Modeling of corrosion-mechanical behavior of composition rotation shells in a temperature field

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Abstract: In the process of exploitation, vessels and apparatuses of chemical productions can be subjected to the joint action of long-acting loads, temperatures, and corrosive working media. Real vessels and apparatuses are a combination of shells of rotation of various configurations: cone, torus, sphere, cylinder, etc. When calculating, one should take into account the edge effect at the points of inflection of the guide. Many vessels and apparatuses of chemical engineering work in uneven thermal and power fields, which cause local corrosion. The article considers the problem of calculating geometrically and physically nonlinear composite shells of revolution subjected to corrosion wear in an inhomogeneous temperature field, and the corrosion rate depends on both the stress state and temperature. Equations are obtained that describe the corrosion-mechanical behavior of shells of revolution, taking into account corrosion wear in force and thermal fields. The stress-strain state of the shell of rotation is studied by the method of successive perturbations of the parameters (in this case, time), and the time step value is selected from the condition of satisfying the required accuracy of solving the problem. At each time step, the method of initial parameters with orthogonalization of S. K. Godunov solves the boundary-value problem for a system of resolving equations with the corresponding boundary conditions. The results of calculating an autoclave, which is a combined shell of revolution: a sphere - a spherical torus - a cylinder, are presented.

1. Introduction
In the chemical, oil and gas processing and other industries, elements of many structures, machines, vessels and apparatuses during operation are exposed to aggressive environments in thermal and force fields. One of the most common types of corrosion damage to steel is corrosion wear, which leads to a decrease in the cross sections of the elements [1, 2]. To date, quite a lot of experimental and theoretical material has been accumulated on the issues of corrosion wear of structures.

The identification of the patterns of operation of elements of metal structures under conditions of corrosion wear and the prediction of their service life is currently one of the most urgent tasks, since corrosion destroys about one third of the total metal produced.

The results of studies in the field of calculation of thin-walled structures taking into account the impact of the external environment are used in the prevention of corrosion at the design stage, which provides the greatest efficiency in the fight against corrosion damage.
2. The problem state and problem statement
Existing methods for calculating the strength and durability of structures usually do not take into account the non-uniformity of the field of corrosion wear, the influence of temperature, type and level of stress-strain state on the kinetics of corrosion wear of structures [1-13].

The used mechanical characteristics of metals were obtained on samples tested in laboratory conditions, where the real kinetics of the stress state of the structures, inhomogeneity of the temperature field, and also the time factor were not always taken into account.

In addition, this approach to taking into account the corrosive environment is based on the assumption that corrosion wear is constant over time, and this does not correspond to the actual conditions of operation of the vessels. The kinetics of the stress state of the vessels depends on changes in the power and temperature loads and wall thickness, which changes due to their corrosive wear. A change in wall thickness causes a change in the temperature gradient across the wall thickness. This leads to a change in material properties. In turn, a change in the stress-strain state in the apparatus wall causes a change in corrosion wear. This can lead to a change in the stress-strain state, leading to a reduction in the service life of the structure. Therefore, in order to correctly evaluate the behavior of shell structures under operating conditions, it is necessary to develop methods for taking into account corrosion wear in the calculation of shells. Since under the influence of corrosion wear the shell thickness decreases and the stress level increases, it becomes necessary to take into account both geometric and physical nonlinearity in the calculation.

Many research centers in our country and abroad study the effects of various aggressive environment on the mechanical characteristics of materials and structural elements. A significant contribution to these studies was made by G.V. Karpenko, V.M. Dolinsky, V.G. Karpunin, E.M. Gutman [1-13]. Under the direction of V.V. Petrov and I.G. Ovchinnikov, studies are being conducted related to the construction of mathematical models describing the deformation and fracture of structures in aggressive working environments; identification of these models using experimental data; development of a calculation technique and a computational assessment of the stress state and longevity of structural elements using the constructed models [14-20].

Real vessels and apparatuses are a combination of shells of rotation of various configurations: cone, torus, sphere, cylinder, etc. When calculating, one should take into account the edge effect at the points of inflection of the guide. Many vessels and apparatuses of chemical engineering work in uneven thermal and power fields, which causes local corrosion.

Often it is necessary to solve the problem of assessing the actual state of structures and predicting its changes in order to take timely measures to prevent accidents and assess the reserve of bearing capacity and durability. Currently, a large number of equipment of various industries is in operation, which has worked out a significant resource under aggressive environments. Due to the impossibility of replacing this equipment as a result a lack of production capacity, the issue of an objective assessment of the resource of equipment is of particular relevance. Taking into account uneven thickness corrosion and local corrosion wear will allow structural analysis to be performed according to an updated design scheme, and thereby provide a more reliable structural analysis. Therefore, it is of scientific and practical interest to solve the problem of deformation of loaded shells of complex shape that undergo corrosion wear in a thermal field.

