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APPLICATION OF STIFFNESS RINGS FOR IMPROVEMENT OF OPERATING RELIABILITY OF THE TANK WITH SHAPE IMPERFECTIONS

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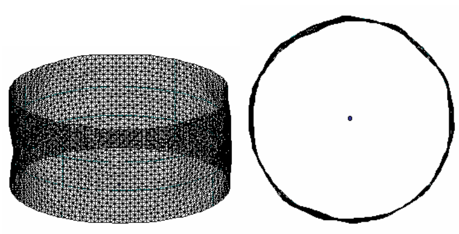
An efficiency of using of two stiffness rings for improvement of operating reliability of the tank with real shape imperfection at the action of combination load was evaluated. The computer model of the tank was constructed in the form of the thin cylindrical shell by of the program complex of finite element analysis. The tank stability problem under separate and joint action of surface pressure and axial compression was solved by the Lancosh method in linear formulation and as a nonlinear static problem by the Newton-Raphson method. The region of the tank failure-free work, which has the graphical presentation, confirmed the improvement of the tank wall stability due to the use of stiffness rings, especially in the area of surface pressure action.
Keywords: finite element method, operating reliability, stability, tank, failure-free region, thin-walled shell, shape imperfection, combined load, stiffness ring.

Introduction. Many works were aimed at investigating the thin-walled shell [1-15], their stability reliability [1, 2, 8], especially the influence of initial imperfections. One of the approaches is V.T. Coiter's one [6], which proposed an asymptotic analysis based on the general theory of supercritical behavior. Another approach consists in a direct analysis of the nonlinear deformation of a shell with a curved shape of the middle surface based on one of the grid methods of discretization of the resolving equations. In present time the apparatus of nonlinear differential equations are used for full description of the general laws of the stress-strain state of shells with shape imperfections. The mathematical methods, which are realized in the program complexes, are used for solving the shells stability problem and make it possible to investigate complicated nonlinear systems with multivariant parameters.

In this article the numerical technique for studying the stability of the oil tank under combined load with application of the program complex of finite element analysis NASTRAN is presented [7, 10, 12]. The presence of shape imperfections of the tank wall significantly reduced its stability. Therefore the strengthening of the wall with the stiffness rings to improve the operating reliability of the imperfect tank is proposed in this article. The tank stability problem is solved by the Lancosh method in linear formulation and as a nonlinear static problem by the Newton-Raphson method. The influence of stiffness rings on the critical values of the combined load and the stress-strain state of the tank at different loading steps are investigated. The region of the tank failure-free work is presented.

1. Finite element model of the tank with real shape imperfection. The oil tank is a cylindrical shell with a radius of R =19,963 m, height H =17,88 m. The shell thickness is variable in height every 1,49 m and is: 15,24; 14,22; 13,0; 11,56; 10,43; 9,46; 8,60; 7,70; 7,53; 7,40; 7,46; 7,16 (mm). The wall of the tank is made of steel with mechanical characteristics: E =2,06·10^{11} Pa, μ =0,3, ρ =7800 kg/m^3. The stiffness ring shows a folded cross section in the form of the brand 100x300x8 mm. The rings are made of steel with the same mechanical characteristics.



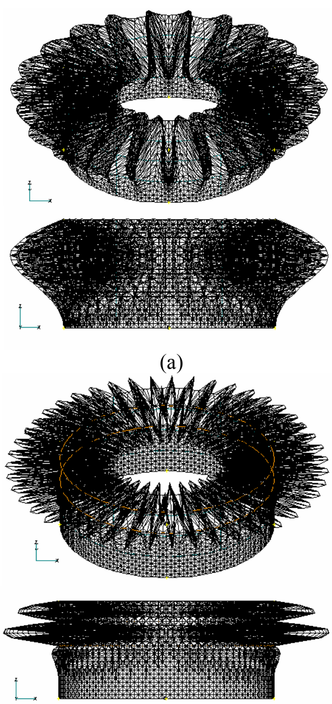
(a) (b)

Fig. 1. Finite element model of an imperfect tank: (a) side view; (b) top view

The tank calculation model is constructed in a finite element program complex [10] in a cylindrical coordinate system. The shape imperfections in the reservoir wall as a result of the theodolite measurements were obtained. The shell wall model with imperfect geometry is represented as a triangular finite element grid. To visualize the real imperfections on a certain scale a special program has been created. Fig. 1 (a), (b) shows the finite element model of the tank in different planes in a 1:20 scale.

The simulation of the combined load is carried out in accordance with a numerical technique [8, 12], which requires solving stability problems of the tank under surface pressure and axial compression separately for each load.

2. The tank stability under surface pressure. First, the stability problem of the perfect tank without and taking into account the stiffness rings under surface pressure in linear formulation is considered. To determine the critical value of surface pressure, a linear stability loss problem (Buckling) is solved by Lancosh method. Fig. 2 presents the first buckling form of the perfect shell without and with stiffness rings.



