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DEFORMATION OF THREADED METAL – COMPOSITE COUPLINGS UNDER THE ACTION OF GAS-DYNAMIC LOADS

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The combination of metal and composite in threaded couplings increases the reliability of the structure operating under conditions of intensive internal pressure. Strength analysis of threaded metal – composite couplings based on the application of modern finite element modeling methods at the stage of design documentation development allows to create more efficient structures that better meet the operational requirements. The strength of threaded couplings of cylindrical shells made of composite material and metal under the action of gas-dynamic internal pressure is analyzed in this paper. A methodology for numerical study of the problem in Ansys / Explicit Dynamics software package is proposed. Detailed modeling of threaded couplings is used. The developed model takes into account the following: dependence of material properties on ambient temperature; nonlinear relations between the components of stress and strain tensors in metal elements, orthotropic properties of composite materials; peculiarities of contact interaction in the zones of threaded couplings of prefabricated shell elements made of different materials. The stress state of a cylindrical structure with a central shell made of carbon fiber-reinforced plastic or fiberglass and with steel shells at the edges, loaded with gas-dynamic internal pressure with a maximum value of 20 MPa at a maximum ambient temperature of 100 °C was studied. It was obtained that plastic deformations are concentrated on the edges of the threaded couplings of steel shells. At the same time, the magnitude of plastic coupling deformations with the inner metal shell is an order of magnitude higher than for couplings with the outer metal shell. The magnitude of plastic deformations in couplings with an inner metal shell is twice less when using fiberglass than when using carbon fiber reinforced plastic. Localization of critical stresses was observed only in metal shells at threaded couplings. In this case, in the thread zone they are within the elasticity limits, and the stress state of the FRP shell is not critical. No local material failure was observed in the structure.

***Keywords**: threaded coupling, load distribution, cylindrical shell construction, friction, FEM.*

Introduction

In modern industry, individual elements of hull structures are increasingly made of composite materials: carbon fiber, fiberglass, or multilayer with honeycomb structure made of polylactic acid [1–3]. These elements often have the form of cylindrical shells: tubular structures in the power and automotive industries, rocket bodies in the aerospace industry. The replacement of load-bearing parts of the metal hull with composite shells is due to a number of key factors: a significant reduction in the weight of structures, resistance to corrosion, aggressive environments, and thermal influences [4]. This creates the need for high-quality and reliable connection of metal and composite parts in the structure with threaded couplings. In view of the above, the assessment of the strength of threaded couplings for shells loaded with rapidly changing internal pressure operating at high temperatures becomes particularly relevant. In this case, the use of an adhesive coupling does not always ensure the integrity of the structure in conditions of high ambient temperature under intense internal loading [5]. At the same time, the combination of metal and composite in threaded couplings increases the reliability of structures operating under conditions of intense internal pressure. Analysis of the strength of threaded metal – composite couplings based on the use of modern finite element modeling methods at the stage of developing design documentation allows to create more effective structures that better meet operational requirements.

Due to the high relevance of this topic, there are a sufficient number of diverse publications on the issue of threaded metal – composite couplings today. Experimental work is mainly aimed at studying the mechanical properties of materials of composite structures. Thus, the results of studying the characteristics of energy consumption and behavior during the destruction of hybrid structures made of metal and composite materials is presented in the paper [6]. The metal part is an aluminum alloy, and the composite part consists of carbon and fiberglass materials reinforced with epoxy resin. In the paper [7], the impact resistance characteristics of hybrid metal – carbon reinforced polymer CFRP tubes were experimentally studied. In the paper [8], the characteristics of carbon fiber are given based on experimental data. It is shown that the mechanical characteristics of the material are orthotropic. The mechanical characteristics of elastic-plastic flow and local fracture of steel under the action of internal gas-dynamic pressure are given in the paper [9].

