Rational design solutions of ensuring the walls of tanks stability to the action of transverse loads

Volodymyr Mushchanov and Maxim Tsepliaev
Donbas National Academy of Civil Engineering and Architecture, Makiyivka, Donetsk region, Ukraine

E-mail: m.n.cepliaev@donnasa.ru

Abstract. The article considers the task of an integrated approach to the study of the rationality of strengthening the cylindrical walls of large volume tanks with stiffening rings under transverse loads. Based on the results of computational studies, the principles of placement and rational boundaries usage of stiffening rings for vertical cylindrical tanks of various volumes are determined. The results were obtained for ideal shells and for cases of the presence of a typical geometric wall defect in the form of the angularity of a vertical weld. To validity the reliability of the results obtained, an experimental verification of the numerical model was carried out.

1. Introduction
The most rational in design structures for oil storage are vertical cylindrical tanks (VCT). About 10% of all cases of emergency failure of such structures are caused by the action of wind and vacuum [1] (Figure 1a). Examples of such accidents are considered in the academic papers of many authors [2–4].

Figure 1. VCT: a) loss of stability from the action of the wind; b) a wall reinforced with SR.
Taking into account the stable demand for the construction of new and maintenance of existing tanks [5, 6], the urgent task is to improve design solutions and methods for their calculation. One of the ways of ensuring the stability of the walls of the VCT is installation of external reinforcing elements, for example, stiffening rings (SR) (Figure 1b). Modern term regulatory techniques of the EU, the USA and the Russian Federation which regulate such method of reinforcement are based on the works of von Mises, Papkovich [3], Southwell [4] and others. In these studies, shells with different fixing of edges under the influence of uniform external pressure were considered. It makes the location of stiffness rings not optimal. With the beginning of the active application of the finite element method (FEM), many authors are considering the possibility of refining the existing methodology for specific types of structures and loads. This is especially true for calculating the stability of the VCT, which allows taking into account the real distribution of the wind flow instead of simplified uniform compression over the ring [5–8]. Bu, as an investigator, in his paper [9], takes into account the actual form of the wind load, considers the possibility of refining the API 650 methodology for the arrangement of stiffening rings. In the papers of other modern authors [10–13], it is marked the effectiveness of rigidity ring application to enhance the stability of the wall under the external transverse pressure. However, the authors do not come to a consensus on the optimal arrangement of the rings. A number of works are devoted to the significant influence of geometric deviations on the stability of cylindrical shells [18, 19]. To common defects of this type it is related the angularity of vertical assembly weld of the tanks’ walls.

It is possible to single out several basic issues the solution of which can significantly increase the effectiveness of the methodology for ensuring the stability of the VCT walls by installing ring stiffeners:

- the SR step is determined from the calculation of bringing the uneven external wind flow to the uniform compression;
- there are no comprehensive studies of the economic efficiency of SR application in comparison with ensuring the stability of the wall by selecting the delivery thickness;
- there is no accounting for typical defects when reinforcing VCT with stiffening rings.

2. Methods
It is proposed to analyze the determination of the rational arrangement of stiffening rings through the example of VCT with a volume of 10000-30000 m³ with a stationary spherical roof (the ratio of the wall height to the shell radius r/H is from 0.79 to 1.27). The research was performed on experimentally verified computational model. It was created in a LIRA-SAPR program complex 2015 R4.

2.1. Methods of experimental verification of a computational

The adequacy of the calculation results of shells is determined on an example of the steel tank with the thickness of 0.5 mm. This tank is under the influence of uniform external pressure, the loss of its stability may be simulated experimentally. Three characteristic experimental models were determined (200 mm in height and 400 mm in diameter), different variations of which will be considered in further computational studies:

- a shell without reinforcing elements and shape defects (model 1);
- a shell with a ring of rigidity – a section of the ring 30×0.5 mm (model 2);
- a shell with a typical defect – depth 5 mm and width 10 mm (model 3).

The common view of installation for testing model 2 is given in Fig.2. Applied equipment: vacuum pump 2NVR-5DM (for creating external pressure), vacuum gauge VP-100/D59, 6 modules of signal introduction OVEN MV110-224.4TD.

The measurement results were transferred to a computer through a commutator RS-485 and specialized software Owen OPC Server and MasterScada.
2.2. Method of principles’ definition of stiffening rings location which give the largest factor of a tank wall stability

For fixing the optimal location of SR it was offered the value of "flexibility" of a tank wall, which is pointed as «λ» and determined by the formula:

$$\lambda = H^2 / \sum_{i=1}^{n} t_i h_i$$  \hspace{1cm} (1)

H is the height of the considered section between SR; t_i – the thickness of the i-zone included in the cell H; h_i – the height of the i-zone, limited by the cell H.

