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EXPERIMENTAL STUDIES OF ELEMENTS OF METAL CYLINDRICAL STRUCTURES STRENGTHENED BY EXTERNAL TRANSVERSAL CFRP REINFORCEMENT

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Abstract. One of the modern ways to increase the bearing capacity of the walls of metal cylindrical structures that perceive the action of internal pressure is the external transversely directed reinforcement by fiber reinforced plastics (FRP), the most effective type of which is made from carbon fibers (CFRP).

Consideration of metal cylindrical shells, which perceive the action of internal pressure and are reinforced with external transversely directed FRP reinforcement, makes it possible to obtain the values of the stress state parameters of the corresponding structures. At the same time, analytical methods for estimating these parameters do not have the necessary experimental justification.

In this connection, experimental studies of the stress state of elements of models of metal cylindrical structures externally reinforced with transversely directed FRP based on *high strength* and *high modulus carbon* fibers were carried out. The results of tests, including taking into account variable operating temperatures, are presented in this paper in comparison with the conclusions of the previously proposed practical methods of the corresponding analytical assessment.

The paper substantiates the applicability of applied analytical methods for determining the parameters of the stress state in the elastic stage of deformation of the elements of the complex walls of metal cylindrical shells externally reinforced with transversely directed FRP elements made on the basis of *normal modulus* and *high modulus carbon* fibers.

Key words: metal cylindrical structures, external transverse reinforcement, FRP systems of external reinforcement, experimental studies.

Introduction. One of the modern ways to increase the bearing capacity of the walls of metal cylindrical structures that perceive the action of internal pressure is the external transversely directed reinforcement by fiber reinforced plastics (FRP), the most effective type of which is made from carbon fibers (CFRP) [1-3].

This method of increasing the bearing capacity of the walls of cylindrical shells can be used both in the manufacture of new structures with reduced weight characteristics, and for the rehabilitation and restoration of existing cylindrical structures, the bearing capacity of the shells of which is reduced due to long service life. The presence of external transverse FRP reinforcement makes it possible to reduce the level of internal ring stresses acting in the metal bases of the walls of these structures, which is most important in the case of reduced values of the design resistances of the base material and the joints of elements, often characterized by fatigue. It is theoretically possible to carry out the installation of external FRP reinforcement of metal cylindrical structures including the cases of presence of internal pressure in them. The degree of effectiveness of this reinforcement can be increased by using the installation methods that provide prestressing [4, 5].

Existing theoretical base. Consideration of metal cylindrical structures that perceive the action of excessive internal pressure and are reinforced by external transversely directed reinforcement, based on the classical theory of the operation of thin-walled shells, makes it possible to obtain the values of internal stresses both in the elements of the shells and in the external transverse reinforcement [6, 7].

The presence of significant differences in the characteristics that determine possible multiple differences in the strength, elasticity and thermal deformation of building steels and various types of structural FRP forces to make clarifications [3, 4, 8] in the classical engineering methods of definition, which are mostly abstracted from these differences in favor of simplifying the final applied dependencies. At the same time, the most significant factors affecting the results of determining the parameters of the stress state of the walls of these complex structures are differences in the elastic modules and coefficients of linear thermal deformation of the materials used, as well as the significant effect of longitudinal deformation of reinforced metal shells in such combinations of materials [8].

Solutions that are consisting in the external transverse reinforcement of metal cylindrical structures, carried out using high-strength steel wires and tapes, which have close values of elastic and temperature-strain characteristics, are distinguished by the presence of the necessary experimental validation of existing engineering practices for determining the stress state parameters [6, 7]. With respect to the methods that are applicable for similar external reinforcement performed by using FRP in general, as well as CFRP in particular, there is no such experimental validation, which hinders the appropriate implementation.

The purpose of the work is an experimental validation of an practical method for determining the parameters of the stress state in the elastic stage of deformation of thin-walled metal cylindrical shells reinforced with external transverse FRP [4, 8] in relation to the case of using *high strength* and *high modulus* CFRP.

Research methodology. To solve the problem, experimental studies were carried out for determining the change in the parameter of the ring strain with an increase in internal pressure in metal cylindrical elements reinforced with external transverse FRP reinforcement made using structural unidirectional tapes based on *high strength* and *high modulus* carbon fiber materials. The reinforcement by CFRP was carried out with the placement of structural tapes in one and several layers without prestressing and in the absence of initial internal pressure in the experimental samples. The studies were carried out taking into account the effect of constant and variable operating temperatures.

The tested specimens were characterized by ratios of the radii of cylindrical curvature to the thickness of the metal walls, not less than 20 units (i.e. $r/t_s > 20$), which allows to consider their stress state related to thin-walled cylindrical shells. The reinforcing tapes were installed in the operational position by winding on the cylindrical surface with the deviation of the fibers from the direction transverse to the axes of the samples by no more than 5°, which makes it possible to conditionally consider the reinforcement as transversely directed [9, 10].

The theoretical values of the researched ring strain in the elastic stage of deformation in the metal components of the complex walls of the considered cylindrical metal shells, reinforced with transversely directed FRP reinforcement, that was installed without prestressing in the absence of initial internal pressure, were determined in accordance with the dependence that was following from [4, 8]:

$$\varepsilon_s = \frac{1}{E_s} \frac{N_{s(x,z)} - t_f \cdot E_f \cdot \Delta T \cdot \Delta\alpha}{t_s + t_f \left(E_f / E_s\right)}, \tag{1}$$

where $N_{s(x,z)} = \Delta P \cdot r\left[1 + \left(E_f / E_s\right)\left(t_f / t_s\right)\left(\mu/2\right)\right]$ – conditional ring force per unit section of the steel layer of the wall, arising from internal pressure ΔP and determined taking into account the combined action of ring and longitudinal strains in the steel part of the structure; t_s, t_f – respectively, the calculated thicknesses of the steel and FRP components of the complex wall of the cylindrical shell; E_s, E_f – respectively, the modules of elasticity of steel and FRP reinforcement; ΔT – the temperature change in all layers of complex wall; $\Delta\alpha = \alpha_s - \alpha_f$ – the difference between the coefficients of linear thermal deformation of steel and the layer of reinforcing FRP; μ – Poisson's ratio of the material of the steel component of the wall; r – radius of cylindrical curvature of the metal shell.

