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Tank shell stability: refined design schemes

M. N. Tcepliaev ✉ **, *V.F. Mushchanov, A.V. Zubenko, A.V. Mushchanov, A.N. Orzhehovsky***

Donbas National Academy of Civil Engineering and Architecture, Makeevka

✉ *m.n.cepliaev@donnasa.ru*

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Abstract. In many ways, the reliability of vertical cylindrical tanks is determined by the resistance to buckling of the wall. In the current work, a variant of a detailed design scheme is considered, taking into account the presence of a spiral technological staircase for servicing the tank roof. The possibility of using the specified structural element as an external reinforcement to increase stability is analyzed. Finite element models of tanks with volumes of 10..30 thousand m^3 were developed. The models took into account the actual distribution of the wind flow for tanks with a circular staircase. Using a multifactorial experiment, an analysis of the stability and stress state of the tank wall was carried out. The variable parameters were: the design solution of the stairs, the dimensions of the tanks and the load. Corresponding graphs and diagrams were constructed. As a result, the design solution and the recommended angle of inclination of the spiral staircase in the range of 30–40° were substantiated. The application of the obtained solutions improved the stability in the annular direction by up to 13 % compared to standard solutions. Wall displacements from wind load are reduced by 14 %, in turn, local stresses in the ladder attachment areas increased by no more than 5 %. In general, the inclusion of spiral staircases significantly increases the stability of the tank wall and can be considered as a good alternative to standard reinforcement methods.

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1. Introduction

1.1. Relevance of the study

Modern trends towards more efficient use of natural resources are also reflected in the construction of buildings and structures. Scroll tanks (ST) are high-risk facilities, so any design choices, especially those that lead to steel economy, should be studied extensively. The relevance of studying new approaches to tank designing is beyond any doubt. There's a case for the increasing demand for such constructions due to the development of petrochemical and other industries [1–4]. Another important factor is the demand for regular renovation of the tank battery, due to the relatively short life span of such constructions.

The shell of variable thickness is basic in steel intensity and the most important element of ST. The durability and rigidity of the shell to a large extent determines the reliability of the whole construction of the tank. Despite significant progress in the field of tank designing and construction, accidents associated with the loss of rigidity of the cylindrical shell still occur. A lot of authors, among which we can note the works of J. I. Chang and C.-C. Lin [5], L. A. Godoy and F.G Flores [6], H.M. Hanukhov and A.V. Alipov [7] studied the causes of tank failures and analysed their consequences. According to the results of their researches, damage from wind and vacuum can account for up to 10 % of the total number of structural failures. At the same time, it is stated in the research of the Melnikov Central Research Institute of Scientific and Technical Problems [8] that no more than 40 % of total number of failures that are happening to facilities of the tank park are registered. The same is confirmed by the data given in the work of V.V. Filippov [9], where upon inspection results of several tank parks, significant violations of geometric shape were found in 30 % of all inspected constructions. Over half of geometry kiks were dents and bulges, caused by the influence of wind and vacuum as well.

There is a great variety of constructive and computational methods to ensure the operational reliability of tank shells. For example, the recommendations for keeping a sufficient filling level of a product to resist the loss of wind rigidity were developed in the work [10]. The contributors [11] suggest using composite materials in the form of a garland of plastic bottles filled with carbonate rock powder. And yet, the modern practice of tank design offers only two principled approaches to ensure the reliability of the tank shell from the condition of rigidity:

- structural analysis of appropriate shell thickness;
- installation of additional shell rigidness of elements.

The second approach is technologically more complicated, but it reduces the weight of the construction. By additional elements of rigidness we mean vertical and stiffening rings, banders and similar constructions. Banding can be made either by sheet-iron plates or composite materials [12, 13]. Various peculiarities of usage of stiffening rings are considered in many scientists' works [14–22]. As a rule, stiffening rings are used to increase rigidity, and banding is used to restore the load-carrying ability of apron rings of the shell. The possibility and effectiveness of external force is also confirmed in the specification documents of the USA (API 650), Europe (Eurocode 3, part 4-2) and Russia (SP 16.13330.2011, STO-SA-03-002-2009).

At the same time there are elements of tanks, consideration of the impact of which is not detailed in the engineering methods of calculation of the shell, the staircases, in particular. Technological staircases are used for maintenance of the roof and peep-holes and belong to the list of required equipment of tanks. There are two principal varieties of staircases: with attachment to the shell (spiral) and freestanding (shaft) – Fig. 1a, 1b, respectively. The variant shown in Fig. 1a doesn't work on the stress-strain state (SSS) of the tank because it has its own understructure. The variant shown in Fig. 1b transmits all the load directly to the shell and changes the stress-strain state of the construction. First of all, the presence of the staircase affects the overall rigidity of the shell. Thus, proper consideration of the combined action of the shell and staircases can allow us to design a more streamlined construction without reducing its design reliability.

Figure 1a. Tank stair tower.

Figure 1b. Spiral tank staircase.

1.2. Overview of the state of the issue

The effectiveness of external reinforcement of cylindrical tank shells is confirmed by many researchers and does not require additional justification. However, searching optimal methods of designing such reinforcement and taking into account their design features is still a relevant objective.

Using experimental and numerical research methods in their works, the authors J.G. Teng and J.M. Rotter 2003 [20] and M. Jaharanjiri et al [21] came to the conclusion in 2012 that installing even one stiffening ring increases the resistance to rigidity loss by 1.5 times. Authors D. Lemak in his paper in 2005 [18], F. Bu and C. Qian [19] in his paper in 2015 [20] based on the results of numerical calculations determine the recommended ring pitch and number of rings for a limited range of constructions. The result of the work cycle by the authors V. F. Mushchanov and M.N. Tsepliaev [14, 15] is a universal methodology of rational stiffening rings location. The range of tank constructions is limited to a volume of 30 thousand m3 in the works of these authors. The authors note that stiffening rings do not increase rigidity in axial direction. The main strengthening effect arises due to increasing amounts of annular critical stresses of rigidity loss.

The authors in their works [23] compare the performance of a spiral staircase with an element in the form of an inclined stiffening rib on the tank shell. The conclusions note that the spiral staircase under wind pressure significantly improves the bending resistance of the tank shell. The authors determined the orientation of the hoop staircase toward the wind flow, at which the ultimate crippling load of rigidity loss increases by 20 %. The research is of significant scientific importance, however, it covers only one size of a tank and cannot be considered to be a complex value.