Theoretical studies on this topic are usually based on finite element modeling. In [10], a comprehensive model that takes into account the tension-torsion relation for a threaded coupling is proposed. In [11], a finite element model is presented for evaluating the failure behavior of point couplings of aluminum alloy and carbon fiber reinforced by polyphenylene sulfide, developed on the basis of the finite element method. A cohesive surface model is used to model the behavior of the coupling between aluminum and a composite. In [12], the authors consider the issue of fracture of threaded metal – composite couplings. Based on the analysis of the fracture mechanism, methods for extending the couplings durability are proposed, and in [13], special attention is paid to methods for connecting structural elements made of metal and composite, including threaded couplings. The subject of study of the authors of the paper [14] was the bearing capacity of threaded metal – composite couplings. In turn, the authors of the paper [15] propose a method for numerical analysis of the strength of prefabricated structures under the action of operational loads, taking into account the ambient temperature.

In this study, the strength of threaded couplings of cylindrical shells made of composite material and metal, which are under the action of gas-dynamic internal pressure, is analyzed. A method for numerical study of the problem in the Ansys / Explicit Dynamics software package is proposed. The developed finite element model takes into account: the dependence of material properties on ambient temperature; nonlinear relation between components of stress and strain tensors in metal elements; orthotropic properties of composite materials; features of contact interaction in the zones of threaded couplings of elements of a prefabricated shell made of different materials.

Problem statement

A folded cylindrical shell is considered (Fig. 1), the elements of which are the central composite shell 1 and two metal shells at the edges 2 and 3. The case when the metal shells are made of 30KhGSA steel, and the composite shell is made of carbon fiber or fiberglass is studied. The metal shells are rigidly fixed at the free edges. The parts of the structure are interconnected by threaded couplings.

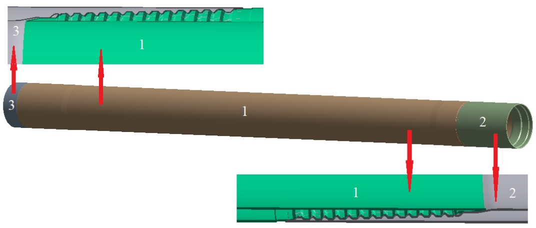

Fig. 1. Sketch of a prefabricated cylindrical structure with threaded couplings at the edges: 1 – composite shell; 2, 3 – metal shells

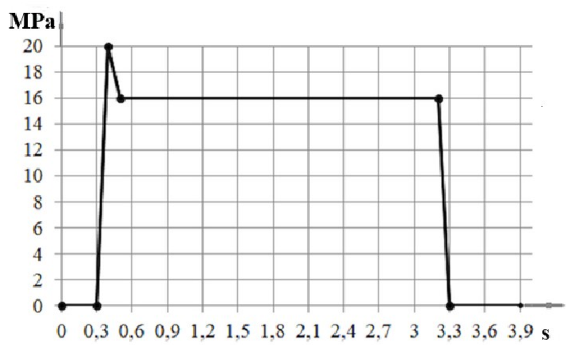

Fig. 2. Change in internal pressure over time

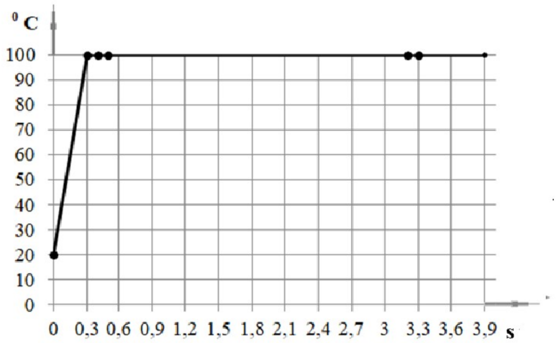

Fig. 3. Temperature change over time

The structure is loaded with non-stationary internal pressure. The change in internal pressure over time is shown in Fig. 2. The deformation process occurs under the temperature regime shown in Fig. 3. Since the mechanical loading of structures begins only when the temperature reaches its stable maximum value of 100 °C, the effect of thermal shock is modeled by a decrease in the mechanical properties of the metal shell material. It is assumed that the increase in temperature does not significantly affect the heat-resistant material of the composite shell and its mechanical properties do not change. The contact in the threaded coupling at the beginning of deformation is modeled as a fit with full contact, which ensures a tight fit of the thread between the two coupling elements, but without loading the material.

