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Influence of internal uniform corrosion on stability loss of a thin-walled spherical shell subjected to external pressure

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ABSTRACT

Stability loss of a thin-walled spherical shell, subjected to external pressure and internal corrosion, is studied. The critical time of stability loss of the shell is found by combining the upper critical load value for static stability loss of the shell without corrosion, and the corrosion rate law. Numerical results, obtained for carbon steel shells with different wall thickness at different temperatures and corrosion activation energy values, indicate that increase in the safety coefficient for stability yields reduction of the relative durability. Temperature growth leads to corrosion rate increase and yields reduction of the vessel "life-time". The value of activation energy of corrosion has great impact on the vessel critical time t^* – the less is this parameter the less is the critical time.

1. Introduction

Many structures, including thin-walled elastic vessels, are exploited in conditions of simultaneous action of corrosive environment and mechanical loads, leading to development of mechanochemical corrosion [1]. The notion 'mechanochemical corrosion' was introduced to differ from the local phenomena (stress corrosion cracking and corrosion fatigue). At present, there exists a progressive tendency to use steels of elevated strength. Therefore, the problems of corrosion-mechanical resistance of steel constructions against accelerated failure and the problems of mutual influence of mechanical stresses and metal general corrosion are of special importance.

The stress state in real metal constructions may change in the process of operation even at a permanent external loading, due to changes in the cross-section areas of the loaded elements, resulting from the corrosion wear. Stress concentration, in turn, intensifies mechanochemical corrosion, which may lead to an accelerated loss of the carrying capacity.

Stress effect on corrosion (mechanochemical corrosion) is intensified in the sites of stress concentrators on the metal surface (threaded and welded joints, undercuts, defects, cracks, etc.), which results in non-uniform corrosion and its localization. The latter ultimately yields corrosion cracking and fatigue and corrosion concentration in the tip of the corrosion-mechanical cracks. A number of ways may reduce the mechanochemical corrosion intensity and, as a result, prevent the accelerated development of failures. Using the principles of analysis presented in [1,2], we can define the durability of high-pressure vessels under conditions of mechanochemical corrosion, i.e., uniform corrosion which proceeds at approximately same rate over the exposed metal surface and this rate depends on the stress state and the temperature of a metal.

Thin-walled elastic vessels, having the form of a closed sphere, are widely used in the industry, for example, in chemical engineering, as high-pressure reservoirs. In this relation the problem of stability loss of a thin closed spherical shell, subjected to a uniform external pressure, is of special importance. A number of mathematical methods have been developed for the stability loss analysis of thin-walled elastic shells, subjected to various loads, particularly, to external pressure (see, for instance, [3–6]).

However, these methods do not take into account the fact that in the process of structure operation, the shell interaction with an active environment is possible. Such interactions can change, for instance, the thickness of the shell's wall. It is known [1] that corrosion leads to sufficiently fast thinning of the supporting elements of metal structures. Moreover, mechanical stresses increase the general (uniform) corrosion rate even in the absence of the local corrosion and the stress corrosion cracking. The accounting for the mechanical stress effect on the corrosion rate makes it possible to

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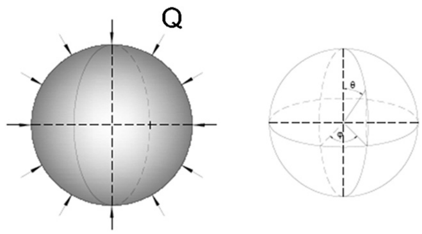

Fig. 1. Spherical coordinate system and scheme of the shell's loading; Q: intensity of external loading, φ: polar angle, θ: spherical angle.

estimate the service life of structural elements under conditions of general corrosion [1].

The onset of breaking is related usually to approaching of certain limiting stress in the shell. Nevertheless, in certain cases of practical importance, the stability loss can occur in the shell before the breaking stress is reached. In such cases the structure life time will be completely determined by the criterion of the stability loss. For instance, the method of the life time estimation for elastic thin-walled closed circular cylindrical shell, subjected to simultaneous actions of uniform external pressure or longitudinal compressive forces, and uniform corrosion, was developed in [7,8].

In the present paper this method is extended for the case of stability loss of a thin-walled elastic closed spherical shell, subjected to simultaneous action of a uniform external pressure and internal uniform (general) corrosion.

2. Problem description

The corrosion is considered here as a uniform dissolution of the internal surface of the shell (general corrosion). This suggestion leads to a model in which the internal wall of the shell is dissolved uniformly over the entire surface, and its thickness h decreases with time t .The rate of this process is equal to the corrosion rate. Experimental data for various metals and steels, received for pure elastic stressed state (see e.g., [1,2]), have shown that corrosion rate depends essentially from the stressed state of the material, which in the case of a spherical shell is characterized by compressive stress σ, caused by external uniform pressure. As a result, the corrosion rate v follows the relation$v = f[\sigma(t), T]$ where T is the temperature. It was shown in [1] that this dependence can be approximated by exponent function. Similar to [7,8], it is possible to write this law in an explicit form, taking into account specific conditions of corrosion and using experimentally established parameters.

