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ANALYSIS OF THE CORRODED PIPELINE SEGMENTS USING IN-LINE INSPECTION DATA

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ABSTRACT

Technical diagnostics of buried gas and oil pipelines is accomplished using magnetic and ultrasonic pigs. At present these methods allow to reveal corroded defects and define their sizes.
Simplified techniques that are widely used all over the world for evaluation of the remaining strength of corroded pipeline segments are conservative and hamper development of the modern in-line inspection tools.
The paper presents computation technology for numerical analysis of multiaxial nonlinear stress state of the corroded pipeline segments. All procedures of pipeline numerical analysis are completely automated.
Developed computation technology along with the modern in-line inspection tools give the opportunity for the transport company experts to obtain the high accuracy values of burst and maximum available operation pressures of the corroded pipeline segments. It allows to decrease accidents, to provide maximal economical effectiveness of technical inspection and reconstruction of pipeline networks.
Moreover, wide application of computation technology allows to give recommendations to the technical diagnostic tool companies for improvement of technical characteristics of their products.

***Keywords**:* Corrosion, Pipeline, Inspection, Computation technology, Strength, Measurement errors

1. Introduction

Generally, the main cause of high pressure gas and oil pipeline ruptures is metal loss in a pipe wall from corrosion. Particularly, GAZPROM gas company data show that corroded defects (general corrosion and pitting corrosion) are the primary causes of accidents. To increase safety level of operating pipelines, to reduce failures entailing harmful consequences it is necessary to reveal, to evaluate remaining strength and to repair timely all critical corroded segments.
Corroded segments of the underground pipelines are revealed on the in-line inspection (ILI) data obtained using magnetic flux leakage (MFL) and ultrasonic pigs. Recently the world-wide leaders in the sphere of ILI tools development achieved some success. For example, utilization of “smart” (or intelligent) MFL and ultrasonic high resolution pigs [1, 2] allows to measure accurately geometric shape (Fig.1) of the corroded regions and establish their location on the pipeline.

Fig. 1: Geometric shape of gas pipeline wall corrosion defined using ILI data.

At the same time to analyze stress state and evaluate remaining strength of the corroded pipeline segments it is used traditionally semi-empirical standard methods [3, 4] and their numerous modifications all over the world. These methods are based on simplified linear equations from theory of strength of materials. The common disadvantage of these methods application is the excessive conservatism. In most cases their usage gives essentially low estimates of remaining strength of the corroded pipeline segments resulting in unnecessary cutouts. It entails ungrounded expenditures for reconstruction. In some cases application of the methods like [3, 4] can entail underestimation of really critical corroded defects (group of defects). This underestimation followed by failure as a rule. That is why all great forces and expenditures of both modern technical inspection tools' vendors and consumers don't lead to decrease of pipeline failures because of conservatism and functional narrowness of standard methods for remaining strength estimation of defective pipes.
It should be noticed that simplified semi-empirical methods do not need the most part of data obtained using modern technical inspection tools. For example, if the methods [3, 4] are used it is necessary to know only two parameters - effective axial extent of the corrosion and maximum depth of corroded area (or the effective area of the metal loss). The detailed information about geometric shape of the corroded defects (Fig. 1) is not needed. So, these methods hamper development and improvement of the modern technical inspection methods and tools.
Computation technology for numerical simulation of multiaxial nonlinear stress state of the corroded pipeline segments considering all technical inspection data was developed at Computation Mechanics Technology Center of SPE VNIIEF-VOLGOGAZ Ltd. (CMTC). This technology allows to obtain the most accurate evaluation of remaining strength of the defective segments.

2. Computation technology for structural analysis of the corroded pipelines

The developed technology is meant for revealing the most critical corroded pipeline segments, computing burst and maximum allowable operating pressure (MAOP) for each segment, planning economically effective repair or replacement of critical segments. Structural analysis of nonlinear stress state of the pipeline segment is executed by finite element method (FEM) considering its multifactor loading and all technical inspection data including ILI-data, external inspection (displacement of the pipeline axis from the design position), geophysical research (soil shear and soil heaving, settlements), and etc.

