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Computation tool for assessing the probability characteristics of the stress state of the pipeline part defected by pitting corrosion

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ABSTRACT

One of the factors affecting the life-time of the main pipelines is their susceptibility to different types of corrosion. A common type of pipeline corrosion is pitting corrosion which is a form of localized corrosion – a random process occurring in a certain section of the pipeline, leading to walls thinning under the influence of the external environment. Such a change in the pipeline geometry accompanied by a significant change in the local stress–strain state leads to a large number of emergencies.

This work deals with the analysis of probability characteristics of the stress–strain state arising in the areas damaged by pitting corrosion. To determine the parameters of the stress–strain state the finite element method is used. The pipe material is modeled as elastoplastic with a bilinear diagram of plasticity.

Pitting corrosion is modeled as a set of randomly positioned half-spheres with the same radius subtracted from the volume of the pipe. Coordinates of pitting defects centers obey to a uniform probability density function (PDF). Using this approach we take into account the mutual influence of defects on the pipe stress–strain state.

A special macro was developed to determine the parameters of the stress–strain state of the corroded pipe. It allows performing automatic calculation and processing of the data for pitting corrosion defects. Parameters of the PDF of stress concentration factor depending on the radius of the defect were determined in accordance with the results of simulation. The kernel density estimation and generalized extreme value distribution was chosen as PDF approximation on the basis of the conditions of the Fisher–Tippett–Gnedenko theorem. The change of the PDF shape was investigated for different defect radii. The coefficient of variation, mean and standard deviation of stress concentration factor as function of defect radii were studied as well as reliability function of the pipe part was obtained using the criterion of plastic deformation occurrence.

Introduction

Pitting corrosion is one of the most common mechanisms of damage to different kinds of pipelines [1]. A distinctive feature of pitting corrosion is predetermined by its local character. As a result of corrosion, complex shape cavities appear, whose size is small in comparison with the size of the pipe. These cavities arise due to the influence of the environment and it may lead over time to perforation of the pipe walls.

Explorations of the pitting corrosion process [2–6] show that the points of corrosion damage initiation are random and depend on the microstructure of the material, surface processing, the presence of surface defects, and other environmental factors. Despite the complexity of the process of evolution of pitting corrosion, researchers single out standard defect types [7]: shallow, elliptical, deep, undercut, and subsurface. In most papers the variety of the above mentioned defect is modeled by even simpler figures: an ellipsoid or a parallelepiped with rounded corners (box defect) [8, 9].

In spite of a large number of papers on developing probabilistic models of evolution of the defect size [2–4, 6, 10–12], the issue of the stress–strain state of structural elements with pitting defects needs further study. In [13], the stress concentration factor (SCF) around a single elliptical cavity was studied. The SCF (K_σ) depending on the parameters of the ellipsoid was obtained:

$$K_\sigma = \frac{1+6.6(a/2c)}{1+2(a/2c)}, \tag{1}$$

where a and c are parameters of the ellipsoid. The disadvantage of this approach can be shown when $a = c$, then $K_\sigma = 2.15$, and does not depend on the size of the defect. In [14], design of the geometry of thick-walled plates with multiple pitting defects was automated using a parametrical model. The mutual influence of defects on the stress–strain state was studied as well. Modeling was performed in the Monte-Carlo stochastic way, but insufficient attention was paid

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Nomenclature

a,c	parameters of the pit ellipsoid
R_1	pipe outer radius
R_2	pipe inner radius
t	pipe wall thickness
l_1,l_2,l_3	pipe part lengths
Rd	defect radius
Rd/t	defect radius divided by pipe wall thickness
K_σ	stress concentration factor (SCF)
$K_\sigma{}^p$	stress concentration factor which corresponds to the yield stress limit
K_Σ	maximum SCF for each iteration of Monte-Carlo algorithm
ρ,φ,z	axes in cylindrical coordinate system
X,Y,Z	axes in Cartesian coordinate system
P	internal pressure
E	Young's modulus
ν	Poisson ratio
σ_y	Yield stress
σ_u	Ultimate stress
δ	Elongation before fracture
E_t	Tangent (plastic) modulus
$\sigma_{(i)},\sigma_{(i)}{}^{nom}$	von Mises stresses
$\sigma_{rr},\sigma_{\varphi\varphi},\sigma_{zz},\sigma_{r\varphi},\sigma_{rz},\sigma_{\varphi z}$	component of stress tensor in cylindrical coordinate system
$f(x)$	probability density function of x
μ,s,k	parameters of generalized extreme value probability density function
$F(x)$	probability distribution function of x
$\Gamma(y)$	gamma function
$\langle x\rangle$	mean of x
$\mathrm{Var}[x]$	variance of x
$1-\alpha$	confident interval
S_l,S_r	the left and the right borders of the spread (confidence interval)
$Q(Rd)$	probability of non-failure pipe operation (reliability function)
$\Pr[]$	operator of the event probability
γ	Euler's constant
N	number of Monte-Carlo algorithm iteration
n	number of nodes of the finite element model
N_p	number of pits