The determination of the theoretical reduced thickness of the FRP reinforcement, taking into account the uneven distribution of forces in the composition of multilayer FRP elements made by *high strength* and *high modulus* carbon fiber structural tapes, was carried out taking into account the coefficients of uneven functioning strains k_i described in [11-13] and establishing the degree of loading of the considered layers of this material , i.e.

$$t_f = \frac{t_{f1}}{n}\sum_{i=1}^{n} k_i \, , \qquad (2)$$

where $n = 1...5$ – the number of monolayers in the equal thickness of reinforcing FRP; t_{f1} – physical thickness of an single monolayer of reinforcing fiber; k_i – coefficients of non-uniform loading of layers, equal for *high strength* (*normally modular*) CFRP $k_1 = 1{,}0$, $k_2 = 0{,}73$, $k_3 = k_4 = k_5 = 0{,}17$, and for *high modulus* CFRP $k_1 = 1{,}0$, $k_2 = 0{,}78$, $k_3 = k_4 = k_5 = 0{,}56$ (Fig. 1).

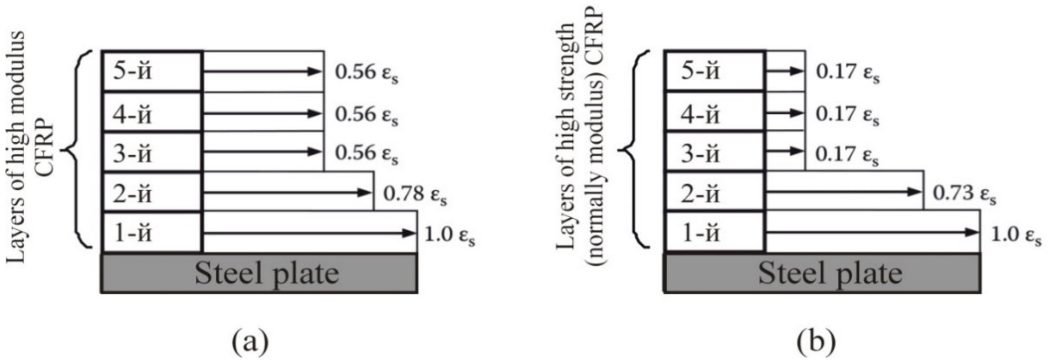

Fig. 1. Distribution of strains in CFRP reinforcement systems of steel elements: a – using *high modulus* carbon fibers, b – using *high strength* (*normal modulus*) carbon fibers [11]

As experimental samples imitating thin-walled cylindrical shells that have undergone external transverse FRP reinforcement, the following were used:

- welded steel pipes with an inner diameter of 150.0 ± 0.1 mm, a wall thickness of 3.0 ± 0.1 mm ($r/t_s = 25 > 20$) and a length of 1200 mm, to the ends of which were welded steel plates of 12 mm thickness, the mark of used steel was *C245* according to *ДСТУ 8539:2015* (Fig. 2, a);
- welded steel cylinders with an outer diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm ($r/t_s = 49{,}3 > 20$), with a volume of 50 liters, intended for liquefying hydrocarbon gases at a pressure of up to 1.6 MPa, corresponding to *ДСТУ ISO 10462:2019* and made of *Cm3cn* steel (Fig. 2, b).

External transverse FRP reinforcement of experimental samples was carried out by systems consisting of:

- normally modular carbon fiber fabric *SikaWrap-230C*, characterized by a monolayer thickness of 0.131 mm, an elastic modulus E_f = 2.38 × 10^4 kN/cm^2 and a tensile strength of 430 kN/cm^2, a 2-component thixotropic epoxy adhesive *Sikadur-330* was used as a matrix;
- high modulus carbon fiber fabric *MapeWrap C UNI-AX HM*, characterized by a monolayer thickness of 0.329 mm, an elastic modulus E_f = 3.90 × 10^4 kN/cm^2 and a tensile strength limit of 441 kN/cm^2, a 2-component epoxy-based adhesive *MapeWrap 31* was used as a matrix resin of medium viscosity.

(a)

(b)

Fig. 2. Experimental samples made of: a – welded pipes with an inner diameter of 150.0 ± 0.1 mm, wall thickness of 3.0 ± 0.1 mm ($r/t_s = 25 > 20$), b – welded steel cylinders with an outer diameter of 299.0 ± 0.1 mm, wall thickness 3.0 ± 0.1 mm, *ДСТУ ISO 10462:2019* ($r/t_s = 49{,}3 > 20$)

The technology of the FRP reinforcement was corresponded to the recommendations of the manufacturers of these systems.

The loading of the tested samples was carried out by creating an internal hydraulic pressure, the stepwise increase of which was provided by the supply of water through hydraulic valves from the intermediate high-pressure leveling tank, into which the liquid was pre-injected by a high-pressure pumping unit. The control of the internal pressure values was provided by replaceable manometers of various working pressures.

The registration of the values of ring strains and the corresponding stresses of the metal parts of the reinforced walls was carried out by the tensoresistoring method in the middle of the height of the tested samples. The readings of the strain gauges were calibrated in accordance with ones obtained during preloading of the samples, which was carried out before the installation of FRP, and compared with the "reference" values of the annular elastic relative strains of their steel cylindrical shells, equal to

$$\varepsilon_s = \frac{1}{E_s}\frac{\Delta P \cdot r}{t_s}. \tag{3}$$

Further transition to the desired values of the ring stresses of the metal elements of the reinforced walls of the tested samples was carried out in accordance with the condition of elastic deformation

$$\sigma_s = E_s \varepsilon_s. \tag{4}$$

Results of the research.