The main points which are the base for the algorithm of structural analysis and evaluation of remaining strength of the defective pipelines can be outlined as follows [5]:

- analysis of nonlinear stress state of the pipelines is executed with minimal simplifications of their structure (including 3D geometry of the corroded defects);
- numerical simulation of the pipelines is executed step-by-step with successive usage of beam, shell and solid FE-models and using the results of the previous step for set of the boundary conditions at the following step;
- two simulation methods of nonlinear interaction between the pipeline and surrounded soil are used at different steps: semi-empirical dependences of soil resistance to axial and lateral pipeline displacements (at the first step); simulation of soil surrounding the underground pipeline segments as elastic-plastic continuum (at the next steps);
- burst pressure and MAOP (accounting safety margin) for each defective pipeline segment are determined basing on analysis results of multiaxial nonlinear stress state in the most stressed zones and basing on direct numerical simulation of pipeline rupture also.

Fig. 2: Solid model of the corroded pipeline segment.

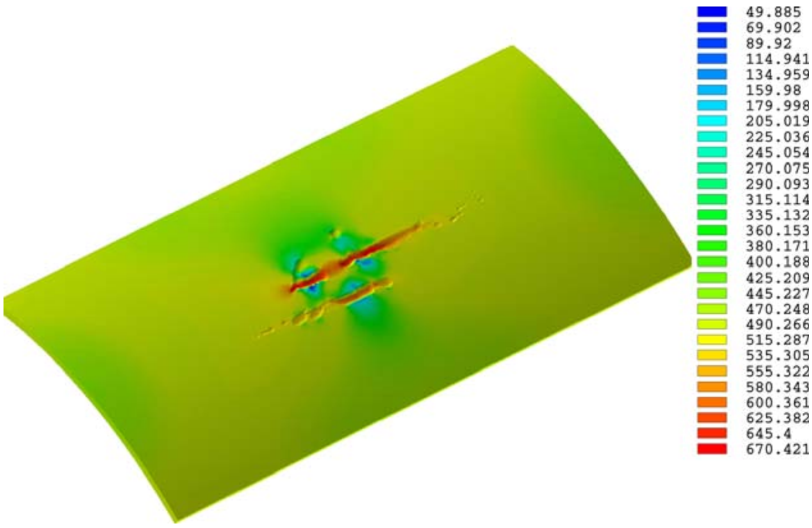

Fig. 3: Pattern of equivalent von Mises stresses [MPa] in the corroded pipeline segment.

Usage of the described technique allows to evaluate actual remaining strength of the corroded pipeline segments with the accuracy essentially exceeding the results of the methods [3, 4] or similar ones. Fig. 2 – 4 present the examples of analysis results for multiaxial nonlinear stress state of the corroded pipeline segments. This analysis was executed using the developed technology. Fig. 2 presents computation solid model of the corroded pipeline segment created according to ILI-data. Fig. 3 presents pattern of equivalent von Mises stresses in this segment under operating loads (pressure and temperature rise). Fig. 4 presents the results of numerical simulation of corroded gas pipeline segment's rupture under failure pressure.
The developed computation technology was validated by the results of full-scale hydrostatic testing for rupture of the pipes having artificial and natural corroded defects. Divergence of the calculated and experimental values of burst pressure did not exceed 5% in all cases.
It should be noticed that calculation of burst pressure for the corroded pipe using standard methods [3, 4] usually gives the error from 30% to 70%.

