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Failure prediction of gas and oil drilling rig pipelines with axial defects

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Abstract

Working conditions of casing pipes in drilling rigs can significantly influence the initiation and development of damage in the material, and therefore also the safe service of the entire system. In this work, an integrity assessment of a steel pipe with initial defect (machined surface crack) is presented. The position of this defect is on the external surface; unlike transport pipes, where internal surface is often endangered due to the contact with the fluid, casing pipes are often exposed to damages at the external surface. Analyzed crack is in axial direction, bearing in mind that this type of defect most significantly decreases the load carrying capacity of the cylindrical pressurized components.
A pipe segment exposed to internal pressure is analyzed experimentally and numerically, using the finite element method. The experimental setup included the tracking of crack mouth opening displacement (CMOD) values, as well as *J* integral, which is determined by application of direct measurement. Criteria for pipe failure are determined on finite element models of the pipe; fracture initiation and plastic collapse are considered as failure mechanisms. The size of the crack is varied in the finite element models; several 3D models with different crack sizes (length and depth) are evaluated. Dependence of maximum internal pressure on the defect size is obtained. 2D plane strain models are also examined, with an aim to determine the applicability limits of this simplified approach. Based on the obtained results, integrity assessment criteria for the analyzed geometries are discussed.

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Nomenclature

a	crack depth
A	percentage elongation at fracture
COD	crack opening displacement
CMOD	crack mouth opening displacement
J_{Ic}	critical value of the J integral
L	crack length
p	pressure
R	pipe radius
t	pipe wall thickness
R_e	yield strength
R_m	ultimate tensile strength

1. Introduction

Working loads of pipelines used in oil and gas drilling rigs, mechanical and thermal loads, are typically coupled with the effects of the corrosive environment which can accelerate the initiation and development of defects in the material. Therefore, structural integrity assessment for pipes with defects is very important for ensuring the safe exploitation and prediction/prevention of possible failure scenarios. In this work, a damaged pipe, manufactured by high frequency contact welding (HF) of API J55 steel, is considered; influence of a defect (machined surface crack) on the load carrying capacity is analyzed. The crack is in axial direction, bearing in mind that this type of defect is the most severe for the cylindrical pressurized components.

Many recent investigations (e.g. Kim et al. (2002), Huh et al. (2007), Berg et al. (2008), Kozak et al. (2010), Gubeljak et al. (2007), Pati et al. (2007), Dutta et al. (2005), Rakin et al. (2012), Dimić et al. (2013), Medjo et al. (2012)) have dealt with the analysis of the deformation behavior, failure, integrity assessment and remaining service life estimate of pipelines. In order to achieve a good assessment, a correlation between the level of damage (expressed through the crack size) and operating conditions is necessary, i.e. an application of the rule that fracture initiates when the applied crack driving force reaches a critical value.

Experimental work presented in this paper includes testing of a pipe segment (taken from a drilling rig pipeline) with axial crack exposed to internal pressure. J integral value for the surface crack on the pipe is determined by so-called direct measurement, which includes the use of combined experimental - computational procedure. Integrity is assessed through determining the loads corresponding to the two distinct failure modes - crack growth initiation and plastic collapse of the ligament ahead of the crack front. Crack growth initiation is predicted by transferring the critical value of the J integral from the fracture specimen, while elastic - perfectly plastic material behavior is applied for plastic collapse analyses, Kim et al. (2002), Huh et al. (2007), Rakin et al. (2012).

Besides the finite element model resembling the tested crack geometry, several 3D models with different crack sizes are evaluated using Abaqus/Standard. Dependence of maximum internal pressure on the defect size is obtained. Simplified 2D plane strain models are also examined, with an aim to determine the applicability of such approach; these models correspond to the pipe with an infinitely long crack.

2. Experimental testing

Specimens for determination of material properties were cut from the casing pipe (the pipe was manufactured by high frequency, HF, welding - producer US Steel, Serbia). The pipe was withdrawn from a drilling rig during a reparation procedure after about 70000 hours (8 years); this period is much shorter than the designed service life (up to 30 years). The pressure test is conducted on a pipe segment capped at both ends (by welding), Fig. 1. The main dimensions of the pipe and the crack are shown in Fig. 1; the nominal pipe wall thickness t is 6.98 mm, crack length L is 200 mm, while crack depth is 3.5 mm. The loading (internal pressure) was increased to the maximum value of 220 bar. The strains in the vicinity of the pre-crack were determined by series of the strain gauges. The crack mouth opening displacement (CMOD) was measured using COD gauge.

