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NUMERICAL SIMULATION OF A TRANSMISSION GAS PIPELINE DESTRUCTION

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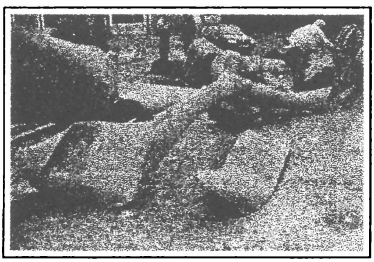
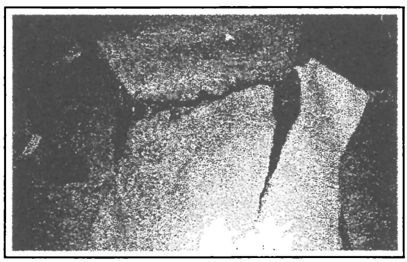
ABSTRACT: Both numerical and experimental investigations of the onset cause of a DN 900 transmission gas pipeline breakdown was undertaken by the research team of the Czech Technical University (CTU). Using retrieved parts of the damaged pipes an extensive surface planary corrosion defect (where the rupture initiated) was reconstructed. The undertaken problem, being extensive, was divided into two parts. This paper deals with the numerical simulation of the problem including an original approach to the pipe limit pressure assessment.

1 Introduction

Submitted to examination was the problem of a rupture on a DN 900 transmission pipeline, having nominal thickness of 12 mm, made of St 52.3 steel, spirally welded pipes, which exploded at the maximum working pressure not exceeding 5.6 MPa. After all parts of the damaged pipes (22 m, see Figure 1(a)) having been picked up, it was stated that the rupture had started in an extensive surface planary corrosion defect (Figure 1(b)).



(a)



(b)

Fig. 1: General view of the broken-down gas pipeline fragments (a) and retrieved parts of the damaged pipe where the responsible corrosion defect can be seen (b).

It was decided its dimensions to be reconstructed and thus a model defect to be manufactured. As the corroded pipeline part having undergone an intensive plastic deformation, main difficulties were to be encountered when the model defect thickness distribution were to be assessed

(which were to correspond most closely to the actual defect state prior to the rupture). Drawings of the model defect obtained are presented in detail in the successive paper *Experimental simulation of a transmission gas pipeline destruction; application of the ANSI/ASME standards* [Experimental ...]. In this paper, shown is the FEM mesh of the model defect.
FEM computations were carried out in two stages: after a preliminary computation to decide where strain gauges are to be placed, further computations were worked out using a finer FEM mesh and applying alternative defect remaining thicknesses of 4 and 3 mm, respectively. A complex of all results of the presented theoretical analysis (together with the experimental results, and the ANSI/ASME standards applications, presented in the next contribution [3]) enabled to estimate the breakdown onset conditions of the DN 900 pipeline.

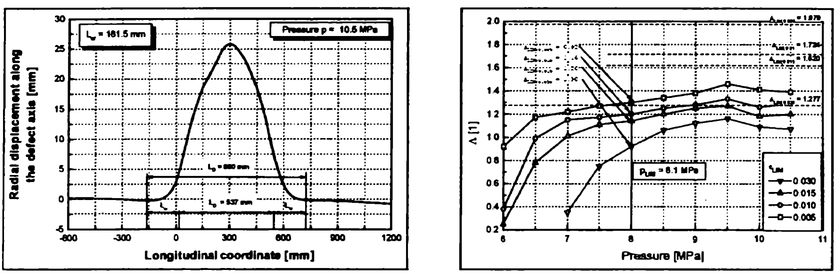
2 Limit analysis

This presented limit analysis, based on the CTU research team results, consists in finding such a pressure at which a relative plastic area length of the defect reaches a certain limit value:

$$\Lambda = L_P/L_C \rightarrow \Lambda_{LIM} \quad ,$$

where

- L_P ... representing a found-out plastic area length depending on a strain limit value εLIM determined from experiments
- $L_C = L_D - 2\,L_W$ ... representing the central part of the defect length (called "defect core") defined as an axial distance between two nearest displacement distribution wave hollows (called "defect length" L_D) reduced by two "wave lengths" (L_W) of an ideally symmetric pipe (see Fig. 2(a))



(a) (b)

Fig. 2: Graphical assessment of the defect core at $p = 10.5$ MPa (a); $\{\Lambda, p\}$ dependencies for different values of ε_{LIM}. Based on the model body actual burst pressure $p_{LIM} = 8.1$ MPa, indicated are corresponding values of Λ_{LIM} for the DN900-St52.3 model body. Λ_{LIM} for the DN800-X60 pipes are plotted in the right upper corner (b).