(a)

(b)

Fig. 2. The first buckling form of the perfect tank under surface pressure: (a) without stiffness rings; (b) with stiffness rings

The critical surface pressure value is

q_{cr}^0 =1179,61 N/m^2 for the unsupported perfect shell and q_{cr}^0 = 4226,44 N/m^2 – for the perfect shell with two stiffness rings. The stiffness rings increased the critical surface pressure by 3,58 times and changed the shell buckling form: increasing the number of waves both in the circumferential and longitudinal directions.

The stability of the imperfect tank with stiffness rings under surface pressure in non-linear formulation is considered. The procedure of solving the non-linear static problem (Nonlinear Static) by the modified Newton-Raphson method is applied. Surface pressure is supplied in the form $q = \beta q_{cr}^0$, where β – loading coefficient, q_{cr}^0 = 4226,44 N/m^2. Fig. 3 shows the loading curves of the shell surface pressure for two nodes, in which maximum displacements (m) were observed at different loading stages.

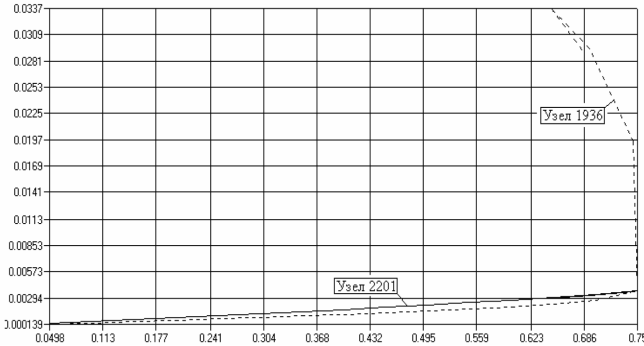


Fig. 3. Loading curves of the imperfect tank with stiffness rings by surface pressure

The imperfect tank with stiffness rings in the postcritical state lost of the stability at the critical loading coefficient β_{cr} =0,684. The critical (limited) value of the surface pressure is q_{cr}^{imp} =4226,44 · 0,684=2890,88 N/m^2. The stress-strain states of an imperfect tank at the different loading stages are shown in Fig. 4.

The maximum equivalent stresses in the wall elements from the outside of the imperfect shell (Plate Top VonMises Stress) under surface pressure $q = [0{,}05;0{,}45;0{,}744;0{,}684]\, q_{cr}^0$ are $\sigma = [0{,}685;6{,}531;40{,}894;65{,}658]$ MPa, which are lower than the design resistance of steel $R_y = 240$ MPa.

3. The tank stability under axial compression. The tank calculation models as a shell and a shell sector are constructed in a finite element program complex [10] in a cylindrical coordinate system. First, the stability problem of the perfect tank without and with stiffness rings under axial compression in linear formulation (Bucling) is solved by Lancosh method. The first buckling forms of the perfect shell sector without and with stiffness rings are shown in Fig. 5.

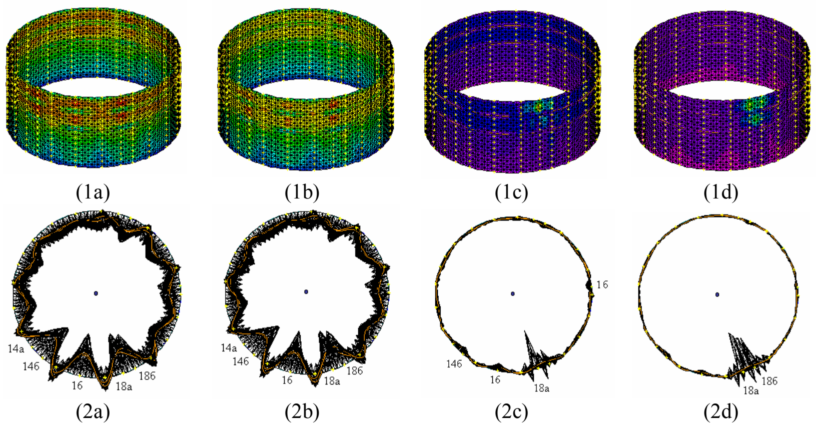
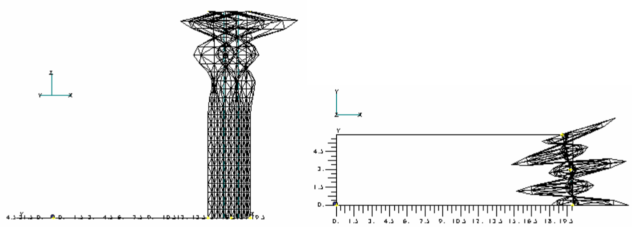
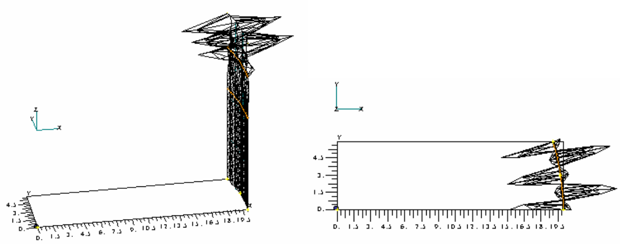


Fig. 4. The stress states (1) and deformated forms (2) of the imperfect tank with stiffness rings under surface pressure: (a) $0,05q_{cr}^{0}$; (b) $0,45q_{cr}^{0}$; (c) $0,744q_{cr}^{0}$; (d) $0,684q_{cr}^{0}$



(a)



(b)

Fig. 5. The first buckling forms of the perfect tank sector under axial compression: (a) - without stiffness rings; (b) with stiffness rings

The critical value of axial compression is P_{cr}^{0}=384957,1 N/m for the unsupported perfect shell and P_{cr}^{0}=389612,8 N/m – for the perfect shell with two stiffness rings. The stiffness rings increased the critical axial compression on 1,2 %.