Chemical composition and main tensile properties of API J55 steel are given in Tables 1 and 2. More details on the specimens testing can be found in the paper Šarkoćević et al. (2009), where experimental testing was performed on the specimens cut from the exploited pipeline, as well as those cut from a new pipe of the same grade.

Table 1. Chemical composition - API J55 steel

C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Al
0.2924	0.233	0.963	0.013	0.0216	0.0995	0.0579	0.0123	0.003	0.131	0.025

Table 2. Tensile properties - API J55 steel

R_e [MPa]	R_m [MPa]	A [%]
380	562	33

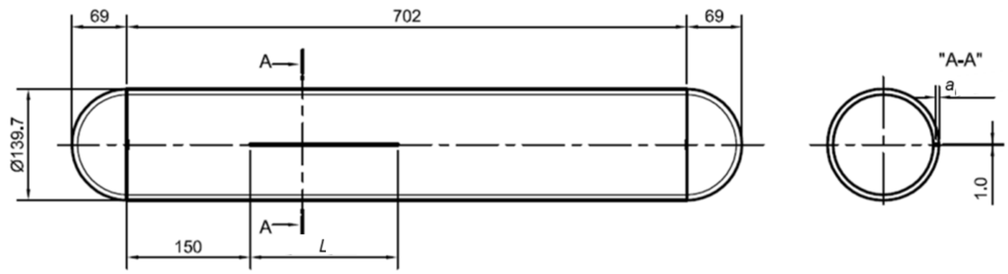

Fig. 1. Dimensions of the pipe and crack

Direct J integral measurement, Read (1983), is applied in this work; unlike the standard evaluation procedure, it is based on the path independence of this parameter. Hence, this method is more universal in comparison with the standard ones. However, it is more complicated and expensive, since it requires the use of the strain gauges and their chains for measuring strains at many locations, with short distances among them.

3. Numerical analysis

Numerical analysis is performed by the finite element method (FEM), using the software package Abaqus (www.simulia.com). Three-dimensional model, consisting of 20-node elements, is shown in Fig. 2 (a). Due to the symmetry of the geometry and loading, one quarter of the pipe is considered. The geometry of the crack is approximated by rectangular shape. To replace the influence of the dished ends, axial loading is introduced at one end of the FE model (of course, in addition to the pressure loading on the internal pipe surface). The J integral is calculated using the domain integral method. An example of domain for J integral calculation is shown on the 2D model of the cracked pipe, Fig. 2(b). The crack dimensions (length and depth) in the finite element models are varied, with the aim to determine the influence of the defect size on the load carrying capacity of the examined pipe.

The FE analysis is also conducted on two-dimensional plane strain models, in order to assess the possibilities for this simplification. The model is shown in Fig. 2(b); this model represents a pipe with an infinitely long axial crack. The goal is determine the crack length which can be correctly represented by this simplified model in terms of failure prediction.

