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STRESS-DEFORMED STATE OF VERTICAL CILINDRICAL METAL SHELL UNDER TEMPERATURE CLIMATE IMPACT

Zhdanov A.A., PhD, Professor,
ajdanow1945@gmail.com, ORCID: 0000-0002-3304-5729
*Odessa State Academy of Civil Engineering and Architectur*e
4, Didrihsona, str., Odessa, 65029, Ukraine
Petrov V.N., PhD, Professor,
0673972002@ukr.net, ORCID: 0000-0003-3262-9463
National University «Odessa Polytechnic»,
1, ave. Shevchenko, м. Odessa, 65044, Ukraine

Abstract. Vertical cylindrical containers are widely used for storage of granular bulk materials. The enclosing side surface of such containers is made in the form of cylindrical metal circular shells with a wall thickness that is constant or piecewise constant along the height of the shell. Known designs for storage of bulk materials of the reservoir type with the installation of a cylindrical shell on the annular foundation with hinged fixed attachment of the shell to the foundation. Thin-walled shells are made suspended from the supporting structures of the storage facilities. To stabilize the cylindrical shape of the shell and its position in space, the suspended shells are pre-tensioned in the vertical direction. During operation, storage facilities are empty and filled with bulk materials, exposed to the environment in the form of wind and temperature climatic influences.

The object of study of this work is the enclosing structures of storages of granular bulk materials in the form of vertical circular cylindrical thin-walled metal shells, in the general case of piecewise constant thickness, subject to temperature and climatic influences of the environment – changes in the temperature of the outside air, direct and diffuse solar radiation.

The subject of the study is the components of the stress-strain state of the shell due to changes in temperature and climatic influences. The performed studies of the temperature fields of storage shells on models and full-scale objects made it possible to substantiate the assignment of the temperature field of cylindrical storage shells by Fourier series.

One-sided solar heating of cylindrical storage shells completely illuminated by the sun induces in the shell wall a flat temperature field symmetrical with respect to the normal of incidence of sunlight, which can be represented by a Fourier series with five terms of the cosine expansion series. In the presence of a structure located next to the shell, which covers half of the shell along the entire height in the circumferential direction, the temperature field is described by a Fourier series containing 10 harmonics of expansion in sines and cosines.

The small thickness of the shell, the significant radius of curvature of the shells, the large thermal diffusivity of metals provides a small variability of the temperature of the shell over the thickness, the ability to describe the stress-strain state of the shell, the momentless theory and a simple edge effect.

Formulas are obtained in Fourier series for the forces of a momentless state, the residuals of which at the joints of shell chords of different thicknesses and in the support zones are eliminated by a simple edge effect.

Keywords: momentless theory of shells, theory of edge effect, temperature climatic influences, forces and displacements in an empty vertical cylindrical shell.

Introduction. Storages of bulk materials in the form of vertical cylindrical metal thin-walled shells, during operation, are empty and filled with bulk material and experience the temperature climatic effects described in [1]. A change in the temperature of the outside air, the intensity of direct and scattered solar radiation induces a flat temperature field in the shell – the temperature of the shell is constant along the generatrix and variable in the circumferential direction, approximated by a Fourier series containing 5 terms of the cosine expansion series for the shell fully illuminated by the sun and 10 members of the series expansion in cosines and sines - for a shell half of which is covered by a screen at its full height. The temperature drop across the thickness of the shell can be neglected due to the small thickness of the shell (3 ... 10 mm) and a significant coefficient of thermal diffusivity of metals (steel, aluminum). Has a direct effect on the stress-strain state (SSS) of the shell? In this case, it is necessary to take into account the variability in time of the position of the sun in the sky and the corresponding change in the position of the normal of the incidence of sunlight on the shell. The stress-strain state of the walls of bulk materials storages under temperature climatic influences is necessary to know when designing new bulk materials storages and assessing the strength of existing ones.