The stability of the imperfect shell with stiffness rings under axial compression in non-linear formulation (Nonlinear Static) is considered using the modified Newton-Raphson method. Axial compression is supplied in the form $P = \beta P_{cr}^{0}$, where β – loading coefficient, P_{cr}^{0} = 389612,8 N/m. Fig. 6 presents the loading curves of axial compression for three tank nodes, in which maximum displacements (m) were observed at different loading stages.

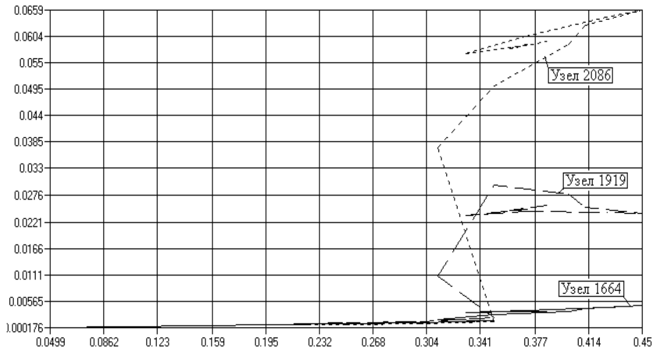


Fig. 6. Loading curves of the imperfect tank with stiffness rings by axial compression

Imperfect tank with stiffness rings in the postcritical state lost of the stability at the critical loading coefficient β_{cr}=0,386. The critical (limited) axial compression value is P_{cr}^{imp}=389612,8 · 0,386=150390,54 N/m. Fig. 7 shows the stress-strain states of an imperfect tank at the different stages of axial compression loading.

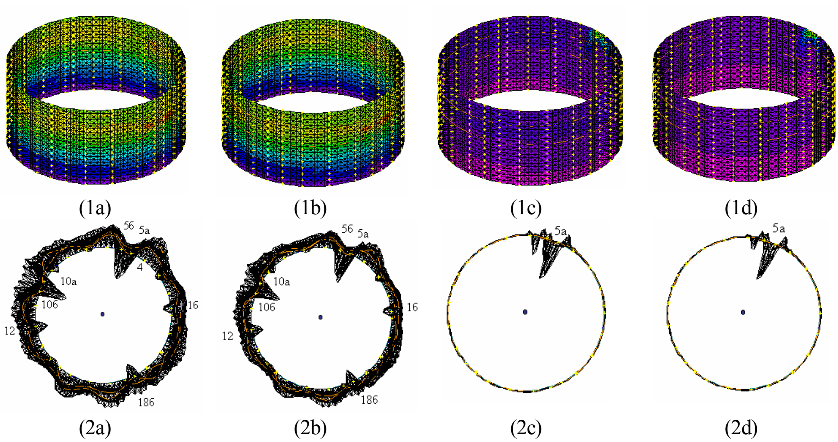


Fig. 7. The stress states (1) and deformated forms (2) of the imperfect tank with stiffness rings under axial compression: (a) $0,05q_{cr}^{0}$; (b) $0,35q_{cr}^{0}$; (c) $0,426q_{cr}^{0}$; (d) $0,386q_{cr}^{0}$

The maximum equivalent stresses on the outside of the shell (Plate Top VonMises Stress) at different loading stages by axial compression

$P=[0{,}05;0{,}35;0{,}426;0{,}386]P_{cr}^0$ are $\sigma=[3{,}144;22{,}384;151{,}647;139{,}736]$ MPa and less than the design resistance of steel $R_y=240$ MPa.

4. The tank stability under combined load. The first step of the research is determining of the critical combination of axial compression and surface pressure which act on the perfect tank without and with the stiffness rings. The perfect tank stability problem in a linear formulation is solved by Lancosh method. The critical combinations of axial compression and surface pressure are determined by the formulas:

$$\left[\tilde{P}_{cr}^*;\tilde{q}_{cr}^*\right]=\left[\tilde{\mu}\,\alpha P_{cr}^0;\tilde{\mu}(1-\alpha)\,q_{cr}^0\right],\ \left[P_{cr}^*;q_{cr}^*\right]=\left[\mu\,\alpha P_{cr}^0;\mu\,(1-\alpha)q_{cr}^0\right],$$

where $P_{cr}^0=384957{,}1$ N/m, $q_{cr}^0=4226{,}44$ N/m^2 – the critical values, respectively, of axial compression and surface pressure at their separate action on the perfect tank as defined above; α – a dimensionless combination factor with values from 0 to 1 in 0,1.