1. *Experimental specimens made of steel welded pipes* with an internal diameter of 150.0 ± 0.1 mm, wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP reinforcement with the normally modular *SikaWrap-230C* system installed in 1 and 2 layer, were characterized by the coefficients of external reinforcement of the walls, which were respectively $k_f = (t_f / t_s) \times 100\% = 4.37\%$ and $k_f = 8.73\%$, providing a theoretical increase in the bearing capacity in comparison with unreinforced samples, which were 4.08% and 6.82%, respectively.

The results of experimental studies of the ring strains of the metal component of the complex walls of these samples, obtained during tests carried out without taking into account changes in operating temperatures, are presented in Figures 3 and 4 in comparison with theoretical values corresponding to unreinforced (3) and reinforced by CFRP samples (1).

2. *Experimental samples made from steel welded cylinders* with an outer diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP reinforcement with a normally modular *SikaWrap-230C* system installed in 1 and 2 layer, were characterized by the coefficients of external reinforcement of the walls, which were respectively $k_f = 4.37\%$ and $k_f = 8.73\%$, providing a theoretical increase in the bearing capacity in comparison with unreinforced samples, which were 4.08% and 6.82%, respectively.

The results of experimental studies of the ring strains of the metal component of the complex walls of these samples, obtained during tests carried out without taking into account changes in operating temperatures, are presented in Figures 5 and 6 in comparison with theoretical values corresponding to unreinforced (3) and reinforced by CFRP samples (1).

3. *Experimental specimens made of steel welded cylinders* with an outer diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP reinforcement with the high modulus *MapeWrap C UNI-AX HM* system installed in 1 and 2 layers, were characterized by the coefficients of external reinforcement of the walls, which were respectively $k_f = 10.97\%$ and $k_f = 21.93\%$, providing a theoretical increase in the bearing capacity in comparison with unreinforced samples, which were 14.61% and 22.94%, respectively.

The results of experimental studies of the ring strains of the metal component of the complex walls of these samples, obtained during tests carried out without taking into account changes in operating temperatures, are presented in Figures 7 and 8 in comparison with theoretical values corresponding to unreinforced (3) and reinforced by CFRP samples (1).

Similar experimental results, comparable to the theoretical ones, obtained during testing of the samples reinforced with 1 layer of reinforcement and experiencing additional thermal stresses determined by heating the supplied liquid, respectively, by +25°C and +36°C, are shown in Figures 9 and 10. At the same time, the theoretical values of additional thermal stresses were –1.05 kN/cm^2 and –1.51 kN/cm^2, respectively.

Experimental results, comparable to theoretical ones, obtained during testing of a sample reinforced with 2 layers of reinforcement and experiencing additional thermal stresses determined by heating the supplied liquid by +24°C, are shown in Figure 11. The theoretical value of additional thermal stresses in this case was –1.58 kN/cm^2.

The comparison of the analytical dependencies consequent to (1) and determining the elastic ring strains of the metal components of the complex walls of the cylindrical shells, with the results of experimental studies of this parameter (Fig. 3-11), indicates their practical correspondence.

Conclusion. The obtained results of experimental studies substantiate the validity of using the applied method for determining the parameters of the stress state of the elements of the complex walls of metal cylindrical shells externally reinforced by transversely directed FRP elements [4, 8], made on the basis of normally modular and high modulus carbon fibers with reinforcement coefficients of 4.4 ... 22.0%, and variable temperature operating conditions.

The needed further research. Further experimental substantiation requires the application of the considered method of applied theoretical determination of the parameters of the stress state of elements of metal cylindrical structures reinforced by transverse FRP in relation to reinforcing elements of various thicknesses made of materials based on glass and aramid fibers.

