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EFFECTIVENESS OF STRENGTHENING CASES OF METALLIC CYLINDRICAL TANKS BY FRP REINFORCEMENT BASED ON FIBERS OF DIFFERENT TYPES

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Abstract. The park of metal cylindrical tanks in Ukraine is characterized by significant wear of load-bearing structures, corrosion of elements and metal fatigue of vertical connections. One of the solutions to the replenishment of the lost load-bearing capacity of their walls is the reinforcement by external transverse FRP. It is also make it possible to ensure tightness and anti-corrosion protection of these constructions. At the same time, existing recommendations assessing the effective use of various types of FRP, differing in strength, deformation and thermal deformation parameters, are insufficient in relation to the strengthening of metal cylindrical shells.

This work systematizes systematize the method of practical determination of the parameters of the stressed state of elements of metal cylindrical shells reinforced with external transversely directed FRP reinforcement and detecting the main factors influencing the effectiveness of the use of FRP based on fibers of various types in combination with steels of different strengths.

The analysis of the given theoretical dependencies allows to conclude that the mandatory factors to be taken into account for strengthening of the metal cylindrical shells by external transversely directed FRP reinforcement that perceives the actions of ring forces are the temperature deformations of used FRP materials, as well as the longitudinal deformations of the metal components of complex walls.

The main factors determining the effectiveness of the obtained solutions are the residual strength of the material of the metal shells and the modulus of elasticity of the used FRP. The influence of thermal deformations can repeatedly change the required degree of external reinforcement of structures in the case of the using FRP based on various types of structural fibers in combination with steel shells that characterized by low material strength, while similar combinations with high-strength steels can neutralize the influence of temperatures.

The effective use of low-modulus FRP can be achieved for reinforcements of the structures with high strength characteristics of steel. For the structures characterized by low steel strength effective external reinforcement is achieved in combination with high-modulus FRP.

The influence of temperature deformations leads to that the FRP reinforcements made on the basis of aramid fibers demonstrate relative ineffectiveness in combination with shells characterized by low steel strength.

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

Introduction. Ukraine has an extensive park of metal cylindrical tanks, characterized by long service life and significant wear, which reduce the reliability of their operation [1- 3]. The complex of problems solved when extending the effective operation of metal tank bodies includes the replenishment of the lost load-bearing capacity of their walls, which turns out to be a reason for the most dangerous and economically expensive emergency of such constructions. One of the solutions to the problem can be the reinforcement of the metal shells of these structures by external transverse FRP [3, 4]. The use of high-modulus materials makes it possible to obtain effective solutions that do not require the use of pre-stressing reinforcing elements. It is also important that such systems make it possible to solve connected problems associated with ensuring tightness and anti-corrosion protection.

The relative novelty of the solutions that combine the joint force work of metal and FRP elements as part of complex cylindrical shells, the theoretical unresolvedness of certain calculation issues, as well as the lack of an adequate regulatory framework for their use [5-11], significantly hamper the practical implementation of FRP reinforcement methods for steel tanks [3, 4, 12]. The problem is considerably complicated by the heterogeneity of elastic modulus of possible FRP, as well as by the significant differences in their thermal deformation characteristics from the steel, which can in some cases significantly reduce the degree of effectiveness of the resulting solutions [4, 13, 15-18]. At the same time, existing recommendations assessing the effective use of various types of FRP, differing in strength, deformation and thermal deformation parameters, are insufficient in relation to the strengthening of metal cylindrical shells.

The purpose of the work is to systematize the method of practical determination of the parameters of the stressed state of elements of metal cylindrical tanks that perceive internal pressure and are reinforced with continuous external transversely directed FRP reinforcement, taking into account the differences in temperature deformation of the materials used, as well as detecting the main factors influencing the effectiveness of the use of FRP based on fibers of various types in combination with steels of different strengths.

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 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, 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 [4, 13, 15-18]:

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

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 temperature regimes of operation of metal tanks imply a smooth change in temperatures with the same values ΔT in all layers of complex walls.