Cases of tank shell rigidity loss due to storm wind are considered in the work [24] – Fig. 2a, b. It is noted that the tank shell at the location of the spiral staircase has not lost its rigidity. Differences in the buckling mode due to the presence closely spaced objects and the magnitude of the vacuum. Taking into account the combined actions of the shell and the hoop staircase, the authors got the following results:

- motions of the shell from the wind load are reduced by 5 %;
- the weight of the cylindrical shell can be reduced to 15 %.

a) **b)**

Figure 2. Buckling under the influence of wind.

The specification documents of the Russian Federation, Europe and the USA do not specify the question of taking into account the combined actions of the shell and the hoop staircase in the design of tanks. Design requirements for spiral staircases coincide in most parameters.

According to the reviewed publications the possibility of increasing the rigidity of the tank shell using the hoop staircase raises no doubts. The consideration of the calculations of spiral staircases can be an excellent alternative to the established shell reinforcement. However, many variations in the location and design of spiral staircases opens up a wide range of scientific and practical issues that require more detailed study.

The article aimed to determine the rational, in terms of ensuring maximum rigidity of the cylindrical tank shell, parameters of a hoop staircase.

The objectives were:

- computer modeling of wind flow distribution for the tank with the hoop staircase in SolidWorks;
- a redetermined finite element model of ST for SSS analysis in the complex LIRA-SAPR 2019 R1 was developed;
- calculation of general shell rigidity at different parameters of hoop staircases was done;
- local stresses in the shell at the attaching points of the staircases were determined;
- the recommendation on the best positioning of the staircases were formed.

2. Materials and methods

2.1. Formation of the experiment matrix

A review of existing designs allowed us to identify two principal variants for attaching spiral staircases:

- with attachment of each step to the tank shell – Fig. 3a;
- with attachment of platforms to the shell – Fig. 3b.

Figure 3a. Spiral staircases – variant 1

Figure 3b. Spiral staircases – variant 2.

The variant in Fig. 3b is more steel-intensive due to the presence of strings, and also has higher stiffness. However, a small number of points of attachment to the tank shell does not allow unambiguously determining the most preferred variant without performing calculations.

The general requirements of regulatory documents indicate the maximum slope of the staircase (up to 50°), the minimum width of the flight is 700 mm; the minimum width of the step is 200 mm. The lower limit of the investigated slope angle of staircases (30°) is justified by analysis of existing structures. Russian and USA documents require installation of half paces with a step of not more than 7.5 meters along the shell height. EU regulations do not stipulate the requirements for the location of half paces. By analyzing existing designs in this paper, the tank models with two variants of spiral staircases will be made. Schematic view of staircases is given in Fig. 4 a,b.

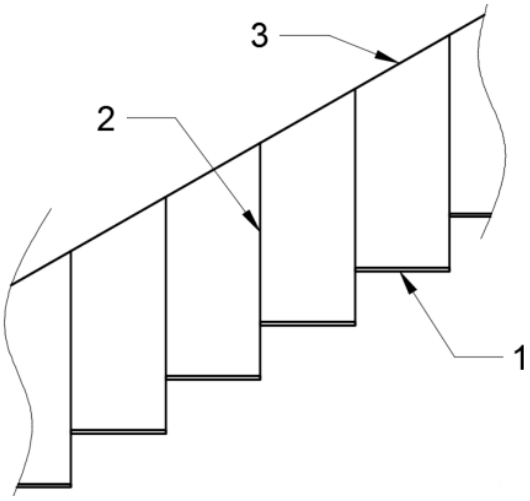


Figure 4a. Spiral staircase diagram – variant 1.

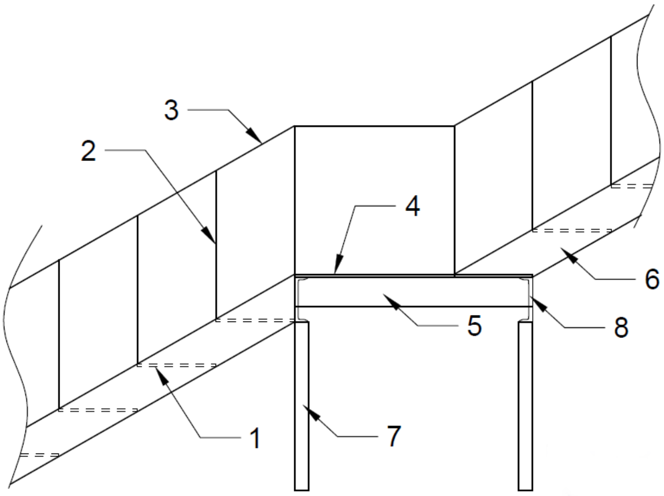


Figure 4b. – Spiral staircase diagram – variant 2.

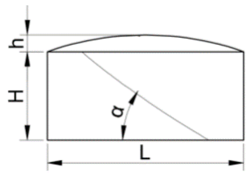
Based on the experience of existing projects, the cross sections of elements for two variants of spiral staircases have been determined – Table 1.

Table 1. Sections of elements of described staircase types.

Staircase type	The number of the element in the diagram	Section type	Element length, mm
Variant 1 (V1)	1	Sheet 250×6	800
	2	Angle 45×45×3	800...1000
	3	Angle 45×45×3	Depends on the slope
Variant 2 (V2)	1	Sheet 250×6	700
	2	Angle 45×45×3	Depends on the slope 800...1000
	3	Angle 45×45×3	Depends on the slope
	4	Sheet 900×6	700
	5	Channel120×60×4	900
	6	Channel 180×50×4	Depends on the slope
	7	Angle 63×6	1100
	8	Channel 120×60×4	900

The performed analysis of publications as well as the results of the current study allowed to limit the considered range of tanks. As the diameter of the tank increases, the influence of the presence of stairs decreases. The most representative values are noted for tanks with a diameter of up to 50 meters, the volume of which does not exceed 30 thousand m^3. Taking into account the existing tank farm, several typical variants were selected. Different stair locations were considered for each tank size. For the second structural variant of staircases, the number of platforms was 5 pcs. Parameters and a complete list of variants under consideration for numerical studies are given in Table 2.