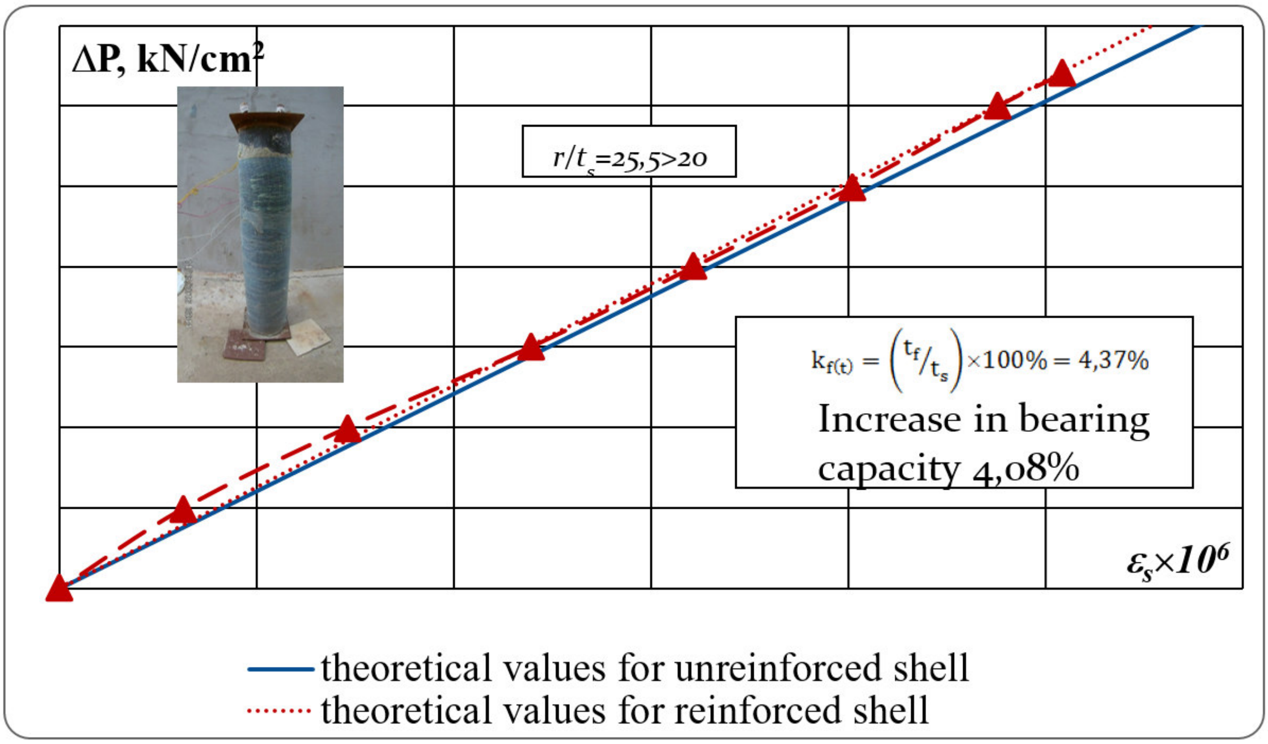

Fig. 3. The dependences of the ring strains ε_s on the internal pressure *ΔP* in a steel cylindrical shell with an inner diameter of 150.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *SikaWrap-230C* system installed in 1 layer

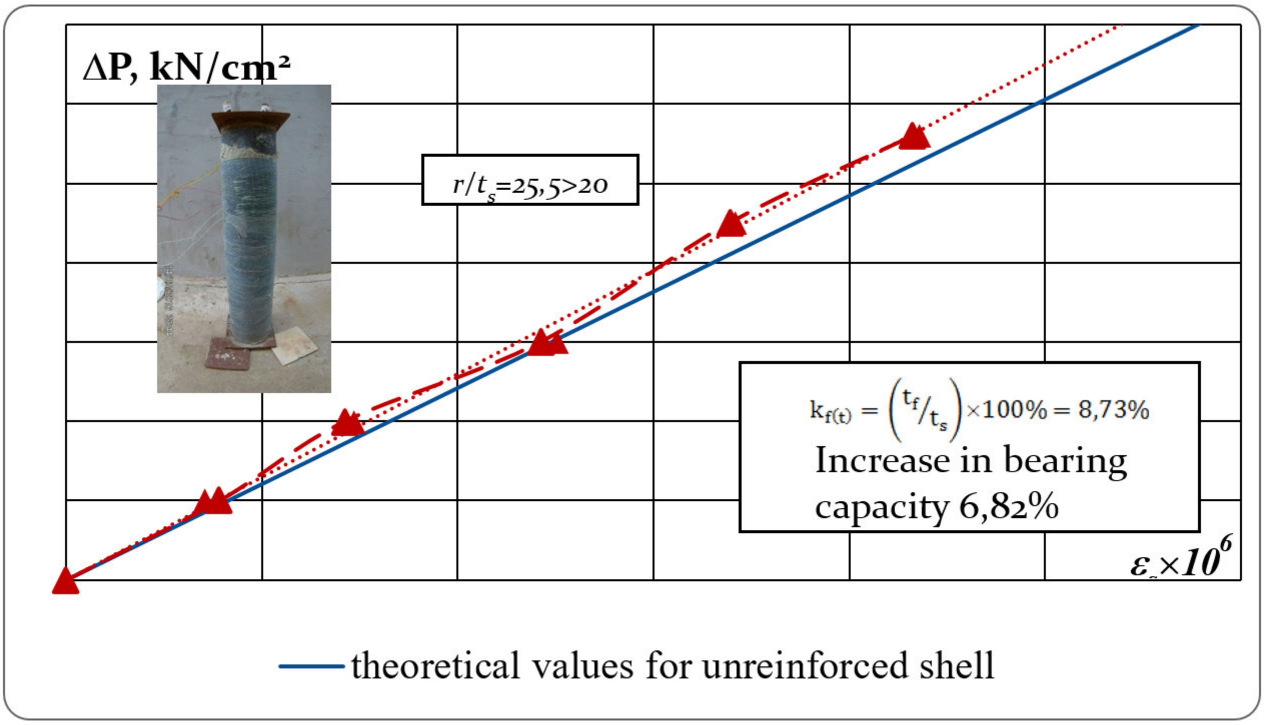

Fig. 4. The dependences of the ring strains ε_s on the internal pressure *ΔP* in a steel cylindrical shell with an inner diameter of 150.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *SikaWrap-230C* system installed in 2 layers

