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DEFORMATION BEHAVIOR OF REINFORCED SHELLS UNDER THE ACTION OF WIND: AN EXPERIMENTAL STUDY

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Abstract

Introduction. The trends of increasing the cost-effectiveness and reliability of structures come into conflict and require the search for new approaches to design. Steel vertical cylindrical tanks, the use of which is constantly growing, are no exception. This study addresses the issue of buckling of a cylindrical tank wall due to the action of wind and vacuum loads. The **purpose of the study** was to conduct experimental verification of design solutions for improving the stability of the walls of vertical cylindrical tanks. **Methods**: Based on the previously performed numerical studies, a two-stage experimental procedure was developed to test the applicability of the reinforcement designs. Stage I includes the investigation of the shell behavior under the action of vacuum. Stage II considers different tank model designs under the action of actual wind load. The height of the stiffening rings and the angle of the stairs served as variable parameters. **Results**: An increase in the critical buckling load of up to 7 % in case of vacuum action and 27 % in case of wind action was established in the presence of stairs with the recommended parameters. The effect of an increase in stability due to the presence of stairs was noted only when they were oriented in the direction of maximum compressive wind action. In this case, stairs of sufficient stiffness reduce the risk of total structural failure from wind and vacuum, regardless of its location. Reinforcement with stiffening rings should be considered a more preferable method. The study results in the experimental confirmation of the effectiveness of the analyzed designs and the adequacy of the numerical models used.

Keywords: stability; tank; stress-strain state; finite element method; cylindrical shell; wind, stairs.

Introduction

Advances in technology, growth of liquid storage volumes, environmental and economic considerations drive the development of design methods for *vertical cylindrical tanks (VCTs).* The risk of man-made damage (Chang and Lin, 2006; Megdiche et al., 2022) requires the development of safer tank designs (Dong et al., 2021; Fedosov et al., 2019; Sengupta, 2019). At the same time, reliability and cost-effectiveness are in many respects mutually exclusive, which requires the development of new solutions (Fig. 1).

Wall strength and stability is the basis for the reliability of the entire tank. In real practice, buckling of a cylindrical tank wall is not uncommon (Azzuni and Guzey, 2022; Hornung and Saal, 2002; Jahangiri et al., 2012; Pasternak et al., 2022) — see Fig. 3b, c. Most damage is caused by wind and vacuum (Godoy, 2016). This is largely due to the use of approximate buckling analysis methods (Godoy and Flores, 2002; Hornung and Saal, 2002; Konopatskiy et al., 2023; Pasternak et al., 2022). Safe operation of tanks with such damage as well as their repair are impossible. Restoring the geometry of the metal makes it more brittle and prone to fatigue cracking (Zdravkov and Pantusheva, 2019). A more appropriate solution is to apply structural and technological (Zhao et al., 2020) methods to improve stability. Additional elements increasing tank wall stability can include *ring stiffeners (RS)* (Bu and Qian, 2015; Lemák and Studnička, 2005; Mushchanov and Tsepliaev, 2020; Sun et al., 2018; Uematsu et al, 2018; Zeybek et al., 2015), technological stairs (Hussien et al., 2020; Shokrzadeh et al., 2020; Tcepliaev et al., 2023), and alternative structures (Mushchanov et al., 2010).

Ring stiffeners represent a common design solution to increase wall stability under the action of wind and vacuum (Fig. 2a, b).

The perception of axial loads is only possible if the rings are regularly arranged throughout the height of the wall (Pasternak et al., 2022; Shiomitsu and Yanagihara, 2021). However, such solutions are rarely applied in practice. Among the studies addressing various peculiarities of using stiffening rings, studies by Bu and Qian (2015), Lemák and Studnička (2005), Sun et al. (2018), Uematsu et al. (2018) can be mentioned. These authors justified the overall effectiveness of RS use, without specifying the optimal arrangement or dimensions of the structures. Mushchanov and Tsepliaev (2020) filled in these gaps by offering recommendations on the optimal arrangement of stiffening rings in terms of ensuring maximum stability. The validity of the results in case of vacuum action is supported by experimental verification and comparison with similar studies (Fakhim et al., 2009; Rastgar and Showkati,

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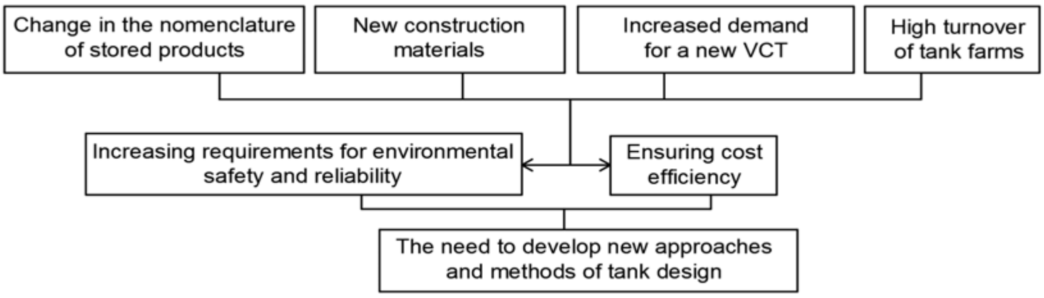


Fig. 1. Relevance of developing tank design methods

2017; Shokrzadeh and Sohrabi, 2016). The obtained method was not tested under the action of actual wind load.