3. The model of shell deformation taking into account corrosion wear and the method of its calculation
Consider a composite shell of arbitrary shape, representing a combination of cylindrical, conical, spherical, toroidal shells with a variable along the thickness of the meridian under the combined action of load, temperature and corrosion. The shell material is elastic, but its properties are temperature dependent. According to the meridian of the shell, a different number of linear and angular elastic supports can be established, a different number of ring concentrated forces and moments can act on the shell (Figure 1). The shell may be subjected to uneven heating in thickness and uniform or uneven corrosion wear, causing one-sided or two-sided reduction in thickness.
It is assumed that the temperature along the thickness of the shell varies linearly. The components of thermal deformation given by thickness are equal to:

$$
\varepsilon_r = (\alpha_t + \nu \alpha_z) T_0; \kappa_r = (\alpha_t + \nu \alpha_z) k,
$$

where

$$
T_0 = \frac{T_1 + T_2}{2}; k = \frac{T_1 - T_2}{h}.
$$

**Figure 1.** The design scheme of the autoclave.

Corrosion wear of the shell surfaces is described by the equation:

$$
\frac{d\delta_j}{dt} = V_j(t) \chi_j(T) \phi_j \sigma_e, j = 1, 2
$$

where \( j = 1 \) - corresponds to the inner, \( j = 2 \) - to the outer surfaces of the shell; \( \delta_j \) - depth of corrosion wear; \( V_j(t) \) - corrosion rate in an unstressed state at some base temperature; \( T_i; \chi_j(T) \) and \( \phi_j(\sigma_e) \) are functions of the influence of temperature and stresses; \( \sigma_e \) - some equivalent stress.

The stress-strain state of the shell of rotation is studied by the method of successive perturbations of the parameters (in this case, time). The value of the time step \( \Delta t \) is selected from the condition of satisfying the required accuracy of the solution of the problem. At each time step, a boundary-value problem is solved for a system of resolving equations with corresponding boundary conditions.

$$
\begin{align*}
\frac{d\xi}{dz} &= -\nu_2 \cos \phi \frac{\xi - \nu \sin \phi + 1 - \nu \nu_2 \cos^2 \phi (r \cdot N) + 1 - \nu \nu_2 \sin \phi \cos \phi F(\xi) + (\alpha_t + \nu \alpha_z) T \cos \phi}{E_i h^2} \\
\frac{d\zeta}{dz} &= -\nu_2 \cos \phi \frac{\xi - \nu \sin \phi + 12 - \nu \nu_2 \cos^2 \phi (r \cdot M_1) + (\alpha_t + \nu \alpha_z) k T}{E_i h^3} \\
\frac{d(r \cdot N)}{dz} &= \frac{E_i h}{r} (\xi + \nu_2 \cos \phi (r \cdot N) + \nu_2 \sin \phi F(\xi) - r q_{(t)} - E_2 \alpha_T h T) \\
\frac{d(r \cdot M_1)}{dz} &= \frac{E_i h^3}{12 r} (\xi + \nu_2 \cos \phi (r \cdot N) + \nu_2 \sin \phi F(\xi) - \frac{E_i \alpha_T k T \cos \phi h^3}{2 \pi}) \\
\frac{d\xi}{d\zeta} &= -\nu_2 \sin \phi \frac{\xi + \cos \phi \cdot \xi + \nu_2 \sin \phi \cos \phi F(\xi) + (\alpha_t + \nu \alpha_z) T \sin \phi}{E_i H} \\
\frac{d\zeta}{d\theta} &= \nu_2 \cos \phi \cdot \xi + \cos \phi \cdot \xi + \nu_2 \sin \phi \cos \phi F(\xi) + (\alpha_t + \nu \alpha_z) T \sin \phi,
\end{align*}
$$

where indicated: \( \xi, \zeta \) - respectively, radial and axial movements; \( \theta \) - angle of rotation of the normal; \( E_i, E_z \) - elastic moduli; \( \nu_1, \nu_2 \) - Poisson ratios; \( \zeta \) - distance along the meridian; \( \alpha_t, \alpha_z \) - linear expansion coefficients; \( r \) - radius of a parallel circle; \( F(\xi) \) - axial force; \( q_{(t)} \) - radial component of
the load. The system of resolving equations is solved by the method of initial parameters with orthogonalization of S. K. Godunov.