The stressed state of the structure under the action of internal non-stationary pressure is studied, taking into account the effect of temperature on the mechanical characteristics of materials. The problem is solved in a nonlinear formulation. Large deviations during deformation are taken into account, as well as the plastic flow of 30KhGSA steel.

Table 1. Mechanical properties of 30KhGSA steel depending on temperature

T, °C	σ_u, MPa	$\sigma_{0,2}$, MPa	E, GPa	δ, %	$\alpha\cdot10^{-6}$, °C^{-1}	ν
20	1080.0	932.0	196.2	13.5	12.4	0.3
100	1062.6	878.6	189.3	13.4	12.5	0.3
250	1030.0	843.0	176.4	13.0	13.0	0.3

When modeling the stress state of prefabricated structural elements made of 30KhGSA steel, the change in the elastic-plastic properties of the material depending on the temperature is taken into account. Table 1 shows the experimental data obtained at temperatures of 20 °C and 250^{0}C, as well as the mechanical properties of the material for the intermediate temperature of 100 °^{0}C, obtained by linear interpolation.

To simulate the plastic flow of steel, a bilinear isotropic hardening model is used. During plastic deformation, the relation between stresses and strains is given by [16]:

$$\sigma_{eq} = \sigma_y(T) + H\left(\varepsilon_{eq} - \frac{\sigma_y(T)}{E(T)}\right), \quad (1)$$

where $\sigma_y(T)$ is the yield strength for a given temperature; $H = \dfrac{d\sigma_{eq}}{d\varepsilon_{eq}}$ is the strengthening module.

Both fiberglass and carbon fiber core are heat-resistant materials. Temperature changes from 20 °C to 100 °C do not significantly affect their mechanical properties.

The following fiberglass characteristics were used in this research: density ρ=1800 kg/m^3, Young's modulus E=6 GPa, shear modulus G=0.6 GPa, Poisson's ratio ν=0.3. At the same time, carbon fiber as an orthotropic material has the following mechanical characteristics: Young's moduli E_{xx}=2.25 GPa, $E_{\varphi\varphi}$=2.96 GPa, E_{zz}=2.41 GPa, shear moduli $G_{x\varphi}$=0.667 GPa, $G_{\varphi z}$=0.889 GPa, G_{xz}=0.829 GPa, Poisson's ratios $\nu_{x\varphi}$=0.31, $\nu_{\varphi z}$=0.26, ν_{xz}=0.33, density ρ=1267 kg/m^3. The materials are elastic and not subject to plastic flow. The stress limits for carbon fiber are as follows: σ_{xx}=56.5 MPa, $\sigma_{\varphi\varphi}$=47.0 MPa, $\sigma_{x\varphi}$=30.0 MPa; and for fiberglass, the tensile strength is equal to 150 MPa. The given values are obtained experimentally. The methods of experimental studies and their numerical processing are described in [8, 17]. The relation between stresses and strains is given in the form of Hooke's law

$$\sigma_{\alpha\beta} = C_{\alpha\beta\gamma\delta}\cdot\varepsilon_{\gamma\delta}, \quad (2)$$

where $C_{\alpha\beta\gamma\delta}$ are coefficients of the tensor of elastic moduli.

The problem is solved in a dynamic formulation under internal pressure P=$P(t)$, shown in Fig. 2. Static solution at internal pressure P=20 MPa is used to verify the obtained results.

Methodology for solving the problem using the FEM method

The numerical solution of the problem was implemented in the Ansys / Explicit Dynamics software package based on the finite element method. A nonlinear dynamic model with explicit integration methods within the framework of direct dynamic analysis was applied.

In the general case, internal gas-dynamic pressure can cause deformation of the composite shell in a wide range of deformation rates. At high deformation rates, the dependence of stresses on deformations and their rates must be taken into account. It is assumed that damping is small, so it is not taken into account. Thus, the classical equation of motion [16] can be presented in a modified form

$$[M]\{\ddot{u}\} + [K(\varepsilon_i, \dot{\varepsilon}_i)]\{u\} = \{F\}, \quad (3)$$

where $[M]$ is the finite element model mass matrix; $\{u\}$ is the vector of generalized nodal displacements of the finite element model; $[K]$ is the stiffness matrix of the finite element model; $\{F\}$ is the vector of forces reduced to nodes.