With account for the trend of increasing the cost-effectiveness of structures, another solution considered is the reinforcement of tanks with technological stairs (Fig. 3a). Their interaction with the wall is not considered in engineering practice. At the same time, conducted studies (Davarzani et al., 2023; Fakhim et al., 2009; Hussien et al., 2020; Mushchanov et al., 2010; Rastgar and Showkati, 2017; Shiomitsu and Yanagihara, 2021; Shokrzadeh and Sohrabi, 2016; Shokrzadeh et al., 2020; Tcepliaev et al., 2023) show the positive effect of stairs on the overall stability of tanks.

Based on numerical studies and accident analysis (Fig. 3b, c), some papers (Hussien et al., 2020; Pasternak et al., 2022; Shokrzadeh et al., 2020) provide a rationale for specific types of stairs to improve stability. Based on numerical studies, Tcepliaev et al. (2023) determined recommended design parameters of stairs for tanks of different dimensions, making it possible to increase the critical buckling load by up to 28 %. The proposed solutions have not been verified experimentally under the action of actual wind. In this case, the justification for the use of such methods can be characterized as inadequate.

Therefore, the *purpose of the study* was to conduct experimental verification of design solutions for improving the stability of the walls of vertical cylindrical tanks.

The main objectives were as follows:

- experimental verification of a numerical model of a tank with stairs under the action of vacuum;
- analysis of the stress-strain state of a model of a tank with stairs;
- experimental verification of the effectiveness of the previously proposed methods for the arrangement of stiffening rings and technological stairs under the action of wind.

The problem statement makes the current study a logical continuation of comprehensive research (Mushchanov and Tsepliaev, 2020; Tcepliaev et al., 2023). The arrangement of stiffening rings and spiral stairs is determined based on the recommendations proposed in the above-mentioned works.

Materials and methods

The magnitude and direction of wind load corresponding to buckling of a tank wall can be ensured by continuous long-term observations. An alternative solution is to use scaled-down tank models that make it possible to reproduce the effect of buckling for the required number of times. Stress-strain state parameters, effects of buckling from uniform loads (Mushchanov and Tsepliaev, 2020; Pasternak et al., 2022; Shiomitsu and Yanagihara, 2021), and wind flow distribution (Davarzani et al., 2023; Mushchanov et al., 2013) are mainly studied on scaled-down tank models. Among the publications addressing experimental studies of buckling due to wind, a work of Uematsu and Uchiyama (1985) can be distinguished.

a) truss ring (https://www.flamax.ru) b) solid section ring (https://tdrzmk.com)

Fig. 2. Use of stiffening rings for tanks

a) general view (https://www.everypixel.com) b) buckling due to wind (Pasternak et al., 2022) c) buckling due to vacuum (Shokrzadeh et al., 2020)

Fig. 3. Tanks with technological stairs

The results of the study by Uematsu et al. (2014) describe the specifics of the shape of polyester film shell deformations using wind-tunnel tests. The researchers recorded critical wind load and wall displacement values up to the moment of buckling. However, in terms of dimensions, the studied structures are similar to silos and the obtained results cannot be applied to compare the buckling parameters of the structures considered in this work. Uematsu et al. (2014) focused on studying the distribution of the wind flow over open-topped tank walls. In addition, using a laser detector, they recorded the deformations of the tank model in a wind tunnel. Due to the high elasticity of the shell material, the buckling effect was ambiguous. The shape of the shell was partially restored after the cessation of exposure to wind load. Both works did not consider the influence of structural reinforcement elements on the stability of the shell. Nevertheless, the results obtained by the researchers (Uematsu and Uchiyama, 1985; Uematsu et al., 2014) allow for a qualitative comparison of buckling shapes and provide a visual reference for the current tests. The applied principles of experimentation formed the basis for the method underlying the current tests, with account for the necessary modifications.

Buckling due to wind can only be captured for an ultra-thin shell model. In this case, the measurement of stresses is accompanied by excessive errors. A two-stage experimental procedure is a compromise solution.

Stage I consists in testing the reinforced steel tank model for buckling under the action of vacuum. The experimental testing method is based on the recommendations of researchers (Mushchanov and Tsepliaev, 2020; Tcepliaev and Mushchanov, 2018). This step makes it possible to verify the numerical model in terms of arising stresses and critical buckling force in case of buckling due to vacuum. Further, it will make it possible to determine the fundamental possibility of using the previously developed finite element model for the analysis of tanks with stairs (Tcepliaev et al., 2023).

Stage II consists in the experimental modeling of buckling effect from wind action using a wind tunnel, following the principles applied by researchers in their studies (Uematsu and Uchiyama, 1985; Uematsu et al., 2014). Structural solutions based on techniques of reinforcement with stiffening rings (Mushchanov and Tsepliaev, 2020) and spiral stairs (Tcepliaev et al., 2023) are considered. The implementation of this stage will allow for an experimental verification of the quality of the proposed techniques for reinforcement against the action of actual wind load.

Testing stage I method

The parameters of the experimental models were determined with account for the possibility of direct comparison with the results of previously performed experimental studies. The model is assembled from three separate elements made of 0.5 mm thick galvanized steel and corresponds to the parameters of a tank with a volume of 20,000 m^3 on a scale 1:100 (height — 200 mm, diameter — 400 mm). The wall is connected to the lid and bottom by a single lock joint, with the use of sealant. The shell end attachment assembly should be considered rigid. This is additionally ensured by the wooden frame inside the model body, which prevents the bottom and lid from tearing off. A 2NVR-5DM vacuum pump was used to create vacuum. The stairs were modeled by rigidly attaching a 0.5 mm thick and 10 mm wide steel strip to the cylindrical wall by soldering. The maximum increase in wall stability for the tank of the volume under consideration was observed at stairs angles (α) of 30…40° (Tcepliaev et al, 2023). The specified boundaries were adopted as options to consider. The length of the stairs in the models was 370 and 480 mm.