At present, two approaches have been formed to the practical consideration of the nature of the operation of metal cylindrical shells reinforced by external transverse reinforcement. Classical works [19, 20], which analyze the strengthening of metal cylindrical shells by winding high-strength metal elements, under the influence of considerations of a significant simplification of practical calculations, state the assumption of the applicability of the statement $N_{f(x,z)} \approx N_{s(x,z)} \approx (\Delta P)r$. But the distinguishing features of the use of external FRP reinforcement from reinforcing by metal are a much larger possible range of ratios of the elastic modules of the wall parts, 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 $\alpha_s = +10{,}4\times 10^{-6}{}^{\circ}C^{-1}$.

In the case of abstraction from longitudinal deformations of metal shells (i.e. $N_{f(x,z)} \approx N_{s(x,z)} \approx (\Delta P)r$) taking into account uniform change in temperatures ΔT of materials it is possible to get the interdependence between stresses in the layers of complex walls

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

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

In the absence of initial internal pressure (i.e. $P'=0$) and prestressing forces ($\sigma_{f0}=0$), the last interdependence is

$$\sigma_s = \frac{\sigma_f}{m} - \Delta\sigma_T \ , \qquad (3)$$

where $\Delta\sigma_T = \Delta\alpha \cdot \Delta T \cdot E_s$ – the change in stresses under the influence of temperature deformations,
$\Delta\alpha = \alpha_s - \alpha_f$ – the difference between the coefficients of linear thermal deformation of steel and the layer of FRP;.

Limiting the stress value of the steel component σ_s by the yield strength of the material f_{yd} or by stress value premised from the fatigue conditions of the joints of steel structure and taking into account the condition of equilibrium of the acting forces it becomes possible to obtain the required thickness of an external transverse FRP reinforcement and coefficient of the external FRP reinforcement

$$t_f = \frac{N_{\Delta P(x)} - f_{yd}t_s}{\left(f_{yd} + \Delta\sigma_T\right)m}, \qquad k_{f(t)} = \frac{t_f}{t_s} = \frac{\Delta\sigma_{s+}}{\left(f_{yd} + \Delta\sigma_T\right)m} \qquad (4)$$

where $N_{\Delta P(x)} = \Delta P \cdot r$ – conditional ring force per unit section of the complex wall, $\Delta\sigma_{s+} = \frac{N_{\Delta P(x)}}{t_s} - f_{yd}$ – excess of stresses over its limiting value in a metal shell in the absence of external reinforcement.

In the case of accounting for longitudinal deformations of the metal shells and 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, it is possible to get

$$\sigma_f = \frac{m}{A}\left[\sigma_s - \sigma'_{s0(x)} + \sigma_{f0}\frac{t_f}{t_s} + \Delta\alpha \cdot \Delta T \cdot E_s \frac{At_s + t_f m}{t_s + t_f m}\right] + \sigma_{f0} \ , \qquad (5)$$

where $\sigma'_{s0(x)} = P' \cdot r / t_s$ – stresses in the steel shell before the start of the reinforcement process, $A = \left[1 + m\left(t_f/t_s\right)\left(\mu/2\right)\right] / \left(1 - \mu/2\right)$ – auxiliary value.

In the absence of initial pressure at the moment of reinforcement (i.e. $\sigma'_{s0(x)}=0$) and the installation of FRP without prestressing ($\sigma_{f0}=0$), expression (5) takes the form

$$\sigma_f = \frac{m}{A}\left[\sigma_s + \Delta\sigma_T \frac{At_s + t_f m}{t_s + t_f m}\right] , \qquad (6)$$

In accordance with the allowable stresses in FRP from the condition of ensuring the operability of the steel part f_{yd} and according the condition of equilibrium of ring forces it is possible to obtain the required thickness of FRP and coefficient of the external FRP reinforcement

$$t_f = \frac{A}{m} \cdot \frac{N_{\Delta P(x)} - f_{yd} t_s}{f_{yd} + \Delta\sigma_T \dfrac{At_s + t_f m}{t_s + t_f m}}, \quad k_{f(t)} = \frac{t_f}{t_s} = \frac{A}{m} \cdot \frac{\Delta\sigma_{s+}}{f_{yd} + \Delta\sigma_T \dfrac{At_s + t_f m}{t_s + t_f m}}, \tag{7}$$

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.

The results of the above theoretical studies were confirmed when testing models of metal cylindrical structures strengthened by external transverse CFRP [21].

