Application of a discrete model of fatigue defect growth for assessment of the safe operation life of the main pipeline section with a corrosion defect

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Abstract. The article proposes a model of fatigue defect growth obtained on the basis of the analysis of the three-dimensional stress state at the apex of the corrosion defect. To study the stress-strain state the actual operational loads of the pipeline were simulated by the finite element method. The scientific novelty of the study is that when developing a model of fatigue defect growth, it is assumed that the growth of the defect, which develops by the opening fracture mode, is controlled only by normal stresses. In one loading cycle, the intensity of the fracture process is determined by both the maximum tensile stresses during the loading period and the maximum compressive stresses during the unloading period. Based on the assumptions made, it has been established that the growth rate of fatigue defects of corrosion origin depends on the magnitude of the coefficient of the average stresses change ahead of the crack front during full loading cycle.

To ensure non-stop operation of main pipelines, it is necessary to effectively assess the residual life of pipelines. During the operation of pipeline systems, structural changes in pipe steels occur [1]. This is due to the fact that the metal pipe is under load: static and cyclic. Under the influence of cyclic loads deformational aging of pipe steels occurs, which leads to reducing their resisting strength and brittle fracture.

It is accepted that:

A corrosion defect can be modeled as a crack-like defect, and the force pushing the crack can be calculated by means of elastic-plastic fracture mechanics [2].

In this paper, we propose a method for assessing the development of surface cracks and estimating the residual life of the main pipeline under cyclic loads, taking into account the biaxial stress state in the pipeline wall.

The object of study is the main pipeline with a crack-like defect of corrosion origin. The defect model was created on the basis of a real operational conclusion statement: a corrosion defect is, first of all, the loss of the pipe metal [3].

The annular stresses depend on the magnitude of working pressure in the pipeline; therefore, they are always tensile, i.e. positive [4]:

$$\sigma_{\text{annular}} = \frac{P \cdot D_\text{in}}{2\delta},$$
where $P$ is pipeline pressure (Pa); $D_{in}$ – pipe inner diameter (m); $\delta$ – pipe wall thickness (m).

Longitudinal stresses, depending on the temperature drop or bending direction, can be both tensile and compressive, i.e. negative. For a pipeline element clamped at both ends, the longitudinal stresses are determined as follows [5]:

$$
\sigma_{long} = -\alpha \cdot \Delta t \cdot E + \mu \cdot \sigma_{annular} \pm \frac{E \cdot D_{out}}{2 \rho_{eb}}
$$

where $\alpha$ – temperature coefficient of linear expansion ($1/\degree C$); $\Delta t$ – temperature differential ($\degree C$); $\mu$ – Poisson's ratio; $D_{out}$ – pipe outer diameter (m); $\rho_{eb}$ – radius of elastic bending of the pipeline axis (m); $E$ – elastic modulus (Pa).

The development of fatigue defects occurs primarily due to the effect of annular stresses, which are the largest in magnitude and in their direction are perpendicular to the plane of growth of these cracks [6].

In this paper the bearing capacity of the pipeline is estimated by creating a mathematical model of corrosion defect using the ANSYS Workbench program. For this purpose, various loads that the pipeline undergoes during operation are simulated, taking into account the biaxial stress state.

To create the defect model shown in figure 1, the graphic editor ANSYS-Design Modeler was used (figure 2). The section of the pipe with a surface defect having a slight curvature.

![Figure 1. Corrosion defect.](image1)

![Figure 2. Corrosion defect model.](image2)
The experience of observing the growth of surface cracks indicates that they tend to take a semi-elliptical shape, which greatly simplifies the simulation.

After determining the principal stresses, it can be concluded that the largest values of the principal stresses are found at the points located in the area “lagging” behind the propagation of the crack front, which brings them in the process of growth to a semi-elliptical form (figure 3).

**Figure 3.** The semi-elliptical shape of the defect distribution.

The parameter $Tr$ reflecting the change in the rate of growth of fatigue cracks under various types of biaxial loading of the pipe wall is the triaxial coefficient of the stress state [1]

$$Tr = \frac{\sigma_0}{\bar{\sigma}},$$

where $\sigma_0 = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$ is medium stress.

Given the triaxial coefficient, the equivalent stress intensity factor can be represented as:

$$K_{1Tr} = Tr^x \cdot K_1,$$

where $Tr$ is the triaxial coefficient of the stress state; $x$ is an exponent sign to be determined by the results of biaxial tests.

Taking into account (1), the expression for the rate of growth of cracks under various types of loading can be written similarly to the Paris formula:

$$\frac{da}{dN} = C \cdot \left(\Delta K_{1Tr}^T\right)^n.$$

In paper [1], a constant for steel 20 was defined as $C = 0.26 \cdot 10^{-10}$, and the equation for the growth rate of fatigue cracks, taking into account the nature of the stress state at its apex, will be as follows:

$$\left(\frac{da}{dN}\right) = 0.26 \cdot 10^{-10} \cdot \left(Tr^{0.5} \cdot \Delta K_1\right)^{4.0}.$$

The proposed model for the growth of fatigue cracks allows us to estimate the residual life of the pipeline in the presence of a surface or non-through crack. For this, equation (2) is integrated and the residual resource is determined $N_{r1}$ i.e. the number of loading cycles from the moment of the crack registration $t_{\text{reg}}$ to the critical size of the crack $l_{\text{cr}}$:
\[ N_{r,1} = \int_{l_{\text{reg}}}^{l_2} \frac{1}{C_1 \left( \Delta K \sigma_0 \right)^n} da. \]

In this paper, a study has been conducted to assess the risk of defects of corrosive origin, as a result a mathematical model of pipeline fatigue defect has been developed; it allows to assess the development of identified defects, to estimate the safe operation life, and to impose restrictions on operating loads of the defective section of the main pipeline.

References

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