Analysis of recent research and publications. In [1], the temperature climatic effects on cylindrical metal shells were investigated, in [2, 3], the stress-strain state of the shell on an elastic foundation with a piecewise constant was investigated, and in [4] with a piecewise linear bed coefficient with axisymmetric cooling of the shell.

The small thickness of the shells, the absence of significant gradients of changes in the shell temperature led to the application in [2-4] of the momentless theory of shells, supplemented, to eliminate the residuals of the momentless solution, the theory of a simple edge effect. In this study, we use a similar proven approach.

Goals and objectives. The purpose of this work is to study the stress-strain state of an empty vertical cylindrical metal thin walled shell of piecewise constant (in height) thickness, (Figure 1, a), caused by temperature climatic influences – non-axisymmetric heating-cooling of the shell to the state of the same temperature in all of its points.

Methods and Results. Let us write down the basic equations of the momentless theory of thin cylindrical shells [5, 6]. Geometric Equations:

$$\varepsilon_1 = \frac{1}{R}\frac{\partial u}{\partial \alpha} + \alpha_t t, \qquad \varepsilon_2 = \frac{1}{R}\left(\frac{\partial v}{\partial \beta} + w\right) + \alpha_t t, \tag{1}$$

where u, v, w – components of displacements of points of the middle surface of the shell (positive directions are shown in Figure 1, *a*);

$\varepsilon_1, \varepsilon_2$ – deformation of the middle surface, respectively, in the axial and circumferential directions;

α, β – dimensionless coordinates of the points of the middle surface: $a = x/R$, (angular coordinate;

t – shell temperature is a given function of coordinates α and β;

R – radius of the middle surface of the shell;

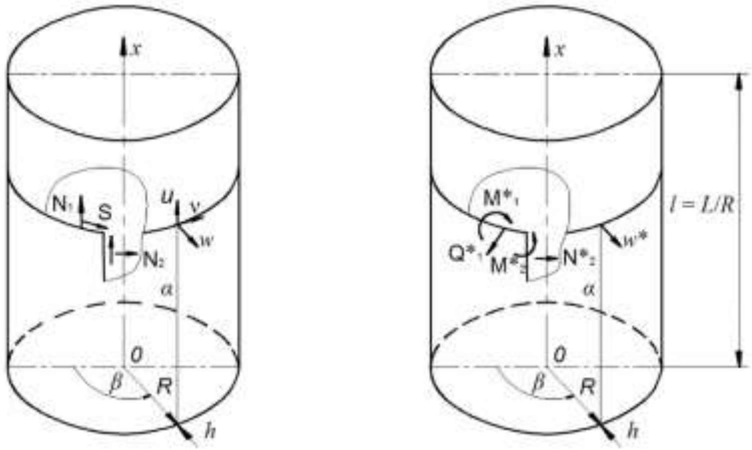
h – shell thickness;

E, μ, α_t – Young's modulus, Poisson's ratio and coefficient of linear thermal expansion of the shell material.

Positive directions of efforts and displacements are shown in Fig.1.

Physical equations for a cylindrical circular shell have the form:

$$\left.\begin{aligned}
N_1 &= \frac{Eh}{\left(1-\mu^2\right)R}\left[\frac{\partial u}{\partial \alpha} + \mu\left(\frac{\partial v}{\partial \beta} + w\right) - (1+\mu)\cdot\alpha_t\cdot R\cdot t\right],\\
N_2 &= \frac{Eh}{\left(1-\mu^2\right)R}\left[\frac{\partial v}{\partial \beta} + w + \mu\frac{\partial u}{\partial \alpha} - (1+\mu)\cdot\alpha_t\cdot R\cdot t\right],\\
S &= \frac{Eh}{2(1+\mu)\cdot R}\left(\frac{\partial u}{\partial \beta} + \frac{\partial v}{\partial \alpha}\right).
\end{aligned}\right\} \tag{2}$$



a) b)

