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PARAMETERS DETERMINING THE DEGREE OF THE REQUIRED EXTERNAL TRANSVERSAL FRP REINFORCEMENT OF METAL CYLINDRICAL TANKS

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Abstract. The main reasons for the wear of the walls of metal cylindrical tanks are corrosion and fatigue of the metal of their vertical joints. It is possible to replenish for the corrosion losses of the material, as well as to reduce the level of acting stresses to values allowed by the conditions of metal fatigue, with external transverse reinforcement with fiber reinforced plastic (FRP).

Sequential consideration of the operation of steel shells of cylindrical tanks reinforced with external transverse FRP reinforcement allows to obtain the values of the corresponding hoop stresses. The necessary limitation of the values of the maximum stresses of the metal components makes it possible to determine the coefficients of the external FRP reinforcement of these structures. Herewith the analysis of the obtained theoretical results indicates the mandatory need to take into account the temperature deformations of structural elements that exhibit different temperature-deformation properties, as well as a significant impact on the results obtained by the longitudinal deformations of the metal shells of these structures.

The calculation methods proposed in the article make it possible to determine the necessary parameters for strengthening the bodies of metal cylindrical tanks with an external transversely directed FRP reinforcement that perceives the actions of ring forces. The main factors determining the effectiveness of the obtained solutions are the residual strength of the material of the metal shells of the tanks, as well as the modulus of elasticity of the used FRP.

The theoretical expediency of the effective use of low-modulus FRP is confirmed for structures with high strength indicators of metal bases, and high-modulus – in cases of significant limitation of the stress level of metal elements.

Key words: metal cylindrical tanks, methods of strengthening the walls of tanks, external transverse reinforcement, FRP systems of external reinforcement.

Introduction. Long-term operation of tank structures is one of the main reasons that determine their physical wear and associated accident rate. The main cause of physical wear of the walls of tanks of small and medium capacity (1000…5000 m^3) is corrosion. The performance of the walls of metal tanks of large sizes (with a capacity of more than 5000 m^3), having a large thickness of elements (12 mm or more), is largely determined by the fatigue of the metal used, which is most critically manifested in vertical welded joints [1].

The problem of combating wall corrosion of tanks is usually solved using widely used paint and varnish protection methods, including the introduction of thick-filmed (2…3 mm) epoxy-containing coating systems, which may include glass fiber layers. To strengthen the tank shells, providing for the reinstatement of the bearing capacity of their walls, various methods can be used as replacing damaged elements, the general banding, the installation of various horizontal stiffeners that cover defective vertical joints, welding along the entire length of vertical connections of the special inserts, etc [2]. As alternative solutions, it was also proposed to use continuous winding of high-strength wires or tapes installed with prestressing on the shells of metal cylindrical tanks [3, 4].

The traditional strengthening methods described above, giving quite acceptable results, are associated with a number of design and technological shortcomings, often leading to the fact that the complete replacement of these structures is considered as a more effective solution. It becomes possible to avoid many disadvantages of widely used reinforcing structures, significantly simplify the technology and reduce the time of the mounting within the using of the methods of external transverse reinforcement of the walls of cylindrical tanks by high-strength FRP materials, the most effective type of which is carbon fiber reinforced plastic (CFRP) [5].

Thus the complex of problems to be solved when extending the effective operation of metal tank bodies includes the reinstatement of the lost bearing capacity of their walls, which is a potential cause of the most dangerous and costly accidents of these structures [1]. It becomes possible to replenish the working material of the walls of the tanks, as well as to reduce the level of acting stresses with external reinforcement by transverse FRP [2].

Existing theoretical base. The operability of reinforcements of structures of a closed geometric shape, carried out by external transverse reinforcement with high-strength FRP materials, has been evaluated in engineering practice for a relatively long time. In construction, such design solutions are widely used to increase the bearing capacity of reinforced concrete columns and cylindrical structures, in particular tanks [6-9]. At the same time, the existing regulatory framework for strengthening reinforced concrete structures with FRP is quite extensive, there are national and interstate documents that cover this issue quite fully. With regard to metal structures, the reinforcement of which by FRP began almost 20 years later, there are no national defining regulatory documents [5]. The recommendations that exist in the world on the calculation and design of building structures combining metal and FRP materials are very limited and do not cover all cases of their possible operation [10-15]. The problem is complicated by the fundamental differences in the nature of the operation and destruction of reinforcements of metal structures from, for example, reinforced concrete structures, as well as there is the impossibility of using pure solutions tested in the aircraft industry and astronautics, which is explained by significant differences in the dimensions of the cross sections of the elements, the nature of the existing internal forces, the values and the duration of the applied loads, the impossibility of an empirical approach with multiple series of experimental studies of full-scale elements of building structures and the peculiarities of using cheaper reinforcing and, most importantly, matrix-adhesive materials.