Below the stability loss of a thin-walled elastic closed spherical shell, subjected to simultaneous action of uniform external pressure and internal uniform corrosion, is studied. The formulas for determining of the critical time (live-time), corresponding to the moment of stability loss, are obtained.

3. Shell stability loss in the absence of corrosion

Consider the problem of stability loss for a thin elastic closed spherical shell with thickness $h(t)$and radius of the middle surface $R(t)$, subjected to external pressure of intensity Q. Assuming that changes of the wall thickness and, consequently, the radius $R(t)$, are quasi-static, the equations of static stability loss in linear approximation can be applied. Spherical coordinates of the shell middle surface are characterized by the radius $R(t)$ and the angles ϑ and φ (Fig. 1). It is assumed that the initial stress state of the shell is membrane like [9] and, therefore, from equations of the thin elastic shells theory it follows that the loadings, arising from the external pressure with intensity Q, in all normal cross-sections of the curvilinear coordinate system have the form [4,6,9]:

$$S = S_1 = S_2 = -\frac{QR}{2} \tag{1}$$

Assuming that the compressing loadings S and the corresponding stresses σ in the shell are positive, we obtain from Eq. (1):

$$S = \frac{QR}{2}; \sigma = \frac{QR}{2h} \tag{2}$$

At solving of the linear problem for stability loss of elastic closed spherical shell we assume that on the middle surface of the shell many dents are formed. According to [4,6,9], the changes in the middle shell surface within one dent can be considered as gentle. Taking into account Eq. (2) and using equations of the shallow shells theory, we obtain the following homogenous differential equation of stability loss for a closed spherical shell, subjected to external uniform pressure of intensity$Q$ [4,6]:

$$\frac{Eh^2}{12(1-\nu^2)}\nabla^6 w + \sigma\nabla^4 w + \frac{E}{R^2}\nabla^2 w = 0 \tag{3}$$

Here E is the Young module, ν is the Poisson coefficient; w is the normal deflection of the middle surface of the shell. Differential operators∇^2, $\nabla^4$and ∇^6 are defined as follows:

$$\nabla^2 F(\theta, \phi) = \frac{1}{R^2}\left(\frac{\partial^2}{\partial\theta^2} + \frac{\partial^2}{\partial\phi^2}\right)F, \quad \nabla^4 F = \frac{1}{R^4}\left(\frac{\partial^2}{\partial\theta^2} + \frac{\partial^2}{\partial\phi^2}\right)^2 F,$$

$$\nabla^6 F = \frac{1}{R^6}\left(\frac{\partial^2}{\partial\theta^2} + \frac{\partial^2}{\partial\phi^2}\right)^3 F \tag{4}$$

where $F = F(\theta, \varphi)$ is a function having partial derivatives of a corresponding order. According to [10], we accept that solution of Eq. (3) must satisfy the relation:

$$\nabla^2 w = -\lambda^2 w \tag{5}$$

where λ is an indefinite parameter. Then we receive from Eq. (3): $\frac{Eh^2}{12(1-\nu^2)}\lambda^4 - \sigma\lambda^2 + \frac{E}{R^2} = 0$

which yields the relation:

$$\sigma = \frac{Eh^2}{12(1-\nu^2)}\lambda^2 + \frac{E}{R^2\lambda^2} \tag{6}$$

The value of λ, corresponding to minimum of σ, is equal to:

$$\lambda^2 = \frac{\sqrt{12(1-\nu^2)}}{Rh} \tag{7}$$

Substituting Eq. (7) into Eq. (6), we obtain the upper critical stress σ^* and the corresponding upper critical pressure Q^*:

$$\sigma^* = \frac{Eh}{R\sqrt{3(1-\nu^2)}}, Q^* = \frac{2Eh^2}{R^2\sqrt{3(1-\nu^2)}} \tag{8}$$

Note that the upper critical stress σ^* for a spherical shell, defined by Eq. (8), coincides with that one for a thin elastic circular cylindrical shell with the radius R of the middle surface, subjected to longitudinal compressive forces and external general corrosion [8].

Eq. (8) was derived at the assumption that the shell wall thickness is specified, whereas the critical value of the external pressure Q is the unknown quantity. It follows from Eq. (8) that if to assume, on the contrary, that the external pressure Q value is specified, then the shell wall thickness h_*, corresponding to the stability loss, will be equal to

$$h_* = \frac{\sqrt[4]{3(1-\nu^2)}\cdot\sqrt{Q}\cdot R}{\sqrt{2E}} \tag{9}$$