Fig. 1. Positive directions of effort and displacement:
a – momentless stress-strain state; b – the state of the edge effect

Equilibrium equations in displacements have the form:

$$\left.\begin{aligned}
&\frac{\partial^2 u}{\partial\alpha^2}+\frac{1-\mu}{2}\frac{\partial^2 u}{\partial\beta^2}+\frac{1+\mu}{2}\frac{\partial^2 v}{\partial\alpha\partial\beta}+\mu\frac{\partial w}{\partial\alpha}=(1+\mu)\cdot\alpha_t\cdot R\cdot\frac{\partial t}{\partial\alpha},\\
&\frac{1+\mu}{2}\frac{\partial^2 u}{\partial\alpha\partial\beta}+\frac{1-\mu}{2}\frac{\partial^2 v}{\partial\alpha^2}+\frac{\partial^2 v}{\partial\beta^2}+\frac{\partial w}{\partial\beta}=(1+\mu)\cdot\alpha_t\cdot R\cdot\frac{\partial t}{\partial\beta},\\
&\mu\frac{\partial u}{\partial\alpha}+\frac{\partial v}{\partial\beta}+w=(1+\mu)\cdot\alpha_t\cdot R\cdot t.
\end{aligned}\right\}\qquad(3)$$

The external influence is the flat temperature field of the shell of the form:

$$t(\beta)=t_0+\sum_{n=1}^{10}\left(t_{nc}\cos n\beta+t_{ns}\sin n\beta\right).\qquad(4)$$

The amplitudes of harmonics in (4) can be calculated according to the recommendations [1].

For stitching the belts and on the supporting edges of the shell, we use the theory of a simple edge effect, the main dependences of which are presented below [5]:

$$\frac{d^4 w_i^*}{d\alpha^4}+4g_i^4 w_i^*=0,\qquad(5)$$

where: $g_i^4=3\left(1-\mu^2\right)\frac{R^2}{h_i^2}$, $D_i=\frac{Eh_i^3}{12\left(1-\mu^2\right)}$.

Geometric Equations:

$$\varepsilon_2^*=\frac{w^*}{R},\ \gamma^*=\frac{1}{R}\frac{dw^*}{d\alpha},\ \varepsilon_1^*=0.\qquad(6)$$

Physical equations:

$$\left.\begin{aligned}
&N_1^*=0,\quad N_2^*=\frac{Eh}{R}w^*,\quad M_1^*=-\frac{D}{R^2}\frac{d^2w^*}{d\alpha^2},\\
&M_2^*=\mu\cdot M_1^*,\quad Q_1^*=\frac{D}{R^3}\frac{d^3w^*}{d\alpha^3}.
\end{aligned}\right\}\qquad(7)$$

The positive directions of forces, bending moments and displacements of the edge effect are shown in Figure 1, *b*.

Taking into account the form of the temperature field (4), the equilibrium equations (3) for each belt of the shell take the form:

$$\left.\begin{aligned}&\frac{\partial^2 u}{\partial\alpha^2}+\frac{1-\mu}{2}\frac{\partial^2 u}{\partial\beta^2}+\frac{1+\mu}{2}\frac{\partial^2 v}{\partial\alpha\partial\beta}+\mu\frac{\partial w}{\partial\alpha}=0,\\&\frac{1+\mu}{2}\frac{\partial^2 u}{\partial\alpha\partial\beta}+\frac{1-\mu}{2}\frac{\partial^2 v}{\partial\alpha^2}+\frac{\partial^2 v}{\partial\beta^2}+\frac{\partial w}{\partial\beta}=(1+\mu)\cdot\alpha_t\cdot R\cdot\frac{\partial t}{\partial\beta},\\&\mu\frac{\partial u}{\partial\alpha}+\frac{\partial v}{\partial\beta}+w=(1+\mu)\cdot\alpha_t\cdot R\cdot t.\end{aligned}\right\} \tag{8}$$

In expressions (6-8), the index of the belt, for which the system of equations is written, is omitted.