The limit analysis, presented on several international conferences [3],[2], had been developed for DN 800 pipes made of material X 60 (with very satisfactory results), and thus, not adhering to the quite proper input presumptions, the limit analysis methodology - applied on DN 900 pipe made of the St 52 steel (being markedly stiffer) - was considered as to be an informative one only. In this case, used were two FEM basic models, based on the minimum thickness area in the defect having $t_{min} = 4$ mm, with different mesh quality. The two model meshes were marked as CM 4 for the coarse mesh and FM 4 for the fine mesh and differ as follows: CM 4/FM 4 having 448/1489 isoparametric elements; with the number of nodes and degrees of freedom being 2160/7728 and 6480/23184, respectively. The dependence of the defect relative plastic area length on pressure, i.e. $\{\Lambda, p\}$, is plotted in Fig. 2(a) for different values of ε_{LIM}. Illustrated in Fig. 2(a) are also the limit values L_{LIM} based on the authors' research results obtained as far for DN 800 pipes, made of X 60 steel.

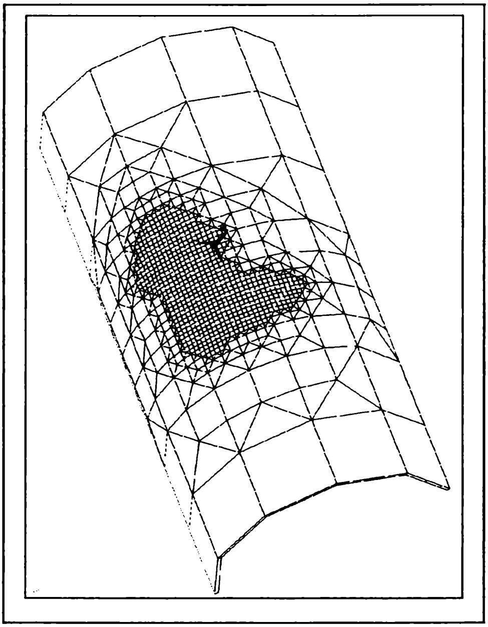


Fig. 3: FEM mesh of the model defect

It can be seen that none of the curves (computed up to the pressure $p = 10.5$ MPa) intersects its limit value. This result could be expected regarding to the higher value of the yield stress of the St 52.3 steel comparing with X 60. Nevertheless, the authors' results (DN 800, X 60) were further utilized to predict an approximate interval into which the limit pressure value of the DN 900 pipe, made of St 52.3 steel, could be laid. Used for the prediction were the test results of the DN 800 pipes, having machined artificial defects of the 360 mm length, [1]. Chosen from them were:

Defect no.	min. thickness t_{min} [mm]	limit pressure p_{LIM} [MPa]
I	3.7	9.5
II	4.5	11.72

Values of circumferential (σ_c) and equivalent (σ_e) peak stresses, obtained for the model defect, were compared with a fictive theoretical stress state (σ_f) resulting from considering the DN 800 pipe having its wall reduced to the defect minimum thickness. In this way, a coefficient $k_{800} = (\sigma_{c,e})/(\sigma_f)$ was determined. For the model defect ($t_{min} = 4$ mm) machined on the DN 900 pipe, a similar coefficient k_{900} was assessed. Plotted in Fig. 2(b) is a constructed dependence of the k magnitude on the pressure substituted by the linear regression.
Based on the limit pressures of the comparative (DN 800) areal defects, critical values of the coefficient k_{800}, being $k_{crit} = 0.78 \rightarrow 0.84$, were assessed. Presuming a similarity in the limit states of the compared areal defects, similar values of their critical coefficients k_{crit} could be expected. The two regression straight lines for the coefficient k_{900}, plotted in the Fig. 2(b), resulted from applying:

1. the preliminary computation as only as to $p = 4$ MPa (the dash line)

2. the further carried-out computation up to $p = 8$ MPa (the solid line)

Examining the intersections of the dash line with the horizontal lines corresponding to k_{crit}, a preliminary limit pressure interval: $p_{LIM} = 7.2 \rightarrow 7.8$ MPa, was estimated; whereas from the solid line resulted a new interval: $p_{LIM} = 8.1 \rightarrow 9.0$ MPa. The experiment on the model body determined the burst, i.e. limit pressure being $p_{LIM} = 8.1$ MPa, and thus confirmed this methodology may deliver a quality prediction. Furthermore, the computed dependencies $\{\Lambda, p\}$, plotted above in Fig. 2(a), in combination with the experimentally obtained $p_{LIM} = 8.1$ MPa, delivered very valuable parameters for the limit analysis of the DN 900 - St 52.3 pipes, namely the limit relative plastic area lengths of defect Λ_{LIM}. In further assessment procedure, the parameters Λ_{LIM} served to a satisfactory defect minimum thickness (t_{min}) estimation for the broken-down pipeline.
As the DN 900 - St 52.3 pipeline ruptured at the pressure of 5.6 MPa and the model body, though having an adequate size and shape of the model defect, burst at the markedly higher pressure, being $p_{LIM} = 8.1$ MPa, it was evident that the model defect minimum thickness $t_{min} = 4$ mm was overestimated. So that the model defect minimum thickness was reduced to be $t_{min} = 3$ mm and was denoted as FM 3. The FM 3 model was derived from the FM 4 model by reducing the defect remaining thickness from 4 mm to 3 mm in all the corresponding identification points. Resulting was a mesh having 350 isoparametric elements with 1868 midside nodes representing 5604 degrees of freedom. Since in this case both the defect identification and FEM meshing errors did not exceed in geometry the value of 1 mm, assessed was the lower boundary of the limit pressure estimation The new limit pressure prediction, based on the FM 3 model, utilized the experimentally assessed value $L_{LIM} = 1.20$ (being determined for $\varepsilon_{LIM} = 0.015$ and $p_{LIM} = 8$ MPa, Fig. 4(b)).