Table 2. Variants of tank models for numerical studies

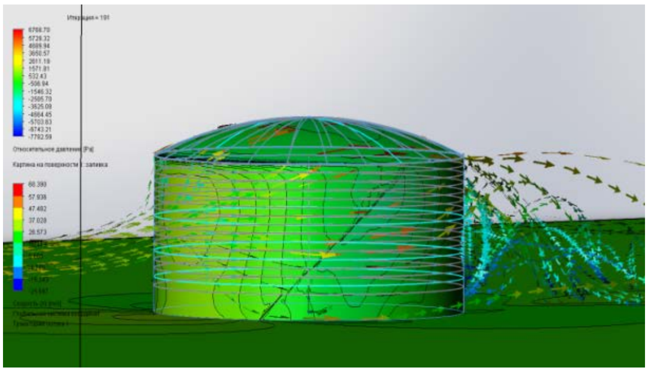
No	Volume, m^3	Tank diagram	Dimensions, m	Variants of staircases	Slope angels of staircases, α◦
1	10000		H=18, h=3.5, L=28.5	V1, V2	30, 35, 40, 45, 49
2	20000		H=18, h=3.4, L=40 H=18, h=3.4, L=40		
3	30000		H=18, h=4, L=45.6		

Thus, the formed numerical experiment matrix includes 33 variants (including 3 models without stairs). Account of the actual distribution of wind flow for a tank with a staircase has been implemented by an additional calculation of 3 models. The total number of variants under consideration was 36 pcs.

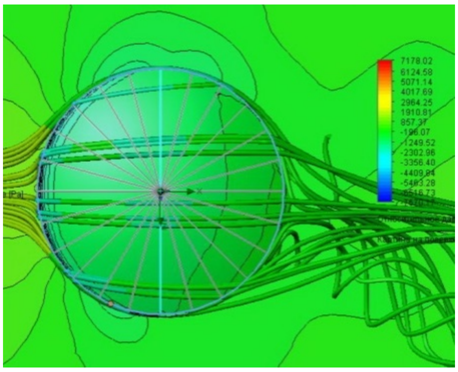
2.2. Development of a numerical model to determine the refined distribution of wind flow

For a comprehensive study the actual distribution of wind flow should be taken into account in the case of a spiral staircase. The complex allows obtaining wind pressure values on the surface of the object in question without physical modeling of the process. The parameters of the design model are substantiated in detail in the works [25–27] and recommendations on the main dimensions of the design area are proposed. Thus, for isolated structures, the vertical size of the design area for isolated structures should be at least 5H, the distance along the flow should be at least 5H, and the distance behind the structure should be more than 15H (H is the height of the structure).

The variant of placing the staircase in the zone of maximum wind pressure on the shell was considered. All considered tank volumes are modeled with the following ratio of height (H) to diameter (D): 0.63, 0.45 and 0.4. The general view and top view of the three-dimensional model for calculating the wind pressure taking into account the presence of a spiral staircase is shown in Fig. 5a and b, respectively.



a) general view



b) top view

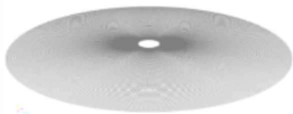
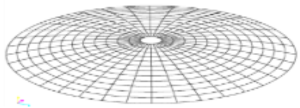
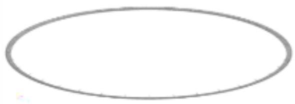
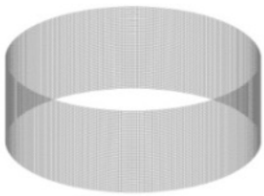
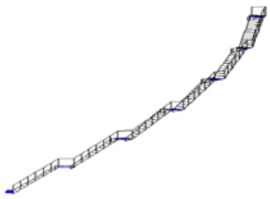
Figure 5. Model in SolidWorks for wind pressure calculation.

Based on the obtained data the wind pressure values for the calculation of VAT and stability in LIRA-SAPR 2019 R1 have been determined.

2.3. Development of a numerical model for tank calculation

Based on the experience of previous studies [16, 17, 30, 31], the parameters of the finite element model of the tank for calculating stability and VAT have been determined. To perform calculations the LIRA-SAPR 2019 R1 software package was used. Element sampling was carried out on the basis of ensuring the convergence of analytical and numerical stresses from hydrostatic load. The main structural components of the finite element model are given in Table 3.

Table 3. Experimental matrix for numerical studies

Model element	Graphic image	Types of a finite element used
Plate coating FE No44		Plate finite element No44
Ribbed-ring dome		Rob finite elements No10 The joint of the bearing dome rib with the supporting ring was simulated by combining movements.
Stiffening support ring		Plate finite elements No42 and 44
Variable thickness wall plate FE No44		Plate No44 (width up to 1/480 of the circle, height up to 1/82 of the wall height)
Spiral staircase		Platforms – plate finite elements No44, the rest of the elements are rod.
Bottom		Plates No44 and 42 (flashing places of the bottom to the wall)

Formed finite element model of one of the tank variants (without displaying loads) is shown in Fig. 6.

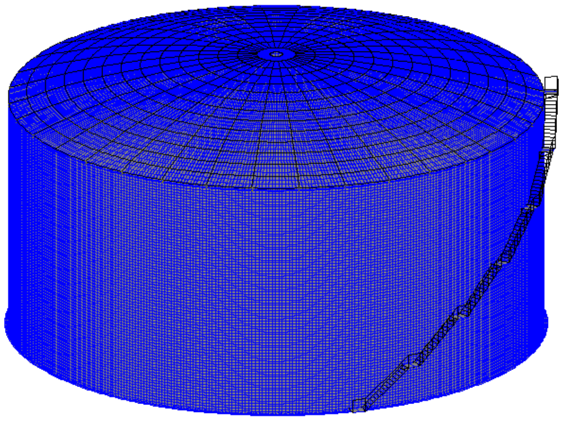


Figure 6 Tank model LIRA-SAPR 2019 R1.

According to the objectives of the study, two characteristic design cases of loading were considered - an empty and filled reservoir. Design load combinations used in this study are given in Table 4.

Table 4. Design load combinations.

No	Method of calculation	Combination of load
1	VAT	dead load + hydrostatic pressure (oil 0.9 t/m^3) + overpressure (2 kPa)
2	Rigidity	wind (0.5 kPa) + vacuum (0.25 kPa)

The mounting points of the stairs are stress concentrators. The maximum stresses in the tank shell result from hydrostatic stress action (combination #1 in Table 5). Both grid clustering was made and stress jumps were determined in the specified areas of the finite-element model.

The design load for structural rigidity design is to be presented as a combination of wind and vacuum (combination No2 in Table 5). The form of wind flow distribution was considered in two variants:

- according to the Eurocode;
- specified wind flow distribution for a tank with staircase (based on the results of structural analysis in SolidWorks Flow Simulation).