Research results. *Axisymmetric temperature action* $(n=0)$. In this case, $v=0$, all derivatives with respect to β are equal to zero, and the system of equations (8) takes the form:

$$\left.\begin{aligned}&\frac{d^2u_0}{d\alpha^2}+\mu\frac{dw_0}{d\alpha}=0,\\&\mu\frac{du_0}{d\alpha}+w_0=(1+\mu)\alpha_t Rt_0.\end{aligned}\right\} \tag{9}$$

Integrating the first equation (9) and substituting it into the second, we find:

$$\frac{du_0}{d\alpha}=\mu w_0+C_1, \tag{10}$$

$$w_0=\frac{\alpha_t Rt_0}{1-\mu}-\frac{\mu}{1-\mu^2}C_1. \tag{11}$$

Substituting (11) into (10) and performing the integration, we obtain:

$$u_0(\alpha)=-\mu\frac{\alpha_t Rt_0}{1-\mu}\alpha+\frac{C_1}{1-\mu^2}\alpha+C_2. \tag{12}$$

Arbitrary constants C_I and C_2 included in (11) and (12) must be determined from the tangential boundary conditions:

$$u_{10}(0)=0,\ N_{1m}(l)=N_1^H-\vartheta u_m(l) \tag{13}$$

and tangential conditions for joining the belts:

$$\left.\begin{aligned}&u_i(l)=u_{i+1}(0),\\&N_{1i}(l)=N_{1i+1}(0).\end{aligned}\right\}(i=1,2,...,m-1) \tag{14}$$

where m – the number of belts of the shell of different thickness, the numbering of the belts starts from the fixed edge of the shell;

N_1^H – pre-tensioning of the suspension shell in the axial direction;

ϑ – stiffness coefficient of elastic fastening of the shell at the edge $\alpha_m=l_m$.

Taking into account [2], tangential conditions (13) and (14) explicitly look like this:

$$C_{21}=0,$$

$$\left.\begin{aligned}&\frac{l_i}{1-\mu^2}C_{1i}+1\cdot C_{2i}+0\cdot C_{1,i+1}-1\cdot C_{2,i+1}=\frac{\mu\cdot l_i}{1-\mu}\alpha_t Rt_0,\\&h_i\cdot C_{1i}+0\cdot C_{2i}-h_{i+1}\cdot C_{1,i+1}+0\cdot C_{2,i+1}=(1+\mu)\alpha_t Rt_0(h_i-h_{i+1}),\end{aligned}\right\}(i=1,2,...,m-1) \tag{15}$$

$$\left[\frac{Eh_m}{(1-\mu^2)R}-\vartheta\frac{l_m}{(1-\mu^2)}\right]C_{1m}-\vartheta\cdot C_{2m}=N_1^H+\vartheta\cdot\frac{\mu l_m}{1-\mu}\alpha_t Rt_0+\frac{Eh_m}{(1-\mu)}\alpha_t t_0.$$

Discrepancies of the momentless solution arise due to different thicknesses of adjacent belts. To satisfy the nontangential boundary conditions and the conditions for the continuity of radial displacements and angles of rotation at the joints of the chords, we will use the theory of a simple edge effect, with success used earlier [2-4]. In the corresponding formulas [4], it is necessary to set the bedding coefficient of the base $k(\alpha)=0$.

Impact of non-axisymmetric components of the temperature field $(n \geq 1)$. We seek the solution of the system of inhomogeneous equations (8) in the form of the sum of the general solution of the corresponding homogeneous and particular solution of the inhomogeneous system. Let's get a solution for an arbitrary belt. We omit the belt index in the calculations.