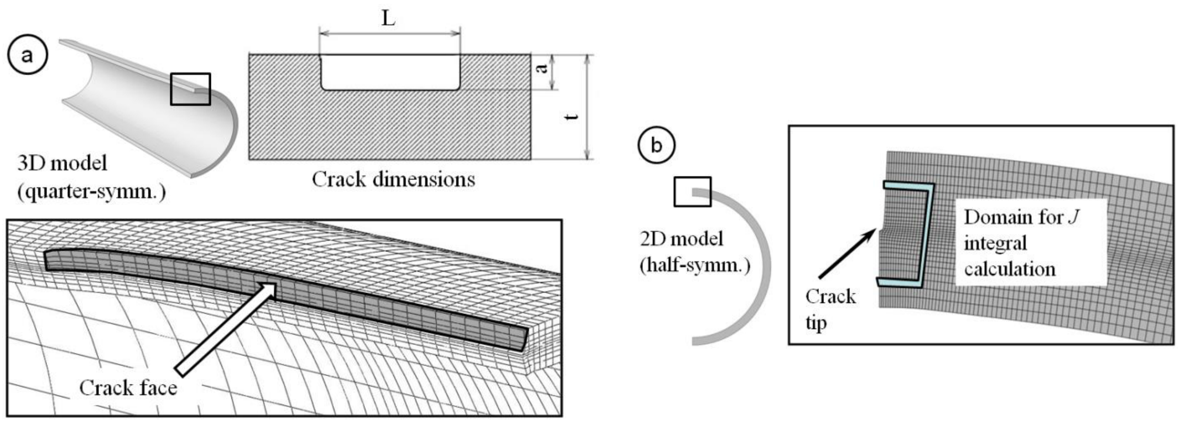

Fig. 2. 3D (a) and 2D (b) finite element models of the pipe with enlarged view near the cracks

4. Results and discussion

The CMOD values during the increase of loading obtained by FEM and experimentally are very similar, as shown by Rakin et al. (2012). The increase of the *J* integral with increase of loading level is shown in Fig. 3(a). Numerically determined values do not deviate significantly from the experimental ones, although certain differences exist. The differences become lower for higher pressure values (especially close to the critical value J_{Ic}). Extrapolation of experimental results is applied, due to the fact that the experimental test did not result in the pipe final failure.

The influence of the crack length on the *J* integral values is shown in Fig. 3(b). The model with crack length 200 mm corresponds to the experimentally examined pipe, while additional 3D models with 50 and 300 mm long cracks and a 2D model are analyzed. *J* integral increases more slowly for the shorter crack, while the 3D models with 200 and 300 mm long cracks give similar results as the 2D model. Due to the plane strain calculation, 2D model actually resembles an infinitely long crack. This leads to the conclusion that two-dimensional simplification is justified for longer cracks, which is further examined by comparing the failure conditions.

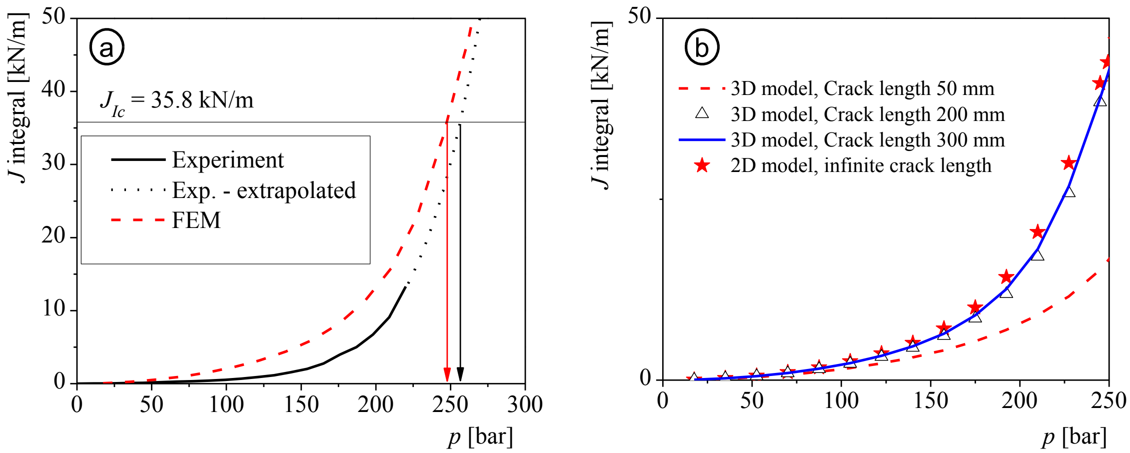

Fig. 3 (a) Experimental and numerical *J* integral values, (b) *J* integral - 2D model and 3D FE models with different crack lengths