The angularity of the vertical mounting weld is accepted as the wall geometrical defect under consideration (Fig. 2a, b). Variable parameters of the defect will be its depth h and width B of the shell – Fig. 3c. The limits of variation in the form of the ratio of B to h are determined according to the statistical data. The defect parameters resulting in maximum reduction of the stability factor (SF) of the wall are determined based on the LIRA-SAPR 2015 R4 program.

![Figure 2](image)

**Figure 2.** The angularity of the mounting weld: a - photo, b - a fragment of the FE model, c - defect variable parameters

At the first stage of the study the sequential arrangement from 1 to 3 stiffening rings are made by means of the verified computational model. At the same time, the stability analysis is made and the flexibility of sections (λ) is fixed. In general, the following cases are considered:

- the arrangement on the basis of Mises-Papkovich formula (API-650 technique [20]);
- alternative arrangement in which the position of one to three stiffening rings providing the maximum wall stability is determined by means of systematic sequential modeling of various positions.

The examples of the design models of rings alternative arrangement are shown in Figure 3a-d.

Since in the case of more than three SR the number of possible combinations of rings arrangement increases, both specified and alternative options for rings placement providing maximum stability for fewer rings are considered. By means of the LIRA-SAPR 2015 R4 program, the stability factors of the wall are determined and compared depending on the number of rings for each of the selected placement options. According to the results of study of more than 200 FE models, the recommended arrangement of stiffening rings has been determined expressed by flexibility ratio for considered sections.
To reduce the number of models, the options most likely providing the increased stability compared to specified cases are selected. For each selected placement principle, computational models of defective tanks are generated. In total, a stability analysis of 60 FE models of tanks of various capacity with different SR placement is made. As a result, the placement principle providing the maximum stability factor in case of the defect considered is fixed.

3. Results and discussion

3.1. Results of experimental verification of the finite element model

The parameters and characteristics of the computational model of the reservoir are selected sequentially in order to ensure close results in comparison with experimental data when calculating the stability of shell structures. The indicated values of various quantities for the case of finally adopted parameters of the FE model are given. A detailed description of the parameters of the adopted model, the final values of the annular ($\sigma_x$) and meridional stresses ($\sigma_y$), as well as the actual and theoretical forms of buckling for each model, are given in Table 1. The compared experimental and theoretical values of the maximum stresses determined on the basis of finite elemental analysis, corresponded with the moment of loss of the wall stability.

Table 1. The form of stability and stress loss in the experimental and numerical models of shells under the influence of external pressure.

| Model type | Model №1 | Model №2 | Model №3 |
|------------|-----------|-----------|-----------|
| Experimental model | $\sigma_x$:13.1 MPa | $\sigma_y$:6.9 MPa | $\sigma_x$:23.2 MPa | $\sigma_y$:11.7 MPa | $\sigma_x$:13.2 MPa | $\sigma_y$:6.2 MPa |
The discrepancy between the computation and experimental values of the stresses does not exceed 10%. The values of the averaged critical loads loss of stability of the considered options in relation to $P_{cr}$ for model No. 1 are given in Table 2.

Table 2. Comparison of SF through the values of the critical strength of the stability loss.

| Data source | Increment $P_{cr}$ in comparison with constructive option No. 1 |
|-------------|---------------------------------------------------------------|
|             | № 1 (perfect shell) | № 2 (with a ring) | № 3 (with a defect) |
| Experiment  | 1                  | 1.87              | 1.08               |
| FEM         | 1                  | 1.82              | 1.12               |
| Compared to FEM % | 0        | 2.7               | 3.7                |

Based on the results of the experiment, it is concluded that the calculation results for stability in the LIRA-SAPR 2015 R4 complex are adequate, the structural components of the adopted FE model for the wall with ideal geometry and a typical defect in the form of the angularity of the welded joint are edited.

3.2. The results of establishing a rational arrangement of stiffening rings, providing the greatest SF of the tank wall with ideal geometry

A detailed methodology for finding the SR placement that provides the greatest SF of the tank wall with ideal geometry is given in this paper [9]. In the current paper, the main task is to verify the results obtained on verified computational model. As a result, heights of the location of the rings are determined and the ratio between the flexibilities ($\lambda_i / (\lambda_i + 1)$) are fixed, due to the wall turned out to be the most stable. The final results for the case of SR arrangement from 1 to 3 are given in Table 3.