A significant difference in the values of the coefficients of linear thermal deformation of FRP and steels determines the substantial effect of changes in operating temperatures on the stress state of cylindrical shells strengthened by such type of the external transverse reinforcement.

The results of numerical calculations (Fig. 1) that considered the change in the coefficient of FRP reinforcement $k_{f1(t)}$, obtained with excess of stresses $\Delta\sigma_{s+} = 1$ over the limiting value f_{yd} (yield strength of the shell material or the limiting stress value that is permissible from the fatigue conditions of the material of the joints of its non-reinforced structure) in different ranges of operating temperatures ΔT=*-40…+40℃*, indicate their multiple variability.

The presented calculation results considered the transverse reinforcement of steel shells, which had indicators of limiting the strength of the material $f_{yd} = 18...42 kN/cm^2$, by FRP that had different longitudinal resistances f_{fk}, made on the basis of different reinforcing fibers: E-glass fiber (Fig. 1,a: $f_{fk} = 200 kN/cm^2$, $E_f = 0{,}7 \times 10^4 kN/cm^2$, $\alpha_f = 5{,}0 \times 10^{-6} {}^\circ C^{-1}$), aramid fiber (Fig. 1,b: $f_{fk} = 380 kN/cm^2$, $E_f = 1{,}8 \times 10^4 kN/cm^2$, $\alpha_f = -2{,}0 \times 10^{-6} {}^\circ C^{-1}$), high strength – normal modulus carbon fiber (Fig. 1,c: $f_{fk} = 410 kN/cm^2$, $E_f = 2{,}4 \times 10^4 kN/cm^2$, $\alpha_f = -0{,}6 \times 10^{-6} {}^\circ C^{-1}$) and high modulus carbon fiber (Fig. 1,d: $f_{fk} = 240 kN/cm^2$, $E_f = 7{,}6 \times 10^4 kN/cm^2$, $\alpha_f = -1{,}45 \times 10^{-6} {}^\circ C^{-1}$). The calculation results corresponding to the case of abstraction from the influence of longitudinal deformations of metal shells are presented in the indicated graphs by solid lines and the results obtained in cases of taking them into account are represented by broken lines.

An analysis of the dependences of the coefficients of FRP reinforcement for conditional excesses of permissible stresses $k_{f1(t)}$ by operating temperatures ΔT indicates a general tendency for the influence these parameters by the elastic moduli of the used FRP, as well as the strength characteristics of the material of steel parts f_{yd} (the yield strength of steel or the limiting stress value determined by the fatigue condition). The characteristic influence of the temperature factor is determined by the condition of limiting the strength of metal shells: in the case of the using FRP based on various types of structural fibers, thermal deformations can repeatedly change the value of the considered coefficient in combination with steel shells that characterized by low material strength (Fig. 1, curves for $f_{yd} = 18 kN/cm^2$), while similar combinations with high-strength steels (Fig. 1, curves for $f_{yd} = 42 kN/cm^2$) practically neutralize the influence of temperatures.

It is also important that when considering the definition of coefficient $k_{f1(t)}$, the classical assumption about the possibility of abstracting from the effects of longitudinal deformations of steel shells (Fig. 1, curves shown with solid lines) turns out to be applicable only in certain cases when combining high-strength steel shells with predominantly high-modulus FRP external reinforcement in the temperature range ΔT=*0…+40℃*. Otherwise, failure to take into account the longitudinal deformation of steel shells leads to significant differences from calculations performed taking it into account (see Fig. 1, curves shown with broken lines).