The stress values were determined by strain gauge method, using OWEN MV110-224.4TD modules for 24 sensors. Communication with the computer was established via an RS-485 switch and Owen OPC Server software. MasterScada software shell was used to output the final values. The moment of buckling was captured using high-speed video recording. Fig. 4 shows a diagram and photo of the test rig for Stage I of testing.

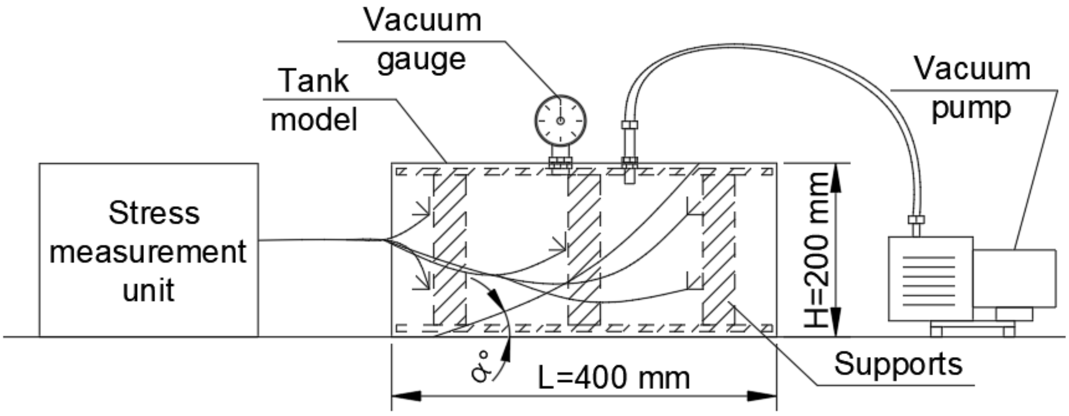
Testing stage II method

The MAT-1 wind tunnel of the Donbas National Academy of Civil Engineering and Architecture (Fig. 5) with the test section of the closed type has the following dimensions: height — 700 mm; turntable diameter — 900 mm; maximum air flow speed — 20 m/s; fan power — 8 kW. The moment of buckling is captured using high-speed video recording and compared to Owen device readings. Using an installed Pitot tube and low pressure sensors connected to the Owen system, the total wind flow pressure was recorded. The actual wind speed was determined by the following equation:

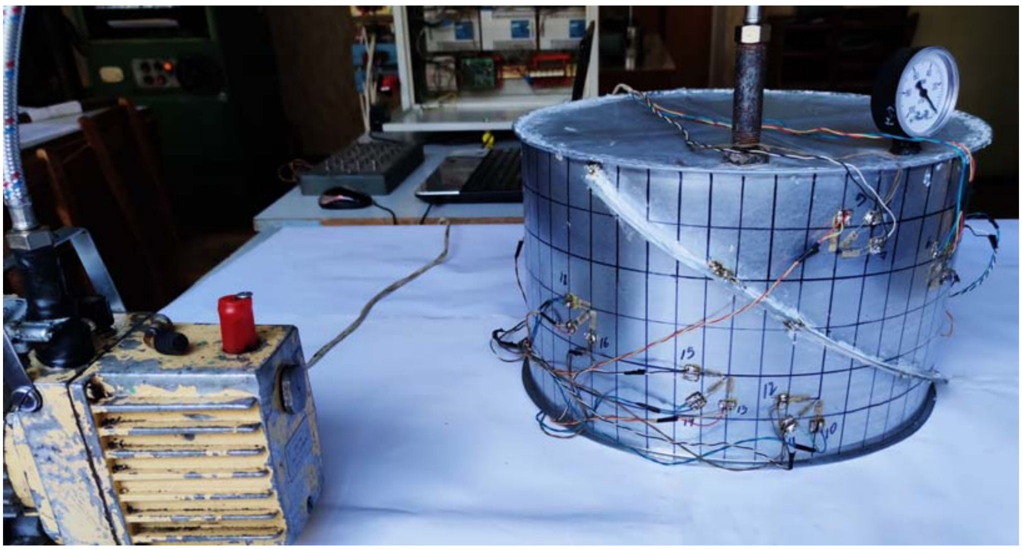
$$V = \sqrt{\frac{2P}{\rho}}, \tag{1}$$

where P is the wind flow pressure, ρ is the air density.

The choice of model scale was justified by Tcepliaev and Mushchanov (2018), Tominaga et al. (2004). Fig. 6 shows schemes, photos and parameters of the options considered. The basis is the “mid-section” requirement, when the maximum area of the model projection on a plane perpendicular to the air flow should not exceed 10 % of the test section. The model is represented by a wooden frame (Fig. 6a), on which the wall is wound. As the shell material, 0.1 mm thick paper (Fig. 6b) with modulus of elasticity $E = 0.04 \cdot 10^5$ MPa and 0.02 mm thick aluminum foil ($E = 0.7 \cdot 10^5$ MPa) were considered. In addition to the shell without reinforcement (Fig. 6c, d), various arrangements of conditional rings and stairs were considered. Two options of stairs inclination (α) of 30° and 40° were taken as a variable parameter. The chord length (L) was 242 and 305 mm, respectively (Fig. 6e, f). The stiffening rings were at a height (h) of 100 and 147 mm from the base (Fig. 6g, h). The second option of RS arrangement was determined according to the recommendations of Mushchanov and Tsepliaev (2020). Tin wire with a diameter of 3 mm ($E = 0.55 \cdot 10^5$ MPa) served as the material for the stairs and rings. The stiffness ratio of the