The law of corrosion wear is selected in the form that most adequately describes the experimental data on the kinetics of corrosion wear for the considered combination of metal - temperature - corrosion medium. The most common types of wear models and their comparative analysis are given in [19, 20]. As a criterion for stopping the computational process, one of the following conditions is violated: the maximum equivalent stress (at any point of the shell) reaches the limit value \(\sigma_e \geq \sigma_{\text{limit}}\) - achievement of the specified operating time of the shell \(t \geq t_{\text{giv}}\); achievement of maximum permissible shell thickness \(h \leq h_{\text{min}}\).

4. Calculation results and discussion

This algorithm is implemented as a software package. The following were used as test calculations: calculation of a conical shell at a constant temperature without corrosion wear; calculation of a composite shell (cone, sphere, cylinder) at a constant temperature without corrosion wear; calculation of a cylindrical shell of variable thickness in a temperature field; calculation of a cylindrical shell at a constant temperature, internal pressure and corrosion wear.

In all cases, the calculation results for the developed program almost coincided with the test calculations. In order to analyze the possibilities of the proposed methodology, the calculation of the autoclave, which is a combined shell of revolution: a sphere - a spherical torus - cylinder.

It is accepted in the calculations: \(V = V_0 (1 + k\sigma_e)\), where the values of the coefficient \(k\) and rate of corrosion \(V_0\) in an unstressed state are determined by processing the experimental data and are: \(V_0 = 0.74 \text{ mm/} \text{year}\), \(k = 0.0084 \text{ MPa}^{-1}\).

The design scheme is presented in Figure 1. Material VSiZ \((E = 1.825 \times 10^5 \text{ MPa})\) operating temperature \(T_{\text{work}} = 175^\circ \text{C}\); Poisson's ratio - 0.3; working pressure - 1.35 MPa; linear expansion coefficient - \(11 \times 10^{-6} \text{ deg}^{-1}\).

The reliability of the calculation results of the developed method at the stage of corrosion wear is verified by its comparison with the results obtained by solving the nonlinear differential equation by the finite difference method for the cylindrical part of the shell. The calculations showed a practical coincidence of stresses, shell bends in the case of using uniform corrosion wear. When the kinetics of wear depends on the level of stresses (inhomogeneous corrosion wear), the deflections of the shell obtained by various methods coincide over a large time interval of its operation \((\approx 0.65 \tau_d)\); then the results are stratified and by the time of shell destruction \((\tau = \tau_d)\) at \(\sigma_i = \sigma_{\text{lim}}\) (failure condition: stress intensity reaches the ultimate stress), the difference in deflections is up to 5-7%. Therefore, in the time interval \(0.65 \tau_d \leq \tau \leq \tau_d\) the step size must be reduced, i.e. calculated to lead in variable steps.
Figure 2. The stresses for the cylindrical part of the shell.

Figure 2 shows the stresses for the cylindrical part of the shell, corresponding to different points in time: \( \tau = 0; \ \tau = 0.3; \ \tau = 0.6 \). The solid lines correspond to data obtained by the method used, and the dashed lines correspond to the finite difference method. Due to corrosion wear, the thickness of the shell in each section becomes variable and there is a redistribution of deflections and stresses along the length of the shell. The shell was calculated at various steps of partitioning along the length of the section. Table 1 shows the stress of the shell at the step values: \( S_1 = 85 \text{ mm}, \ S_2 = 42.5 \text{ mm} \) - for section 1 (the cylindrical part of the shell); \( S_1 = 72 \text{ mm}, \ S_2 = 3.6 \text{ mm} \) - for 2 sections (torospherical part of the shell); \( S_1 = 26.8 \text{ mm}, \ S_2 = 13.4 \text{ mm} \) - for 3 sections (spherical part of the shell). The largest difference in stresses up to 1.5\% is observed in narrow edge sections of the shell and in the zones of inflection of the shell meridian. With an increase in the coordinate, the difference in stresses in the region decreases to 0.06\%. Therefore, the calculation must be carried out with a variable step along the length of the plot \( \Delta S \). Analysis of the calculation results showed that in the marginal zones and zones of the meridian inflection, the step of splitting along the length of the section is 1.5-2 times less than in the middle of the section.