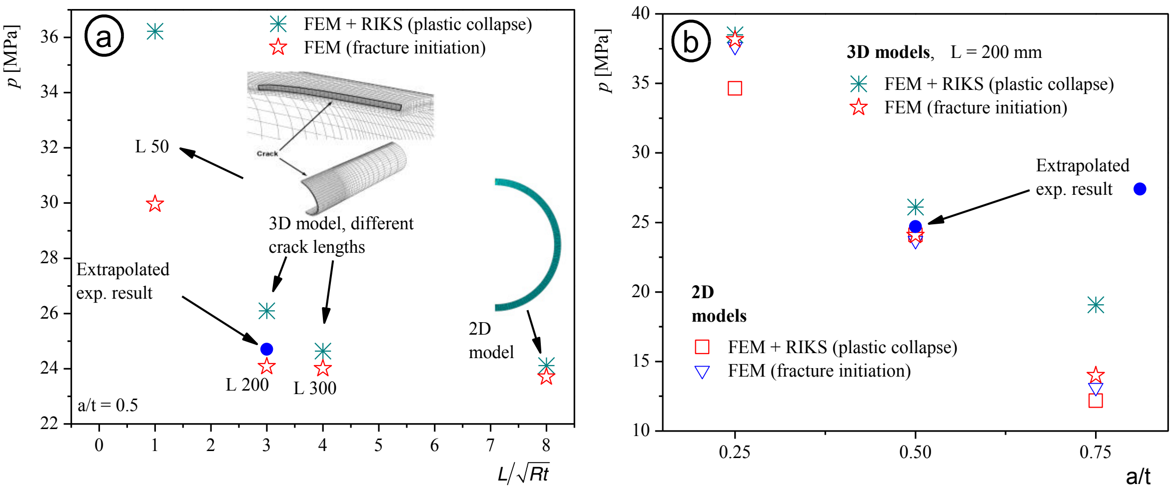

Fig. 4. Dependence of maximum pressure (corresponding to fracture initiation and plastic collapse) on the crack length (a) and depth (b)

The critical value of the J integral for the material of the analyzed pipe is determined on CT specimens by Šarkoćević et al. (2009). When this limit is set to the J integral obtained on the pipeline, the pressure corresponding to crack initiation in the experimentally examined configuration is about 250 bar, Fig. 3(a). However, the structure can also fail by plastic collapse of the ligament, which is assessed in this work by utilizing the elastic - perfectly plastic material behavior in the FE model, Kim et al. (2002), Huh et al. (2007), Rakin et al. (2012). The problems related to convergence in such calculations are treated by application of the modified RIKS option in Abaqus. These calculations resulted in the limit loads (pressure values) for the analyzed configurations.

The decrease of the load carrying capacity with the increase of the crack length L (crack depth a=3.5 mm, ratio of crack depth and pipe wall thickness a/t=0.5) is shown in Fig. 4(a); the plastic collapse is predicted at higher loading levels than the fracture initiation for all the crack lengths. This difference decreases with the increase of the crack length. The depth of the crack a is also varied, for the constant crack length L=200 mm, Fig. 4(b). It can be seen that both 3D and 2D models give similar fracture initiation and plastic collapse predictions for the ratio a/t=0.5. For the cracks with increased depth (a/t=0.75), 3D model predicts a higher loading value corresponding to the plastic collapse. On the other hand, 2D calculation with shorter crack (a/t=0.25) gives lower level of plastic collapse load.

From Figs. 3 and 4, it can be seen that the usage of simplified 2D model is justified for longer axial cracks, because both J integral values and maximum pressure values for these cracks approach the results of the plane strain model. Of course, the advantage of the simplified model can be seen through much shorter computation time (up to 100 times shorter than for the analyzed 3D models). Conservatism, as one of the important principles of structural integrity assessment, is not endangered by the use of the 2D models, which are shown to result in minimum values.

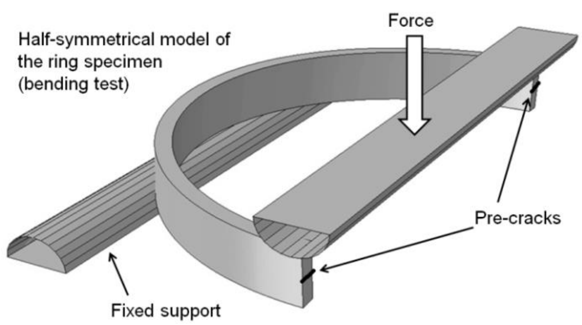

Fig. 5. Pipe-ring specimen - FE model

Current authors' efforts are directed towards the analysis of transferability of fracture mechanics parameters from non-standard pipe ring specimens, Gubeljak et al. (2014) and Likeb et al. (2013), to pre-cracked pipes. The stress-strain state in these geometries, as well as their failure conditions, will be considered. The pipe-ring specimens can easily be produced (i.e. simply cut from the pipe), which enables a quick and efficient testing of the pipeline material, for example in their as-delivered state. Also, the material history in these specimens is the same as for the pipes (e.g. residual stresses caused by manufacturing, welding, thermal treatment, etc.). The FE model of one such specimen exposed to bending is given in Fig. 5; half of the geometry is used due to the symmetry.

