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

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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).

The solutions that are consisting in the external transverse reinforcement of metal cylindrical structures, carried out using high-strength steel wires and tapes, are distinguished by the presence of the necessary experimental validation of existing engineering practices for determining the stress state parameters. With respect to the methods that are applicable for similar external reinforcement performed by using FRP there is no such experimental validation, which hinders the appropriate implementation.

The purpose of the studies 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 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 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

$$\varepsilon_S = \frac{1}{E_S} \frac{N_{S(x,z)} - t_f \cdot E_f \cdot \Delta T \cdot \Delta\alpha}{t_S + t_f \left(E_f / E_S \right)},$$

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; 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 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 by Xiao-Ling Zhao and establishing the degree of loading of the considered layers of this material , i.e.

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

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 $k_1 = 1{,}0$, $k_2 = 0{,}78$, $k_3 = k_4 = k_5 = 0{,}56$.

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*;
– 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 *Ст3сп* steel.

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.

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 comparison of the analytical dependencies that 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, 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, 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.