Tables 1 and Table 2 present the combined load values for the various axial compression and surface pressure combinations $\left[\alpha P_{cr}^0;\,(1-\alpha)\,q_{cr}^0\right]$, the critical combined load coefficients for the perfect shell without $\tilde{\mu}$ and taking into account μ the stiffness rings and the corresponding values of critical combined load $\left[\tilde{P}_{cr}^*\,/\,P_{cr}^0;\tilde{q}_{cr}^*\,/\,q_{cr}^0\right]$, $\left[P_{cr}^*\,/\,P_{cr}^0;q_{cr}^*\,/\,q_{cr}^0\right]$.

Table 1

Critical combined load values for perfect shell without stiffness rings

α	$\left[\alpha P_{cr}^0;\,(1-\alpha)q_{cr}^0\right]$ [N/m; N/m^2]	$\tilde{\mu}$	$\left[\tilde{P}_{cr}^*;\tilde{q}_{cr}^*\right]$ [N/m; N/m^2]	$\left[\tilde{P}_{cr}^*/P_{cr}^0;\tilde{q}_{cr}^*/q_{cr}^0\right]$
0	[0; 4226,44]	0,279	[0; 1179,18]	[0; 0,279]
0,1	[38961,28; 3803,80]	0,30429	[9848,07; 1265,76]	[0,02528; 0,29949]
0,2	[77922,56; 3381,15]	0,33439	[27354,56; 1186,95]	[0,07021; 0,28084]
0,3	[116883,84; 2958,58]	0,37098	[46389,55; 1174,19]	[0,11907; 0,27782]
0,4	[155845,12; 2535,86]	0,41634	[70506,03; 1147,25]	[0,18096; 0,27145]
0,5	[194806,4; 2113,22]	0,47391	[101386,2; 1099,82]	[0,26022; 0,26022]
0,6	[233767,68; 1690,5]	0,54899	[127346,4; 920,95]	[0,32685; 0,21790]
0,7	[272728,96; 1267,93]	0,64997	[181138,2; 842,12]	[0,46492; 0,19925]
0,8	[311690,24; 845,29]	0,78943	[257255,7; 697,67]	[0,66029; 0,16507]
0,9	[350651,52; 422,64]	0,97323	[373700,1; 450,42]	[0,95916; 0,10657]
1	[389612,8; 0]	0,988	[384937,4; 0]	[0,988;0]

Table 2

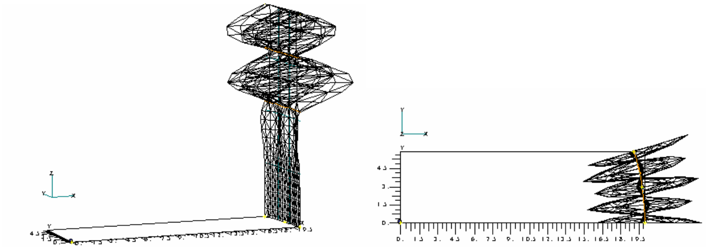
Critical combined load values for perfect shell with stiffness rings

α	$[\alpha P_{cr}^{0};\,(1-\alpha)q_{cr}^{0}]$ [N/m; N/m²]	μ	$[P_{cr}^{*};q_{cr}^{*}]$ [N/m; N/m²]	$[P_{cr}^{*}/P_{cr}^{0};q_{cr}^{*}/q_{cr}^{0}]$
0	[0; 4226,44]	1	[0; 4226,44]	[0; 1]
0,1	[38961,28; 3803,80]	0,83067	[32364,08; 3159,71]	[0,08307; 0,74761]
0,2	[77922,56; 3381,15]	1,04982	[81804,35; 3549,59]	[0,20996; 0,83985]
0,3	[116883,84; 2958,58]	1,06983	[125045,96;3165,10]	[0,32095; 0,74888]
0,4	[155845,12; 2535,86]	1,08664	[169347,23;2755,57]	[0,43466; 0,65198]
0,5	[194806,4; 2113,22]	1,09820	[213935,61;2320,73]	[0,54910; 0,54910]
0,6	[233767,68; 1690,5]	0,99229	[231964,86;1677,54]	[0,59537; 0,39692]
0,7	[272728,96; 1267,93]	1,02185	[278687; 1295,63]	[0,71529; 0,30655]
0,8	[311690,24; 845,29]	1,04551	[325875,26; 883,76]	[0,83641; 0,20910]
0,9	[350651,52; 422,64]	1,09505	[383979,19; 462,81]	[0,98554; 0,10950]
1	[389612,8; 0]	1	[389612,8; 0]	[1; 0]

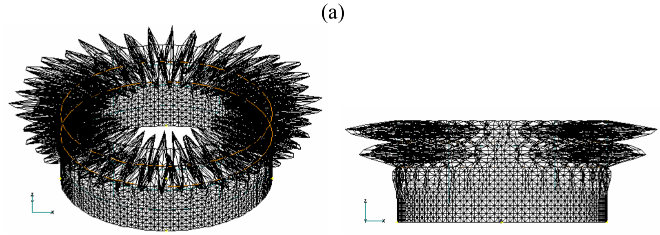
In the case of considering the tank with the stiffness rings (Table 2) at the action of combined load with $\alpha = [0,1;\ 0,6;\ 0,7]$ the critical load coefficients μ were defined for the shell sector. If we compare the critical combined load coefficients for the shell without stiffness rings (Table 1) and taking them into account (Table 2), we see that using of stiffness rings increases the overall stability of the tank with ideal wall shape. Fig. 8 shows the buckling forms of the perfect tank with stiffness rings at the different combination factor.