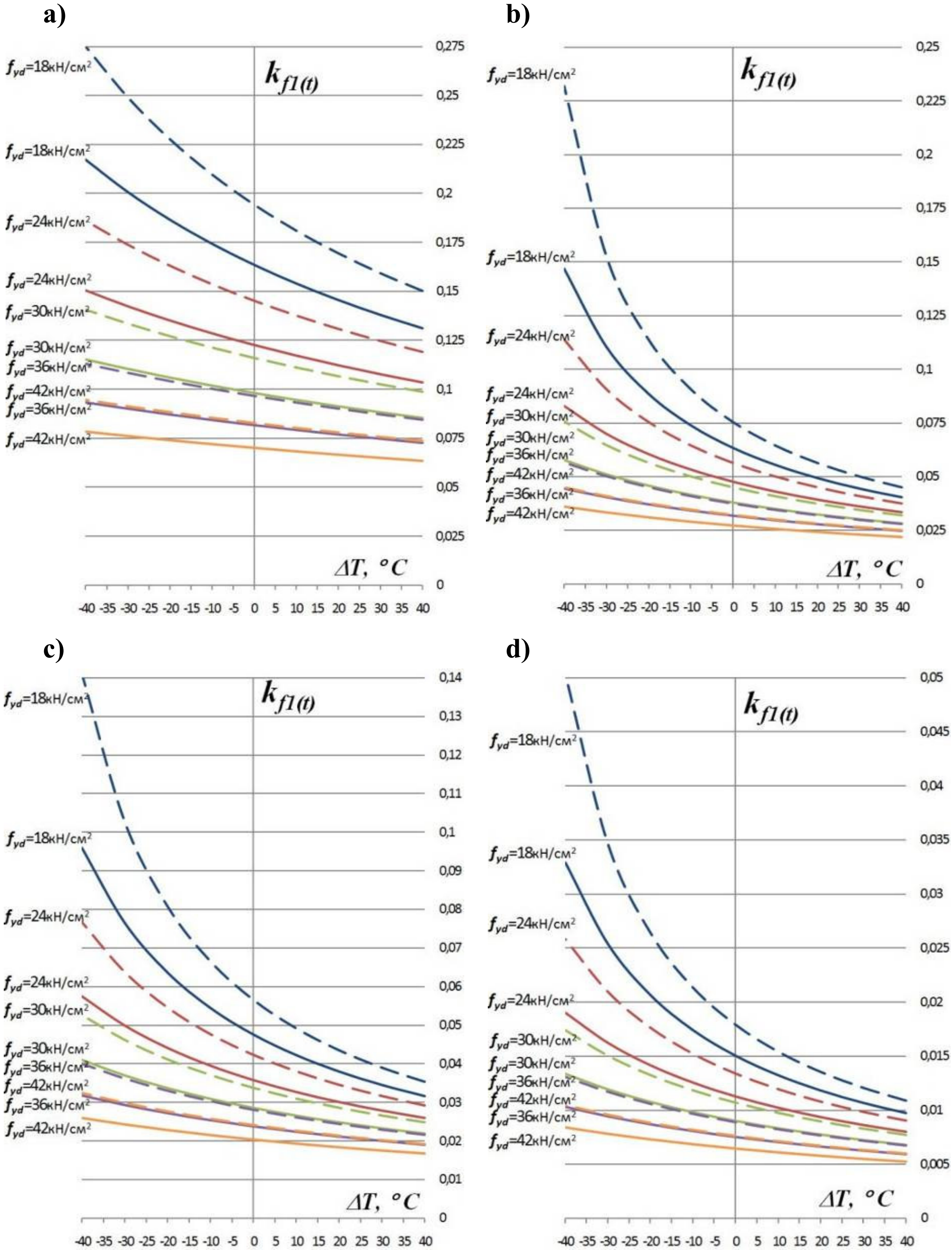

Fig. 1. The changes in the values of the coefficients of the required FRP reinforcement $k_{f1(t)}$ for a single excess of stress $\Delta\sigma_{s+} = 1$ over the limiting values f_{yd} in the operating temperature range ΔT=*-40…+40℃*

It should also be noted that from the point of view of the influence of mutual temperature deformations the relative inefficiency of using aramid fibers as part of complex structures that involve combination with low-strength steels of shells. Thus, even in the presence of an elastic modulus of some aramid FRP $E_{f-AFRP} = 1{,}8 \times 10^4 kN/cm^2$ two and a half times higher than the elastic modulus of E-fiber GFRP $E_{f-GFRP} = 0{,}7 \times 10^4 kN/cm^2$, taking into account a possible decrease in temperatures ΔT=*-40 ℃* these materials have comparable coefficients of external reinforcement $k_{f1(t)}$ (respectively Fig. 1,a and Fig. 1,b).