In this study, due to the low speed of the deformation process occurring due to mechanical loading (Fig. 2), the deformation speed is not taken into account in equation (3), and the plastic flow of metal shells is modeled according to (1).

Time discretization is performed according to the central differential scheme of second-order integration [16]

$$\{\ddot{u}\}_n = [M]^{-1}(\{F\} - [K(\varepsilon_i(\{u_n\}), \dot{\varepsilon}_i(\{u_n\}))]\{u_n\});$$
$$\{\dot{u}\}_{n+\frac{1}{2}} = \{\dot{u}\}_{n-\frac{1}{2}} + \{\ddot{u}\}_n \Delta t; \qquad \{u\}_{n+1} = \{u\}_n + \{\dot{u}\}_{n+\frac{1}{2}} \Delta t.$$

For this system to be stable, the conditions for the time integration step must be met [16]

$$\Delta t_{cr} \le \frac{2}{\omega_{\max}},$$

where $\omega_{\max}$ is the maximum natural frequency of this system.

The maximum natural frequency should be equal to [16]

$$\omega_{\max} \approx \frac{2c}{\Delta x_{\min}},$$

where c is the speed of sound in a material; $\Delta x_{\min}$ is the minimum characteristic element size.

Thus, to ensure the convergence of the problem solution, it is sufficient to choose the appropriate characteristic element size.

The mass matrix $[M]$ of equation (3) is determined from the expression for the kinetic energy during deformation. In finite element discretization, it has the form [16]

$$T = \frac{1}{2}\iiint_V \rho \dot{v}^{\mathrm{T}} N^{\mathrm{T}} N \dot{v}\, dV = \frac{1}{2}\dot{v}^{\mathrm{T}} M_e \dot{v},$$

where V is the body volume; ρ is the material density; $u=v\cdot N$ is the displacements; v is the vector component of nodal displacements; N is a matrix of shape functions that determines the position of nodal elements; $M_e = \iiint_{V_e} \rho N_e^{\mathrm{T}} N_e\, dV$ is the element mass matrix.

Stiffness matrix $[K]$ of equation (3) is determined from the expression for internal virtual work. The modeling of geometric nonlinearities is carried out by the Lagrange method. At the time t, all variables (coordinates x_i, displacements u_i, deformations ε_{ij}, stresses σ_{ij}, speeds v_i, volume V, etc.) are known. The problem is solved for a set of linearized synchronous equations with displacements as input data to obtain a solution to the problem at time $t+\Delta t$ [16]

$$\delta W = \int_V \sigma_{ij}\delta\varepsilon_{ij}\, dV = \int_V f_i^B \delta u_i\, dV + \int_S f_i^S \delta u_i\, dS,$$

where W is the internal virtual work; σ_{ij} are components of the Cauchy stress tensor; $\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$ is the strain tensor; u_i are displacements; x_i is the current coordinate; f_i^B are components of solid bodies; f_i^S are components of surface forces; V is the volume of a deformed body; S is the surface of a deformed body on which the load acts.

Now, the relation (2) for an orthotropic material is considered. They have a well-known form [8]. On their basis, the increments for direct stress are determined. The increase in deformation $\Delta\varepsilon_{ij}$ is expressed through the growth of volumetric $\Delta\varepsilon_v \approx \varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}$ and deviant $\Delta\varepsilon_{ij}^d$ deformation components as follows: $\Delta\varepsilon_{ij} = \frac{1}{3}\Delta\varepsilon_v + \Delta\varepsilon_{ij\,ij}^d$. The differential linear relations between the increments of direct stress and the increase in strain for an orthotropic material have the form:

$$\begin{bmatrix} \Delta\sigma_{11} \\ \Delta\sigma_{22} \\ \Delta\sigma_{33} \\ \Delta\sigma_{23} \\ \Delta\sigma_{31} \\ \Delta\sigma_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{11}^{d} + \frac{1}{3}\Delta\varepsilon_{v} \\ \Delta\varepsilon_{22}^{d} + \frac{1}{3}\Delta\varepsilon_{v} \\ \Delta\varepsilon_{33}^{d} + \frac{1}{3}\Delta\varepsilon_{v} \\ \Delta\varepsilon_{23} \\ \Delta\varepsilon_{31} \\ \Delta\varepsilon_{12} \end{bmatrix}.$$