The exact shape of the wind load was modeled in LIRA-SAPR 2019 R1 by means of a text file. The detailed methodology of this way of setting the load is described in the paper [28]. The type of both the basic wind load and the load on the model for the characteristic cross section of the cylindrical shell is given in Fig. 7a, 7b respectively.

a) basic wind flow distribution

b) wind load simulated by LIRA-SAPR 2019 R1 system

Figure 7. Wind load on the tank wall.

2.4. Methods for evaluating the results

For the present study, the main comparative parameter will be the value of critical stresses of instability in the cylindrical shell of the tank. This parameter is manifested by the rigidity factor (SF) of the cylindrical shell. It allows us to define the theoretical value of the critical pressure corresponding to the moment of rigidity loss (formula 1).

$$SF = \frac{P_{cr}}{P}, \quad (1)$$

where P_{cr} is the critical pressure of the cylindrical shell rigidity loss, P is the operating pressure.

The value of the SF was determined by means of LIRA-SAPR 2019 R1 software system (in case of load combination No. 2 from Table 5). Since the design combination does not include axial loads, the SF is directly related to the circular critical stress of rigidity loss.

The stress state analysis was made for a limited list of options and it includes two criteria, such as:

- the value of tank shell deformations for different structural variants of the staircase (load combination 1 – Table 5);
- the value of stress concentration in the mounting points of the staircase (load combination 2 – Table 5).

The general procedure for determining the recommended parameters of the staircases is as follows:

1. structural rigidity designing for determining the SF for each variant of tanks under consideration;
2. constructing dependency graphs of the SF and the dimensions and design solution of the tank staircases;
3. local stresses analysis in the attachment zones of the staircases to the tank shell under the hydrostatic load;
4. determination of the most preferable structural variant of the staircases on the basis of the rigidity design and strain-stress state;
5. determination of the recommended slope of the selected structural variant of the staircases on the basis of the rigidity design;
6. conclusion on the applicability of the obtained results for the case of the specified wind pressure diagram (obtained by SolidWorks Flow Simulation).

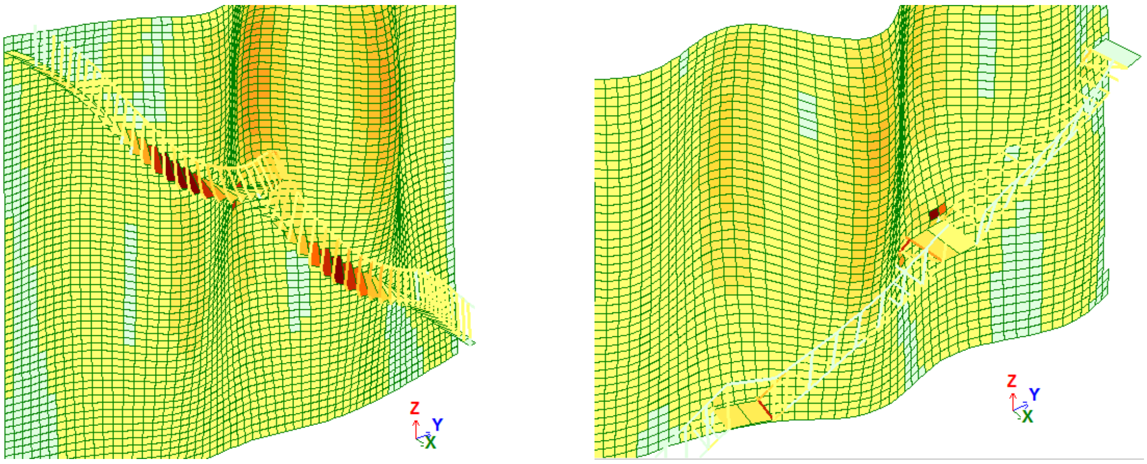
The resulting array of data has allowed us to give recommendations for choosing parameters of staircases for the considered types of structures.

3. Results and Discussion

3.1. Results of rigidity design

According to the research algorithm (Sec. 2.4) the structural design for 36 tank models in the design variations listed in Table 2 has been made. As a result, values of critical stresses of rigidity loss and a picture of the stress-strain state have been obtained. Since the graphical representation of the deformed models does not give a qualitative assessment of the results obtained, only a few typical variants for a tank in the volume of 20 thousand m^3 will be given in the paper.

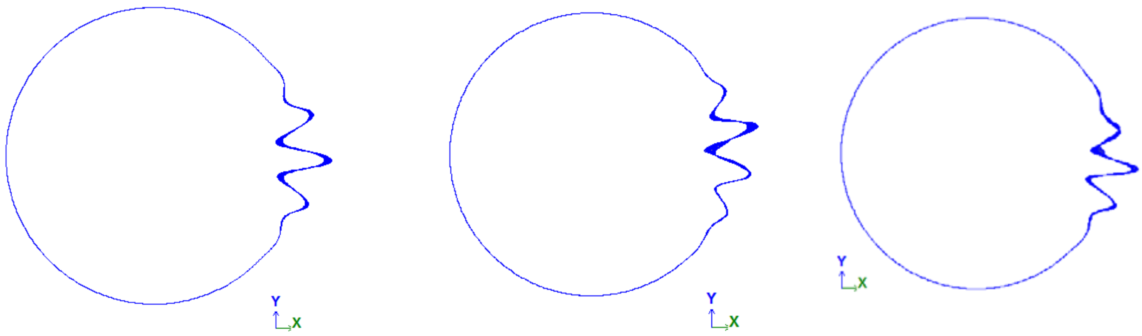
Fig. 8 a and b shows the first forms of rigidity loss of the tank shell fragment for two structural variants of the staircases. The first variant of the staircase deforms by repeating the form of the shell, unlike the second structural variant. It is explained by the fact that the attachment points of the second variant transmit the stiffness of the staircase to the shell to a lesser extent. The location of the buckling waves corresponds to the case of the prevailing action of circumferential stresses.



a) B1 – 40° slope b) B2 – 40° slope

Figure 8. General view of the loss of rigidity of the shell fragment of the tank with a volume of 20 thous. m^3.

Rigidity loss occurs from the windward side of the tank shell. This is clearly seen in the characteristic section of the cylindrical shell at the height of 9 meters – Fig. 9. The cases without modeling staircases and with staircases in the two considered design variants are given – Fig. 9 a, b, c, respectively. The forms of rigidity loss for the model without staircase (Fig. 9a) and with structural variant No. 2 (Fig. 9c) are similar. For the structural variant of staircase No. 1 (Fig. 9b) the number of waves is greater while their amplitude is smaller.



