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COMPARISON OF THE RESULTS OF SOLVING THE PROBLEM OF FRACTURE MECHANICS FOR A PIPE WITH A NON-THROUGH CRACK

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ABSTRACT

Dangerous conditions with respect to pipelines are often caused by sharp defects which occur in pipe walls. Non-through surface cracks attract particular interest. Generally such cracks have a compound front form, in other words, they are multiparameter. Modern methods of nondestructive inspection do not give complete information on the front shape with adequate accuracy. In global practice defects are approximated with the semielliptical cracks to simplify calculation methods. In this case the defect is considered as a two-parameter one, and it is only defined by the maximum depth and length.

This paper examines a steel pipe, which has been weakened by the semielliptical non-through surface crack. The crack has a longitudinal orientation and is common to the external pipe area. The pipe is exposed to internal pressure. Fracture mechanics problem is resolved with the ANSYS CAE-system. Stress intensity factor distribution for the crack front points is under analysis. These values were obtained by using invariant J-integral. J-integral values were calculated using the integration over a region technique. The obtained results are compared with the data published by other authors. These data resulted from the analysis of pipes and cylindrical pressure vessels weakened by non-through cracks. The results of numerical modelling correlate accurately with the existing solutions. The accuracy of the fracture mechanics problem solution can be significantly increased by using regular mesh with multiple finite elements along the crack front. The investigation of fracture mechanics parameters identified the presence of the edge effect, common to the area where the crack front goes to the pipe surface. Edge effect refers to the local maximum values which are much higher than the crack front end points. These values should be used while investigating the crack propagation under variable loadings, that is when pulsations take place in loaded condition.

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Dangerous conditions to the pipelines, and in some cases, destruction of pipelines used for transportation of hydrocarbons are often caused by sharp crack-shaped defects of a technological or operational origin [1, 2]. Non-through surface cracks (taking into consideration relatively small thickness of the pipe wall) attract particular interest. Such defects have a dimensional nature and are generally multiparameter. Modern methods of operational nondestructive inspection give complete information on the found defects only in some cases. Therefore in national and global practice, defects are approximated with the semielliptical cracks in case of simplification of calculation methods and incomplete information on the defect [3–16].

This paper examines a steel pipe 220×10, which has been weakened by the semielliptical non-through surface crack that has a longitudinal orientation and is common to the external pipe area. The defect has following dimensions: depth $l = 5$ mm; half of the length $a = 10$ mm. The pipe is exposed to the following internal pressure: $p = 5$ MPa. In order to increase the effect of the shell curvature on the obtained results, a quite thick-walled pipe with a small diameter was chosen.

Fracture mechanics problem is solved with the ANSYS CAE-system using macro programs described in the paper [17]. The modelled fragment of the pipe wall with a crack is shown in Fig. 1, where

$$s = 4\max(l, a)\,; \quad \varphi = \frac{2s}{D}.$$

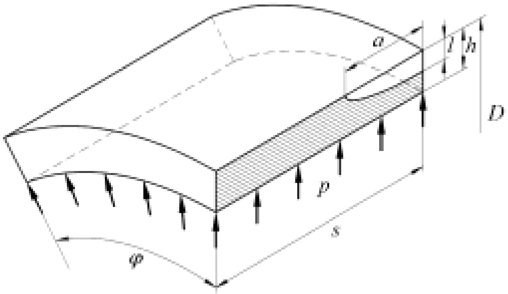

Fig. 1. Wall fragment with a longitudinal external crack

The loading is applied by pressure p, which is applied to the inner surface of the pipe. Boundary conditions applied to all the side faces of the fragment under examination act as symmetry conditions. In this case they do not have any effect on the stress-strain state in the area of the examined defect since the dimensions of the fragment s and φ are large enough.

The finite element layout in the vicinity of the crack is shown in Fig. 2. It should be noted that the use of a regular radial grid in the volume surrounding the crack front provides a high accuracy of calculation of the fracture mechanics parameters.