The contact interaction between bodies in the area of threaded couplings is described by the frictional contact model. The friction force is calculated based on the normal contact force and the friction coefficient

$$F_f = \mu \cdot F_n ,$$

where F_f is the friction force; μ is the coefficient of friction between surfaces; F_n is the normal contact force, which is calculated using the penetration method

$$F_n = k_p \cdot \delta ,$$

where k_p is the contact stiffness coefficient; δ is the penetration of one surface into another.

Numerical analysis results

The stress state of the prefabricated structure shown in Fig. 1, loaded with unsteady internal pressure, the change in time of which is shown in Fig. 2, at an ambient temperature of 100 °C, is studied. Detailed modeling of threaded couplings is used. To break the shell structure into finite elements, a volumetric finite element TET10 is used – a tetrahedron with 10 nodes, which has three degrees of freedom each. The use of this element makes it possible to model plasticity and large deflections during deformation, therefore the computational model of the problem includes the option of large deflections, known as Large Deflection, and Bilinear Isotropic Hardening model for 30KhGSA steel. The composite is specified as an orthotropic material with elastic properties, and the plastic flow of this material is not foreseen. To match the directions of the coordinate axes to the orthotropic properties of the composite in the central shell, the orientation of the finite elements "Element Orientation" is specified as follows: axis *Ox* is directed along the generating cylindrical shell, axis *Oz* – normal to its outer surface, the third axis defines a right triple.

Solving the problem in a dynamic formulation is time-consuming in terms of calculations. To reduce the time at the initial stage of design, it is advisable to perform a number of auxiliary calculations in the static analysis module [9].

Table 2. Simulation results for different sizes of finite elements

"Element Size" Parameter	12 mmм	6 mmм	3 mm
Maximum displacements, mm	5.81	5.79	5.79
Maximum plastic deformations	0.077	0.076	0.076
Maximum equivalent stresses, MPa	1 168.1	1 167.2	1 167.1

The convergence of the numerical solution of the problem is studied. Calculations are carried out at internal pressure *P*=20 MPa for a structure with a central shell made of carbon fiber. The convergence study was carried out by the traditional method of successively reducing the mesh size. The convergence of displacements, plastic deformations and Von Mises equivalent stresses was analyzed. Table 2 shows the results of this analysis for the maximum values of the quantities. The mesh size was set by determining the size of the finite element by the parameter "Element Size". As a result of test studies, a finite element model of the problem with the parameter "Element Size", which is equal to 6 mm, was selected.

Rapidly increasing gas-dynamic pressure in the structure leads to an uneven distribution of stresses in the thread, since steel and composites have different elasticity and sensitivity to the loading rate. In this regard, uneven load distribution in the contact zone can lead to the occurrence of plastic flow of steel and, as a result, to a local violation of the integrity of the threaded coupling. To avoid this, at the stage of design documentation development, it is advisable to analyze the presence of plastic deformations in metal – composite pairs at maximum operational loads.

The stress state in a structure with a central shell made of carbon fiber and fiberglass was studied. Numerical modeling was carried out to determine the zones of occurrence of plastic deformations in the structure at maximum internal pressure *P*=20 MPa and at a temperature of 100 °C. Calculations were performed in the

Static Structural static analysis module. Fig. 4 shows plastic deformations in the steel parts of the prefabricated structure with a central shell made of carbon fiber.

It should be noted that in the area of the left threaded coupling, the pressure acts on the steel shell, and in the area of the right one – on the composite shell. Plastic deformations are concentrated on the edges of the threaded couplings of the steel shells. In this case, the magnitude of the plastic deformations of the coupling with the inner metal shell is an order of magnitude higher than for the coupling with the outer metal shell.

