Limit of Long-term Strength of Shells Operated in an Aggressive Environment

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Abstract: The paper proposes a method for determining the limit of long-term strength of metal thin-walled structures in contact with an aggressive hydrogen-containing medium. The method is demonstrated on a structure in the form of a steel cylindrical pipe, which is used for wells and gas gathering pipeline networks. The indicator of the long-term strength of typical structures proposed in the article will allow the consumer to better navigate the market of the proposed pipes when choosing them.

1 INTRODUCTION

In various industries, including transport, the issues of assessing the degree of degradation of the strength properties of various materials during the operation of structures are topical. The change in mechanical properties leads to various types of destruction of structures. In (Collins Jack, 1981), more than 20 types of mechanical failure during operation are given.

It is known that many metals during operation in various environments change their mechanical properties in comparison with tests in air. The environment can have both beneficial and harmful effects on the material and affects the value of the long-term strength of the structure. The ability of a material to resist fracture under long-term static loading is called long-term strength. The limit of long-term strength of a material is the maximum stress that causes destruction in a certain time at a fixed temperature. It is designated $\sigma_{t_{ult}}^{T}$, where t_{ult} is the limiting time to failure, T is the temperature (Troshchenko, 1994).

The calculation of the durability of materials under long-term static loading can be carried out in two ways. The first method develops methods for predicting the time to failure using various parameters depending on the level of acting stresses, i.e., it models parametric long-term strength curves. The second method is associated with the development of methods for extrapolation of long-term strength curves for a time exceeding the time for which the initial curves were experimentally obtained.

Apparently, for standard structures loaded with a known static load, it is possible to determine the limit of long-term strength of the structure $q_{t_{ult}}^{T}$, where q is the generalized force, t_{ult} is the limiting time before the destruction of the structure, T is the operating temperature of the structure. Therefore, the introduced limit will depend on the operating conditions causing the destruction of the structure in a certain time. Such an entered value will be useful when choosing the geometric parameters and materials of typical structures (for example, pipes for wells) based on their operating conditions.

At present, the issues of assessing the degree of degradation of the strength properties of steels during the operation of various structures in aggressive environments are becoming relevant.

The effect of aggressive media, including hydrogen-containing media, on the mechanical characteristics of metals is actively studied by various physical methods and by mechanical tests for samples (Jemblie, 2017; Fassina, 2012; Miresmaeili, 2010; Mironov, 2020; Gorkunov, 2008). A variety of phenomenological effects that arise when exposed to

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hydrogen-containing media will determine the long-term strength of steels.

Predicting the behavior of loaded metal structures that are operated in an aggressive hydrogen-containing environment is an important scientific problem of great practical importance. One of these problems is the problem of changing the strength of steels for pipes that transport the so-called "sour gas". This is natural gas with a high content of hydrogen sulfide. Predicting the behavior of the material in such metal structures is a very important and not completely solved problem. The issue of assessing the strength and durability of structures during their operation in corrosive media containing hydrogen sulfide remains very important.

In this paper, a method is proposed for determining the ultimate strength of a typical structure, which is operated in an aggressive environment under static loading. The method is demonstrated on a structure in the form of a steel cylindrical pipe, which is used for wells and gas gathering pipeline networks. The indicator of the long-term strength of typical structures proposed in the article $q^T_{t_{ult}}$ will allow the consumer to better navigate the market of the proposed pipes when choosing them.

2 METHOD FOR SOLVING THE PROBLEM AND BASIC EQUATIONS

Statement of the problem and methods of solution. The general problem of determining the long-term strength limit of a metal structure in contact with an aggressive environment consists of several independent tasks:

- development of a model that allows determining the stress state of the structural element under study,
- determination of the mechanical parameters of the material depending on the time of contact with an aggressive environment,
- the choice of the interpolation method for determining the mechanical parameters of the material, depending on the operating time of the structure,
- development of a model that determines the limit of long-term strength of the structure.

Determination of the stress-strain state of the shell. The investigated thin-walled structure is a shell of revolution with variable geometric and mechanical parameters along the generatrix. We will consider a shell of thickness h using a continuous middle surface with curvilinear orthogonal coordinates S, θ, γ. Where s and θ are the meridional and circumferential coordinates, and the γ ($-h/2 \le \gamma \le h/2$) coordinate is in the direction of the outer normal to the shell surface. A cylindrical shell loaded with a distributed mechanical force q is shown in fig. 1.

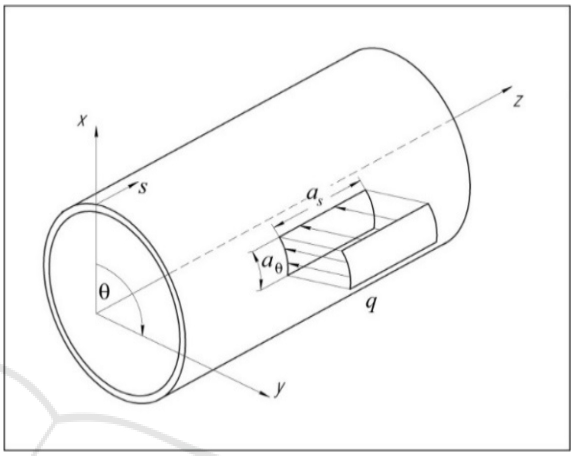

Figure 1: Shell of revolution.