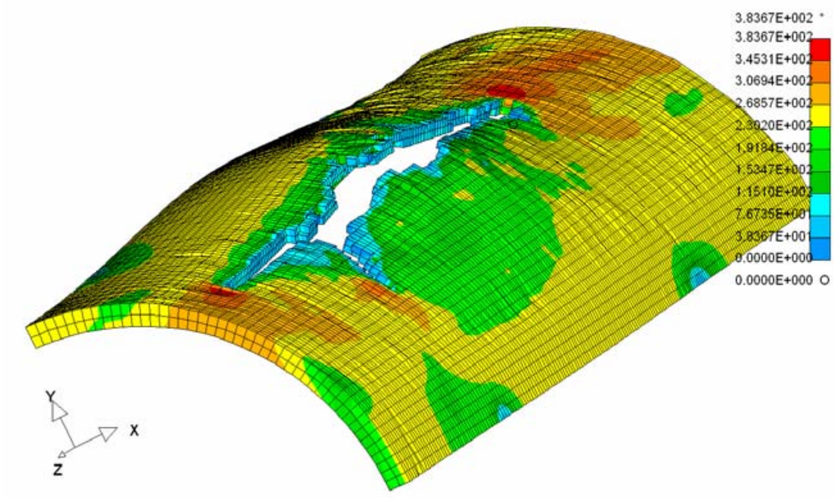

Fig. 4: Simulation of corroded pipeline rupture. Equivalent von Mises stresses [MPa] are shown.

3. Automation of corroded pipeline numerical analysis

Effective application of the developed computation technology can be proved by successful solutions of many practical problems concerned with analysis of remaining strength of corroded segments and maintenance of pipelines. These problems were solved by CMTC experts mutually with the experts from gas and oil companies. Solution of these problems has shown that it is necessary to develop program procedures allowing maximum automation of computation model generation, application of loads and assignment of boundary conditions, control for numerical analysis and assessment of the results. On the one hand, usage of theses procedures reduces essentially time which is necessary for analysis of the particular defective pipeline segment and excludes possible user's errors. On the other hand, it gives the opportunity to the users to become quickly familiar with the technology and apply it in their practice.
General-purpose commercial FEM-software were used as the tool for structural analysis of pipeline networks while development of the technology. At present the program modules for automated numerical analysis of stress state and evaluation of remaining strength of the corroded pipelines were realized in the environment of ANSYS (Fig. 5) and ABAQUS.
The user has to form the initial data file to work with the program modules meant for automated numerical analysis of stress state of the selected pipeline segment. This file is the spreadsheet of specified format which contains spatial coordinates of the key points of the pipeline axis line, physical properties of materials (pipes and soils), outside diameter (OD) and wall thickness of

the pipes. Also the user has to have the specified format file containing information about geometric shape of corroded region surface (“matrix of remaining thickness” [5]). The methods for this file formation can be different depending on the type and capabilities of the user’s technical inspection tools. For example, while using the smart pigs this information is in output data of ILI. This information has to be converted into the specified format only.

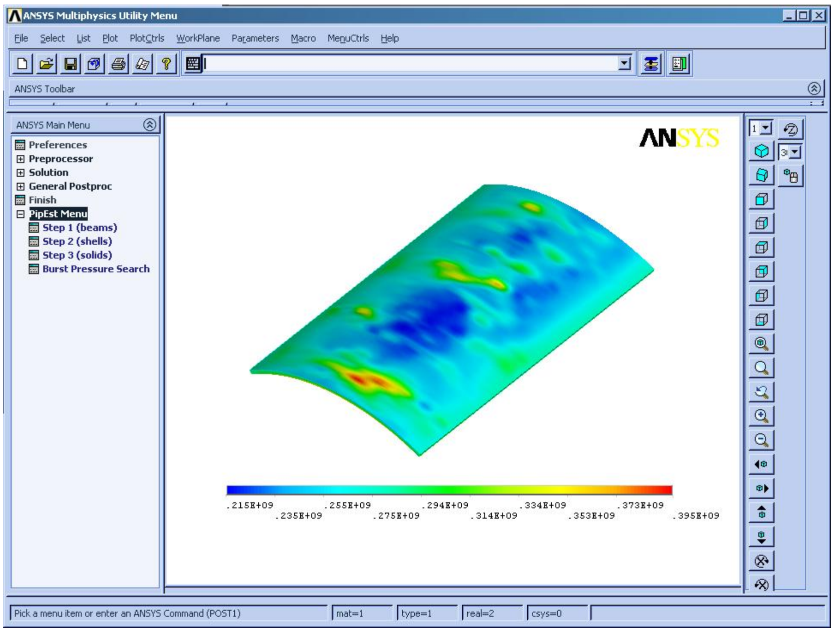

Fig. 5: Command menu of the computation technology in ANSYS GUI.