a) test rig diagram



b) model photo No. 1

Fig. 4. Test rig for Stage I of testing

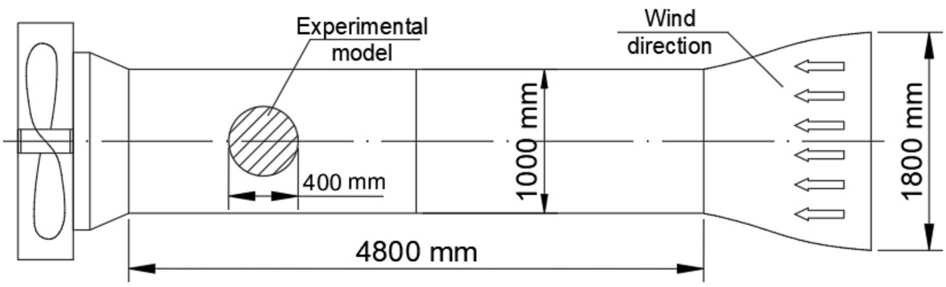


Fig. 5. Wind tunnel (top view)

reinforcing elements in the experimental model corresponds to that in the existing tanks. The elements were connected by a special adhesive composition ensuring a rigid connection (Fig. 6f, h).

Parameters of the numerical models of tanks

The parameters of the finite element model are set to the experimental ones as close as possible to allow for direct comparison of the test results. The model designed in the LIRA-SAPR 2017 analysis software represents a shell, at the ends of which rods of 10x0.5 mm cross-section are added, modeling the joint with the lid and bottom. For four equidistant nodes at each end, linear displacements are forbidden. The wall shell is defined by finite element No. 44. The finite element mesh was selected based on the preliminary calculation of stress convergence. The difference in the results of finite element and analytical calculations was less than 3 %. The shell consists of 149 elements along the circumference and 12 rows along the height (Fig. 7a). Vacuum is modeled as uniform external pressure on the tank wall, wind is specified through a text file (Tcepliaev, 2016) — Fig. 7b, c. The values of the indicated loads are equal to the values at which buckling of the corresponding experimental model occurred. For vacuum, it is the P_{cr} parameter (Table 2), for wind — the P_w parameter (Table 3). The shape of wind pressure distribution corresponds to the standard one for tanks of corresponding dimensions — see more details in (Tcepliaev, 2016). The stairs are oriented in the direction of the greatest wind pressure.

The arising stresses, the value of the critical force, and the model deformation shape are taken as the documented parameters of finite element analysis. Since the design combination does not include axial loads, the stability is directly related to the load in the circular direction. This allowed us to determine the critical pressures through the *stability factor (SF)* by the following equation:

$$SF = \frac{P_{cr}}{P}, \tag{2}$$

where P_{cr} is the critical buckling pressure, P is the acting pressure.

The variable parameters of the tank models for the experimental studies are summarized in Table 1.

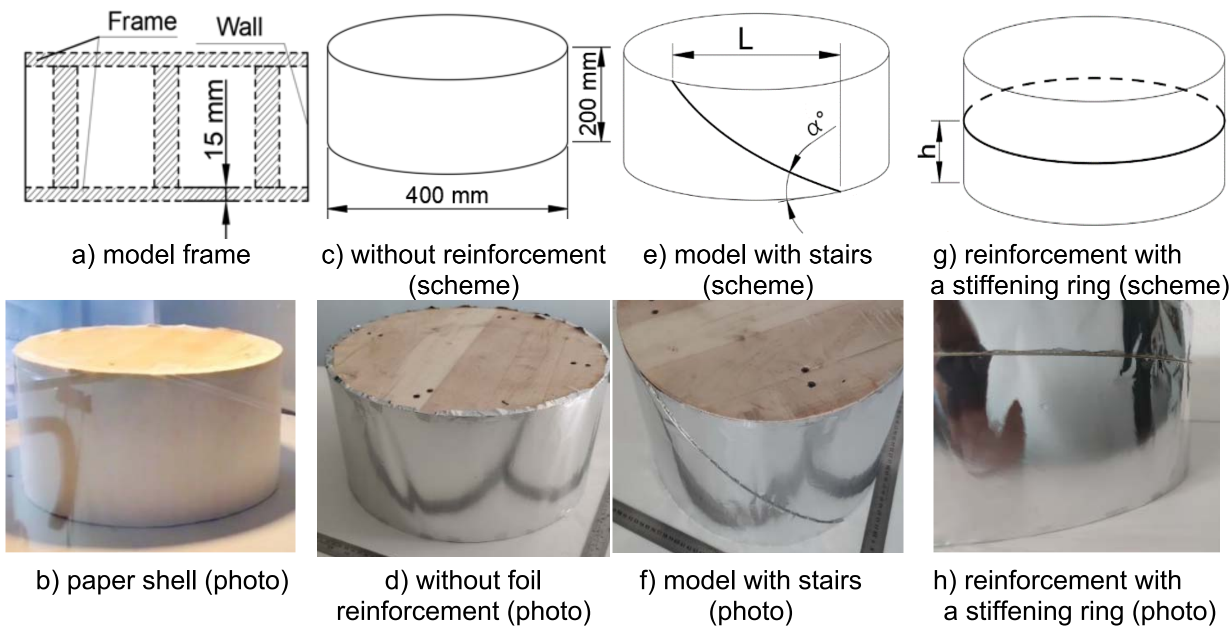


Fig. 6. Scheme and general view of the models with reinforcement for Stage II of testing

With account for the studies conducted earlier, the value of critical force increase — increment S (%) (Eq. 3) — is adopted as an indicator of the effectiveness of reinforcement methods:

$$S = 100 \cdot \left(\frac{P_{cr,i}}{P_{cr,0}} - 1 \right), \quad (3)$$

where $P_{cr,0}$ is the pressure at the moment of buckling for the shell without reinforcement, $P_{cr,i}$ is the pressure at the moment of buckling for the *i*-th design.