We represent the sought solutions in terms of two scalar functions $\Phi(\alpha,\beta)$ and $\Phi_t(\alpha,\beta)$. In this case, the function $\Phi(\alpha,\beta)$ determines the solution of the homogeneous system of equations and is introduced in accordance with [6] as follows:

$$\left.\begin{aligned} u_0 &= \frac{\partial}{\partial\alpha}\left(\frac{\partial^2\Phi}{\partial\beta^2}-\mu\frac{\partial^2\Phi}{\partial\alpha^2}\right), \\ v_0 &= -\frac{\partial}{\partial\beta}\left(\frac{\partial^2\Phi}{\partial\beta^2}+(2+\mu)\frac{\partial^2\Phi}{\partial\alpha^2}\right), \\ w_0 &= \nabla^2\nabla^2\Phi \end{aligned}\right\} \tag{16}$$

where: $\nabla^2 = \dfrac{\partial^2}{\partial\alpha^2}+\dfrac{\partial^2}{\partial\beta^2}$ – Laplace operator.

By direct substitution, one can make sure that the introduced function satisfies the first two equations of the system. After substitution in the third equation (8), we obtain the resolving equation for the function $\Phi(\alpha,\beta)$:

$$\mu\frac{\partial^4\Phi}{\partial\alpha^2\partial\beta^2}-\mu^2\frac{\partial^4\Phi}{\partial\alpha^4}-\frac{\partial^4\Phi}{\partial\beta^4}-(2+\mu)\frac{\partial^4\Phi}{\partial\alpha^2\partial\beta^2}+\nabla^2\nabla^2\Phi=0. \tag{17}$$

Expanding the double Laplace operator and reducing similar terms in (17), we obtain the resolving equation for the function $\Phi(\alpha,\beta)$ in the form:

$$\frac{\partial^4\Phi}{\partial\alpha^4}=0. \tag{18}$$

A particular solution is determined by the function $\Phi_t(\alpha,\beta)$, which, taking into account [7], we, introduce so that through it the displacements u_t, v_t and w_t are expressed as follows:

$$\left.\begin{aligned} u_t &= (1-\mu)\frac{\partial^3\Phi_t}{\partial\alpha^3}, \\ v_t &= -(1-\mu)\frac{\partial^3\Phi_t}{\partial\alpha^2\partial\beta}, \\ w_t &= (1-\mu)\frac{\partial^2}{\partial\alpha^2}\nabla^2\Phi_t. \end{aligned}\right\} \tag{19}$$

$$\Phi(\alpha,\beta)=\sum_{n=1}^{10}\left[\Phi_c^n\cos n\beta+\Phi_s^n\sin n\beta\right], \tag{20}$$

$$\Phi_t(\alpha,\beta)=\sum_{n=1}^{10}\left[\Phi_{tc}^n\cos n\beta+\Phi_{ts}^n\sin n\beta\right], \tag{21}$$

Further calculations, without loss of generality of transformations, are carried out for the shell completely illuminated by the sun, i.e. containing 5 terms of the cosine expansion series. Substitution of (19) into (3) leads to the fact that all three equations coincide and the resolving equation for the function $\Phi(\alpha,\beta)$ can be written in the form:

$$\frac{\partial^4 \Phi_t}{\partial \alpha^4} = \frac{\alpha_t Rt}{1-\mu}. \tag{22}$$

Taking into account (20) and (21), the resolving equations (18) and (22) for the nth term of the series are transformed into ordinary differential equations of the fourth order:

$$\frac{d^4 \Phi^n}{d\alpha^4} = 0, \tag{23}$$

$$\frac{d^4 \Phi_t^n}{d\alpha^4} = \frac{\alpha_t Rt}{1-\mu}. \tag{24}$$

The solutions to these equations are written in the form:

$$\Phi_c^n(\alpha) = C_{1c}^n \alpha^3 + C_{2c}^n \alpha^2 + C_{3c}^n \alpha + C_{4c}^n, \tag{25}$$

$$\Phi_{tc}^n(\alpha) = \frac{\alpha_t Rt_{nc}}{1-\mu} \cdot \frac{\alpha^4}{24}. \tag{26}$$