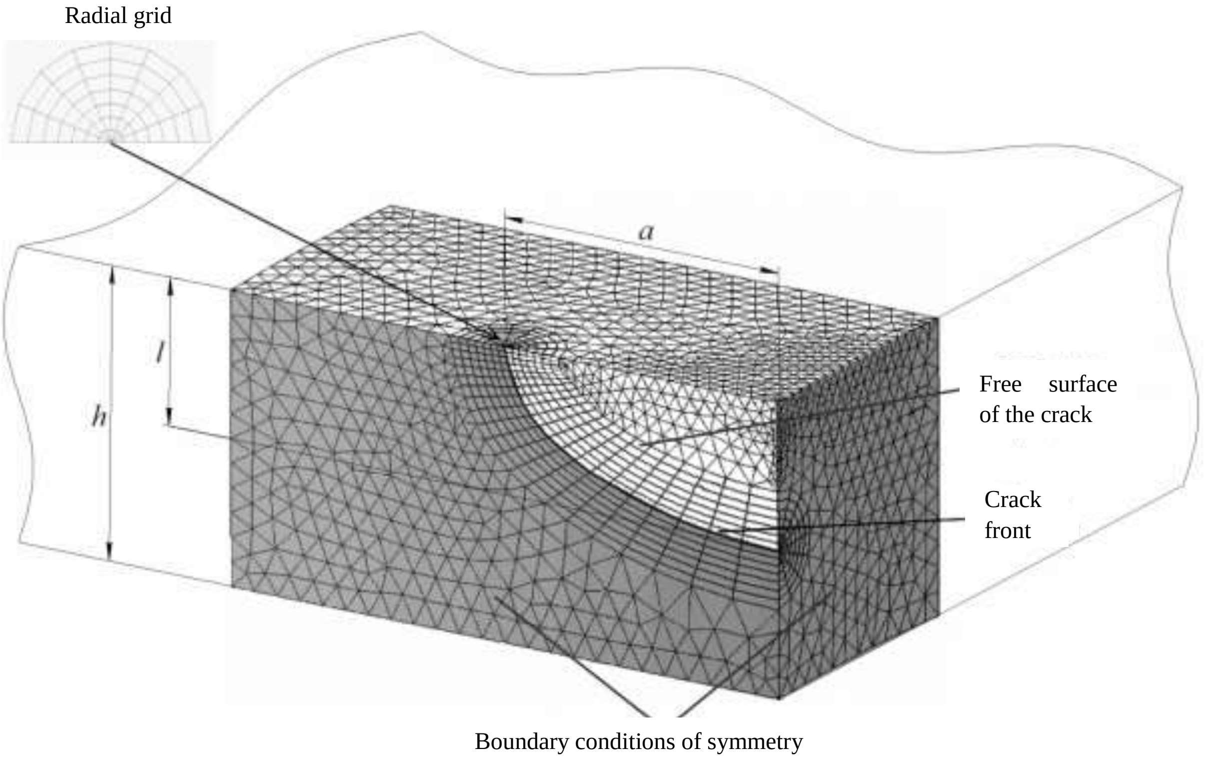

Fig. 2. Finite element layout

Stress intensity factor values along the crack front are calculated using the formula

$$K_{\mathrm{I}}(\theta) = \sqrt{\frac{E}{1-\mu^2}\,J(\theta)}\,,$$

where E and μ define elasticity module and the Poisson ratio of the pipe material; $J(\theta)$ means values of the *J*-integral at the front points, calculated numerically using integration over a region technique, which is currently the most accurate in the finite element modeling; θ means the angular coordinate of the front line point [17].

It should be pointed out that the literature contains a considerable amount of formulas for calculating stress intensity factors in pipes and pressure vessels with surface cracks.