The accuracy of the calculations depends on the value of the time step \( \Delta \tau \). To this end, a study was made about the influence of the time step \( \Delta \tau \) on the counting results. Table 1 shows the shell stresses obtained at time \( \tau = 0.3 \) at various values: \( \Delta \tau \). The largest difference in stresses is observed at the marginal sections and inflection points of the meridian, and towards the middle of the section this difference gradually decreases. Studies of the data in Table 1 show that the required number of time steps to obtain a satisfactory calculation accuracy from the initial level of stress intensity \( \sigma_i = 0.4 \sigma_{\text{lim}} \) to the final one \( \sigma_i = \sigma_{\text{lim}} \) is about 10.

Table 1. Meridional stresses on the outer surface of the shell, MPa

| \( S, \text{ mm} \) | 1 region | 2 region | 3 region |
|-----------------|---------|---------|---------|
| 0 | 724 | 1689 | 2530 | 3370 | 74.8 | 142 | 216.9 | 0 | 277 | 555 | 804.7 |

\( \Delta \tau_1 = 0.02 \)

\begin{align*}
-125 & 39.59 & 39.52 & 39.52 & 78.8 & -25.3 & 108 & 187.4 & -37.3 & -61.7 & 3.3 & 129 & 0
\end{align*}
5. Conclusions

It is shown that shell structures models that take into account corrosion wear as a decrease in their thickness in an inhomogeneous temperature field can be successfully used to study the thermo-stress-strain state of thin-walled structural elements of vessels and apparatuses, which during operation are exposed to aggressive environments in thermal and force fields. An effective research method is the method of successive perturbations of parameters, which allows one to obtain linearized equations of shell structures and to study the change in the stress-strain state in the process of motion with respect to a certain parameter. In the article, time was used as such a parameter, however, this does not exclude movement along another perturbed parameter (load, temperature, material model parameter, shell length).

References

[1] Suhotina L Schreider A Archakova Yu 1974 Corrosion and protection of existing devices Chemistry 576 p
[2] Schreyer L 1981 Corrosion 632 p
[3] Gutman E 1981 Mechanochemistry of metals and protection against corrosion 270
[4] Gutman E 1984 Durability of gas production pipes under conditions of corrosion wear 75 p
[5] Gutman E et al 1977 The longevity of high-pressure vessels in conditions of mechanochemical corrosion Corrosion and protection in the oil and gas industry 9 p 3-5
[6] Gutman E et al 1984 Kinetics of mechanochemical fracture and durability of tensile structural elements during elastoplastic deformations FKhMM 2 pp 14-17
[7] Dolinsky Z 1975 Bending of thin plates subject to corrosion wear Dynamics and strength of machines Sat articles p 16-19
[8] Dolinsky V 1967 Calculation of loaded pipes susceptible to corrosion Chemical and petroleum engineering 2 p 9
[9] Dolinsky V 1983 Calculation of structural elements subject to uniform corrosion Deformation of materials and structures in aggressive environments Sat articles p 61-67
[10] Zaynullin R 1983 To the procedure for corrosion testing of specimens under bending Oil industry, ser. Corrosion and protection in the oil and gas industry p 3
[11] Karpunin V 1967 On the calculation of flexible physically non-linear plates taking into account continuous corrosion Studies in the theory of shells 7 p 37
[12] Karpunin V 1970 Durability of plates and shells under corrosive conditions Strength and durability of structures p 35
[13] Karpunin V 1975 To the calculation of plates and shells, taking into account general corrosion *Difficulties of the X All-Union Conference on the Theory of Shells and Plates* 1 p 166
[14] Ovchinnikov I Petrov V 1982 Determination of the durability of structural elements interacting with an aggressive environment *Structural Mechanics and Structural Analysis* 2 p 13
[15] Ovchinnikov I and Petrov Z 1983 Mathematical modeling of the interaction of structural elements with aggressive environments *Deformation of materials and structural elements with aggressive environments SPI* p 3-11
[16] Ovchinnikov I and Sabitov H 1984 To the calculation of a nonlinear elastic cylindrical shell taking into account corrosion wear *Izv universities Construction and Architecture* 6 p 38
[17] Ovchinnikov I 1984 About one scheme for taking into account the effects of a corrosive environment when calculating structural elements *Izv Universities Construction and architecture* 1 p 34
[18] Ovchinnikov I and Goncharova G 1987 Corrosion-mechanical behavior of a bent rectangular plate *FKHMM* 3 p. 121
[19] Naumova G and Ovchinnikov I 2000 *Strength calculations are rod and pipe structures taking into account corrosion fluctuations*. Ggt. Saratov 227 p
[20] Ovchinnikov I and Naumova G 2007 *Overhead holes in rod and plate reinforced structures interacting with aggressive environments* Volgograd 272 p