Consideration of the existing theoretical basis for strengthening metal structures with FRP poses a number of problems when considering the walls of cylindrical tanks. Currently, there is an insistent need for a corresponding systematization and adaptation of the existing world practice of reinforcing metal structures by FRP (within extremely limited national practice), in relation to the operation of cylindrical tank shells. It is necessary to develop methods for strengthening the walls of metal tanks in the absence of working loads, as well as with prestressing of reinforcing elements installed in the time of continuous operation of structures. It is required to determine the degree of influence of thermal stresses on the operation of cylindrical shells of tanks made up of layers, the materials of which have significant differences in the values of the coefficients of linear thermal deformations.

Thus the lack of an adequate regulatory framework [2, 16] largely hinders the practical implementation of the method of transverse FRP reinforcement of steel tanks.

The purpose of the work is to determine an applied method acceptable for the calculation of metal cylindrical tanks that perceive internal pressure and are reinforced by external transversely directed FRP reinforcement, taking into account differences in the temperature deformation of the used materials, as well as the definition of general factors affecting the efficiency of the applied solution.

Results of the research. Sequential consideration of the operation of the steel shell of a cylindrical tank, having a radius r and thickness t_s , being under the action of the initial internal pressure P' and than strengthened by transverse prestressed FRP elements with prestress σ_{f0} and thickness t_f continuously located along its height, experiencing a subsequent increase in pressure by an amount ΔP (Fig. 1), made it possible to obtain the values of the maximum hoop stresses, respectively, in the elements of FRP reinforcement and the steel wall of the tank [16]:

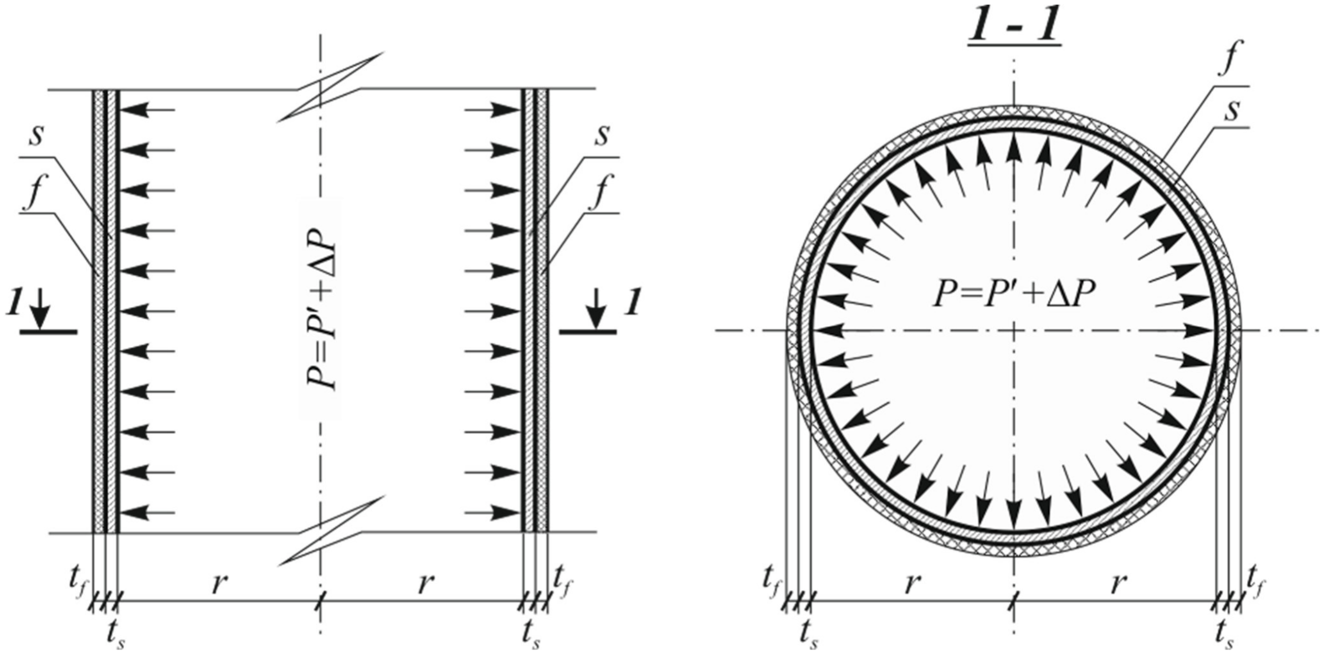

Fig. 1. Calculation drawing of a steel cylindrical shell of a tank reinforced with external transverse FRP: *s* – the steel shell of the tank, *f* – the layer of external transverse FRP reinforcement

$$\sigma_f = \sigma_{f0} + \frac{m\left[N_{f(x,z)} + t_s E_s\left(\alpha_s \Delta T_{s2} - \alpha_f \Delta T_{f2}\right)\right]}{t_s + t_f m}, \sigma_s = \frac{P' \cdot r}{t_s} - \sigma_{f0}\frac{t_f}{t_s} + \frac{N_{s(x,z)} + t_f E_f\left(\alpha_f \Delta T_{f1} - \alpha_s \Delta T_{s1}\right)}{t_s + t_f m}, \quad (1)$$

where $N_{f(x,z)} = \Delta P \cdot r(1 - \mu/2)$, $N_{s(x,z)} = \Delta P \cdot r\left[1 + m\left(t_f/t_s\right)(\mu/2)\right]$ – conditional hoop forces per unit section of the FRP and steel layers of the tank wall, arising from a change in internal pressure by the value ΔP and determined taking into account the combined action of hoop and longitudinal stresses in the steel part of the structure; E_s , E_f – respectively, the moduli of elasticity of steel and elements of FRP reinforcement; $m = E_f / E_s$ – the ratio of the elastic modules of the constituent layers of the wall; μ – Poisson's ratio of the material of the steel component of the tank wall; σ_{f0} – prestressing in the elements of fiber-reinforced plastic; α_s and α_f – coefficients of linear thermal deformation of steel and a layer of FRP; ΔT_{s1} and ΔT_{f1} – the most critical temperature changes of the steel and FRP components of the shell, causing maximum additional stresses in the steel; ΔT_{s2} and ΔT_{f2} – the most critical changes in the temperatures of the steel and FRP components of the shell, causing the maximum additional stresses in the FRP.

The most typical case that determines the temperature regimes of operation of the absolute mass of metal tanks is a smooth change in temperatures with the same values ΔT in all layers of complex walls.

At present, two fundamental approaches have been formed to the practical consideration of the nature of the operation of metal cylindrical shells reinforced by external transverse reinforcement, which perceives the action of only ring forces.

On the one hand, classical works [3, 4], which analyze the strengthening of metal cylindrical shells by winding high-strength metal wires and tapes, state that taking into account the longitudinal stresses of these structures leads to a slight increase in the thickness of the steel parts of the walls and a decrease in the thickness of the reinforcing layers, refining the calculation by no more than by *4...5%*. Thus, in this case, under the influence of considerations of a significant simplification of practical calculations, the assumption of the applicability of the statement $N_{f(x,z)} \approx N_{s(x,z)} \approx (\Delta P) r$.

On the other hand, the distinguishing features of the use of external FRP reinforcement of tanks from reinforcing winding by metal elements are a much larger possible range of ratios of the elastic modules of the working parts of the wall structure, which in the general case is $m = 0{,}3...3{,}8$, as well as the presence of coefficients of linear thermal deformation of FRP are $\alpha_f = (-2{,}0...+5{,}4)\times 10^{-6}{}^{\circ}C^{-1}$, which cause a significant increase in stresses during joint work with steel, that demonstrates a similar value equal to $\alpha_s = +10{,}4\times 10^{-6}{}^{\circ}C^{-1}$. The foregoing limits the applicability of simplifications of the classical approach, abstracted from steel deformations directed along the axes of the tank shells.

The solution of the problem of determining the required working thicknesses of the FRP components of the complex walls of the cylindrical tanks under consideration, without taking into account the longitudinal deformations of the metal shells and with their presence, is given below.