The dependences of the change in the values of the coefficients of external transverse FRP reinforcement $k_{f1(t)}$ by the strength parameter of the material of steel shells f_{yd} with the considered most unfavorable change in operating temperatures ΔT=*-40 ℃* are presented in Figure 2. The obtained indicators compared for FRP made on the basis of E-glass and S-glass fiber (Fig. 2,a, respectively: E- glass fiber $f_{fk} = 200 kN/cm^2$, $E_f = 0{,}7 \times 10^4 kN/cm^2$, $\alpha_f = 5{,}0 \times 10^{-6} {}^{\circ}C^{-1}$ and S-glass fiber $f_{fk} = 480 kN/cm^2$, $E_f = 0{,}9 \times 10^4 kN/cm^2$, $\alpha_f = 2{,}9 \times 10^{-6} {}^{\circ}C^{-1}$), aramid fiber (Fig. 2,b, $f_{fk} = 380 kN/cm^2$, $E_f = 1{,}8 \times 10^4 kN/cm^2$, $\alpha_f = -2{,}0 \times 10^{-6} {}^{\circ}C^{-1}$), as well as on the basis of high-strength (normal modulus) and high-modulus carbon fibers (Fig. 2,c, respectively: high strength (normal modulus) carbon fiber $f_{fk} = 410 kN/cm^2$, $E_f = 2{,}4 \times 10^4 kN/cm^2$, $\alpha_f = -0{,}6 \times 10^{-6} {}^{\circ}C^{-1}$ and high modulus carbon fiber $f_{fk} = 240 kN/cm^2$, $E_f = 7{,}6 \times 10^4 kN/cm^2$, $\alpha_f = -1{,}45 \times 10^{-6} {}^{\circ}C^{-1}$).

The given graphs (Fig. 2,a-c) emphasize the tendency of the determining influence on the reinforcement coefficient $k_{f1(t)}$ of the modulus of elasticity of FRP E_f, as well as the strength of the steel shells under consideration f_{yd}: with an increase in these indicators, a decrease in this coefficient is observed. At the same time, a sharp increase in the required degree of reinforcement is observed when the strength of the material of the steel bases of the shells is limited by a value of less than $f_{yd} = 18 kN/cm^2$. Not taking into account the influence of the factor of longitudinal deformations of the reinforced shells is justified only when combining high-modulus carbon FRP with a base material that has a strength index $f_{yd} = 24...42 kN/cm^2$ (Fig. 2,c).

A joint consideration of the dependencies obtained for various external reinforcement materials, taking into account the influence of longitudinal deformations of shells (Fig. 2,d), allows to conclude the efficiency of use of low-modulus (much cheaper [4, 12]) FRP for reinforcement structures with high strength characteristics of steel bases $f_{yd} \approx 30...42 kN/cm^2$. At the same time, for structures characterized by low steel strength limits $f_{yd} \approx 15...20 kN/cm^2$, effective external reinforcement is achieved only when using high-modulus FRP.

To assess the influence of an increase in the level of stresses on the value of the coefficient of the required transverse FRP reinforcement $k_{f(t)}$, it can be introduced a coefficient of stress excess in metal shells in the absence of corresponding reinforcement

$$k_{\Delta\sigma(s+)} = \frac{\Delta\sigma_{s+}}{f_{yd}} \quad , \tag{8}$$

where $\Delta\sigma_{s+}$ – conditional excess of stresses over the limiting value f_{yd} in the absence of external reinforcement.

In this case, consideration of the operation of complex structures strengthened with external transverse FRP reinforcement similar to adopted in Fig. 1, when the operating change of temperatures is ΔT=*-40 ℃*, allows us to obtain the dependencies presented in Figure 3 (E-fiber FRP – Figure 3,a, aramid FRP – Figure 4,b, high-strength carbon FRP – Figure 4,c and high-modulus carbon FRP – Figure 4,d; graphs obtained by abstracting from longitudinal deformations of metal shells are shown by solid lines, and when they are taken into account – by broken lines).