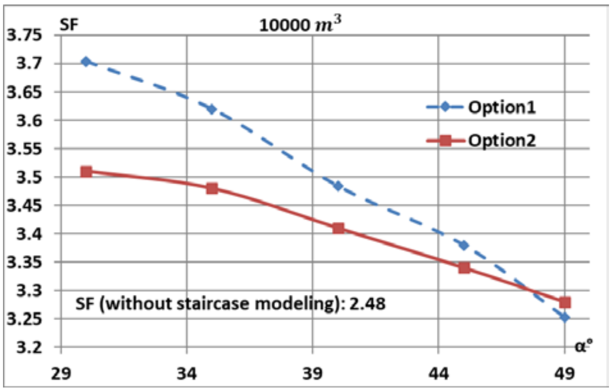
a) without staircase modelling b) B1 – 40° slope c) B2 – 40° slope

Figure 9. The shape of the loss of rigidity of the shell of the tank with a volume of 20 thousand m^3 at the level of +9.000 m.

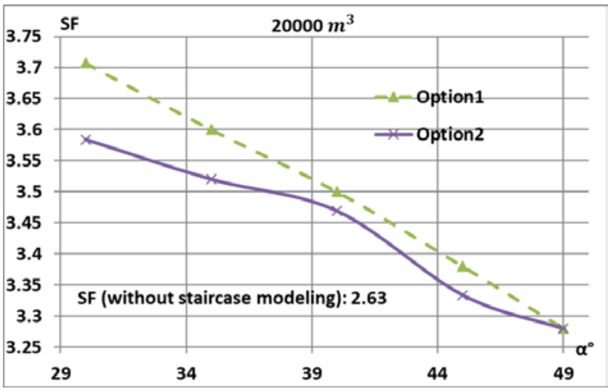
The resulting data for the other studied volumes of the tanks confirms the conclusion. The shapes of the tank shell rigidity loss coincide with the results of other authors [6, 19, 21, 29]. However, when analyzing the buckling of a real structure (Fig. 2), some differences were noted. In particular, a significant dispersal of buckling waves along the length and height of the tank wall. The change in geometry in a real design occurs mainly in the upper part of the tank wall on the windward side, and not along the entire height. The differences are due to the lack of accounting for supercritical work. In addition, for research purposes, the stability calculation does not take into account the weight of the roof, which changes the type of wall buckling.

Graphs of SF changes depending on the slope of the staircase α (Table 3) and the volume of the tank are shown in Fig. 10 a-c. The structural variants of the stairs are described in item 2.1 (B1 – option 1, B2 – option 2). Each graph additionally shows the SF value for the model without staircase.

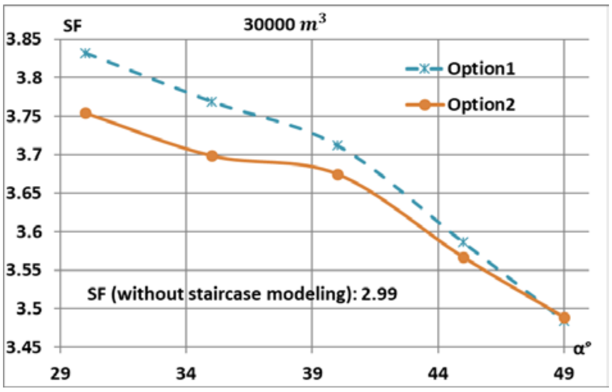
The values of the maximum effective circular stresses do not change in case of staircase modeling which is also typical of other types of shell reinforcement [15, 17]. Taking into account the absence of axial loads, the dependence between the SF and the circular critical stresses of rigidity loss can be considered directly proportional.



a) VCT of 10 thousand m³ volume



b) VCT of 10 thousand m³ volume



c) VCT of 10 thousand m³ volume

Figure 10. Rigidity of the tank shell for different staircase parameters.

The foregoing graphs made it possible to determine the most typical features for all the considered volumes of tanks:

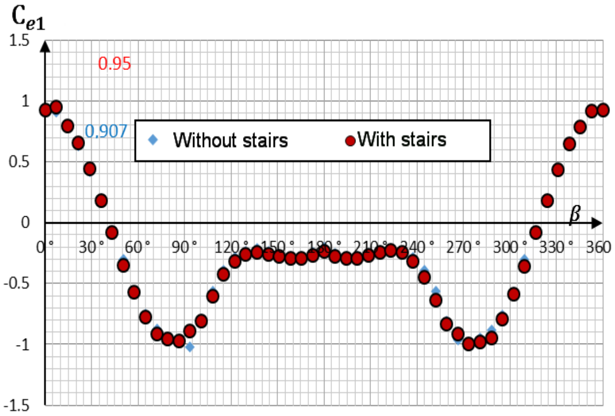
– the range of SF values depending on the slope of the staircase changes by up to 13 %;
– availability of a circular staircase increases the critical stresses of shell rigidity losses (under active wind pressure) by 20...50 % depending on its slope and design;
– the structural variant of staircase No.1 provides greater rigidity in comparison to the structural variant No. 2 (SF is 6 % greater);
– the α angle increasing, the difference between the values of SF for the considered structural variants of staircases is reduced;
– dependences of SF on α angle are close to the linear ones in the ranges of α angle = 30...40°;
– SF sharp decrease is noted for the tanks of 20 and 30 thousand m³ volume for α angles > 40°.

The value of critical buckling stresses increases by up to 42 %, which generally correlates with the results obtained in the current work [23]. It was noted in the work [24] that a decrease in the acting stresses for a vertical cylindrical tank with a staircase by up to 5 % under the action of a wind load, which could not be confirmed in the current study. The difference may be due to the parameters of the reservoir and wind load.

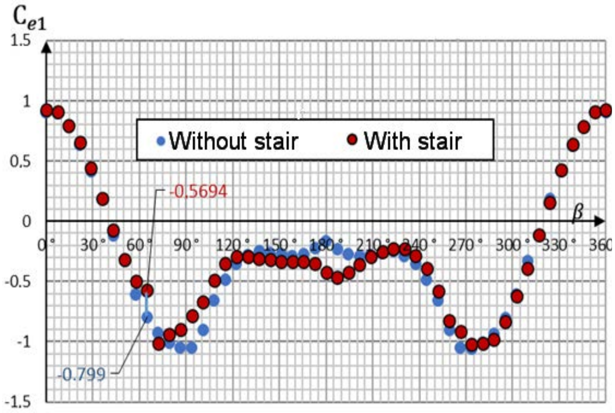
Based on the results presented in paragraph 3.1, the constructive version of staircase No. 1 was chosen for further research as more preferable in terms of increasing the rigidity of the tank shell. The recommended staircase inclination angle α is 30..40°.