Based on the comparison of increments (S) obtained numerically and experimentally, a conclusion about adequacy and reliability of the results can be made. The calculated values and parameters S for vacuum and wind load are given in Tables 2 and 3, respectively.

Results and discussion

Results of testing stage I

According to Table 1, two steel models of tanks reinforced with stairs were tested under vacuum. The section without reinforcement was the first to buckle (Fig. 8a), which followed by the shell separation from the conditional stairs (Fig. 8c). The load value at the moment of buckling in the wall section without reinforcement varies from 29 to 31 kPa. The reinforced part lost stability in the range of 33…38 kPa. The pressure difference between the stages ranged from 6 to 27 % (2…8 kPa), depending on the design — see Table 2 for details. The shapes of buckling in experimental models 1 and 2 have no fundamental differences, the number of waves and their basic dimensions coincide. Fig. 8 shows a general view of the deformed shell shapes.

The deformed structures obtained by the finite element method (Fig. 8b) have some differences from the final experimental ones. For proper assessment, the comparison should be made with the original buckling shape (Fig. 8a). This is justified by the linear numerical calculation considering the first buckling shapes and not taking into account the post-buckling wall behavior. Similar buckling shapes for a tank reinforced by stairs were obtained by Shokrzadeh et al. (2020).

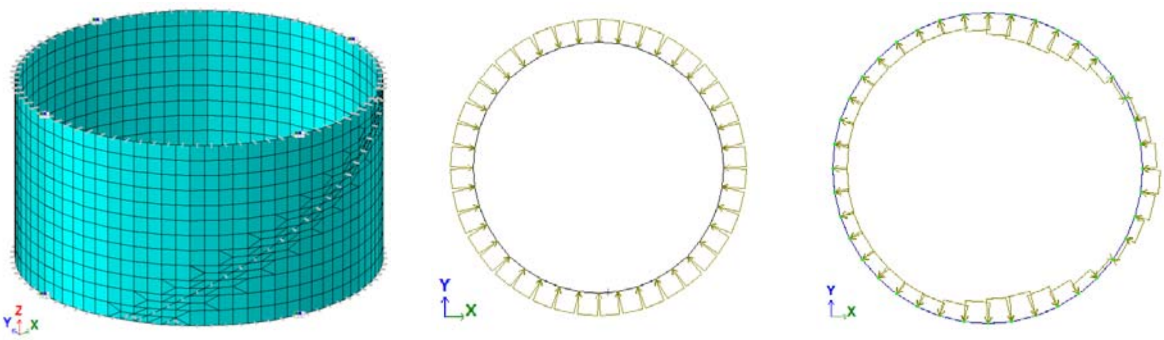
The readings of 24 strain gauges for each model were grouped by the type of measured stresses, and average logarithmic dependencies up to the moment of buckling were determined with the use of mathematical algorithms (Fig. 9). In addition to the results of the current experiment, the results for the shell without reinforcement from the study by Mushchanov and Tsepliaev (2020) are given.

The strain gauges did not record significant differences in the stress state of the considered shells at the moment of buckling, except for the areas where the conditional stairs were located, where the following was noted:

- the circular stresses decreased by up to 20 % compared to the free part of the shell;
- the axial stresses in the analytical formulation should be close to 0, and in the experiment, their value reached 2.8 MPa;
- the reinforcing elements restrain the deformation of the wall, which is confirmed by buckling beyond the free part of the wall.

Another important recorded parameter is vacuum at the moment of buckling — the critical force. The comparison of the experimental ($P_{CR,i}$) and numerical values ($P_{CR,F}$) for the different model options was made with the use of the S_{EXP} and S_{FEM} parameters, respectively (Eq. 3). The results of the calculations are given in Table 2.

The experimental values of the axial stresses exceed those obtained by the finite element method. However, the mentioned parameter remains within the range of small values not exceeding 2.8 MPa and is caused by some pliability of the wooden frame. The differences between the experimental and numerical values of the circular stresses differ by no more than 3 %, which confirms the applicability of the design model. The reinforcing effect in case of uniform compression is observed only in the areas where the stairs are located and manifests itself after the beginning of buckling. Thus, the local perturbations of the axial and circular stresses in the stairs



a) general view b) vacuum load c) wind load

Fig. 7. Finite element model of the tank

Table 1. **Options of experimental models**

Experimental stage	Model material	Type of reinforcement	Recorded parameters
Stage I (load: vacuum)	Galvanized steel t = 0.5 mm	1. Stairs with a 30° incline. 2. Stairs with a 40° incline. *Reinforcement material — steel: 10x0.5 mm strip*	- stresses; - vacuum at the moment of buckling; - buckling shape.
Stage II (load: wind)	Paper (t = 0.1 mm) or foil (t = 0.02 mm)	1. No reinforcement. 2. RS at a height of 100 mm. 3. RS at a height of 147 mm. 4. Stairs with a 30° incline. 5. Stairs with a 40° incline. *Reinforcement material — tin: round bar with a diameter of 3 mm*	- wind speed at the moment of buckling; - buckling shape.

attachment areas do not affect the overall stability of the shell.