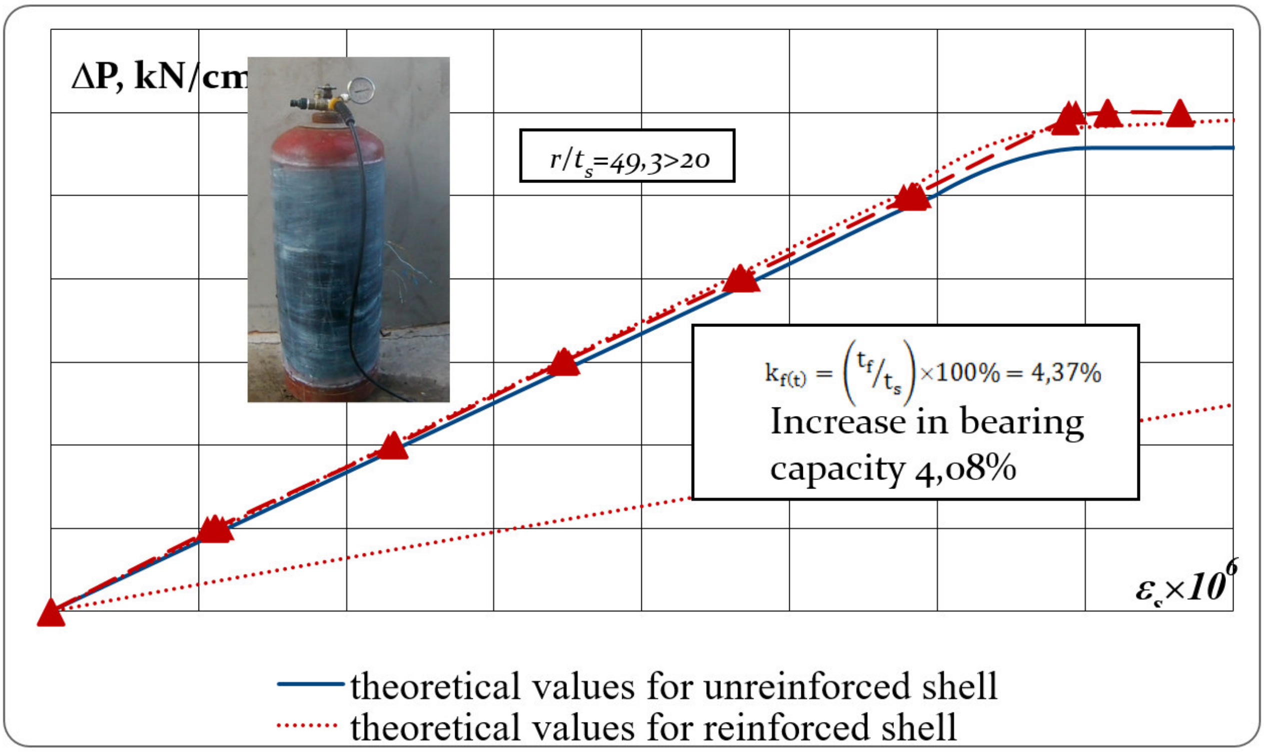

Fig. 5. The dependences of the ring strains ε_s on the internal pressure ΔP in a steel cylindrical shell with an inner diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *SikaWrap-230C* system installed in 1 layer

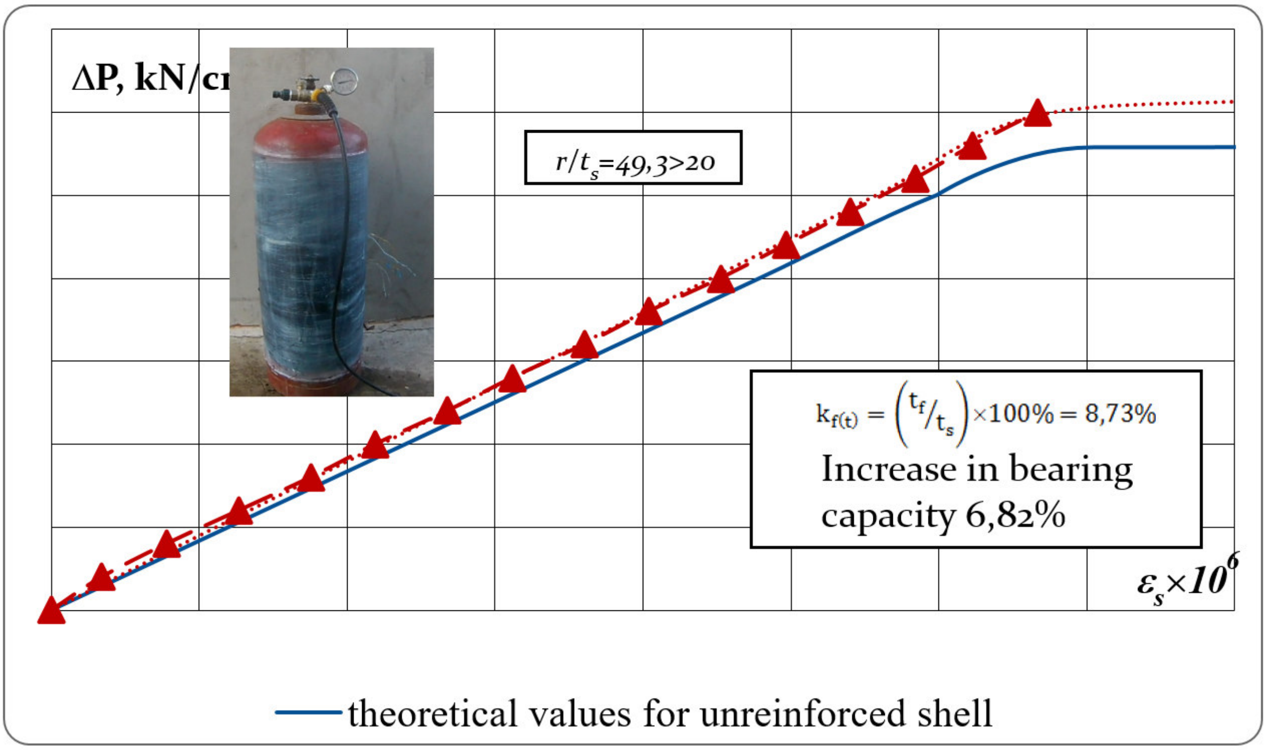

Fig. 6. The dependences of the ring strains ε_s on the internal pressure ΔP in a steel cylindrical shell with an inner diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *SikaWrap-230C* system installed in 2 layers