The case of abstraction from longitudinal deformations of metal shells of tanks. Combined consideration of expressions defining stresses in the steel wall of the tank and reinforcing FRP elements (1), abstracted from the longitudinal stresses of the shell (i.e. $N_{f(x,z)} \approx N_{s(x,z)} \approx (\Delta P)r$) and taking into account uniform change in temperatures ΔT of materials of all layers of the structure, allows to get the interdependence between the considered stresses

$$\sigma_s = \sigma'_{s0(x)} + \frac{1}{m}\left(\sigma_f - \sigma_{f0}\right) - \sigma_{f0}\frac{t_f}{t_s} - \Delta\alpha\cdot\Delta T\cdot E_s \ , \tag{2}$$

where $\sigma'_{s0(x)} = \dfrac{P'\cdot r}{t_s}$ – stresses in the steel shell before the start of the reinforcement process,

$\Delta\alpha = \alpha_s - \alpha_f$ – the difference between the coefficients of linear thermal deformation of steel and the layer of reinforcing FRP.

In the absence of initial pressure at the moment of reinforcement of the reservoirs (i.e. $P'=0$) and installation FRP reinforcement without applying prestressing forces ($\sigma_{f0}=0$), the last interdependence is

$$\sigma_s = \frac{\sigma_f}{m} - \Delta\sigma_T \ , \tag{3}$$

where $\Delta\sigma_T = \Delta\alpha\cdot\Delta T\cdot E_s$ – the value that determines the change in stresses under the influence of temperature deformations.

Limiting in the last expression the stress value of the steel component σ_s of the complex wall of the tank by the yield strength of the material f_{yd} or the limiting stress value that is permissible from the fatigue conditions of the material of the joints of its non-reinforced structure, it becomes possible to obtain the maximum stresses of the FRP component corresponding to the case of maintaining the overall performance

$$\sigma_f^{\max} = \left(f_{yd} + \Delta\sigma_T\right)m \, . \tag{4}$$

Taking into account the condition of equilibrium of the acting forces

$$N_{\Delta P(x)} = \Delta P\cdot r = \sigma_s t_s + \sigma_f t_f \, , \tag{5}$$

where $N_{\Delta P(x)} = \Delta P\cdot r$ – conditional ring force per unit section of the complex wall of the tank, arising when the internal pressure changes by ΔP,

and limiting condition (4), it becomes possible to obtain the required thickness of an external transverse FRP reinforcement

$$t_f = \frac{N_{\Delta P(x)} - f_{yd}t_s}{\left(f_{yd} + \Delta\sigma_T\right)m} \, . \tag{6}$$

Entering the coefficient of the required degree of external FRP reinforcement $k_{f(t)} = t_f / t_s$ is possible to get

$$k_{f(t)} = \frac{\left(N_{\Delta P(x)}/t_s\right) - f_{yd}}{\left(f_{yd} + \Delta\sigma_T\right)m} = \frac{\Delta\sigma_{s+}}{\left(f_{yd} + \Delta\sigma_T\right)m}, \tag{7}$$

where $\Delta\sigma_{s+} = \frac{N_{\Delta P(x)}}{t_s} - f_{yd}$ – conditional excess of stresses over its limiting value (yield strength of steel or maximum stresses determined by the fatigue of the material of the joints) in a metal shell in the absence of external reinforcement.

The case of accounting for longitudinal deformations of the metal shells of tanks. Similar to the previous case, the combined consideration of the expressions that determine the stresses in the steel wall of the tank and the reinforcing FRP elements (1), taking into account the effect of longitudinal stresses in the shell on conditional ring forces $N_{f(x,z)}$, $N_{s(x,z)}$, as well as a uniform change in the temperatures ΔT of materials of all layers of the structure, allows to get the interdependence between these stresses

$$\sigma_f = \frac{m}{A}\left[\sigma_s - \sigma'_{s0(x)} + \sigma_{f0}\frac{t_f}{t_s} + \Delta\alpha \cdot \Delta T \cdot E_s \frac{At_s + t_f m}{t_s + t_f m}\right] + \sigma_{f0}, \tag{8}$$

where $\sigma'_{s0(x)} = P' \cdot r/t_s$ – stresses in the steel shell before the start of the reinforcement process; $\Delta\alpha = \alpha_s - \alpha_f$ – the difference between the coefficients of linear thermal deformation of steel and the layer of FRP; $A = \left[1 + m\left(t_f/t_s\right)\left(\mu/2\right)\right]/\left(1 - \mu/2\right)$ – auxiliary value.