Table 3. Location of SR for archiving max SF of the wall.

| The ratio of radii (r) to height of the wall (H) in VCT | No. of SR, pcs | The ratio between the flexibilities of cell $\lambda_i$, SF is max | A gap between $\lambda_i / (\lambda_i + 1)$, % |
|-------------------------------------------------------|----------------|-----------------------------------------------------------------|-----------------------------------------|
| 0.79..0.85                                            | 1              | $\lambda_1 / \lambda_2 = 0.68..0.77;$                           | 14                                      |
|                                                      | 2              | $\lambda_1 / \lambda_2 = 0.81..0.88$ и $\lambda_2 / \lambda_3 = 0.79..0.81$ | 9                                       |
|                                                      | 3              | $\lambda_1 / \lambda_2 = 0.82..0.86$ и $\lambda_2 / \lambda_3 = 0.78..0.82$ и $\lambda_3 / \lambda_4 = 0.78..0.81$ | 5                                       |
|                                                      | 1              | $\lambda_1 / \lambda_2 = 0.74..0.79$                            | 7                                       |
|                                                      | 2              | $\lambda_1 / \lambda_2 = 0.83..0.86$ и $\lambda_2 / \lambda_3 = 0.8..0.82$ и $\lambda_3 / \lambda_4 = 0.75..0.82$ | 4                                       |
|                                                      | 3              | $\lambda_1 / \lambda_2 = 0.83..0.88$, $\lambda_2 / \lambda_3 = 0.77..0.8$ и $\lambda_3 / \lambda_4 = 0.72..0.78$ | 9                                       |
| 1.11..1.27                                            | 1              | $\lambda_1 / \lambda_2 = 0.68..0.77;$                           | 14                                      |
|                                                      | 2              | $\lambda_1 / \lambda_2 = 0.81..0.88$ и $\lambda_2 / \lambda_3 = 0.79..0.81$ | 9                                       |
|                                                      | 3              | $\lambda_1 / \lambda_2 = 0.82..0.86$ и $\lambda_2 / \lambda_3 = 0.78..0.82$ и $\lambda_3 / \lambda_4 = 0.78..0.81$ | 5                                       |
|                                                      | 1              | $\lambda_1 / \lambda_2 = 0.74..0.79$                            | 7                                       |
|                                                      | 2              | $\lambda_1 / \lambda_2 = 0.83..0.86$ и $\lambda_2 / \lambda_3 = 0.8..0.82$ и $\lambda_3 / \lambda_4 = 0.75..0.82$ | 4                                       |
|                                                      | 3              | $\lambda_1 / \lambda_2 = 0.83..0.88$, $\lambda_2 / \lambda_3 = 0.77..0.8$ и $\lambda_3 / \lambda_4 = 0.72..0.78$ | 9                                       |
Of all the options considered, two main dependencies between the flexibility of the cells where SF of the wall is max are established:

- for the case of placing one SR: $\lambda_1/\lambda_2=0.74$; (2)
- for the case of placing two or more SR: $\lambda_1/\lambda_2=0.85$ и $\lambda_i/\lambda_{i+1}=0.8$ (3)

For reservoirs of other volumes under consideration, similar calculations show an increase in SF of the wall, even in a slightly larger range of 4-7%. Therefore, all further research will be carried out taking into account the fact that the rings are located based on the principle of the ratio between the flexibilities, formulated in the form of the first and the second expressions.

3.3. Results of establishing a rational arrangement of SRs, providing the greatest SF of the defective tank wall

The calculation results of the effect of defect size on the stability of a cylindrical wall under the action of the calculated load are shown in Table 4.

**Table 4.** The stability of the tank wall without SRs depending on the defect parameters.

| B/h | SF of the wall due to radius to height of the wall: |
|-----|-----------------------------------------------|
|     | 0.79 | 1.11 | 1.27 |
|      | Without defect | 1.141 | 1.157 | 1.345 |
| 10  | 1.125 | 1.175 | 1.323 |
| 20  | 1.1  | 1.15  | 1.295 |
| 60  | 1.065 | 1.124 | 1.263 |

Exemplified by VCT with a volume of 20000 m³ with a defect in the absence of circular amplification, it is determined that a decrease of SF is shown in ratio B / h = 20-60, where h = 10-30 mm and B is not more than 800 mm. At high values of h, the angular imperfection begins to work as a stiffener plate. This fact leads to an increase in the stability of the shell. For the shell with the selected defect parameters, a search for the rational arrangement of SR is made. The calculation results are shown in Table 5.