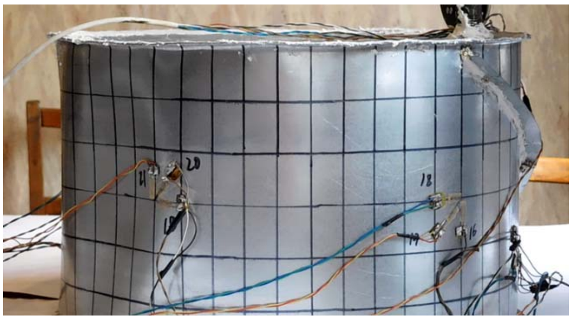
An increase in critical force in the range of 2…7 % compared to the shell without stairs was observed. In this case, the actual critical load values increase by no more than 2 kPa. Reliability of bucking analysis is further supported by the similar buckling shape (Rastgar and Showkati, 2017; Shokrzadeh and Sohrabi, 2016) and critical load values (Fakhim et al., 2009).

The results of the first stage of the experiment make it possible to adopt the available numerical model with reinforcement in the form of stairs for subsequent studies in case of actual wind flow, as well as to experimentally verify the findings of Tcepliaev et al. (2023). It was also found that stairs cannot be considered an effective design solution to improve the overall stability under the action of vacuum.

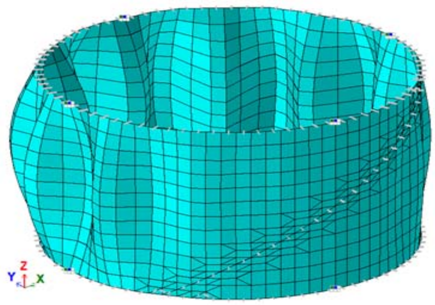
Results of testing stage II

The second stage is the experimental verification of the effectiveness of the structural methods to increase the stability of the shells under the actual wind action. In terms of meeting the set research objectives, the experimental model with a wall made of foil of t = 0.02 mm is preferable. This is largely due to the high elasticity of the paper model and the different behavior of the shell depending on the orientation of the sheet (Fig. 10a). If a thinner material in the form of foil is used, the model collapses at the moment of buckling (Fig. 10b, c). In addition to recording the load, this makes it possible to assess the extent of damage to the models.

Buckling of the shells without reinforcement was observed only in the windward area, which is consistent with the findings of the experimental studies conducted by Uematsu and Uchiyama



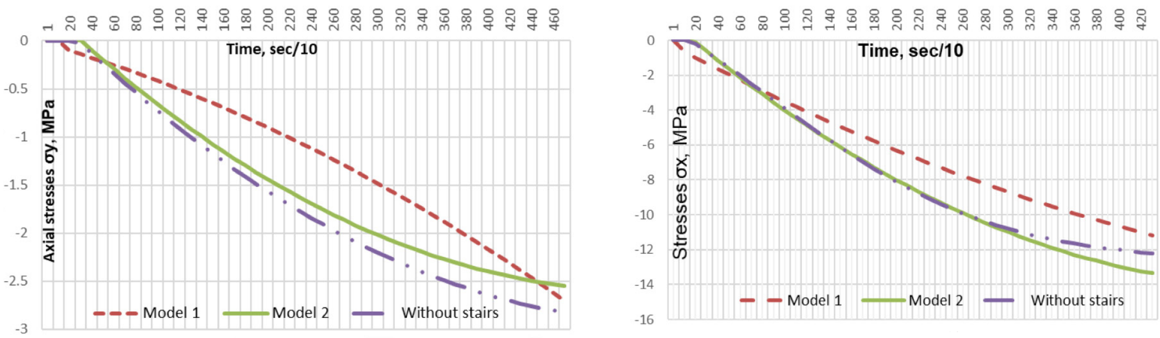
a) experimental model 1: buckling in the section without reinforcement



b) numerical model 1: buckling shape (with stairs α = 30°)

c) experimental model 2: buckling in the entire shell

Fig. 8. Deformed tank model structure with deformations due to the action of vacuum



a) axial stresses b) circular stresses

Fig. 9. Experimental values of stresses under the action of vacuum

(1985), Uematsu et al. (2014). The shapes of wall deformation up to the moment of buckling are also similar. Therefore, the adopted test models reflect the realistic behavior of the studied structures.

Fig. 1 shows the photos of the reinforced shells after exposure to wind load. The deformed scheme at the moment of buckling (Fig. 11a, c, e, g) and the resulting damage (Fig. 11b, d, f, h) are shown separately. To improve the validity of the results, each type of model was brought to failure at least twice. The availability of reinforcing elements prevented complete destruction of the models, which is confirmed by the consequences of real accidents (Fig. 3b, c).

The shape of buckling just before the wall failure is close to the numerical solution — refer to Fig. 8b and (Shokrzadeh et al., 2020). The extent of damage to the wall depending on the design is as follows:

1) model without reinforcement (most damaged);

2) wall with conditional stairs (30° incline); the wall is reinforced with a stiffening ring at a height of 100 mm;

3) wall with conditional stairs (40° incline);

4) the wall is reinforced with a stiffening ring at a height of 147 mm (least damaged).

Recording of the strain gauge readings in the Pitot tube, synchronized with video recording, was performed once per second. The obtained data array was transformed into load vs. time diagrams (Fig. 12).