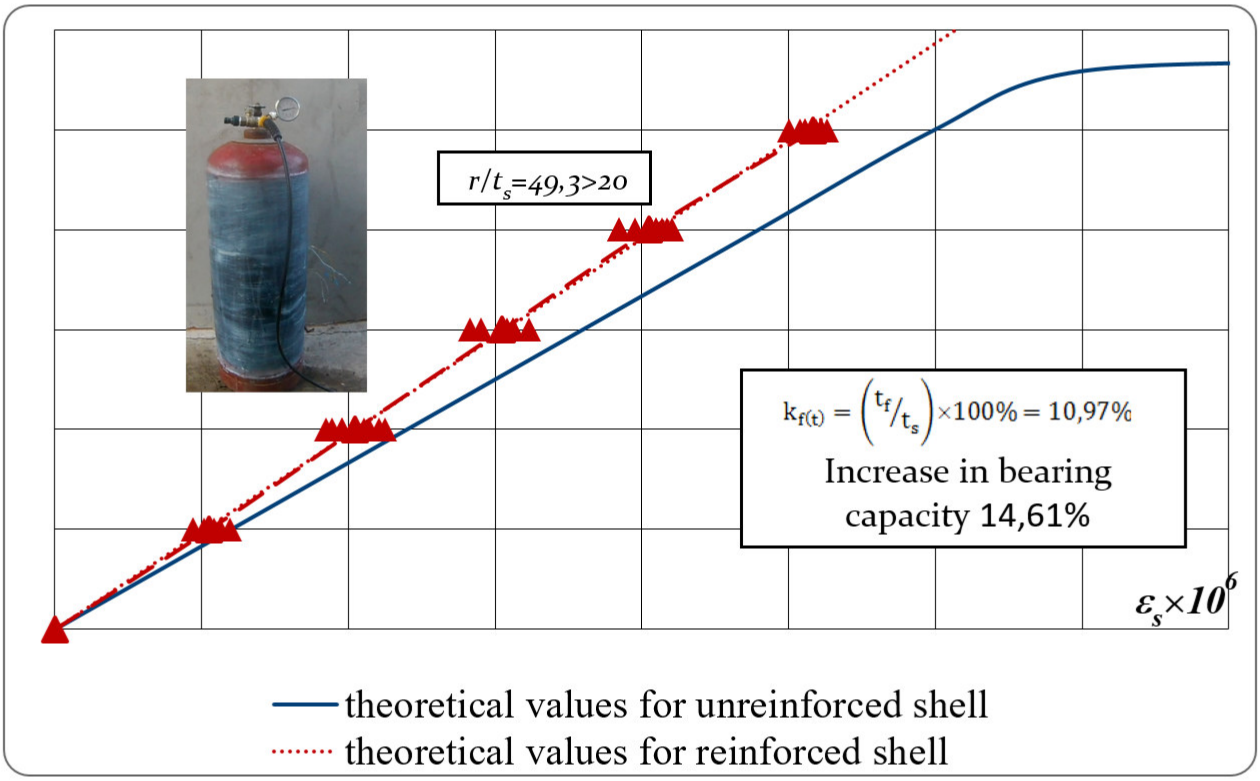

Fig. 7. The dependences of the ring strains ε_s on the internal pressure ΔP in a steel cylindrical shell with an inner diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *MapeWrap C UNI-AX HM* system installed in 1 layer

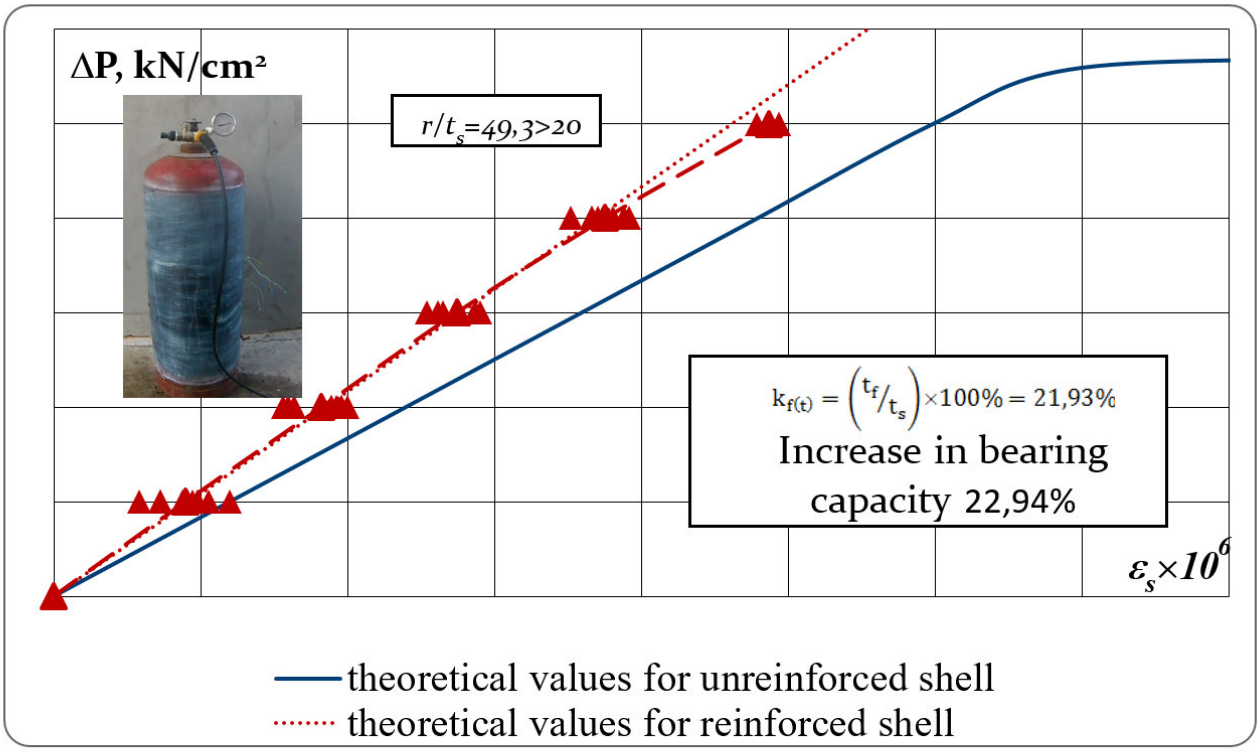

Fig. 8. The dependences of the ring strains ε_s on the internal pressure ΔP in a steel cylindrical shell with an inner diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *MapeWrap C UNI-AX HM* system installed in 2 layers