5. Conclusions

Integrity of pipes with axial surface cracks exposed to internal pressure is experimentally and numerically analyzed. Dependence of the maximum pressure on the defect length and depth is established, for both fracture initiation and plastic collapse as failure criteria. Finite element software package Abaqus is used for all computations. The crack length variation shown that a significant difference in loading levels corresponding to fracture initiation and collapse is obtained only for relatively short cracks. Besides the length, the depth of the crack is also varied; difference in predicted maximum loads between the 2D and 3D models exists for plastic collapse failure criterion. Limits for usage of simplified 2D plane strain models (in terms of the minimum crack length) are determined.

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References

Berg, E., Østby, E., Thaulow, C., Skallerud, B., 2008. Ultimate fracture capacity of pressurised pipes with defects - Comparisons of large scale testing and numerical simulations. Engineering Fracture Mechanics 75, 2352–2366.

Dimić, I., Arsić, M., Medjo, B., Stefanović, A., Grabulov, V., Rakin, M., 2013. Effect of welded joint imperfection on the integrity of pipe elbows subjected to internal pressure. Technical Gazette 20, 285–291.

Dutta B.K., Saini S., Arora N., 2005. Application of a modified damage potential to predict ductile crack initiation in welded pipes. International Journal of Pressure Vessels and Piping 82, 833–839.

Gubeljak, N., Vojvodić Tuma, J., Šuštaršić, B., Predan, J., Oblak, M., 2007. Assessment of the load-bearing capacity of a primary pipeline. Engineering Fracture Mechanics 74, 995–1005.

Gubeljak N., Likeb A., Predan J., Matvienko Y., 2014. Comparison between fracture behaviour of pipe-line ring specimens and standard specimens. Key Engineering Materials 577-578, 637–640.

Huh, N.S., Kim, Y.J., Kim, Y.J., 2007. Limit load solutions for pipes with through-wall crack under single and combined loading based on finite element analyses. Journal of Pressure Vessel Technology - Transactions of ASME 129, 468–473.

Kim, Y.J., Shim, D.J., Huh, N.S., Kim, Y.J., 2002. Plastic limit pressures for cracked pipes using finite element limit analyses. International Journal of Pressure Vessels and Piping 79, 321–330.

Kozak, D., Ivandić, Z., Konjatić, P., 2010. Determination of the critical pressure for a hot-water pipe with a corrosion defect. Materials and Technology 44, 385–390.

Likeb A., Gubeljak N., Predan J., Matvienko Y., 2013. Determination of ηpl factors for pipe - ring specimens using finite element analysis. 13th Conference New Trends in Fatigue and Fracture, Mechanical Engineering, Moscow, Russia.

Medjo, B., Rakin, M., Arsić, M., Šarkoćević, Ž., Zrilić, M., Putić, S., 2012. Determination of the load carrying capacity of damaged pipes using local approach to fracture. Materials Transactions - JIM 53, 185–190.

Pati, P.K., Shrivastava, S.K., Basu, S., 2007. Numerical analysis of crack initiation and growth in cylindrical geometries with an axial flaw. International Journal of Fracture 148, 291–301.

Rakin, M., Arsić, M., Medjo, B., Šarkoćević, Ž., Ivanović, I., Sedmak, A., 2012. API J55 steel casing pipe with an initial surface crack under internal pressure - determination of fracture parameters. Key Engineering Materials 488-489, 577–580.

Read, D.T., Experimental Method for Direct Evaluation of J-Contour Integral, ASTM STP 791, Philadelphia, Vol. II, pp. 199–208, 1983.

Šarkoćević, Ž., Arsić, M., Međo, B., Kozak, D., Rakin, M., Burzić, Z.,, Sedmak, A., 2009. Damage level estimate of API J55 steel for welded seam casing pipes. Strojarstvo: J Theory Appl Mech Eng 51, 303–311.