Fig. 5 shows the plastic deformations in the steel parts of the prefabricated structure with the central fiberglass shell.

Plastic deformations, as before, are concentrated on the edges of the threaded couplings of the steel shells. In this case, the width of the annular layer of plastic flow of the metal decreases compared to the previous case. The maximum value of plastic deformations in the coupling with the inner metal shell is half as small when using fiberglass, not carbon fiber.

Thus, the use of fiberglass as the material of the central shell for a given loading mode is preferable.

The dynamics of the distribution of displacement and stress fields in a prefabricated structure with a fiberglass inner shell under the action of a given non-stationary internal pressure was studied (Fig. 2). Fig. 6 shows the displacements in the prefabricated structure. The maximum displacements are achieved in the central part of the structure, they do not exceed 2 mm. They reach their maximum at 0.5 s, and then retain their values over time. In the zones of threaded couplings, displacements are practically absent.

Fig. 7 shows the Von Mises equivalent stresses in a prefabricated structure with a central fiberglass shell.

Analysis of the results shows that in the thread zone the stresses are distributed evenly. At the same time, they remain within the elastic limits. The localization of critical stresses is observed only at the edges of the metal shells near the threaded couplings. The stressed state of the fiberglass shell is not critical. Local material failure is not observed.

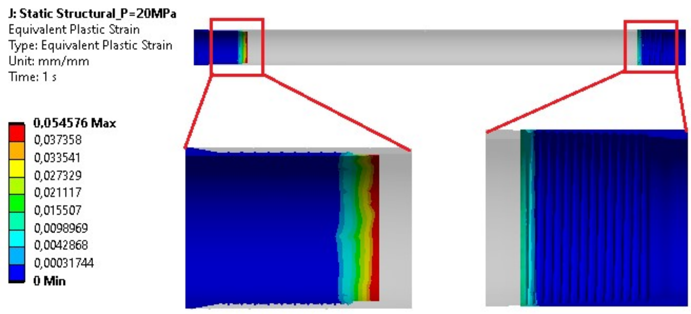

Fig. 4. Plastic deformations in steel parts of a prefabricated structure with a central shell made of carbon fiber

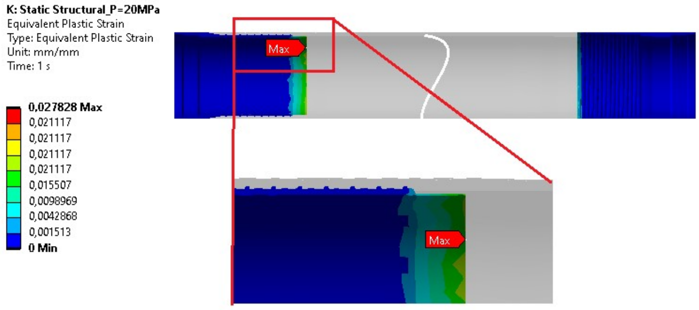

Fig. 5. Plastic deformations in steel parts of a prefabricated structure with a central fiberglass shell

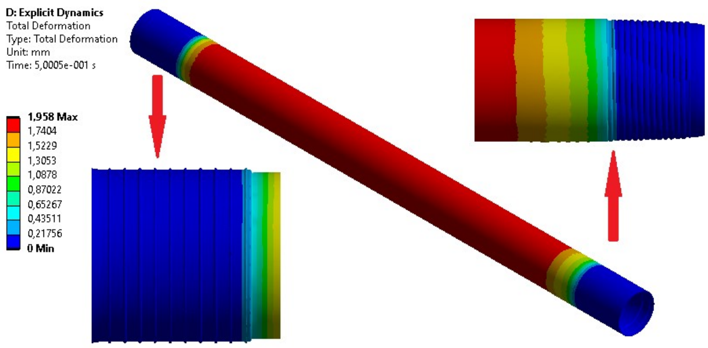

Fig. 6. Displacement at time 0.5 s in a prefabricated structure with a central fiberglass shell