In the absence of initial pressure at the moment of reinforcement of the tanks (i.e. $\sigma'_{s0(x)}=0$) and the installation of FRP reinforcement without prestressing ($\sigma_{f0}=0$), expression (8) takes the form

$$\sigma_f = \frac{m}{A}\left[\sigma_s + \Delta\sigma_T \frac{At_s + t_f m}{t_s + t_f m}\right], \tag{9}$$

In accordance with (9), the allowable stresses in FRP from the condition of ensuring the operability of the steel part of the structure is

$$\sigma_f^{\max} = \frac{m}{A}\left[f_{yd} + \Delta\sigma_T \frac{At_s + t_f m}{t_s + t_f m}\right], \tag{10}$$

where f_{yd} – design yield strength of steel or the limiting stress value permissible from the conditions of fatigue of the material of the shell joints.

Joint consideration of the condition of equilibrium of ring forces $N_{\Delta P(x)} = \Delta P \cdot r = \sigma_s t_s + \sigma_f t_f$ and the constraint (10) allows obtaining the required thickness of a continuous external transverse FRP

$$t_f = \frac{A}{m} \cdot \frac{N_{\Delta P(x)} - f_{yd} t_s}{f_{yd} + \Delta\sigma_T \dfrac{At_s + t_f m}{t_s + t_f m}}. \tag{11}$$

The value of the coefficient that determines the degree of required external FRP reinforcement $k_{f(t)}$, in this case is

$$k_{f(t)} = {}^{t_f}\!\!\diagup_{t_s} = \frac{A}{m} \cdot \frac{\left(N_{\Delta P(x)}/t_s\right) - f_{yd}}{f_{yd} + \Delta\sigma_T \dfrac{At_s + t_f m}{t_s + t_f m}} = \frac{A}{m} \cdot \frac{\Delta\sigma_{s+}}{f_{yd} + \Delta\sigma_T \dfrac{At_s + t_f m}{t_s + t_f m}}, \tag{12}$$

where $A = \dfrac{1 + m\dfrac{t_f}{t_s}\dfrac{\mu}{2}}{1 - \mu/2} = \dfrac{1 + mk_{f(t)}\dfrac{\mu}{2}}{1 - \mu/2}$ – auxiliary value.

Transformation of (12) allows obtaining the following equation

$$A_1 k_{f(t)}^2 + A_2 k_{f(t)} - A_3 = 0, \tag{13}$$

where $A_1 = m\left[(1-\mu/2) f_{yd} - (\mu/2)\Delta\sigma_{s+} + \Delta\sigma_T\right]$; $A_2 = (1-\mu/2) f_{yd} - (1+\mu/2)\Delta\sigma_{s+} + \Delta\sigma_T$;

$A_3 = \Delta\sigma_{s+}/m$.

The meaningful solution of equation (13) determines the required value of the coefficient of external FRP reinforcement

$$k_{f(t)} = {}^{t_f}\!\!\diagup_{t_s} = \frac{1}{2A_1}\left[\left(A_2^2 + 4A_1A_3\right)^{\frac{1}{2}} - A_2\right] = A_3' - {}^{A_2}\!\!\diagup_{A_1}, \tag{14}$$

where $A_3' = 1/m$.

Numerical studies and related analysis. A significant difference in the values of the coefficients of linear thermal deformation of FRP and steels determines the significant effect of changes in operating temperatures on the stress state of cylindrical tanks reinforced with appropriate external transverse reinforcement.

Thus, the results of numerical calculations that considered the change in the coefficient of FRP reinforcement $k_{f1(t)}$ for plastics based on various reinforcing fibers (*E-glass fiber*, *aramid fiber*, *high strength (normal modulus) carbon fiber*, *high modulus carbon fiber*), obtained with a single excess of stresses $\Delta\sigma_{s+} = 1$ over the limiting value f_{yd}, in different ranges of operating temperatures ΔT, indicate their multiple variability.

An analysis of the dependences of the coefficients $k_{f1(t)}$ on operating temperatures ΔT indicates a general trend of the supreme influence on this parameter of the values of the elastic modules E_f of the used FRP, as well as the strength characteristics of the material of steel shells f_{yd} (with an increase in these indicators, a decrease in these coefficients is observed).