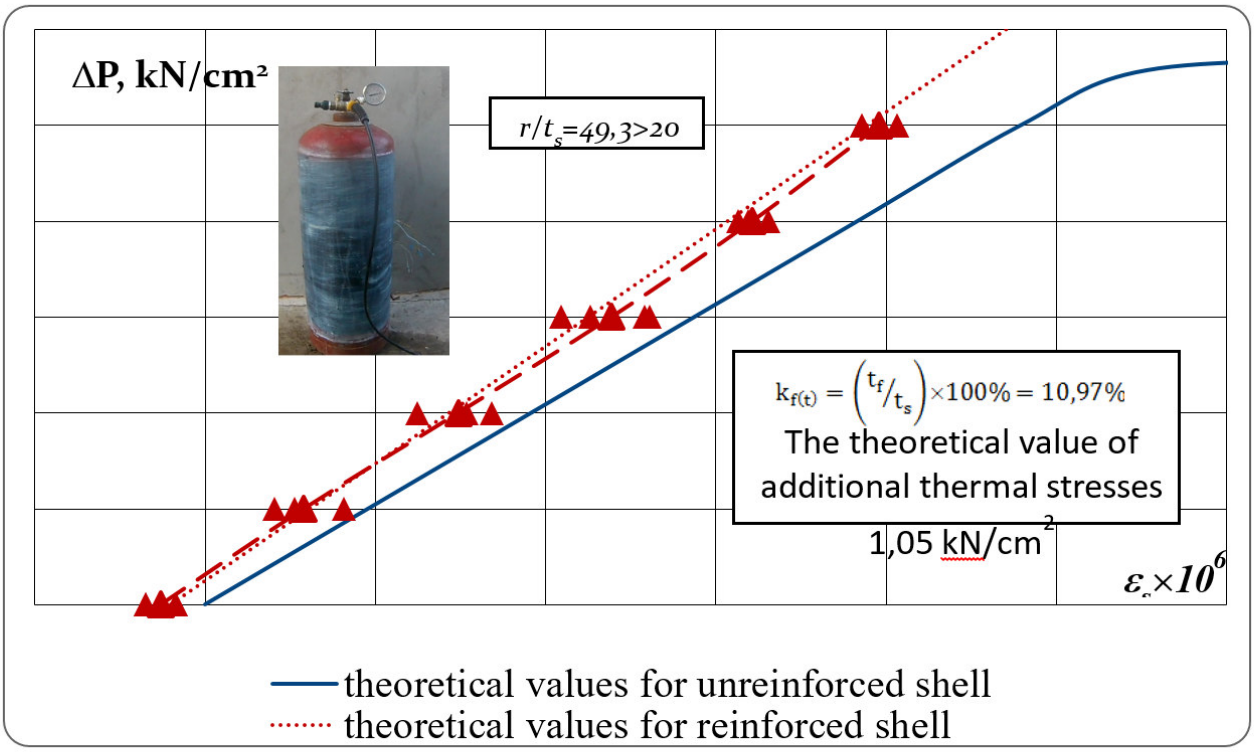

Fig. 9. The dependences of the ring strains ε_s on the internal pressure ΔP, obtained with a change in operating temperature by +25°C in a steel cylindrical shell with an inner diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *MapeWrap C UNI-AX HM* system installed in 1 layer

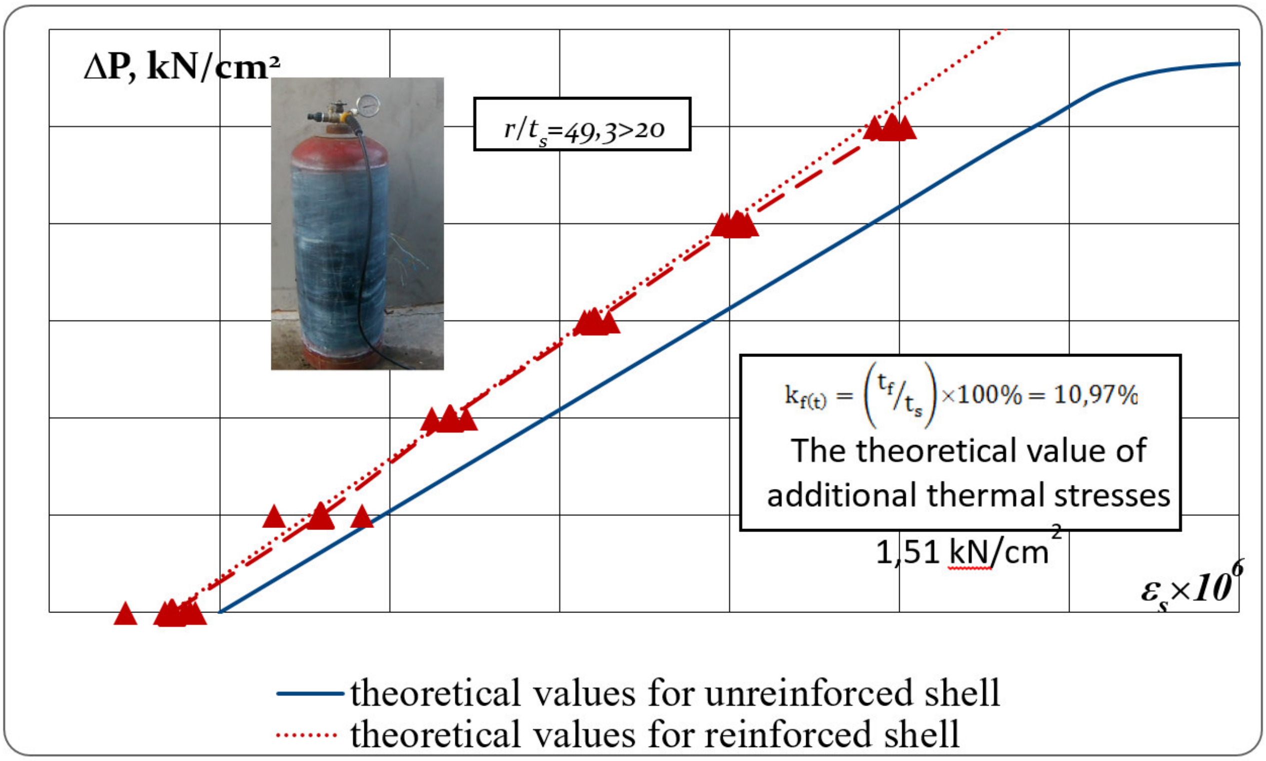

Fig. 10. The dependences of the ring strains ε_s on the internal pressure ΔP, obtained with a change in operating temperature by +36°C in a steel cylindrical shell with an inner diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *MapeWrap C UNI-AX HM* system installed in 1 layer