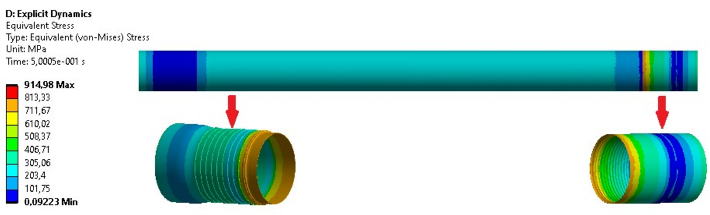

Fig. 7. Von Mises equivalent stresses at time 0.5 s in a prefabricated structure with a central fiberglass shell

Conclusions

The process of deformation of threaded couplings of cylindrical shells made of composite material and metal under the action of gas-dynamic internal pressure is analyzed. A method of numerical study of the problem in the Ansys software complex is proposed. Detailed modeling of threaded couplings is used. The developed finite element model takes into account: the dependence of material properties on ambient temperature; nonlinear relation between components of stress and strain tensors in metal elements; orthotropic properties of composite materials and features of contact interaction in the zones of threaded couplings of elements of a prefabricated shell made of different materials.

The study of the stress state in a structure with a central shell made of carbon fiber and fiberglass, loaded with gas-dynamic internal pressure with a maximum value of 20 MPa at an ambient temperature of 100 °C, was carried out. It was found that plastic deformations are concentrated at the edges of threaded couplings of steel shells. At the same time, the magnitude of plastic deformations of the coupling with the inner metal shell is an order of magnitude higher than for the coupling with the outer metal shell. The magnitude of plastic deformations in the coupling with the inner metal shell when using fiberglass is half as small as in the case of using carbon fiber. The localization zone of critical stresses was observed only at the edges of the metal shells in threaded couplings. At the same time, in the thread zone, the stresses are distributed evenly, and their values are within the limits of elasticity. The stressed state of the fiberglass shell is uniform and is not critical. Local material failure in the structure was not observed.

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Деформування різьбових з'єднань метал – композит під дією газодинамічних навантажень

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Поєднання металу й композиту в різьбових з'єднаннях підвищує надійність конструкції, що працює в умовах впливу інтенсивного внутрішнього тиску. Аналіз міцності різьбових з'єднань метал – композит на основі застосування сучасних методів скінченно-елементного моделювання на стадії розроблення проєктної документації дає змогу створювати більш ефективні конструкції, які краще відповідають експлуатаційним вимогам. У цій публікації представлено результати аналізу міцності різьбових з'єднань циліндричних оболонок із композитного матеріалу й металу, що перебувають під дією газодинамічного внутрішнього тиску. Запропонована методика чисельного дослідження задачі в програмному комплексі Ansys / Explicit Dynamics. Використовується деталізоване моделювання різьбових з'єднань. Розроблена модель враховує: залежність властивостей матеріалів від температури довкілля; нелінійний зв'язок між компонентами тензорів напружень і деформацій у металевих елементах, ортотропні властивості композитних матеріалів; особливості контактної взаємодії в зонах різьбових з'єднань елементів збірної оболонки з різного матеріалу. Досліджено напружений стан циліндричної конструкції з центральною оболонкою з вуглепластику або зі склопластику та зі сталевими оболонками по краях, навантаженої газодинамічним внутрішнім тиском із максимальним значенням 20 МПа за максимальної температури навколишнього середовища 100 °С. Отримано, що пластичні деформації зосереджені на краях різьбових з'єднань сталевих оболонок. При цьому величина пластичних деформацій з'єднання з внутрішньою металевою оболонкою на порядок вища, ніж для з'єднання із зовнішньою металевою оболонкою. Величина пластичних деформацій у з'єднанні з внутрішньою металевою оболонкою при використанні склопластику вдвічі менша, ніж у випадку використання вуглепластику. Локалізація критичних напружень спостерігалася тільки в металевих оболонках біля різьбових з'єднань. При цьому в зоні різьби вони в межах пружності, а напружений стан склопластикової оболонки не є критичним. Локального руйнування матеріалу в конструкції не спостерігалося.

***Ключові слова**: різьбове з'єднання, розподіл навантаження, циліндрична оболонкова конструкція, тертя, МСЕ.*

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