The inner surface of the shell is in contact with an aggressive water-containing medium with an overpressure p. The stress state of a thin-walled structure will be determined using the classical theory of shells based on the Kirchhoff–Love hypotheses (Donnell, 1976). Given that the structure under study is loaded only with pressure, its stress state will be axisymmetric. Thus, the problem of determining the stress-strain state of the shell will be described by a system of ordinary differential equations in the Cauchy normal form of the following form (Shevchenko, 2001; Shevchenko, 2006)

$$\frac{d\bar{Y}}{ds} = P_{ij}\bar{Y} + \bar{f}, \quad (i,j = 1,2,....6), \ (s_0 \le s \le s_L) \tag{1}$$

with boundary conditions

$$B_1\bar{Y}(s_0) = \bar{b}_1, \ B_2\bar{Y}(s_L) = \bar{b}_2 \tag{2}$$

Here $\bar{Y} = \{N_r, N_z, M_s, u_r, u_z, \vartheta_{s,}\}$ – vector–function of the required solution N_r, N_Z – radial and axial forces; u_r , u_z - displacement; M_s – meridional bending moment; ϑ_S - angle of rotation of the normal to the shell surface. Matrix elements P_{ij} depend on the geometric and mechanical parameters of the shell,

$\bar{f}$ – the vector depends on the loads applied to the shell. B_i – given matrices; $\bar{b}_i$ are the given vectors.

When solving the linear boundary value problem (1), the Runge-Kutta method with discrete orthogonalization and normalization of S.K. Godunov is used [11].

Solution of a physically nonlinear problem for a shell. When the plastic deformation of the material is considered, the problem becomes physically nonlinear. The problem will be described by the same system (1), and the relationship between stress and strain is presented in the form of Hooke's law, with additional terms that consider the dependence of the mechanical properties of the material on strain. In this case, the volumetric stress state of the shell will be compared with the uniaxial state in a simple tension of the sample.

$$S = \frac{\sigma}{\sqrt{3}},\ H = \frac{1+\mu^*}{\sqrt{3}}\varepsilon \qquad (3)$$

where σ and ε are stresses and strains during simple tension of the sample

$$\mu^* = \frac{1}{2} - \frac{1-2\mu}{2E}\frac{\sigma}{\varepsilon} \qquad (4)$$

In formula (4) E – young's modulus, μ^* – Poisson's ratio

The intensities of the shear stress S and shear strain H for the shell are determined as follows

$$S = \sqrt{(1/3)\cdot(\sigma_s^2 - \sigma_s\sigma_\theta + \sigma_\theta^2)} \qquad (5)$$

$$H = \sqrt{(1/6)\cdot[(\varepsilon_s-\varepsilon_\gamma)^2 + (\varepsilon_\gamma-\varepsilon_\theta)^2 + (\varepsilon_\theta-\varepsilon_s)^2} \qquad (6)$$

where σ_s and σ_θ are the meridional and circumferential stresses, respectively, and ε_s, ε_θ, ε_γ are the components of deformations along the meridian, circumference and normal to the shell surface.

Determination of the mechanical parameters of the material. Since an aggressive environment usually has a negative effect on the metal of structures and changes the mechanical characteristics, experimental studies are needed to record changes in the mechanical properties.

To demonstrate the method for determining the ultimate strength of thin-walled structures, we will investigate shells made of 12GB pipe steel (an analogue of X42SS steel API).

The article (Gorkunov, 2008) presents the results of measurements of the mechanical and magnetic characteristics of samples of pipe steel 12GB, exposed to hydrogen sulfide for 384 hours, directly under the action of uniaxial tensile stresses up to the destruction of the sample. Tests were also carried out for samples in the initial state. The temperature during testing is 20°C.

In (Gorkunov, 2008), stress-strain diagrams are given for a given material at fixed times t=96 h, t=192 h and t=384 h of contact with an aggressive medium. It can be seen from the above diagrams that they can be approximated quite accurately by bilinear straight lines with points of yield strength σ_Y, ε_Y, and ultimate strength σ_{ult}, ε_{ult} both for the initial state and after contact with an aggressive medium (where σ_{ult} and ε_{ult} are the maximum values of stress and deformation upon failure). Table 1 shows the points for plotting diagrams.

Table 1: The points for plotting stress-strain diagrams.

Time, hour	point 1	point 2	point 3
0	$\varepsilon_0 = 0$ $\sigma_0 = 0$	ε_Y =0,00187 σ_Y =374 MPa	ε_{ult} =0,23 σ_{ult} =474 MPa
96	$\varepsilon_0 = 0$ $\sigma_0 = 0$	ε_Y =0,00181 σ_Y = 361 MPa	ε_{ult} =0,22 σ_{ult} =458 MPa
192	$\varepsilon_0 = 0$ $\sigma_0 = 0$	ε_Y =0,00213 σ_Y = 426 MPa	ε_{ult} =0,14 σ_{ult} =498 MPa
384	$\varepsilon_0 = 0$ $\sigma_0 = 0$	ε_Y =0,00218 σ_Y = 437 MPa	ε_{ult} =0,12 σ_{ult} =500 MPa

Approximation of stress state components. After solving system (1), taking into account the mechanical properties (Table 1), meridional and circumferential stresses and strains σ_s, σ_θ, and ε_s, ε_θ, and invariant characteristics S and H will be determined at each point of the shell. Considering that the mechanical properties depend on time, these characteristics will also depend on time of contact with aggressive environment.