Let's consider the shell stability, taking into account the stiffness rings and imperfections of wall shape. The stability problem in non-linear formulation (Nonlinear Static) is considered using the modified Newton-Raphson method. The critical combined load coefficient β_{cr} are determined for the load with a combination factor values $\alpha = \left[0;\, 0{,}3;\, 0{,}5;\, 0{,}8;\, 1\right]$. The critical combinations of axial compression and surface pressure in the action on the imperfect tank with stiffness rings are determined by the formula: $\left[\,P_{cr}^{imp};q_{cr}^{imp}\right] = \beta_{cr}\left[\,P_{cr}^{*};q_{cr}^{*}\right]$ and are presented in Table 3 (the values $\left[\,P_{cr}^{*};q_{cr}^{*}\right]$ are shown in Table 2).

As an example, the behavior of the imperfect shell with stiffness rings under combinated load with a combination factor $\alpha = 0{,}3$ is showed. Fig. 9 presents a loading curves for two model nodes with maximum displacements at different stages loading. A dimensionless loading coefficient β is deposited along the abscissa axis and maximum nodal displacements (m) along the ordinate axis.



(a)



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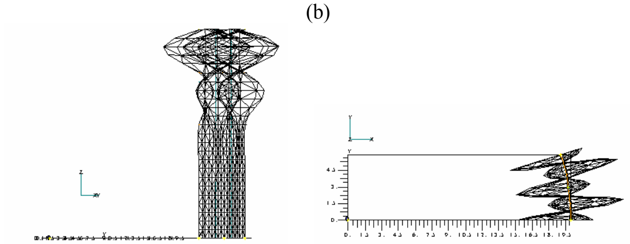


(c)

Fig. 8. Buckling form of the perfect tank with stiffness rings under combained load:
(a) α =0,1; (b) α =0,5; (c) α =0,7

Table 3

Critical combined load values for imperfect shell with stiffness rings

α	$[P_{cr}^{*};q_{cr}^{*}]$ [N/m; /m^2]	β_{cr}	$[P_{cr}^{imp};q_{cr}^{imp}]$ [N/m; N/m^2]	$\left[P_{cr}^{imp}/P_{cr}^{0};q_{cr}^{imp}/q_{cr}^{0}\right]$
0	[0; 4226,44]	0,684	[0; 2890,88]	[0; 0,684]
0,3	[125045,96; 3165,10]	0,559	[69900,69; 1769,29]	[0,17941; 0,41862]
0,5	[213935,61; 2320,73]	0,43	[91992,31; 997,91]	[0,23611; 0,23611]
0,8	[325875,26; 883,76]	0,3	[97762,58; 265,13]	[0,25092; 0,06273]
1	[389612,8; 0]	0,386	[150390,54; 0]	[0,386; 0]

The imperfect tank with stiffness rings in the postcritical state under combined load with a combination factor $\alpha = 0,3$ lost of the stability at β_{cr} =0,559. The critical (limited) combined load values are presented in Table 3. Fig. 10 shows the corresponding stress-strain states of the imperfect tank at the different stages of combined loading.

The values of the maximum equivalent stresses and maximum nodal displacements for all values of the combination factor α are given in Table 4. All values of the maximum equivalent stresses in the shell wall elements are less than the design resistance of steel $R_y = 240$ MPa.

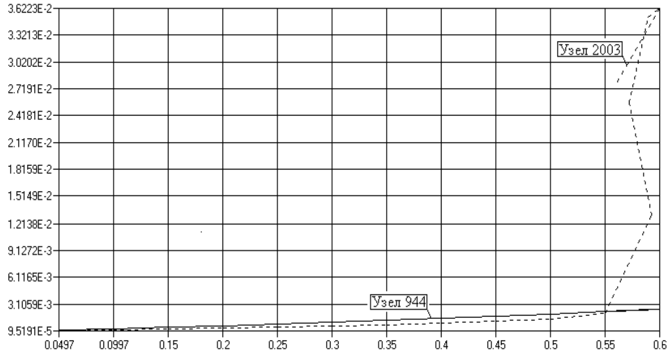


Fig. 9. Loading curves of the imperfect tank with stiffness rings by combined load ($\alpha = 0,3$)