3.2. Results of calculating the adjusted wind pressure

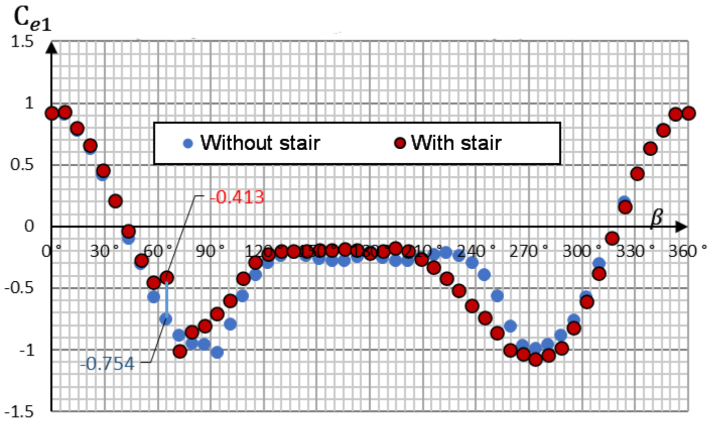
Using the method given in paragraph 2.3, wind flow distributions were obtained, taking into account the presence of a spiral staircase on the tank shell. Using the built-in capabilities of the SolidWorks program, an array of data was formed to establish the dependences of the change in the aerodynamic coefficient for the tanks of the considered volumes – Fig. 11a-c.



a) vertical cylindrical tank with a volume of 10 thousand m³ with H/D = 0.63



b) vertical cylindrical tank with a volume of 10 thousand m³ with H/D = 0.45



c) vertical cylindrical tank with a volume of 10 thousand m³ with H/D = 0.4

Figure 11. Improved aerodynamic coefficients for a tank with a spiral staircase.

The obtained data on changes in the aerodynamic coefficient made it possible to determine the following features for the structures under consideration:

- with an increase in the volume of the tank, a change in wind pressure is observed in the area of adjacency of the staircase, in contrast to a tank without a staircase;
- the maximum discrepancy up to 20 % is noted in the zones of negative pressure (tearing effect on the tank shell);
- in the zone of active pressure, there is a decrease in the vacuum pressure, depending on the size, up to 6 %.

Since the data obtained show a difference from the normative approaches, the calculation of the stress-strain state and rigidity for the reservoirs under consideration was carried out, taking into account the specified parameters.

3.3. The results of the tank shell rigidity calculation for the refined distribution of the wind flow

The impact on the rigidity of the adjusted values of wind pressure is determined for the constructive version of staircase No. 1 (angle of inclination 30°). The methodology for setting the load and the parameters of the finite element model are given in clause 2.3. The obtained results are presented in the form of a diagram showing the change in the factor of rigidity y for various options in Fig. 12. The values of the factor of rigidity of the tank shell obtained earlier (in clause 3.1) for the standard wind load, for greater information content, are repeated in the current diagram.

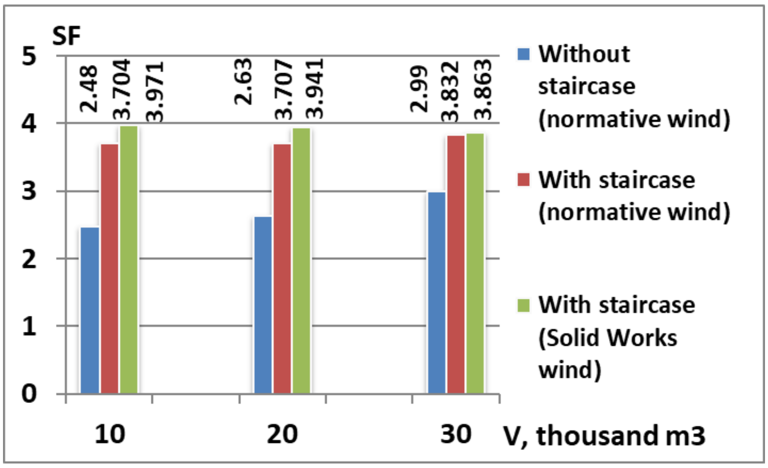


Figure 12. The tank shell rigidity for various variants of the finite element model.

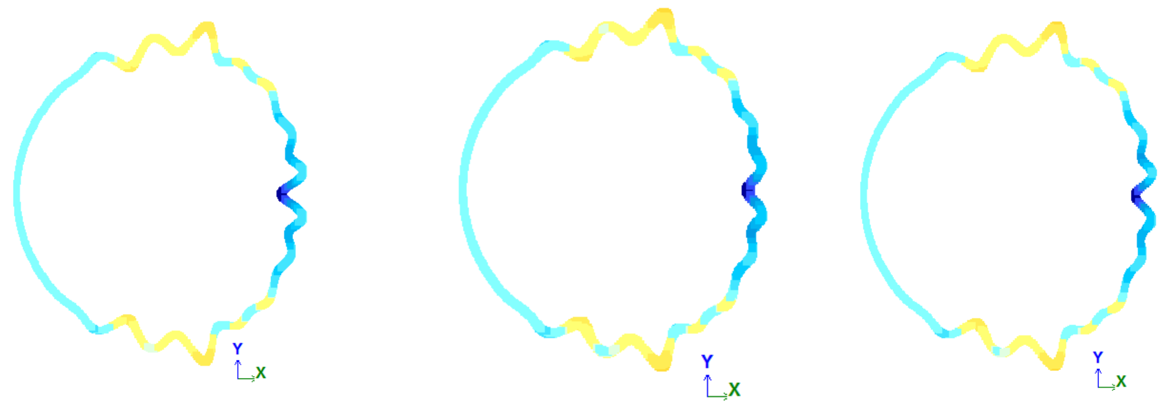
From the diagram in Fig. 12 it follows that the adjusted wind load causes an increase in the ultimate buckling load by up to 7 % compared to the normative distribution. With an increase in the volume of vertical cylindrical tank, the difference in the factor of rigidity between the standard and specified wind pressure becomes less pronounced. In general, taking into account the staircase and the refined wind pressure in the model makes it possible to increase the ring critical buckling stresses by up to 50 %.

3.4. Results of stress-strain state analysis

According to the research algorithm (clause 2.4), the analysis of the stress-strain state includes:

- calculation of the tank shell deformations from the action of wind load for two versions of staircase;
- calculation of local stresses in the area of staircase fastening from the effect of hydrostatic load.