The characteristic of influence of the temperature factor is determined by the condition of limiting the strength of the material of metal shells: when using FRP based on various types of structural fibers, thermal deformations can repeatedly change the value of the considered coefficient $k_{f1(t)}$ in combination with steel shells that are characterized by low material strength ($f_{yd} = 18kN/cm^2$), while similar combinations with high-strength steels ($f_{yd} = 42kN/cm^2$) practically neutralize the effect of temperatures.

It is also important that in the considered determination of the coefficient $k_{f1(t)}$, the classical assumption about the possibility of abstracting from the effect of longitudinal deformations of steel shells is applicable only in some cases when high-strength steel shells are combined with predominantly high-modulus FRP of external reinforcement in the ranges of increasing temperatures. Otherwise, not taking into account the longitudinal deformation of steel shells leads to significant differences from the calculations performed with it taken into account.

Consideration of the dependences obtained for various types of external FRP, taking into account the effect of longitudinal deformations of tanks, allows to conclude that it is quite expedient to use low-modulus and much cheaper FRP to reinforce structures that have high strength characteristics of steel basics $f_{yd} \approx 30...42kN/cm^2$. At the same time, as for structures characterized by low strength limits of steel $f_{yd} \approx 15...20kN/cm^2$, effective external reinforcement is achieved only when using high-modulus FRP.

Conclusion. The proposed calculation methods make it possible to determine the necessary parameters for strengthening the bodies of metal cylindrical tanks with an external transversely directed FRP reinforcement that perceives the actions of ring forces. In this case, the mandatory factors to be taken into account are the temperature deformations of the materials used, as well as the longitudinal deformations of the metal components of complex structures. The main factors determining the effectiveness of the solutions obtained are the residual strength of the material of the metal shells of the tanks, as well as the modulus of elasticity of the used FRP. The theoretical expediency of the effective use of low-modulus FRP is confirmed for structures with high strength indicators of metal bases, and high-modulus – for the walls of tanks, which are characterized by significant restrictions on the level of allowable stresses of their metallic shells.

The needed further research. The indicators of effective external FRP reinforcement of the walls of the bodies of metal cylindrical tanks require further determination, taking into account the geometric features of the structures, the thickness of the metal elements, the characterization of the initial loads, the methods of montage and the calculated characteristics of the fiber used.

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ПАРАМЕТРИ, ВИЗНАЧАЮЧІ СТУПЕНЬ НЕОБХІДНОГО ЗОВНІШНЬОГО ПОПЕРЕЧНОГО ФІБРОПЛАСТИКОВОГО АРМУВАННЯ МЕТАЛЕВИХ ЦИЛІНДРИЧНИХ РЕЗЕРВУАРІВ

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Анотація. Основними причинами зношування стінок корпусів металевих циліндричних резервуарів є корозія та втома металу їх вертикальних з'єднань. Відновити корозійні втрати матеріалу, а також знизити рівень напружень до величин, що допускаються умовами втоми металу, можливо при зовнішньому поперечному армуванні фібропластиковими матеріалами.

Послідовний розгляд роботи сталевих оболонок циліндричних резервуарів, посилених безперервним зовнішнім поперечним фібропластиковим армуванням, дозволяє отримати величини відповідних кільцевих напружень. Необхідне обмеження величин максимальних напружень металевих складових дає можливість визначення коефіцієнтів зовнішнього фібропластикового армування даних конструкцій. При цьому аналіз одержуваних теоретичних результатів свідчить про обов'язкову необхідність урахування температурних деформацій елементів конструкцій, що виявляють різні температурно-деформаційні властивості, а також про суттєвий вплив на результати дефініції поздовжніх деформацій металевих оболонок аналізованих споруд.

Запропоновані у статті методи розрахунку дозволяють проводити визначення необхідних параметрів посилення корпусів металевих циліндричних резервуарів зовнішнім поперечно спрямованим фібропластиковим армуванням, що сприймає дії кільцевих зусиль. Основними факторами, що визначають ефективність одержуваних рішень, є залишкова міцність матеріалу металевих оболонок резервуарів, а також модуль пружності фібропластиків.

Теоретична доцільність ефективного використання низько модульних фіброармованих пластиків підтверджується для конструкцій, що мають високі показники міцності металевих основ, а високо модульних – у випадках істотного обмеження рівня напруг металевих елементів.

Ключові слова: металеві циліндричні резервуари, методи посилення стінок резервуарів, зовнішнє поперечне армування, фібропластикові системи зовнішнього армування.