For example, the papers [18, 19] which examine the calculation of K_{I} along the front of a semielliptical non-through surface crack in a cylindrical shell exposed to internal pressure contain the following formula:

$$K_{\mathrm{I}}(\theta) = \frac{pR_o}{h}\sqrt{\pi l}\,\frac{C_h C_c}{\Phi}\left(\sin^2\theta + \frac{l^2}{a^2}\cos^2\theta\right)^{0,25}, \quad (1)$$

where R_o and h define outer radius and thickness of the shell respectively.

Φ here means a complete elliptic integral of the second kind, calculated by the formula

$$\Phi = \int\limits_0^{\pi/2}\sqrt{1-\frac{a^2-l^2}{a^2}\sin^2\varphi}\,d\varphi = \sqrt{1+1,464\left(\frac{l}{a}\right)^{1,65}}\,.$$

The value C_h in formula (1) is a crack geometry correction and is calculated by

$$C_h = \frac{1+0,122\left(1-\dfrac{l}{2a}\right)^2}{\sqrt{1-\left(\dfrac{l}{a}\right)^4}}\,,$$

whereas the value C_c has a meaning of a shell curvature correction and a shell thickness correction, it is calculated by the following formula:

$$C_c = \left[0,481\alpha + 0,386e^{-1,25\alpha} + 0,614 - 1\right]\frac{l}{h} - 1,$$

where $\alpha = \dfrac{a^2}{R_o\,h}\sqrt{12\left(1-\mu^2\right)}$ is a nondimensional parameter characterizing the relative length of the crack.

Another most used and tested formula for calculating stress intensity factors for cylindrical pressure vessels with a semielliptical non-through surface crack on the inner or outer surface is [20]:

$$K_{\mathrm{I}}(\theta) = 0,97\,f_c\,F(\theta)\,\sigma\sqrt{\frac{\pi a}{Q}}\,, \quad (2)$$

where f_c is a shell curvature correction calculated by the formulas [21, 22]:

– for a crack on the inner surface

$$f_c = \left[\frac{R_o^2+R_i^2}{R_o^2-R_i^2} + 1 - 0,5\sqrt{\frac{a}{h}}\right]\frac{h}{R_i}\,;$$

– for a crack on the outer surface

$$f_c = \left[\frac{R_o^2+R_i^2}{R_o^2-R_i^2} - 1 + 0,5\sqrt{\frac{a}{h}}\right]\frac{h}{R_i}\,,$$

whereas R_i and R_o are inner and outer radii respectively.

The value σ in the formula (2) is an average circumferential stress

$$\sigma = \frac{p\left(R_o+R_i\right)}{2h}\,.$$

The value Q is calculated by the formula

$$Q = 1+1,464\left(\frac{l}{a}\right)^{1,65} = \Phi^2\,. \quad (3)$$

And, finally, the function $F(\theta)$ is calculated as follows

$$F(\theta) = \left[M_1 + M_2\left(\frac{a}{h}\right)^2 + M_3\left(\frac{a}{h}\right)^4\right] f(\theta)\,g(\theta)\,;$$

where

$$M_1 = 1,13 - 0,09\frac{l}{a}\,;$$

$$M_2 = -0,54 + \frac{0,89}{0,2+\dfrac{l}{a}}\,;$$

$$M_3 = 0,5 - \frac{1}{0,65+\dfrac{l}{a}} + 14\left(1-\frac{l}{a}\right)^{24}\,;$$

$$f(\theta) = \left[\left(\frac{l}{a}\right)^2\cos^2\theta + \sin^2\theta\right]^{0,25}\,;$$

$$g(\theta) = 1 + \left[0,1+0,35\left(\frac{l}{h}\right)^2\right]\left(1-\sin\theta\right)^2\,.$$