Taking into account (25) and (26) n – e terms of the series of displacements of the momentless solution look like this:

$$\left.\begin{aligned}
u_c^n(\alpha) &= \alpha_t Rt_{nc}\alpha - \left(3n^2\alpha^2 + 6\mu\right)C_{1c}^n - 2n^2\alpha C_{2c}^n - n^2 C_{3c}^n,\\
v_c^n(\alpha) &= \alpha_t Rt_{nc}\frac{n\alpha^2}{2} - \left[n^3\alpha^3 - (2+\mu)6n\alpha\right]C_{1c}^n - \left[n^3\alpha^3 - (2+\mu)2n\right]C_{2c}^n - n^3\alpha C_{3c}^n - n^3 C_{4c}^n,\\
w_c^n(\alpha) &= \alpha_t Rt_{nc}\left(1 - \frac{n^2\alpha^2}{2}\right) + \left(n^4\alpha^3 - 12n^2\alpha\right)C_{1c}^n + \left(n^4\alpha^2 - 4n^2\right)C_{2c}^n + n^4\alpha C_{3c}^n + n^4 C_{4c}^n.
\end{aligned}\right\} \tag{27}$$

Changing the index "c" to "s" in (27), we obtain formulas for calculating the amplitudes of the harmonics of the corresponding displacements at $\sin n\beta$. The first terms in formulas (27) are particular solutions.

Substituting (27) into physical equations (2) after appropriate transformations, we obtain expressions for tangential forces:

$$\left.\begin{aligned}
N_{10c}(\alpha) &= \sum\nolimits_{n=1}^{10} N_{10c}^n(\alpha)\cos n\beta,\\
N_{20c}(\alpha) &= \sum\nolimits_{n=1}^{10} N_{20c}^n(\alpha)\cos n\beta,\\
S_{0c}(\alpha) &= \sum\nolimits_{n=1}^{10} S_{0c}^n(\alpha)\sin n\beta.
\end{aligned}\right\} \tag{28}$$

where:

$$\left.\begin{aligned}
N_{10c}^n(\alpha) &= -\frac{Eh}{R}2n^2\left(3\alpha C_{1c}^n + C_{2c}^n\right),\\
N_{20c}^n(\alpha) &= 0,\\
S_{0c}^n(\alpha) &= \frac{Eh}{R}6nC_{1c}^n.
\end{aligned}\right\} \tag{29}$$

The formulas for the amplitudes of the harmonics of tangential forces (29) do not include particular solutions – they are identically equal to zero. It is characteristic that the circumferential force identically equal to zero, this is a consequence of the free movement of the shell in the radial direction.

Arbitrary constants in the expressions for the displacements (27) and effort (29), are determined from the tangential boundary conditions and docking conditions zones recorded for the amplitudes of the *n*– the term of a similar (15).

Supplementing the obtained solutions with the edge effect written for the nth harmonic similarly to [2, 3], we obtain a complete solution of the problem posed.

An empty vertical metal shell far from the fixed edges freely deforms in the radial direction, which explains the vanishing of the circumferential force of the momentless state N_2 in the shell.

A feature of the temperature climatic effect on a vertical circular cylindrical shell is that the temperature field of the shell seems to follow the sun, enveloping the shell, while in the shell without a screen, the temperature field differs slightly from the one that is symmetric relative to the normal incidence of sunlight.

Conclusions:

1. For a vertical empty cylindrical shell, with one-sided heating-cooling of the shell, a momentless solution in the Fourier series for the components of the stress-strain state (SSS) is obtained.

2. A simple edge effect in the Fourier series eliminates the residuals of the momentless solution.

3. Taking into account [1], five terms of the cosine expansion series are sufficient to describe the SSS components during cooling of a shell heated without a screen.