After preparation of the initial data the user starts the command file in FEM-software environment and inputs the required parameters in the dialog mode at different steps of analysis: the name of job, the names of initial data file and file of remaining thicknesses matrix, the values of operating loads and etc. All procedures of FE-models generation, numerical analysis and presentation of the results are executed automatically at three steps of technology and don’t require from the user any additional actions. Special program module included into the technology allows the user to predict accurately values of burst pressure and MAOP for each defective segment. It is possible as a result of automated execution of the corresponding iterative procedure.

Features of the computation technology are continuously enhanced. It gives to the user the most comprehensive tool for analysis of the defective pipelines. For example, the current version includes the procedures for automated numerical analysis of cold-bent corroded pipe elbows (accounting residual stresses and strains) and excavated and backfilled of the underground pipeline segments.

4. Effect of ILI measurement errors on remaining strength prediction for the corroded pipelines

As it was stated earlier, mathematical models allowing to predict with high accuracy the remaining strength of corroded pipelines are used in the computation technology. At the same time, to apply these models a lot of initial data are needed. These data are obtained on the technical inspection results, special experiments, and from reference literature. Of course, the particular values of initial data used while calculations contain different errors effecting on accuracy of the numerical simulation results. That is why CMTC made series of computation experiments on demand of SPP International gas transport company. These experiments were made to estimate effect of initial data errors on the results of numerical analysis of pipeline strength.

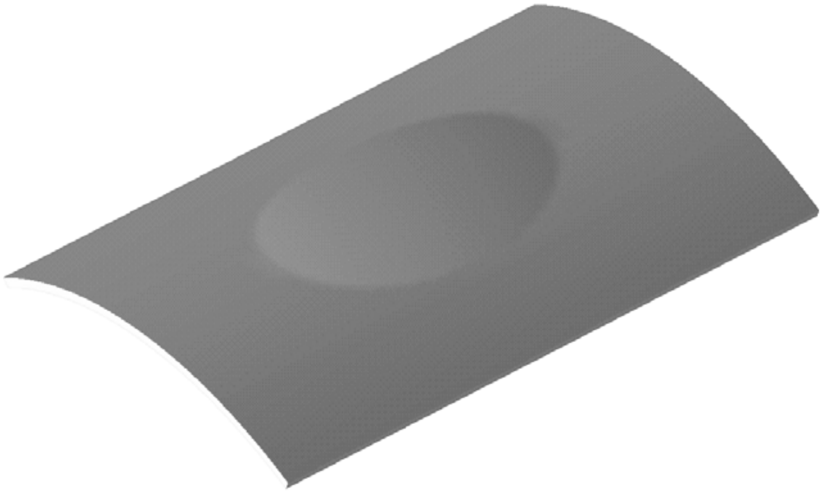

Fig. 6: The model of semi-elliptical corroded cavern of the pipeline.

Let's consider one of the obtained estimation – measurement accuracy of MFL pigs of the corrosion depths. According to data presented by vendors, accuracy of the modern MFL pigs is $\pm 0.1 \div 0.15t$ (*t* – pipe nominal wall thickness) while sizing the depth of the corroded defects. It should be noticed that geometry of the corroded caverns on the pipelines represents 3D surface of complex irregular topology (see Fig. 1). It is obviously that investigation of errors effect of the depth measurement on the arbitrary shape caverns is the problem with infinite set of varying parameters. It can't be solved. That is why idealized semi-elliptical caverns were studied.
The basic structure was the underground gas pipeline segment with *OD=1220mm* and nominal wall thickness *t=13.6mm*; the segment had one semi-elliptical cavern with the sizes $400 \times 300mm$ and the maximum depth *0.4t* (Fig. 6).

Table 1: Analysis results of remaining strength of the model corroded caverns.