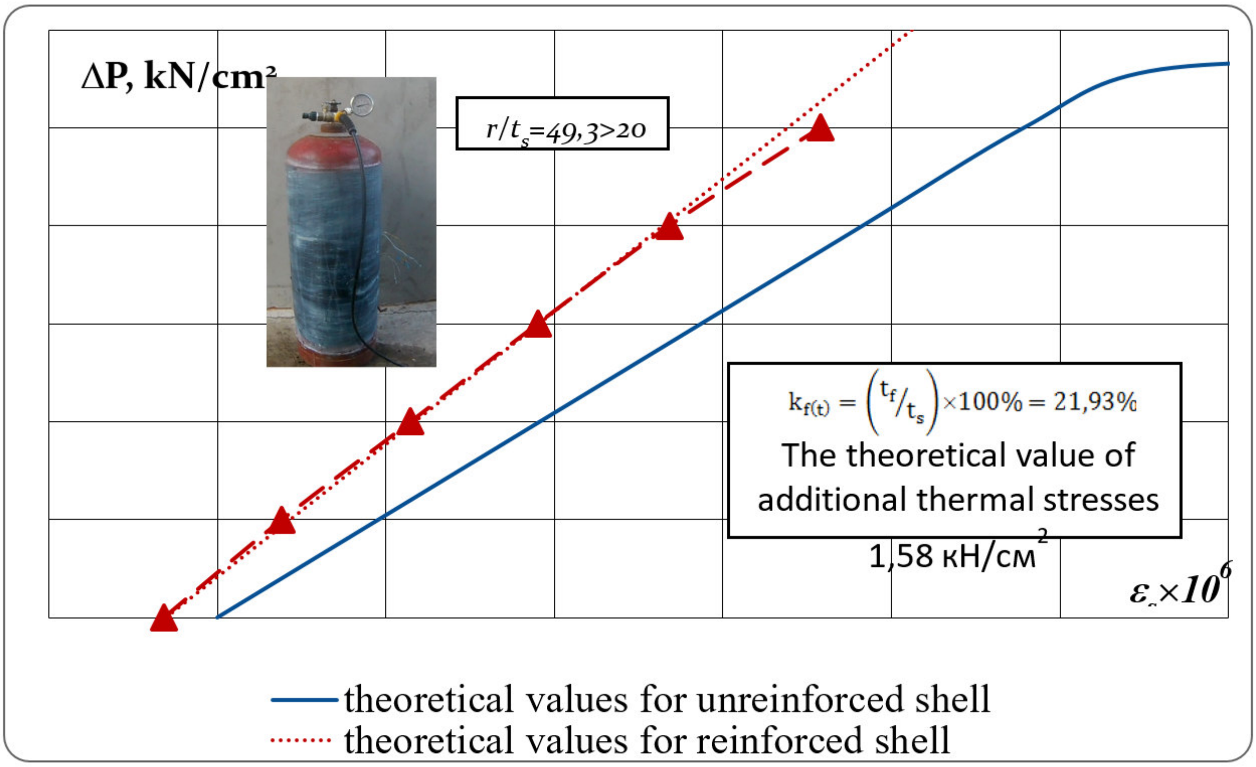

Fig. 11. The dependences of the ring strains ε_S on the internal pressure ΔP, obtained with a change in operating temperature by +24°C in a steel cylindrical shell with an inner diameter of 299.0 ± 0.1 mm and a wall thickness of 3.0 ± 0.1 mm, reinforced by external transverse FRP of the *MapeWrap C UNI-AX HM* system installed in 2 layers

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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ЕЛЕМЕНТІВ МЕТАЛЕВИХ ЦИЛІНДРИЧНИХ КОНСТРУКЦІЙ, ПОСИЛЕНИХ ЗОВНІШНІМ ПОПЕРЕЧНИМ ВУГЛЕЦЕВО-ПЛАСТИКОВИМ АРМУВАННЯМ

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Анотація. Одним із сучасних способів підвищення несучої здатності стінок металевих циліндричних конструкцій, що сприймають дію внутрішнього тиску, є зовнішнє поперечно спрямоване фібропластикове (FRP) армування, найбільш ефективним видом якого є армування на основі вуглецевих матеріалів (CFRP).

Розгляд металевих циліндричних оболонок, що сприймають дію внутрішнього тиску та посилених зовнішнім поперечно спрямованим FRP армуванням, дозволяє отримати величини параметрів напруженого стану відповідних конструкцій. При цьому аналітичні методи оцінки даних параметрів не мають необхідного експериментального обґрунтування.

У зв'язку з вказаним, були здійснені експериментальні дослідження напруженого стану елементів моделей металевих циліндричних конструкцій, зовнішньо армованих поперечно спрямованими фібропластиковими матеріалами на основі *високоміцних* та *високомодульних* вуглецевих волокон. Результати випробувань, здійснених, у тому числі, і з урахуванням змінних температур експлуатації, наводяться у цій роботі у порівнянні з висновками запропонованих раніше прикладних методів відповідної аналітичної оцінки.

Робота обґрунтовує застосування прикладних аналітичних методів визначення параметрів напруженого стану в пружній стадії деформування елементів комплексних стінок металевих циліндричних оболонок зовні армованих поперечно спрямованими фібропластиковими елементами, виготовленими на основі *нормальномодульних* і *високомодульних* вуглецевих волокон.

Ключові слова: металеві циліндричні конструкції, зовнішнє поперечне армування, фібропластикові системи зовнішнього армування, експериментальні дослідження.