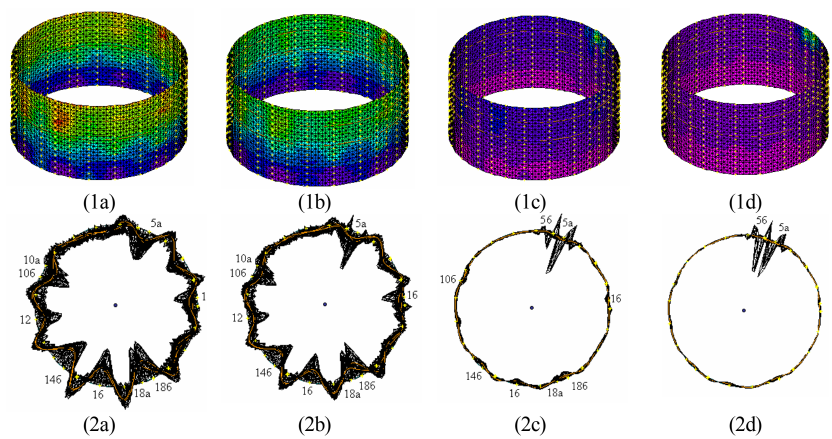


Fig. 10. The stress states (1) and deformated forms (2) of the imperfect tank with stiffness rings under combined load ($\alpha = 0,3$) : (a) $\beta = 0,05$; (b) $\beta = 0,55$; (c) $\beta = 0,592$; (d) $\beta = 0,559$

Table 4

α	$[P_{cr}^{imp}; q_{cr}^{imp}]$ [N/m; N/m^2]	Maximum equivalent stresses, МПа	Maximum nodal displacements, m
0	[0; 2890,88]	65,658	0,0337
0,3	[69900,69; 1769,29]	68,834	0,0362
0,5	[91992,31; 997,91]	102,019	0,0464
0,8	[97762,58; 265,13]	112,706	0,0492
1	[150390,54; 0]	151,644	0,0659

5. The influent of the stiffness rings on the operating reliability of the tank with real wall imperfections.

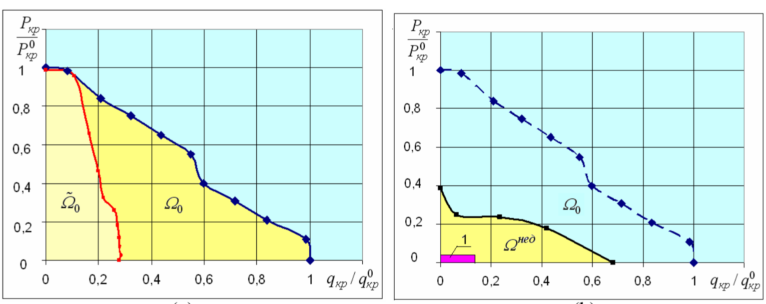
The theory of constructure reliability has one of the basic concepts as a concept of failure [1, 2, 8]. The failure of the shell in stability is considered, because this type of failure for thin-walled shell structures is more dangerous.

In our case, the operating reliability of the imperfect tank R is defined as probability of the shell reaction vector $S(\tau)$ in the stability region Ω^{imp} during the time interval $\left[0 \le \tau \le \mathrm{t}\right]$: $R = P_{suc} = \mathrm{Pr}\,ob\left[S(\tau) \in \Omega^{imp}\right]$. The probability of failure is an addition to the reliability function: $P_{fail}(t) = 1 - P_{suc}$.

An addition the operating reliability of the imperfect tank can be estimated by constructing the region of the design combined load and the stability regions of the perfect tank without and with two stiffness rings.

The design combined load from wind pressure, snow and the weight of the shell coating spacer ring is determined according to DBN B.1.2-2-2006 "Loads and Impacts" [54]. Its value is $[P_r; q_r]$ = [16601,25 N/m; 532 N/m^2]. If we take into account consider the critical values of surface pressure and axial compression, which separately acting on the perfect tank with the stiffness rings $P_{cr}^0 = 384957{,}1$ N/m and $q_{cr}^0 = 4226{,}44$ N/m^2, then the design combined load value is $[P_r; q_r]$=[0,0415; 0,126].

The stability regions of the perfect tank without $\tilde{\Omega}_0$ and with stiffness rings Ω_0 under combined load are shown in Fig. 11(a). Fig. 11(b) presents the stability regions of the imperfect tank with stiffness rings Ω^{imp} and the design combined load as an area 1.



(a) (b)

Fig. 11. The stability regions: (a) the perfect tank without $\tilde{\Omega}_0$ and with stiffness rings Ω_0; (b) the imperfect tank with stiffness rings Ω^{imp} and the design combined load Ω_r

Design reliability of success work of shell for limit states is $P_{suc} = 99{,}9$ % [1]. Let's consider the reaction vectors $S(\tau)$ of the perfect tank without and with the stiffness rings during time interval $[0 \le \tau \le t]$. They located in the according stability regions $\tilde{\Omega}_0$ and Ω_0 in Fig. 11(a). The stability region of perfect tank with stiffness rings Ω_0, which is bigger than stability region $\tilde{\Omega}_0$ on 65,3%. It means, the addition of the stiffness rings into the construction raise the tank general stability, especially, in an area of surface pressure. We see in Fig. 11(b) the imperfects of tank wall reduced stability region of perfect tank with the stiffness rings Ω_0 on 66,6%. The stiffness rings secure an operating reliability in general stability of the imperfect tank: P_{suc}^{imp} = 99,9+65,3-66,6=98,6%. However, the stability reserve factor in the area of axial compression is less than the same one in the area of surface pressure.