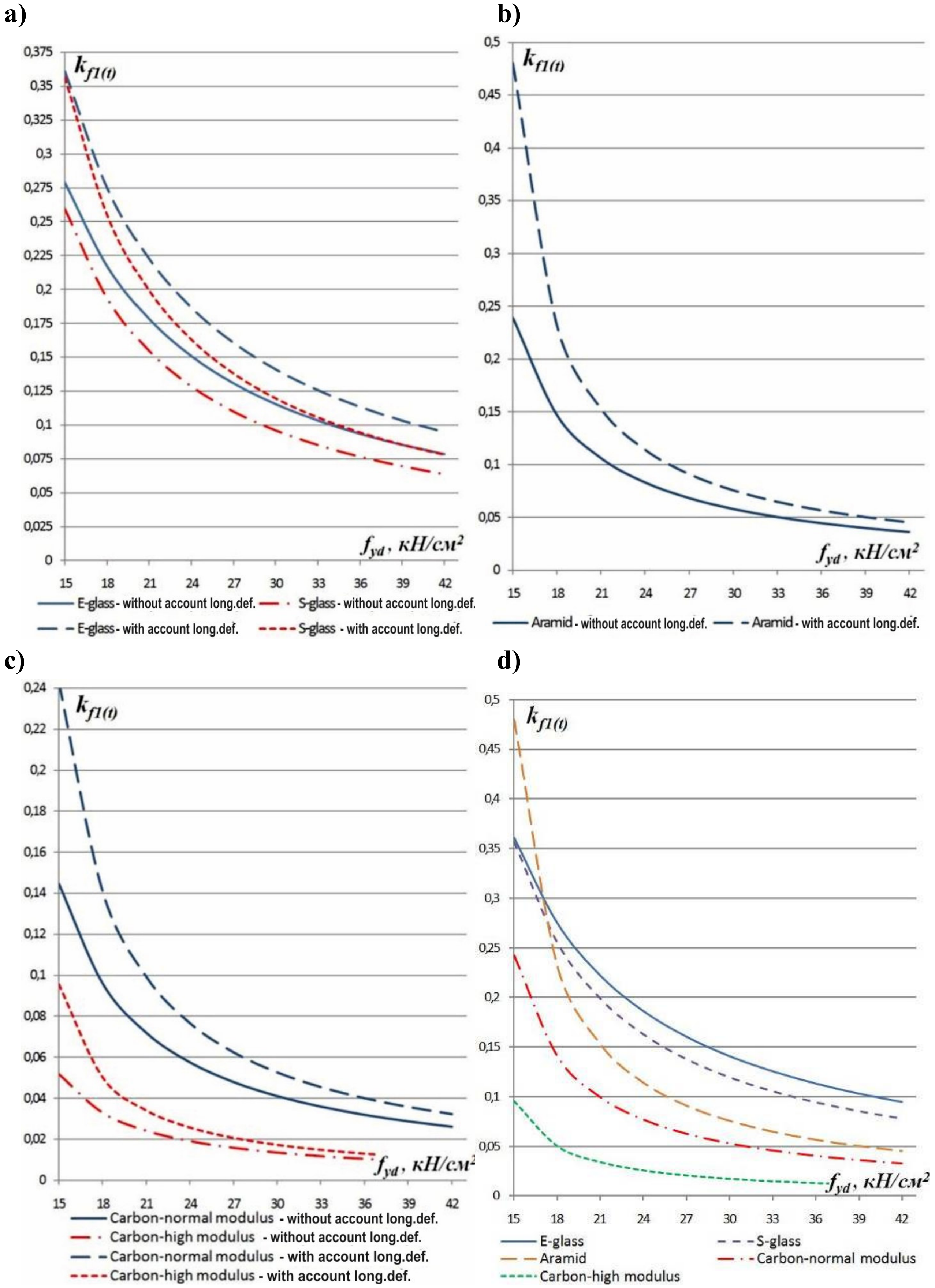

Fig. 2. The changes in the values of the coefficients of the required external transverse FRP reinforcement $k_{f1(t)}$ depending on the strength parameter of the steel shell f_{yd} at differences in operating temperatures ΔT=-40℃