**Table 5.** SF of the defective wall with various SR arrangement (B=600 mm, h=30 mm)

| Location technique | SF of the wall due to the number of SRs |
|--------------------|---------------------------------------|
|                    | 0   | 1   | 2   | 3   | 4   | 5   |
| The same $\lambda$ for cells | 1.14 | 1.9 | 2.72 | 3.48 | 4.85 | 6.1 |
| The same interval for SR | 1.14 | 1.83 | 2.66 | 3.4 | 4.3 | 5.49 |
| API 650 | 1.14 | 2.06 | 2.96 | 3.83 | 5.77 | 6.7 |
| Expressions 2, 3 | 1.14 | 2.21 | 3.15 | 4.03 | 5.89 | 6.99 |

As a result, it was determined that the location of reinforcing plates, based on the relations between the flexibilities (expressions 2 and 3) obtained for sections of the shell wall without defects, are most advantageous even in the case of the angularity of the weld.

The determination of the rational number of SRs is determined through the construction of dependencies in the form of "SF - $\lambda_1$" (Figure 4a-c). In the graphs 0 is a shell without a defect, 10 and 25 are shells with defects with a depth of 10 mm (where B / h = 60) and 25 mm (where B / h = 20).
Figure 4. Changing for SF of the wall depending on the flexibility of the first section $\lambda_1$ for SF with defect, the volume is: a $- 10$ thousand $m^3$; b $- 20$ thousand $m^3$; c $- 30$ thousand $m^3$.

For the considered headways of the shells with ideal geometry, flexibilities due to which SF of the wall increased rapidly are established. Such a point will be considered the transition of the function from linear to quadratic. For SF with the ratio of radius to height of the shell $r / H = 0.79 - \lambda_1 \leq 570$, for $r / H = 1.11 - \lambda_1 \leq 330$, $r / H = 1.27 - \lambda_1 \leq 270$.

For determination recommended $\lambda_1$ in the case of a defect from the obtained data, two dependences are investigated: “$r / H - \lambda_1$” (see - Fig. 5a) and “$\lambda_1 - B / h$” (see Fig. 5b). This fact allows to identify values of the coefficients $k_{def}$, which show the intensity of increase of $\lambda_1$ depending on the defect parameter.

Figure 5. The required flexibility in case of a defect depending on the parameters: a - $r/H$, 20 and 60 – ratio B/h; b - B/h, 10..30 thousand $m^3$ – volume of VCT.

Using expressions 2 and 3, for VCT where $r / H = 0.79..1.27$, the dependence is determined for setting the $\lambda_1$ of flexibility in the case of a defect:

$$\lambda_1 = 1106.8 \left(\frac{r}{H}\right)^2 - 2884.1 \left(\frac{r}{H}\right) + 2137.7 + k_{def} \left(\frac{B}{h} - 20\right),$$

where: $k_{def} -$ when $r/H=0.79..1.11$ is 0.333; when $r/H=1.27$ is 0.5.

The final result of the study is the range of $\lambda_1$, which allows to determine the rational amount of SRs to ensure the stability of the walls of the tanks from the effects of wind and vacuum. The problem of a rational number of SRs from the point of view of steel consumption was solved in the paper [5], and the lower limit of flexibility of the first section was also determined there. The recommended range of $\lambda_1$ is given in Table 6.
Table 6. The values of the parameter $\lambda_1$ for the rational arrangement of RSs

| №  | The ratio of radius to height of the shell $r/H$ | Recommended range value $\lambda_1$, for the shells |
|----|-----------------------------------------------|--------------------------------------------------|
|    | Without defects | Considering a defect |
| 1  | 0.79            | 540..570                  | 540..$\lambda_1$(DEF);                        |
| 2  | 1.11            | 280..330                  | 280..$\lambda_1$(DEF);                        |
| 3  | 1.27            | 245..270                  | 245..$\lambda_1$(DEF);                        |

The upper limit of the range is restricted by the requirement to ensure $\max$ of SF, and the lower limit is restricted by the economic expediency. In comparison to paper [7], as a result of the application of the verified numerical model, improved values of the SF are obtained and, accordingly, the recommended values of the range $\lambda_1$ are refined.