Conclusion. Operating reliability, which was presented as a failure-free in stability of the oil tank with shape imperfections under combined action of axial compression and surface pressure, was investigated. The efficiency of the use of two stiffness rings for improving of the tank stability was confirmed. The developed numerical technique with application of the program complex of finite element analysis NASTRAN was effective. The critical combined load values at the solving of the tank stability problem in nonlinear formulation by Newton-Raphson method were more accurate than the values, which were got by Lancosh method. The graphically presentation of the tank stability regions comfirmed the improvement of the tank wall stability as result of application of the stiffness rings, especially in the area of surface pressure action.

REFERENCES

1. *Augusti G., Baratta A., Kashiati F.* Veroyatnostnyie metodyi v stroitelnom proektirovanii (Probabilistic methods in construction design) / Per. s angl. – M.: Stroyizdat, 1988. – 584 s.
2. *Bolotin V.V.* Metodyi teorii veroyatnostey i teorii nadezhnosti v raschetah sooruzheniy (Methods of probability theory and reliability theory in calculations of structures). – M.: Stroyizdat, 1982. – 351 s.
3. Gavrilenko G. D. Nesuschaya sposobnost nesovershennyih obolochek (Bearing capacity of imperfect shells). – In-t mehaniki im. S.P.Timoshenko NAN Ukrainyi, 2007. – 294 c.
4. ДБН В.1.2-2:2006. Система забезпечення надійності та безпеки будівельних об’єктів. Навантаження і впливи. Норми проектування. – К.: Мінбуд України, 2007. – 60 с.
5. *Donnell L.G., Van K.* Vliyanie nepravilnostey v forme na ustoychivost sterzhney i tonkostennyih tsilindrov pri osevom szhatii (Influence of irregularities in the form on the stability of rods and thin-walled cylinders under axial compression) // Mehanika. Sb. perev. i obz. inostr. period. lit-ryi. – 1951. – №408, S.91 – 107.
6. *Koyter V.T.* Ustoychivost i zakriticheskoe povedenie uprugih sistem (Stability and supercritical behavior of elastic systems) // Mehanika: Sb. perev. inostr. statey. – 1960. – №5, S.99 – 110.
7. *Lukianchenko O.O., Kostina O.V., Haran I.H.* Modeliuvannia pochatkovykh nedoskonalostei tsylindrychnoi obolonky pry doslidzhenni yii stiikosti pry dii kombinovanoho navantazhennia (Modeling of cylindrical shell initial imperfections in the investigation of its stability under the action of combined load) // Opir materialiv ta teoriia sporud. − K.: KNUBA, 2009, Vyp. 84. C. 97-103.

8. *Perelmuter A.V.* Izbrannyie problemyi nadezhnosti i bezopasnosti stroitelnyih konstruktsiy (Selected problems of reliability and safety of building structures). 3-e izd. – Moskva: Izd-vo Assotsiatsii stroitelnyih vuzov, 2007. – 256 s.
9. *Timoshenko S.P.* Ustoychivost sterzhney, plastin i obolochek (Stability of rods, plates and shells) – M.: Nauka, 1971. – 807 s.
10. *Shimkovich D.G.* Raschet konstruktsiy v MSC/NASTRAN for Windows (Calculation of structures in MSC / NASTRAN for Windows). – M.: DMK Press, 2001.– 448 s.
11. *Bazhenov V., Perelmuter V. and Vorona Yu.* Structural mechanics and theory of structures. – History essays LAP LAMBERT Academic Publishing, 2017. – 580 p.
12. *Bazhenov V.A., Lukyanchenko O.O., Kostina O.V., Gerashchenko O.V.* Probabilistic Approach to Determination of Reliability of an Imperfect Supporting Shell // Strength of Materials. − 2014, № 46 (4). − P. 567-574.
13. *Gotsulyak E.A., Luk'yanchenko O.A., Kostina E.V., Garan I.G.* Geometrically nonlinear finite-element models for thin shells with geometric imperfections // International Applied Mechanics. − 2011, № 47(3). − P. 302-312.
14. *Lukianchenko O.O., Kostina O.V.* The finite Element Method in Problems of the Thin Shells Theory. − LAP LAMBERT Academic Publishing, 2019. − 134 p.
15. *Zienkiewicz O.C. and Taylor R.L.* The Finite Element Method. 5th edition. – Butterworth-Heinemann, 2000.

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Lukianchenko O.O.
APPLICATION OF STIFFNESS RINGS FOR IMPROVEMENT OF OPERATING RELIABILITY OF THE TANK WITH SHAPE IMPERFECTION
Strengthening of the tank thin wall taking into account real shape imperfections at the joint action of axial compression and surface pressure was offered with the stiffness rings. An efficiency of the use of two stiffness rings for improvement of operating reliability in the tank stability was evaluated. The numerical technique for studying the stability of thin imperfect shells with application of the program complex of finite element analysis procedures was presented. The computer model of the tank with wall real imperfections were constructed in the form of a thin cylindrical shell using spline-curves in a cylindrical coordinate system.The tank stability problem under separate and joint action of surface pressure and axial compression was solved by the Lancosh method in linear formulation and as a nonlinear static problem by the Newton-Raphson method. Precritical and postcritical behavior of the shell was considered. The influence of stiffness rings on the critical values of the combined load and the stress-strain state of the tank at different loading steps were investigated. The region of the tank failure-free work, which has the graphical presentation, confirmed the improvement of the tank wall stability due to the use of stiffness rings, especially in the area of surface pressure action.
Keywords: finite element method, operating reliability, stability, tank, failure-free region, thin-walled shell, shape imperfection, combined load, stiffness ring.