Fig. 13 a-c shows the deformed schemes of the tank shell with a volume of 20 thousand m^3 at a level of +9.000 meters from the impact of load combination No. 2.



a) without staircase modeling **b) V1 – 40° inclination** **c) V2 –40° inclination**

Figure 13. Deformation of the tank shell with a volume of 20 thousand m^3 at a level of +9.000 meters.

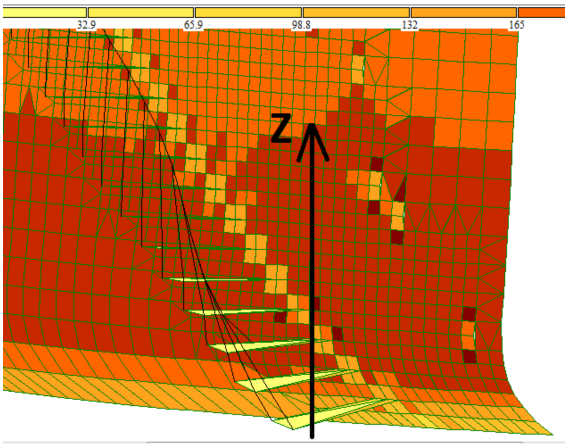
The maximum tank shell displacements compared to the model without a staircase (Fig. 13a) are reduced by:

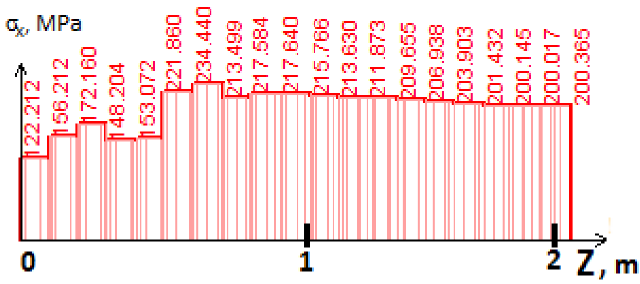
- 9 % for the case of the constructive version of staircases No. 2 (Fig. 13b);
- 14 % for the case of the constructive version of staircases No. 1 (Fig. 13c).

Fig. 13 a-b allow us to conclude that the constructive version of staircases No. 1 provides a greater total stiffness of the tank shell compared to option No. 2.

The results of the study [24] show a reduction in displacement by 5 % for a constructive type of staircases close to type No. 2. It is not possible to perform a direct comparison of the results, since the parameters of the staircase and the studied reservoir are not specified. In this case, the form of displacement is similar.

For the options under consideration, the circumferential (σx, MPa) and axis (σy, MPa) stresses from the action of a hydrostatic load (combination 2 from Table 5) were studied. The main controlled parameter was the concentration of stresses arising at the points of attachment of staircases to the tank shell. The stresses arising in the area of the two lower (most loaded) tank courses (the height of the considered section of the tank shell is up to +4.000 m) were considered. Several typical cases of distributions for a vertical cylindrical tank with a volume of 30 thousand m^3 are shown in Fig. 14–16. The results are presented in the form of images and graphs of changes in circumferential (σx, MPa) and axis (σy, MPa) stresses along the tank shell height. The fragments of the structural design (Fig. 14a, 15a) show the color distribution of stresses, and also show the position of the Z axis along which the stress change diagrams are plotted (Fig. 14b, 15b). The Z axis passes in the plane of the cylindrical tank course, perpendicular to the base. Fragments of structural design in Fig. 14a and 15a are models of real structures shown in Fig. 3a and 3b, respectively.



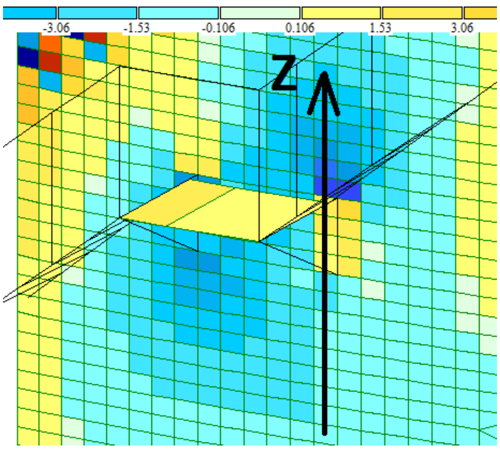


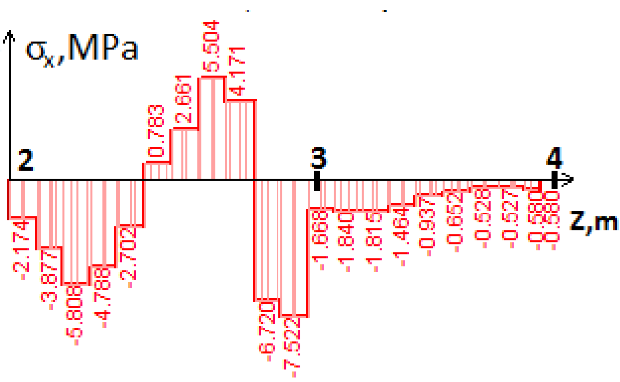
a) fragment of the deformed scheme **b) graph with tank shell height distribution**

Figure 14. Distribution of σ_x (MPa) for vertical cylindrical tank of 30 thousand m^3 in the area of staircase presence (V1).

For the constructive version of staircases No. 1 (V1), the presence of the staircase slightly changes the deformed scheme (Fig. 14a), while the values of hoop stresses increase. Thus on the graph presented in Fig. 14b, the maximum stress value is 234 MPa, which is 5 % higher than the value in areas remote from the staircase (Fig. 16a).

The concentration of meridional stresses is most prominent for the constructive version of staircase No. 2 – Fig. 15a. At the same time, due to the low rigidity of the attachment points of option 2, the value of the hoop stresses changes slightly.