On the bases of the obtained data, the algorithm for the SRs arrangement when calculating the tank wall for stability is the following:

1) the flexibility of the entire wall is determined by the formula 5, where $H$, $t_i$, $h_i$ - $f n$ – the quantity of belts

$$\lambda_0 = H^2 + \sum_{i=1}^n t_i h_i.$$  (5)

2) depending on the dimensions of the tank, in the presence or absence of a defect, the recommended range of flexibility of the first section $\lambda_1$ is selected and adjusted depending on the design wind speed according to the formula 5 ($V_p$ – the design wind speed):

$$\lambda_{1V} = \left(29/V_p\right) \cdot \lambda_1.$$  (6)

3) for the tank of the considered dimensions, a suitable range of flexibility of the first section is determined; the approximate required number of rings is determined by the formula:

$$n = \lambda_0/\lambda_1.$$  (7)

4) The exact required number of rings is determined $n^*$. If $n<1.5$, $n^*=1$, if $n\geq1.5$:

$$n^* = \log_b \left\{1 - \left[\frac{\lambda_0 k}{\lambda_{1V} a} - 1 - \frac{1}{a}\right] (1 - b) \right\} ÷ b}.$$  (8)

5) The required flexibility of each section is calculated from the expressions 2 and 3, and the required height of the rings, which provides the flexibility values, that is as precise to the required ones as possible.

4. Conclusion

1) An experimental verification of the numerical model of the VCT developed with the help of the LIRA-SAPR 2015 R4 complex for carrying out theoretical studies of the stability loss of the shells intensified by SRs from wind and vacuum effect was performed.

2) The boundary parameters of the angular defect of the vertical weld have been established, at which a maximum decrease in the stability of the wall by compressive transverse load is observed.

3) For the VCT with a volume of 10...30 thousand m$^3$ with ideal geometry and with the presence of the considered defect, regularities are established that take into account the influence of the flexibility of individual sections of the wall with annular stiffener rings on its overall stability.

4) A technique of SRs arrangement, which allows providing a larger safety margin factor of the wall without increasing the metal consumption of the wall in contrast to the previously used approaches, is proposed. Herewith the actual distribution of wind over the surface of the tank wall is taken into account.

5) The reserves of the bearing capacity of the wall of VCT were established at 4-6%, due to the use of the developed methodology for the rational arrangement of SRs, which in the future will allow clarifying the values of the critical values of ring stresses provided in regulatory documents.
References

[1] Okuneva S 2017 Trends and prospects of the world oil market Financ. Anal. Probl. Solut. 10 877–94

[2] Kolesov A I and Ageeva M A 2011 Residual life of steel storage tanks for chemical and petrochemical products, that have exhausted their standard operation time Vestn. MGSU 6 388–91

[3] Papkovich P F 1939 Elasticity theory

[4] Southwell R V 1913 LXX. On the collapse of tubes by external pressure Phil. Mag. 687–98

[5] Mushchanov V and Tsepliaev M 2019 Ensuring the stability of the walls of the tanks based on the rational arrangement of the stiffening rings Constr. Unique Build. Struct. 84 58–73

[6] Maraveas C, Balokas G A and Tsavdaridis K D 2015 Numerical evaluation on shell buckling of empty thin-walled steel tanks under wind load according to current American and European design codes Thin-Walled Struct. 95 152–60

[7] Mushchanov V, Tsepliaev M and Zubenko A V 2018 The stress state of a tank shell in the group under wind load Mag. Civ. Eng. 83 49–62

[8] Portela G and Godoy L A 2005 Wind pressures and buckling of cylindrical steel tanks with a dome roof J. Constr. Steel Res.

[9] Bu F and Qian C 2015 A rational design approach of intermediate wind girders on large storage tanks Thin-Walled Struct. 92 76–81

[10] Burgos C A, Jaca R C, Lassig J L and Godoy L A 2014 Wind buckling of tanks with conical roof considering shielding by another tank Thin-Walled Struct. 91 29–37

[11] Uematsu Y, Yamaguchi T and Yasunaga J 2018 Effects of wind girders on the buckling of open-topped storage tanks under quasi-static wind loading Thin-Walled Struct. 124 1–12

[12] Zeybek Ö, Topkaya C and Rotter J M 2015 Strength and stiffness requirements for intermediate ring stiffeners on discretely supported cylindrical shells Thin-Walled Struct. 96 64–74

[13] Zhu Y, Dong J H and Gao B J 2015 Buckling Analysis of Thin Walled Cylinder with Combination of Large and Small Stiffening Rings under External Pressure Procedia Engineering pp 364–73

[14] Godoy L A and Flores F G 2002 Imperfection sensitivity to elastic buckling of wind loaded open cylindrical tanks Struct. Eng. Mech. 13 1–9

[15] Krysko A, Konopatskiy Y, Myronov A and Mushchanov V 2016 Technique of numerical analysis of the intense deformed state of steel vertical cylindrical tanks with taking into account the defects of geometrical form Met. Constr. 22 45–57