass of the tank with winding. When winding with a composite filament at steps 1:2 and 1:3, the mass of the structure is 28,321 kg and 27,996 kg, respectively. Note that when winding with a step of 1:3, the mass of the structure increases by only 3.6 %.

Analysis of the natural frequency spectrum and their corresponding eigenforms of oscillations is the initial and integral stage of analyzing the seismic resistance of a steel vertical cylindrical oil tank.

6. Discussion of results of studying a winding-reinforced vertical oil tank

The reliability of the results of numerical studies depends on a number of factors, including the correspondence between a geometric model and the real structure. Studies of the stressed-strained state of the wall of a steel vertical cylindrical tank with winding at the predefined level of oil loading are based on the use of a finite-element method and a 3D geometric model, which makes it possible to take into consideration the change in the thickness of the tank wall up to 1 mm. Analysis of the strength of the oil-filled structure is carried out taking into consideration the stresses caused by the tension of the winding thread. Finite-element modeling of the stressed-strained state of a tank with a winding at the predefined level of filling with oil makes it possible to assess its strength without conducting a series of experimental studies. And this, in turn, leads to savings in resources and time at the stage of development of project documentation.

A comparative analysis of the stressed-strained state of the wall of a steel vertical cylindrical tank without winding and with a winding of steel wire or composite filament under the condition of maximal filling, half-filling with oil, and without it (Tables 2–4) was carried out. It is established that the application of winding on the wall of the tank significantly affects the nature of the stressed state of the structure. Stresses on the outer surface of the wall caused by tightening the winding compensate for the stresses caused by the pressure of oil on the inner surface of the wall. At the same time, for all winding options, there are no hazardous zones of stress concentration in the structure, unlike a tank without winding. Equivalent Mises stresses do not reach the yield limit, that is, under operational loads, the deformation process occurs in the elastic stage (Fig. 3).

The current study can be advanced through the analysis of the strength characteristics of a tank with oil under seis-

mic loads. As shown here, the stress level in the structure is too small for plastic deformations to occur. In the future, it is planned to study the problem taking into consideration possible elastic-plastic deformations due to seismic loading. Note that the current work is aimed at studying vertical steel cylindrical tanks; no other structures, like linear ones, like pipelines, are considered.

Seismic loads cause forced oscillations of the tank with liquid. In this study, as an initial stage, the shapes of free oscillations of the liquid in the tank at the maximum and half level of filling with oil were obtained, the natural frequencies of oscillations of the tank with different types of winding from high-strength steel wire and from smooth composite filament were determined. It is established that for maximally and half-filled tanks, only the first and second frequencies have a significant difference. And the difference between all subsequent frequencies does not exceed one percent (Table 5). At the same time, the values of the natural frequencies of empty tanks with all types of winding are an order of magnitude greater than the tanks with oil (Fig. 4–6).

The results of our research are planned to be used to strengthen the structure of the tank by applying a winding.

The proposed technique for modeling the preliminary stressed state of a tank wall considering the application of a winding could be used to analyze the dynamic strength of a structure under seismic loads.

7. Conclusions

1. The finite-element modeling based on three-dimensional geometric models was carried out in the ANSYS software package to determine the static stressed-strained state of thin-walled cylindrical tanks with oil, reinforced with a winding of high-strength steel wire or smooth composite filament. The use of three-dimensional geometric models to describe the thin walls of the tank has made it possible to take into consideration the change in the wall thickness along the cylinder generatrix by 12 mm. When modeling the stressed state induced by the winding, the tension force and

the winding step of the wire or thread were taken into consideration. The presence of oil in a tank at the predefined level was simulated by an unevenly distributed pressure acting on the inner surface of the tank wall. The effect of winding on the stressed-strained state of the wall of a steel vertical cylindrical tank with oil has been investigated. The cases of maximum filling with oil, half-filling with oil, and without it were considered. Six winding options were simulated: made from high-strength steel wire and made from a smooth composite thread with a winding step of one to one, one to two, and one to three intervals. For all estimated cases, it was established that the load causes elastic deformations that lead to stresses in the allowable range. However, in the absence of winding in the zones of connection of belts of different thicknesses in the ring layers of the tank wall, the wave nature of the increase in stresses is observed. These stress concentration zones are absent in the tanks with a winding. Applying the winding to the walls of the tank significantly changes the nature of the stress distribution. The stresses caused by the winding tightening compensate for the stresses caused by the pressure of the oil on the tank wall. The lowest maximum equivalent stresses in the structure occur when winding with steel wire in a 1:3 step. In this case, the height of oil loading does not significantly affect their values, which do not exceed 34.2 % of the yield strength. The use of composite filament leads to an increase in the maximum equivalent stresses, from 34.2 % to 47.2 % of the yield strength of the tank material. At the same time, the use of the composite filament makes it possible to reduce the mass of the tank with a winding. When winding with a composite thread in a 1:3 step, the mass of the structure increases by only 3.6 %.

2. The frequencies and shapes of free oscillations of the liquid in the tank at the maximum and half level of filling with oil have been investigated. It is established that only the first and second frequencies have a significant difference. And the difference between all subsequent frequencies does not exceed one percent. At the same time, there is an identity of the shapes of oscillations at different levels of filling the tank with liquid. The values of the natural frequencies of empty tanks with all types of winding are an order of magnitude greater than the values of the natural frequencies of the tank maximally filled with oil.

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