to the influence of plastic deformation of the material, as well as to the statistical analysis of the results.

In [15], a software tool for modeling of the pipeline parts with box defects on the basis of MSC.PATRAN was developed. The paper also explores the effect of the interaction of several rectangular defects in a deterministic way. In [16], a combination of neural networks and the finite element method was used to investigate the mutual influence of the box defects. In [17], a software module for statistical evaluation and reliability characterization of degraded structures was developed.

The works [18–22] study the SCF and ultimate internal pressure in the pipe whose walls thickness decreased due to corrosion. Models there take into account plastic deformation of the material, however, considering one or two box defects, which is insufficient to assess their mutual influence.

Pit depth and pit growing were studied in a stochastic way in various papers [3,5,6,10,11,23]. The biggest attention here was paid to studying the probability characteristics of the pit depth. However, probability characteristics of the stress–strain state of pitted corroded pipeline need further investigation.

Thus, at present there is almost no research aimed at studying probability characteristics of the stress–strain state of the pipeline parts which contain multiple pit defects. For such research creation of new computational tool is needed to automate calculation of the stress state and processing of the calculation results.

1.1. Problem statement

The work aims to explore the probabilistic characteristics of the stress–strain state of pipeline part with pitting corrosion and determine the characteristics of its reliability. One of the common used method to study probabilistic characteristics is Monte-Carlo method [24]. This method involves carrying out a plurality of deterministic calculations using mathematical computer models with random input data. In this paper, a mathematical model used equations of the theory of elasticity and plasticity, which were solved by finite element method. Defect locations on the pipeline have been used as random input data of the mathematical model. Reiterating solution of this problem is connected with a number of difficulties caused by the building of the set of the geometrical models, obtain a numerical solution and post processing of the results.

To solve this problem, it is necessary to develop a software tool that allows automated building of the geometric model, finite element meshing procedures, carrying out the calculations, saving the results with further processing.

1.2. Pipeline part with pitting corrosion modeling

A fragment of the main pipeline in accordance with the National State Standard EN 10208-2, which corresponds to the API Spec.5L, DIN 17120, GOST 31447-2012, BS 4515: 1992 have been modeled. The parametric model of a pipe part with pitting corrosion defects was built (Fig. 1). Only one quarter of middle pipe fragment (l_2) is pitted. The remaining three quarters are defects free. The defect position within cylindrical coordinates system (ρ, φ, z), where *z-axis* coincides with the axis of the pipe, is determined by two coordinates φ, z. The third coordinate is determined on the basis of the condition that the center of the defect is on the outer surface of the pipe. It's assumed that the defects in φ and z directions appear randomly and they coordinates of centers obey to uniform PDF. The number of defects (pits) is assumed equals to 25, 50, 70, and 100 pits, which corresponds to 650, 1300, 1950 and 2600 pits/m^2. The parameters of the model are given in Table. 1. The pipeline part is loaded with internal pressure $P = 2.5$ MPa. The mechanical properties of the material were taken from the recommendations for these standards (Table. 2).

To determine the parameters of the stress–strain state of the pipeline part, the finite element method implemented in ANSYS software was used. A pipeline part geometric model on the basis of a parametric model (Fig. 2a) as well as a finite element model on the basis of the geometric model (Fig. 2b) has been created. The boundary conditions are shown in Fig. 1 (with UX, UY and UZ marked places and direction of model fixation). Such boundary conditions, on the one hand, ensure the absence of edge effects at the ends of the pipeline part; on the other hand, this pipeline appears to be loaded only by the internal pressure. The pitting defect may produce significant local stresses. They can be greater than the yield stress limit. So, it is necessary to take into account plastic deformation. To ensure this, in the finite element model a bilinear elastic-plastic material model was used. Its parameters are given in Table. 2.