Лук'янченко О.О.
ЗАСТОСУВАННЯ КІЛЕЦЬ ЖОРСТКОСТІ ДЛЯ ПОКРАЩЕННЯ ЕКСПЛУАТАЦІЙНОЇ НАДІЙНОСТІ РЕЗЕРВУАРА З НЕДОСКОНАЛОСТЯМИ ФОРМИ
Зміцнення тонкої стінки резервуара з реальною недосконалістю форми при сумісній дії осьового стиснення та поверхневого тиску запропонована кільцями жорсткості. Оцінена ефективність використання двох кілець жорсткості для підвищення експлуатаційної надійності резервуара. Представлена чисельна методика дослідження стійкості тонких недосконалих оболонок із застосуванням процедур програмного комплексу скінченно-елементного аналізу. Комп'ютерна модель резервуара з реальними недосконалостями стінки побудована у вигляді тонкої циліндричної оболонки із застосування сплайн-кривих в циліндричній системі координат. Задача стійкості резервуара при окремій та сумісній дії поверхневого тиску та осьового стиснення досліджувалась методом Ланцоша в лінійній постановці та як нелінійна задача статики методом Ньютона-Рафсона. Розглянута докритична та закритична поведінка оболонки. Досліджено вплив кілець жорсткості на критичні значення комбінованого навантаження та напружено-деформований стан

резервуара на різних кроках навантаження. Область безвідмовної роботи резервуара, яке має графічне представлення, підтвердило підвищення стійкості стінки резервуара внаслідок застосування кілець жорсткості, особливо, в області дії поверхневого тиску.

Ключові слова: метод скінченних елементів, надійність експлуатації, стійкість, резервуар, область безвідмовної роботи, тонкостінна оболонка, недосконаліcть форми, комбіноване навантаження, кільце жорсткості.

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Lukianchenko O.O. **Application of stiffness rings for improvement of operating reliability of the tank with shape imperfection** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA, 2020. – Issue 104. – P. 242-254.
An efficiency of using of two stiffness rings for improvement of operating reliability of the tank with real shape imperfection at the action of combination load was evaluated. The computer model of the tank was constructed in the form of the thin cylindrical shell by of the program complex of finite element analysis. The tank stability problem under separate and joint action of surface pressure and axial compression was solved by the Lancosh method in linear formulation and as a nonlinear static problem by the Newton-Raphson method. The region of the tank failure-free work, which has the graphical presentation, confirmed the improvement of the tank wall stability due to the use of stiffness rings, especially in the area of surface pressure action.
Tab. 4. Fig. 11. References 15 items.

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Лук'янченко О.О. **Застосування кілець жорсткості для покращення експлуатаційної надійності резервуара з недосконалостями форми** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2020. – Вип. 104. – С. 242-254.
Оцінена ефективність використання двох кілець жорсткості для підвищення експлуатаційної надійності резервуара з реальною недосконалістю форми при дії комбінованого навантаження. Комп'ютерна модель резервуара побудована у вигляді тонкої циліндричної оболонки за допомогою програмного комплексу скінченно-елементного аналізу. Задача стійкості резервуара при окремій та сумісній дії поверхневого тиску та осьового стиснення вирішена методом Ланцоша в лінійній постановці і як нелінійна задача статики методом Ньютона-Рафсона. Область безвідмовної роботи резервуара, яка має графічне представлення, підтвердила підвищення стійкості стінки резервуара за рахунок використання кілець жорсткості, особливо, в області дії поверхневого тиску.
Табл. 4. Іл. 11. Бібліогр. 15 назв.

УДК 539.3
Лукьянченко О.А. **Применение колец жесткости для улучшения эксплуатационной надежности резервуара с несовершенствами формы** // Сопротивление материалов и теория сооружений: науч.-тех. сборн. – К.: КНУСА, 2020. – Вып. 104. – С. 242-254.
Оценена эффективность применения двух колец жесткости для повышения эксплуатационной надежности резервуара с реальным несовершенством формы при действии комбинированной нагрузки. Компьютерная модель резервуара построена в виде тонкой цилиндрической оболочки с помощью программного комплекса конечно-элементного анализа. Задача устойчивости резервуара при отдельном и совместном действии поверхностного давления и осевого сжатия была решена методом Ланцоша в линейной постановке и как нелинейная задача статики методом Ньютона-Рафсона. Область безотказной работы резервуара, которая имеет графическое представление, подтвердила повышение устойчивости стенки резервуара за счет использования колец жесткости, особенно в области действия поверхностного давления.
Табл. 4. Ил. 11. Библиогр. 15 назв.

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