Accordingly to the limit pressure assessment explained above (using the FM 4 model) computed were (for the FM 3 model) analogical quantities (their dependencies on the pressure being plotted in series of similar figures) which e.g. for $\varepsilon_{LIM} = 0.015$, $p_{LIM} = 8$ MPa; delivered:

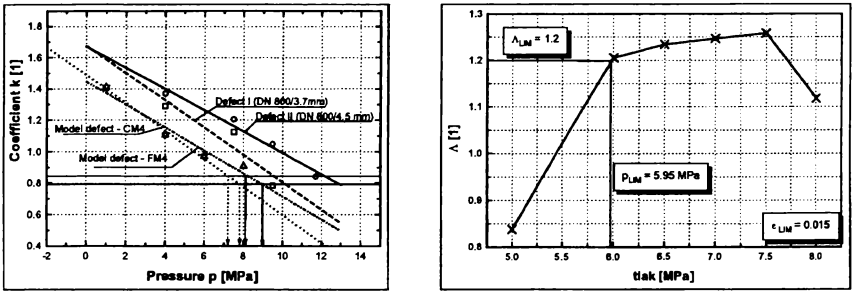
$$L_P = 552.5 \text{ mm}; \qquad L_D = 856 \text{ mm}; \qquad L_W = 181.5 \text{ mm}$$

from which

$$L_C = L_D - 2\ L_W = 493 \text{ mm}$$

and the relative plastic area length of the defect was found to be

$$\Lambda = L_P/L_C = 552.5/493 = 1.12$$



(a) (b)

Fig. 4: Regression and extrapolation of the FEM data obtained for the model defect (DN900-St52.3) and two preceding artificial defects (DN800-X60) (a); Graphical assessment of the limit pressure p_{LIM} (b).

In such a way obtained dependence $\{\Lambda; p\}$, plotted in Fig. 4(b), delivered the limit pressure estimation (for the DN 900 - St 52.3 model body while utilizing $\Lambda_{LIM} = 1.20$) to be $p_{LIM} =$ 5.95 MPa. This result coincides nicely with the actual operational pressure (being 5.6 MPa) of the broken-down pipeline.

3 Conclusion

The break-down cause of a DN 900 - St 52.3 transmission gas pipeline was to be assessed. From a number of distorted pipeline parts, reconstructed were the size and shape of the incriminated actual defect (AD) and, subsequently, according to the AD found-out dimensions designed and manufactured was a model defect (MD). As the AD underwent an extent plastic flow in the course of the rupture process, resulting in an progressive contraction of the AD remaining wall thickness t, the main problem consisted in a realistic assessment of the original t_{min} (i.e. that before the rupture started). Finally, based on a number of preliminary computations, the model defect minimum thickness was assessed to be $t_{min} = 4$ mm and the model defect was machined on the model body (made of a DN 900 - St 52.3 pipe taken from the accident vicinity). The MD theoretical analysis, by applying the FEM 211 software, were verified by the experiments consisting in the model body hydrostatic burst test, connected with the strain gauge measurement of the MD deformations (see [Experimental . . .]).
From the ANSI/ASME - B31.G evaluation modifications, the criterion *85% defect profile area*, delivering $p_{LIM} = 7.21$ MPa, reached very closely the limit pressure values obtained by both the FEM 211 theoretical and experimental examinations. Having gethered all the above mentioned theoretical and experimental results completed with the pipeline material metallographic examination, the following concluding decision about the pipeline breakdown cause was stated:

1. the model defect shape and dimensions were proved to have been determined very realistic

2. comparing the difference between the broke-down pipeline pressure with the model defect pressure (while considering the FM 3 model) being $\Delta_p = 8.1 - 5.6 = 2.5$ MPa, the corrosion defect dimensions could not have been in its limit state, i.e. the DN 900 - St 52.3 defect minimum remaining thickness could not have reduced as thin as $t_{min} = 3$ mm uny-

ielding rock subsoil in the defect locality which could cause an insulation damage and, subsequently, the corrosion process onset

3. another possible influence for the break-down onset could be material inhomogenity on the defect line.

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