DEPTH OF CAVERN	***MAXIMUM EQUIVALENT VON MISES STRESSES,*** *[MPa]*		***BURST PRESSURE,*** *[MPa]*	***DIFFERENCE BETWEEN UTS OF STEEL AND MAXIMUM EQUIVALENT STRESS UNDER BURST PRESSURE,*** *[%]*
	PRESSURE *7.35 MPa*	***BURST PRESSURE***		
0.25t	*470.66*	*656.67*	*12.21*	*-0.41*
0.30t	*480.06*	*654.52*	*11.55*	*-0.08*
0.35t	*483.13*	*654.83*	*10.86*	*-0.13*
0.40t	*489.57*	*649.08*	*10.08*	*0.75*
0.45t	*507.98*	*653.53*	*9.34*	*0.07*
0.50t	*530.44*	*649.65*	*8.51*	*0.66*
0.55t	*599.79*	*649.09*	*7.69*	*0.75*

Model caverns with maximum metal loss *0.25t*, *0.30t*, *0.35t*, *0.45t*, *0.50t*, *0.55t* were created using the basic cavern. Pipe material is steel of grade *X70* (*E=206GPa*, *SMYS=480MPa*, *UTS=600MPa*). Operating loads: pressure *7.35MPa*; temperature rise $40°C$. Structural analysis of all models was executed according to the presented above computation technology including determining burst pressure with accuracy not less than 1%. Table 1 presents the results of the computation experiments.

Table 1 shows that scattering in relative errors while defining remaining thickness of the pipe wall ($\pm 0.1 \div 0.15t$) effects essentially on calculated burst pressure for the defective segments. In our case, burst pressure determined for the cavern with the error *-0.15t* exceeds calculated burst pressure for the basic cavern in 21.1% and on the contrary, burst pressure determined for the cavern with the error *+0.15t* is less than calculated burst pressure in 23.7%.

At present to provide pipeline safety and economical effectiveness of ILI [5] it is necessary to determine the calculated burst pressure for the most critical corroded defects (with the depth about *0.40t*) with the error not more than $\pm$5%. Additional computation experiments showed that accuracy of measured cavern depth has to be not less than $\pm$2.5% from maximal cavern depth (i.e. about $\pm 0.01t$) to meet this requirement. So, application of new computation technologies for numerical analysis of remaining strength of the corroded segments increase safety level of pipeline on the one hand. On the other hand necessity of practical usage of these technologies defines directions and stimulates progress in the sphere of development of non-destructive testing methods and tools and states scientifically justified requirements for technical characteristics of the products made by the company-manufacture.

5. Conclusions

In conclusion it should be noticed the main points of the paper:

- widely applied standard methods for evaluation of remaining strength of the corroded pipeline segments (ANSI/ASME B31G, RSTRENG and etc.) are very simplified, excessively conservative and can't provide the required safety level; they hamper development of modern technical inspection tools also;
- usage of computation technologies developed on the base of modern achievements in computation mechanics and computer technologies allows to execute high accurate evaluation of actual carrying capacity of the defective pipelines, to decrease accidents, to provide maximal economical effectiveness of technical inspection and reconstruction of pipeline networks;
- wide practical application of new computation technologies stimulates progress in the sphere of development of non-destructive control methods and tools and raise competitive capacity of new technical inspection tools for pipeline.

6. References

[1] Duckworth H.N.: "Smart" pigs offer more definitive integrity data, Pipeline and Gas, Vol. 83, No. 6, 2000, 50-52.

[2] Ellis Ch.A., Lopes A.: In-line inspection ensures reliability, Pipeline and Gas, Vol. 1, No. 1, 2002, 43-45.

[3] ANSI/ASME B31G, Manual for determining the remaining strength of corroded pipelines, ASME, New York, 1984.

[4] Kiefner J.F., Vieth P.H.: A modified criterion for evaluating the remaining strength of corroded pipe, AGA Pipeline Research Committee, report PR-3-805, Catalog No. L51609, 1989.

[5] Aleshin V.V., Seleznev V.E., Klishin G.S., Kobyakov V.V.: Numerical analysis of underground pipeline strength, Editorial URSS, Moscow, 2003.