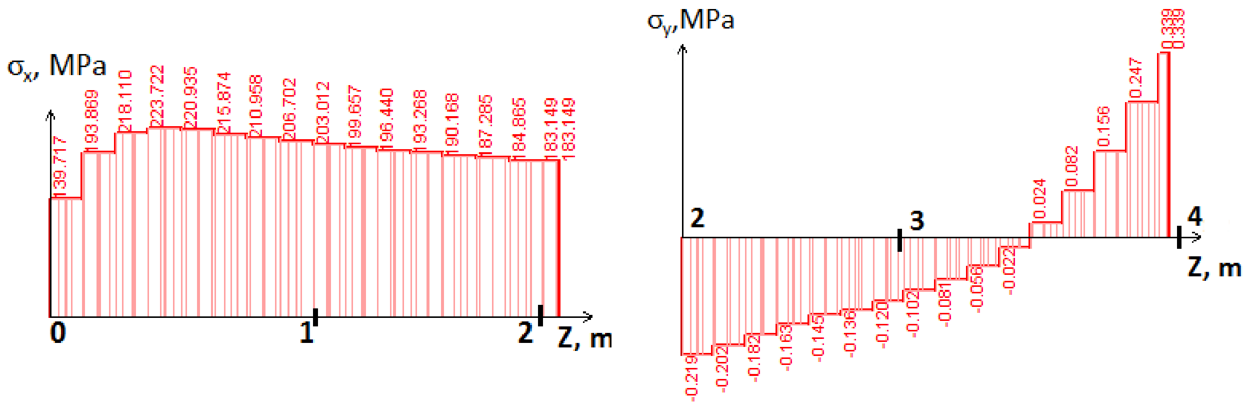




a) fragment of the structural design **b) graph with shell height distribution**

Figure 15 Distribution σ_y (MPa) for a vertical cylindrical tank of 30 thousand m^3 in the area of the presence of a staircase (V2).

It is important to note that the values of the meridional stresses are significantly less than the hoop stresses (up to 5 MPa) and are not a determining factor for this study – Fig. 15b. The graph of the distribution of circumferential (σ_x, MPa) and axis (σ_y, MPa) stresses along the tank shell height in the zone of the lower two tank rings is shown in Fig. 16 a and b, respectively.



a) belt stresses, MPa **б) meridian stresses, MPa**

Figure 16. Stress distribution for VCT 30 thous. m³ without staircase modeling.

Table 5 represents a piece of detailed information about the states of stress in the staircase fastening zones. The maximum of the belt stresses in the two lower chords are determined for two cases. Comparison of meridian stresses is not informative due to their small value and variances in it.

Table 5. Maximum belt stresses of the tank shell

Tank capacity, thous. m^3	Stresses, MPa (design 1)			Stresses, MPa (design 2)		
	For the loose part	For the staircase fastening zone	%	For the loose part	For the staircase fastening zone	%
10	206	210	1.9	208	211	1.44
20	212	218	2.8	216	217	0.46
30	223.22	234	4.9	196	198	1.02

The first design of the staircase leads to a higher concentration of belt stresses in comparison with the second one. There is a tendency to increase the stresses concentration with an increasing in the tank capacity. The maximum stress excess in the staircase fastening zone does not exceed 5 %. It is a case that does not lead to significant overspending of steel.

The subject of stress concentration in the places of staircase fastening is discussed in detail in this paper [30]. The results obtained by the author show an increase in stress by 8 %. The maximum is observed in the zone of the lower chord of the shell.

Steel consumption is chosen as an additional criterion for evaluating the choice of the recommended range. The mass of the spiral staircase (B1) is calculated depending on the slope to solve the problem. The corresponding graph is represented in Fig. 17.

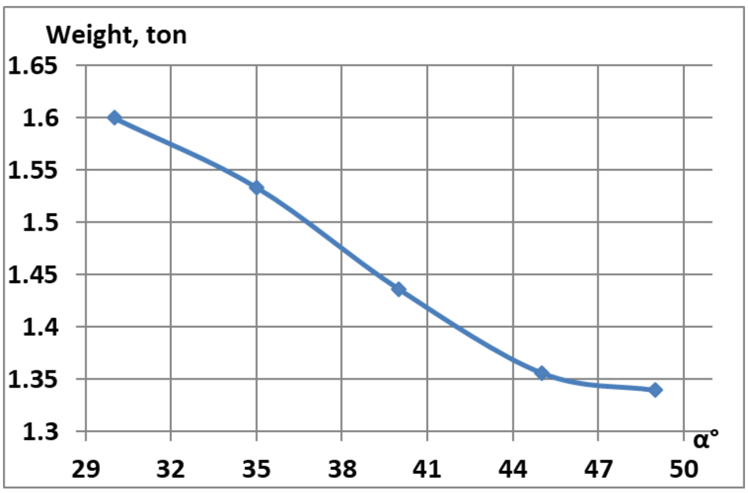


Figure 17. Staircase weight (B1) depending on the slope.

The data show that the staircase weight varies slightly in terms of the weight of the entire structure (less than 1 %) depending on the slope. Thus, the staircase weight cannot be a determining factor. Therefore, the staircase slope recommendations derived from the rigidity analysis and SSS of the tank will be accepted as final in the current study.

4. Conclusions

The study represents additional recommendations for the design solution and the creation of finite element models of vertical cylindrical tanks with a diameter of up to 50 m and a capacity of up to 30 thousand m^3. Considering the results of determining the effect of spiral staircases on the strength and rigidity of tanks, the conclusions of the paper are as follows:

– full-scale design of a spiral staircase significantly refines the stress-strain state of the tank as a whole;
– the most preferable option is staircase number 1 in accounting for increasing rigidity (the value of the belt critical stresses increases to 6 % compared to option number 2);
– the maximum increase in the rigidity of the shell is observed when the staircase slope to the horizon is in the range of 30...40°;
– the refined spreading of the wind layer around the staircase reduces the active pressure on the shell, which leads to a decrease in the acting stresses by up to 7 %;
– full-scale designing of staircases and refined wind load allows to increase critical belt stresses by up to 50 %;
– the weight of the spiral staircase is no more than 1 % of the weight of the entire tank structure and is not a determining factor;
– the stress concentration in the staircase fastening zones does not exceed 5 %.

The results represent the fact that spiral staircases significantly increase the rigidity of the tank shell. Moreover, spiral staircases do not have a significant negative effect on the strength of the VCT. Taking them into account allows expanding the list of methods for strengthening the tank shell s and determining the real reserves of structures. The lightweight and usage of spiral staircases make it possible to consider them as a promising method for increasing the rigidity of the VCT shells, both in new design and reconstruction.

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Information about authors:

Maxim Tcepliaev, *PhD in Technical Sciences*
ORCID: https://orcid.org/0000-0002-1729-4127
E-mail: m.n.cepliaev@donnasa.ru

Vladimir Mushchanov, *Doctor of Technical Sciences*
E-mail: mvf@donnasa.ru

Anna Zubenko, *PhD in Technical Sciences*
E-mail: a.v.zubenko@donnasa.ru

Alexander Mushchanov, *PhD in Technical Sciences*
E-mail: a.v.mushchanov@donnasa.ru

Anatoly Orzhehovsky, *PhD in Technical Sciences*
E-mail: a.n.orzhehovskiy@donnasa.ru

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