4. To describe the components of the stress-strain state of a shell during cooling of a shell heated in the presence of a screen covering half of the shell along its entire height [1], it is necessary to take into account ten terms of the expansion series in the circumferential direction in sines and cosines.

5. The circumferential force $N_2(\alpha)$ of the momentless state is equal to zero as a consequence of the absence in the empty shell of restrictions on the shell displacement in the radial direction.

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НАПРУЖЕНО - ДЕФОРМОВАНИЙ СТАН ВЕРТИКАЛЬНОЇ ЦИЛІНДРИЧНОЇ МЕТАЛЕВОЇ ОБОЛОНКИ ПРИ ТЕМПЕРАТУРНОМУ КЛІМАТИЧНОМУ ВПЛИВІ

Жданов А.А., к.т.н., доцент,
ajdanow1945@gmail.com, ORCID: 0000-0002-3304-5729
Одеська державна академія будівництва та архітектури
вул. Дідріхсона, 4, м. Одеса, 65029, Україна
Петров В.Н., к.т.н., доцент,
0673972002@ukr.net, ORCID: 0000-0003-3262-9463
Національний університет «Одеська політехніка»,
просп. Шевченка, 1, м. Одеса, 65000, Україна

Анотація. Для зберігання зернистих сипких матеріалів широко використовуються вертикальні циліндричні ємності. Огороджувальна бічна поверхня таких ємностей виконується у вигляді циліндричних металевих кругових оболонок з постійною або зі шматково-постійною по висоті оболонки товщиною стінки. Відомі конструкції для зберігання сипких матеріалів резервуарного типу з установкою циліндричної оболонки на кільцевому фундаменті з шарнірно-нерухомим кріпленням оболонки до фундаменту. Тонкостінні оболонки роблять підвісними до несучих конструкцій сховищ. Для стабілізації циліндричної форми оболонки та її положення у просторі підвісні оболонки піддають попередньому натягу у вертикальному напрямку. У процесі експлуатації сховища бувають порожніми та заповненими сипучими матеріалами, схильні до впливу навколишнього середовища у вигляді вітрових та температурних кліматичних впливів.

Об'єктом дослідження даної роботи є огороджувальні конструкції сховищ зернистих сипучих матеріалів у вигляді вертикальних кругових циліндричних тонкостінних металевих оболонок, в загальному випадку кусково-постійної товщини, схильні до температурно-кліматичних впливів навколишнього середовища – зміни температури зовнішнього повітря, прямої та розсіяної сонячної радіації.

Предметом дослідження є компоненти напружено-деформованого стану оболонки, зумовлені зміною температурних кліматичних впливів. Виконані дослідження температурних полів оболонок сховищ на моделях та натурних об'єктах дозволили обґрунтувати завдання температурного поля циліндричних оболонок сховищ рядами Фур'є.

Одностороннє сонячне нагрівання повністю освітленої сонцем циліндричних оболонок сховищ наводить у стінці оболонки плоске, симетричне щодо нормалі падіння сонячних променів, температурне поле, яке можна представити рядом Фур'є з п'ятьма членами ряду розкладання по косинусах. За наявності поруч розташованої з оболонкою споруди, яка закриває по всій висоті половину оболонки в окружному напрямку, температурне поле описується рядом Фур'є, що містить по 10 гармонік розкладання по синусах і косинусах.

Мала товщина оболонки, значний радіус кривизни оболонок, великий коефіцієнт температуропровідності металів забезпечують малу мінливість температури оболонки по товщині, можливість опису напружено-деформованого стану оболонки безмоментну теорію і простий крайовий ефект.

Отримані у рядах Фур'є формули для зусиль безмоментного стану, нев'язки якого в стиках поясів оболонки різної товщини та в опорних зонах ліквідуються простим крайовим ефектом.

Ключові слова: безмоментна теорія оболонок, теорія крайового ефекту, температурні кліматичні впливи, сили та переміщення в порожній вертикальній циліндричній оболонці.

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