The highlighted points show pressure at the moment of buckling in the corresponding model (see details of the models in Table 3). Using Eq. 3, critical wind pressure increments (P_W) for the stability factor (SF) were calculated. Instead of the P_{cr} values, wind speed V and SF (for experimental and numerical models, respectively) were used. Table 3 presents the results of the numerical studies and their comparison with the experiment. The adequacy of the applied models is evaluated by comparing the S_{EXP} and S_{FEM} increments through the ΔS parameter.

Fig. 13 shows the first shapes of buckling of some numerical models. In a visual comparison with similar studies (Rastgar and Showkati, 2017; Shokrzadeh and Sohrabi, 2016; Shokrzadeh et al., 2020; Sun et al., 2018), a similar deformed scheme of numerical models can be noted. As in the case of the experiment, the deformations occur in the areas of negative wind load values. Depending on the design, the amplitude and frequency of the waves change.

The general trends related to the extent of damage to the experimental models were preserved in the numerical experiment. The greatest increase (approx. 50 %) in stability was observed when the stiffening ring was placed with account for the recommendations of Mushchanov and Tsepliaev (2020). The arrangement of longer stairs according to the method proposed by Tcepliaev et al. (2023) increases stability by almost 30 %. The maximum discrepancy for the S parameter between the experimental and numerical studies was 21.47 %. However, the general dynamics and character of deformations in the models allow us to conclude

Table 2. **Stress state of the models under the action of vacuum**

Model option	Critical buckling load of the wall, P_{CR}				Average stresses, MPa			
					circular σ_x		axial σ_y	
	Experimental (Exp.) $P_{CR,i}$, kPA	S_{EXP}, %	$P_{CR,F}$, kPA	S_{FEM}, %	Exp.	FEM	Exp.	FEM
No reinforcement	29	–	57.2	–	12.7	12.4	2.8	0.4
Model 1 (30°)	31; 33 (stairs area)	6.9	58.6	2.4	13	13.3	2.6	0.72
Model 2 (40°)	30 38 (stairs area)	3.4	60.1	5.1	13	12.9	2.5	0.68

a) deformation of paper model 1 b) foil model 1: moment of buckling c) model 1: final view after collapse

Fig. 10. Damage to the shells without reinforcement under the action of wind

that the recommendations on reinforcement of walls with stiffening rings and spiral stairs under the wind action are applicable. The issue of accounting for the joint action of such elements and its reflection in analytical calculations remains open.

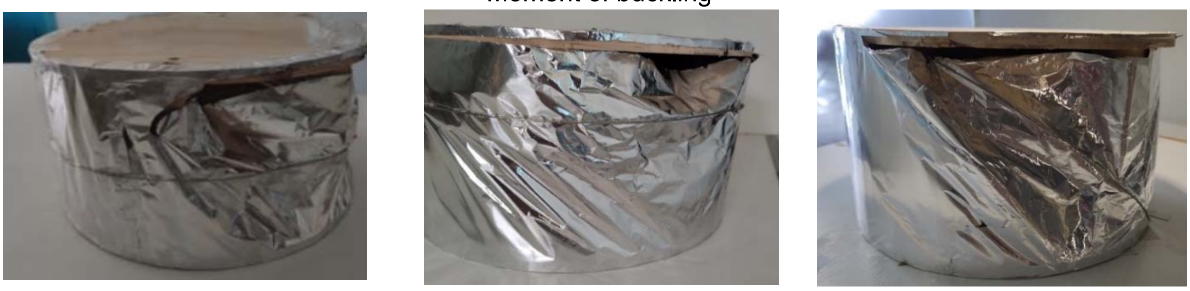
Conclusions

Options of reinforcing the walls of vertical cylindrical tanks with spiral process stairs and stiffening rings were considered. Wind and vacuum served as design loads. The main result of the conducted research is the experimental confirmation of the effectiveness of design solutions to increase the stability of the walls of vertical cylindrical tanks, with account for the advantages and disadvantages listed below.

1. Stairs have little effect on the overall stress-strain state of the shell under the wind action. Minimal

a) model 2 c) model 3 e) model 4:

Moment of buckling



b) model 2: d) model 3: f) model 4:

Damage after buckling

g) model 5: buckling shape h) model 5: final damage

Fig. 11. View of the models after buckling under the action of wind

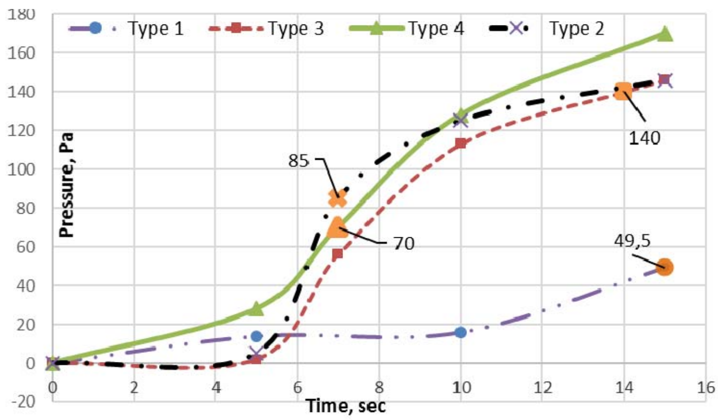


Fig. 12. Rate of wind flow pressure increase

Table 3. **Results of testing stage II**

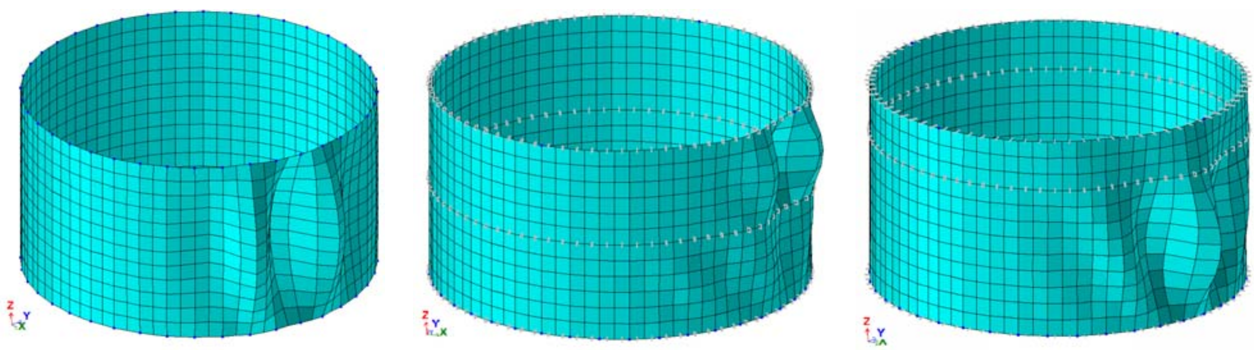
Model type	Pitot values P_w, Pa	Flow speed V, m/s	S_{EXP}, %	SF	S_{FEM}, %	ΔS, %
1. No reinforcement.	49.5	9.18	–	0.56	–	–
2. RS (H = 100 mm)	85	12.03	31	0.732	30.7	1.1
3. RS (H = 147 mm)	140	15.44	68.2	0.86	53.6	21.47
4. Stairs (40°)	70	10.92	18.9	0.67	19.6	3.63
5. Stairs (30°)	80	11.67	27.1	0.715	27.7	2.04

perturbations of axial stresses and reduction in circular stresses (up to 20 %) in the stairs attachment area were recorded experimentally and numerically. Reduction in displacements of the wall with stairs due to an increase in total stiffness was observed. The deformed scheme and magnitude of stresses in the free part of the wall fully correlate with the shell without reinforcement.

2. The availability of stairs does not result in significant changes in the character of the shell buckling under the action of vacuum. The critical load values are minimally different from those obtained for the shell without reinforcement (within 2 kPa). The free section of the wall is the first to buckle, which is confirmed by numerical calculations. Complete buckling of the reinforced shell occurred at further increase of vacuum by the value from 6 to 27 % (2…8 kPa). In this way, the effect of "progressive collapse" is additionally counteracted.

3. The effect of an increase in the critical wind load with increasing stairs length was experimentally recorded. The arrangement of stairs as recommended by Tcepliaev et al. (2023) increases the critical wind load up to 27 % in comparison to the shell without reinforcement.

4. Experimental verification of the recommendations on the arrangement of stiffening rings (Mushchanov and Tsepliaev, 2020) confirmed their effectiveness in terms of improving stability under the action of wind load. A single ring increased the critical wind pressure by 50 % in comparison to the shell without reinforcement.



a) model 1 (without reinforcement) b) model 2 c) model 3

Fig. 13. First shape of buckling of the numerical models under the wind action

5. Stiffening rings increase the critical load under the action of vacuum and wind; the effect of stability improvement due to stairs is less pronounced under the action of vacuum and manifests itself when stairs are oriented in the direction of maximum compressive wind action. Accounting for stairs requires predictable wind direction, therefore, the use of stiffening rings is a more universal method.

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ДЕФОРМАЦИОННОЕ ПОВЕДЕНИЕ УСИЛЕННЫХ ОБОЛОЧЕК ПОД ВОЗДЕЙСТВИЕМ ВЕТРА: ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ

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Аннотация
Введение. Тенденции повышения экономичности и надёжности сооружений вступают в противоречие и требуют поиска новых подходов к проектированию. Не исключением являются стальные вертикальные цилиндрические резервуары, использование которых постоянно растёт. В данном исследовании рассматривается проблема потери устойчивости цилиндрической стенки резервуаров от действия ветровой и вакуумной нагрузок. **Цель исследования**: экспериментальная проверка конструктивных решений повышения устойчивости стенок вертикальных цилиндрических резервуаров. **Методы**: на основе ранее выполненных численных исследований, разработана методика двухэтапного эксперимента для проверки применимости конструктивных вариантов усиления. I этап относится к исследованию работы оболочки под действием вакуума. II этап рассматривает различные конструктивные варианты моделей резервуаров при действии реальной ветровой нагрузки. Вариативными параметрами являлись высота расположения колец жесткости и угол наклона лестницы. **Результаты**: установлено повышение критической нагрузки потери устойчивости от вакуума на величину до 7 % и на 27 % от ветра при наличии лестницы с рекомендуемыми параметрами. Эффект повышения устойчивости от лестниц отмечен только в случае их ориентации в направлении максимально сжимающего ветрового воздействия. При этом, наличие лестницы достаточной жёсткости снижает риск полного разрушения конструкции от ветра и вакуума вне зависимости от расположения. Усиление кольцами жёсткости следует считать более предпочтительным методом. Общим итогом работы является экспериментальное подтверждение эффективности исследуемых конструктивных решений и адекватности применяемых численных моделей.

Ключевые слова: устойчивость; резервуар; напряженно-деформированное состояние; метод конечных элементов; цилиндрическая оболочка; ветер; лестница.