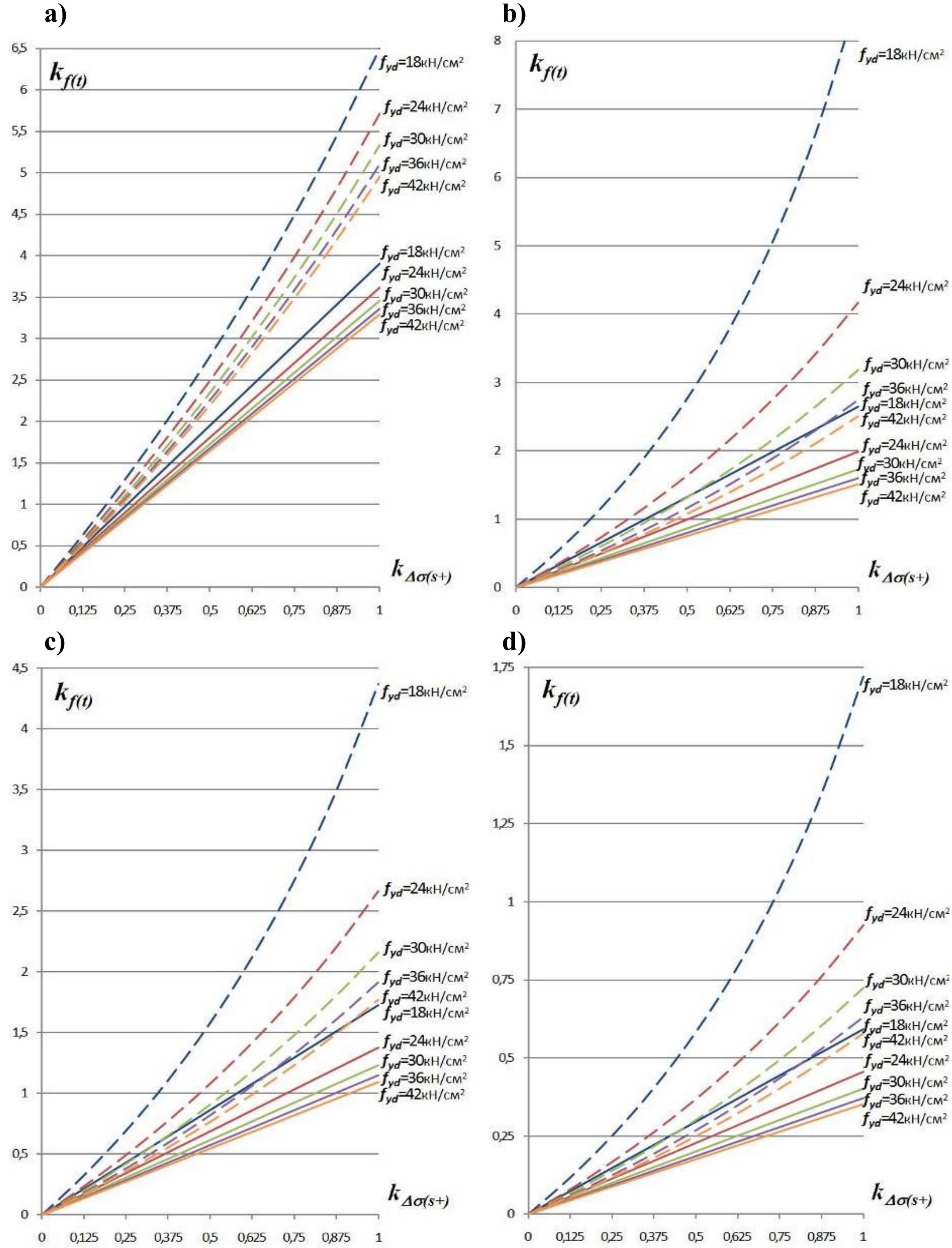

Fig. 3. The changes in the values of the coefficients of the required external transverse FRP reinforcement $k_{f(t)}$ depending on the coefficients of the degree of conditional stresses excess $k_{\Delta\sigma(s+)}$ and the strength parameter of steels f_{yd} at differences in operating temperatures ΔT=-40℃

Analysis of the obtained interdependencies indicates the applicability of abstracting from longitudinal deformations for metal shells under temperature changes $\Delta T=-40\,^{\circ}C$ only in cases of using high-modulus FRP in combination with high-strength steel bases with a range of coefficients $k_{\Delta\sigma(s+)} \leq 0{,}1$ that determine an insignificant degree of required external reinforcement. Otherwise, failure to take into account the factor of longitudinal deformations of shells under conditions of a significant decrease in operating temperatures leads to a substantial distortion of the calculation results. The greatest discrepancy between indicators $k_{f(t)}$ is achieved by combining high-modulus FRP, which demonstrate significant differences from steel in the coefficients of longitudinal thermal deformation, with low-strength bases of reinforced steel shells when it is necessary to endure significant additional forces, i.e. at $k_{\Delta\sigma(s+)} \geq 0{,}4$.