The criterion for the strength of structures is often the condition when the intensity of shear stresses in the shell (5) reaches the stress of the sample material during its destruction. Therefore, the criterion for the long-term strength of structures under fixed loading (*p=const*) will be the condition

$$S(t) \le \sigma_{ult}(t)(\sqrt{3})^{-1} \qquad (7)$$

To determine the values of the intensity of shear stresses $S(t)$ within the time interval of saturation with hydrogen sulfide, you can use the corresponding approximating algebraic polynomial L_n. Therefore, the approximate value of the parameter of interest can be represented in terms of its discrete value and time

$$S_{(i)} = S(t_i),\ L_n(t_i) = S_{(i)}\ \ i = 1..n \qquad (8)$$

Here n is the number of experiments at different times of sample saturation with hydrogen sulfide.

With a well-chosen polynomial L_n, the value of the parameter of interest can be determined outside the time of the experiment, i.e., at the time of interest, such as t_{work}=550 hours.

The limit of long-term strength of the structure. The value of the shear stress intensity during operation can be represented as

$$S(t) = a_0 + \sum_{i=1}^{n} a_i t^i \qquad (9)$$

Since the shell under study is loaded with internal pressure p, therefore, the intensity of shear stresses will be equal to

$$S(t,p) = b_0 + \sum_{i=1}^{n} b_i t^i,\ p = const \qquad (10)$$

Considering the introduced criterion of long-term strength of structures (7), we determine the limit of long-term strength for a given shell structure

$$\sigma^T_{t_{ult}} = S(t,p)\sqrt{3} \le \sigma_{ult}(t), \quad \text{при } T = const \qquad (10)$$

3 CALCULATION EXAMPLE

Limit of long-term strength for a cylindrical shell. Let us determine limit of long-term strength of a cylindrical shell (pipe) operated in a hydrogen sulfide environment. Pipe outer diameter D=0.114 m, thickness h=0.013 m, material - steel 12GB.

During operation, the pipe experiences a plane stress state from a variable internal pressure p. Therefore, the shell can be investigated without edge effects at a point far from the boundary conditions (2).

From table 1, the mechanical parameters change depending on the time of exposure to hydrogen sulfide. From physical considerations, the change in these mechanical parameters should be monotonous, since they should depend on the diffusion coefficient, which characterizes the efficiency of the diffusion movement of hydrogen sulfide into the metal and be proportional to the time of contact with an aggressive environment. Some solutions to the problems of hydrogen diffusion into metal are considered in (Emel’yanov, 2018; Emel'yanov, 2019). Considering the physical monotony of the diffusion process, we represent the change in the yield strength σ_Y, ultimate strength σ_{ult} in the form of power functions. For example, the change in ultimate strength σ_{ult} with an accuracy of 4% can be substituted as a quadratic function

$$\sigma_{ult} = 467.231 + 0.0869794\,t + 0.0000116704\,t^2 \qquad (12)$$

According to the results of the calculation, it was shown that at a pressure of p=80 MPa, the shell material is in the region of elastic deformations. With an increase in excess pressure to p=90 MPa, plastic deformations occur at the most loaded point on the inner surface of the shell. The problem becomes non-linear and an iterative process is applied to achieve the required accuracy of the problem solution.

Table 2 shows the values of the intensity of shear stresses $S = f(p)$ and shear strains $H = f(p)$ for various shell pressure p, when the structure is operated in an environment of hydrogen sulfide t_{work} = 550 hours.

Table 2: The intensity of shear stresses and shear strains for various pressure.

p, МПа	100	110	120	130	131
S, МПа	224	244	269	294	299
H	0.00142	0.00156	0.01734	0.068	0.07828

By increasing the pressure, it is possible to determine the limiting pressure at which the strength condition is violated. For this design, the burst pressure will be p = 132 MPa. Therefore, at p = 131 MPa, it is possible to determine the limit of long-term strength of the structure. Considering the values σ_{ult} calculated by relation (12) at t=550 h and the intensity of shear stresses for pressure p=131 (Table 2), we have $S(t,p)\sqrt{3} \approx \sigma_{ult}$

$$299\sqrt{3} \approx 518.5 \text{ at } T = 20\,^0C \qquad (13)$$

Therefore, the limit of long-term strength of this design for temperature *T*=20°C and pressure *p*=131 MPa is 550 h.

4 CONCLUSION

Thus, it is possible to determine the limits of long-term strength of typical shell structures for various combinations of material, temperature, operating time, and internal pressure.

The proposed method will be useful in the design and installation of various pipelines that operate in contact with aggressive media.

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