For external semielliptical surface cracks with a longitudinal orientation in cylindrical vessels, the paper [23] gives the following formula for calculation of the stress intensity factors at the defect front points:

$$K_{\mathrm{I}}(\theta) = \frac{pR_i}{h}\sqrt{\frac{\pi l}{Q}}F_e(\theta)\,, \quad (4)$$

where Q is calculated by the formula (3); F_e is an adjustment factor calculated as follows

$$F_e(\theta)=\frac{h}{R_i}\cdot\frac{R_i^2}{R_o^2-R_i^2}\times$$
$$\times\left[2G_0+2\frac{l}{R_o}G_1+3\left(\frac{l}{R_o}\right)^2G_2+4\left(\frac{l}{R_o}\right)^3G_3\right].$$

G_j here defines influence coefficients, the values of which are given in the tables of the paper [23].

The European standard SINTAP [24] and the defect estimation technique R6 [25] developed in the UK to calculate the stress intensity factors at certain front points of a longitudinal semielliptic crack on the outer surface of an infinitely long pipe use the following formula:

$$K_{\mathrm{I}}=\sqrt{\pi l}\sum_{i=0}^{3}\sigma_i\ f_i\left(\frac{l}{h},\frac{2a}{l},\frac{R_i}{h}\right), \qquad (5)$$

where σ_i means coefficients of expanding the circumferential stresses in an undamaged part of a pipe into a series

$$\sigma(u)=\sum_{i=0}^{3}\sigma_i\left(\frac{u}{l}\right)^i,$$

u here is the coordinate measured from the outer surface of the pipe in the direction of the defect depth (change limits $0\le u\le l$).

The coefficients f_i in the formula (5) are tabulated functions, which depend on the geometric parameters of the pipe and those of the defect. The values of the coefficients for the deepest point of the crack and the points where the defect is showing on the outer surface are given in the standard [24].

Comparison of different solutions is shown in Fig. 3, which shows the distribution of the parameter K_{I} along the entire front of the examined semielliptic crack. Whereas the continuous line *1* represents our solution, the curves *2*, *3* and *4* are drawn using the formulas (1), (2) and (4) respectively, and the circles indicate the results calculated by the formula (5).

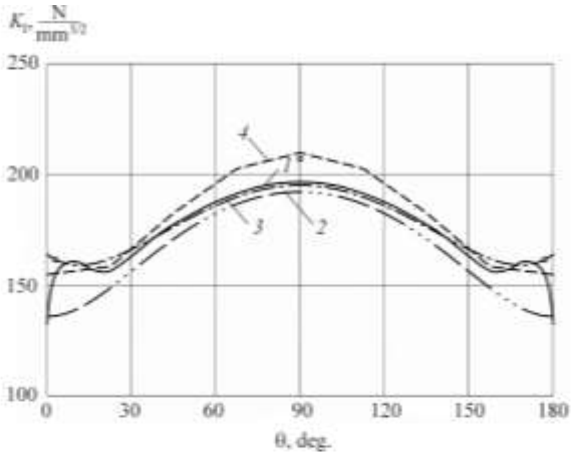

Fig. 3. Stress intensity factor distributions along the crack front

As one can see, our solution obtained with the ANSYS CAE-system is well within the results of other authors. At the same time, the use of a regular grid with a large number of elements along to the crack front significantly increases the calculation accuracy of the fracture mechanics parameters and allows to determine boundary effects in the form of local maxima located near the area where the defect is showing on the outer surface of the pipe. The values at these points are higher than those at the front end points, and these values should be used while investigating semielliptical crack propagation when pulsations take place in load conditions. As shown by the results of the parametric calculations (where the relative depth of the crack l/h varied in the range from 0.1 to 0.8 in increments of 0.1, and the relative length of the crack l/a varied from 0.1 to 2.0 in the same increments), similar boundary effects are found for cracks with other dimensions. This can be explained by the fact that on the free surface of an object the determining factor is the plane stress condition, and inside the object the determining factor is the plane deformation. Boundary effect is caused by the transition from one condition to another.

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