Conclusion

1. The mandatory factors to be taken into account for strengthening of the metal cylindrical shells by external transversely directed FRP reinforcement that perceives the actions of ring forces are the temperature deformations of the used FRP materials, as well as the longitudinal deformations of the metal components of complex walls.
2. The main factors determining the effectiveness of the obtained solutions are the residual strength of the material of the metal shells, as well as the modulus of elasticity of the used FRP.
3. In the case of the using FRP based on various types of structural fibers in combination with steel shells that characterized by low material strength, thermal deformations can repeatedly change the required degree of external reinforcement of structures, while similar combinations with high-strength steels can neutralize the influence of temperatures.
4. Under the influence of temperature deformations the FRP reinforcements made on the basis of aramid fibers demonstrate relative ineffectiveness in combination with shells characterized by low steel strength.
5. The effective use of low-modulus FRP can be achieved for reinforcements of the structures with high strength characteristics of steel bases of the shells $f_{yd} \approx 30...42 kN/cm^2$. At the same time, for structures characterized by low steel strength limits $f_{yd} \approx 15...20 kN/cm^2$, effective external reinforcement is achieved in combination with high-modulus FRP.

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ЕФЕКТИВНІСТЬ ПОСИЛЕННЯ КОРПУСІВ МЕТАЛЕВИХ ЦИЛІНДРИЧНИХ РЕЗЕРВУАРІВ ФІБРОПЛАСТИКОВИМ АРМУВАННЯМ НА ОСНОВІ ВОЛОКОН РІЗНОГО ТИПУ

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Анотація. Український парк металевих циліндричних резервуарів характеризується значним зносом несучих конструкцій, корозією елементів і втомою металу вертикальних з'єднань. Одним із рішень з відновлення втраченої несучої здатності конструкцій стінок резервуарів є зовнішнє армування поперечно направленими фібропластиковими системами. Використання цих систем також сприяє забезпеченню необхідної герметичність і антикорозійному захисту відповідних конструкцій. При цьому існуючі рекомендації щодо оцінки ефективності практичного використання різних типів фібропластикових матеріалів, які відрізняються параметрами міцності, а також силового та термічного деформування, є недостатніми стосовно посилення металевих циліндричних оболонок.

Представлена робота систематизує методику практичного визначення параметрів напруженого стану елементів металевих циліндричних оболонок, посилених зовнішнім поперечним фібропластиковим армуванням, а також визначає основні фактори, що впливають на ефективність використання фібропластиків на основі волокон різних типів у поєднанні зі сталями різної міцності.

Аналіз наведених теоретичних залежностей дозволяє зробити висновок, що обов’язковими факторами, необхідними для урахування при посиленні металевих циліндричних оболонок зовнішнім поперечним фібропластиковим армуванням, яке сприймає дію кільцевих зусиль, є температурні деформації відповідних фібропластикових матеріалів, а також поздовжні деформації металевих складових комплексних конструкцій.

Основними факторами, що визначають ефективність отриманих рішень, є залишкова міцність матеріалу металевих оболонок та модуль пружності використаних фібропластиків. Вплив термічних деформацій може багаторазово змінювати необхідний ступінь зовнішнього армування конструкцій у разі використання фібропластиків на основі різних типів конструкційних волокон у поєднанні зі сталевими оболонками, що характеризуються низькою міцністю матеріалу, одночасно аналогічні комбінації з високоміцними сталями можуть нейтралізувати подібний вплив температур.

Ефективне використання низькомодульних фібропластиків може бути досягнуто для армування конструкцій з високими характеристиками міцності сталі. Для конструкцій, що характеризуються низькою міцністю сталі, ефективне зовнішнє армування досягається в поєднанні з високомодульним фібропластиками.

Слід зазначити, що вплив температурних деформацій призводить до відносної неефективність зовнішнього армування на основі арамідних волокон у поєднанні з оболонками, які характеризуються низькою міцністю сталі.

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