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Strain Based Evaluation of Dents in Pressurized Pipes

Maziar Ramezani and Thomas Neitzert

Abstract**—**A dent is a gross distortion of the pipe cross-section. Dent depth is defined as the maximum reduction in the diameter of the pipe compared to the original diameter. Pipeline dent finite element (FE) simulation and theoretical analysis are conducted in this paper to develop an understanding of the geometric characteristics and strain distribution in the pressurized dented pipe. Based on the results, the magnitude of the denting force increases significantly with increasing the internal pressure, and the maximum circumferential and longitudinal strains increase by increasing the internal pressure and the dent depth. The results can be used for characterizing dents and ranking their risks to the integrity of a pipeline.

Keywords**—**dented steel pipelines, Finite element model, Internal pressure, Strain distribution.

I. Introduction

OIL and gas pipelines are often subject to outside force that causes geometric damages distortions, like dents, ovalizations, smooth localized buckles and wrinkles. The supply of energy has too often been disrupted by local pipeline leaks due to the damages. Historically, mechanical damage is the single largest cause of failures on pipelines [1]. It deforms the shape of the pipe, scrapes away metal and coating, and changes the mechanical properties of the pipe near the damage.

Among those simple geometric distortions, dents deserve special attention. Dents in pipelines are a common result of third-party damage or backfill loads over hard spots beneath the pipeline. They induce high localized stresses and have been the cause of a significant number of pipeline failures [2]. Thus, to ensure a safe pipeline operation, it is necessary to make a consistent assessment of the existing dents.

A dent causes a local stress and strain concentration and a local reduction in the pipe diameter. The dent depth is the most significant factor affecting the burst strength and the fatigue strength of a plain dent. The stress and strain distribution in a dent does depend on the length and width of the dent. Dents in a pipeline can also present operational problems even though they may not be significant in a structural sense [3]. Consequently, any dent remaining in a pipeline should be checked to ensure that it does not significantly reduce flow rates or obstruct the passage of standard or intelligent pigs.

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Few papers have been published previously to investigate the effect of dents on pipeline integrity. Orynyak and Shlapak [4] determined the ultimate load of ductile fracture for defects such as dents in pipelines. They proposed a theoretical model of the ultimate plastic state of a pipe with a dent infinite in longitudinal direction. Liu and Francis [5] developed a quasi-static analysis for in-service pressurized pipelines subjected to an external impact. Based on the assumed simple rigid, perfectly plastic deformation model, a simple relationship was obtained between the external denting force and the maximum dent depth. Iflefel et al. [6] conducted a FE numerical study of the capacity of a dented pipe to withstand combined pressure and moment loading. The strength of the dented pipe was first assessed under pure bending, applied in such a way that the dent was either on the tension side or the compression side. The strength of the dented pipe was then assessed under internal pressure loading. Finally, the behavior of the dented pipe under combined bending and pressure loading was assessed and interaction diagrams prepared.

Hyde et al. [7], [8] determined the elastic-plastic force-deflection analysis of unpressurized pipes with long axial and long offset indentations and unsymmetrical support conditions. Solutions from an analytical method were compared to the corresponding finite element solutions and experimental test results. The analytical method was based on a simple energy-based approach developed to predict the initial gradients of the force-deflection curves and the limit loads of the indented rings using linear beam bending theory and upper bound theories. Błachut and Iflefel [9] discussed the numerical results obtained for pipes subjected to transverse denting by a rigid indenter. They introduced axial cracks and gouges of different sizes to the pipe's outer surface. Damaged pipes were then subjected to denting and results, including denting forces, distortion of the cross-sectional area and limit loads were compared with the corresponding results obtained for non-dented and non-gouged geometries as well as with non-dented but gouged cases.

Noronha et al. [10] presented a critical review of the equations for estimating strains presented in Appendix R of the ASME B31.8 Code [11]. They also presented a procedure based on B-spline curves that interpolates dent geometry from data measured by in-line inspection tools and evaluates strain components. Baek et al. [12] evaluated the plastic collapse behavior and bending moment of dented pipes containing several dent dimensions using finite element and experimental analyses.

However, these papers did not study the effect of dent depth and internal pressure during indentation on the strain distributions of a pressurized pipe. In order to handle the complexities associated with dents, an elastic-plastic finite element simulation of a pressurized dented pipe is conducted and the formation of the dent and strain distribution around the dent location is investigated. The FE model is compared with the results of theoretical model presented in ASME B31.8 Code [11].

II. Strain-Based Assessment

Fig. 1 shows the dimensions of a dent. The parameter used to determine severity of a dent is usually depth. However, depth is not always the most useful parameter for determining if a dent presents a threat to pipeline integrity. Evaluating the significance of flaws or defects from a fitness-for-purpose standpoint, which compares the severity of the flaw against the acceptance criterion for a critical state, may be more informative. Where the flaw is characterized as a deformation, the local strain in the material may be a relevant criterion for judging its severity. The latest version of ASME B31.8 acknowledges this concept and provides strain acceptance criterion, as well as a method for estimating the strain in dents. This estimation procedure and justification for the strain acceptance criterion are discussed below.

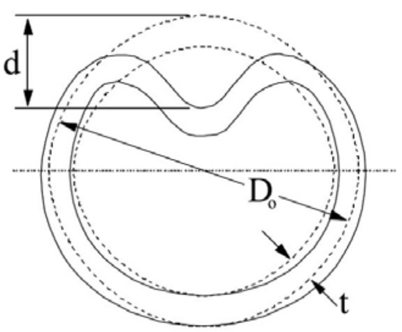

Fig. 1 Dimensions of a dent

According to the Appendix R of the ASME B31.8 [11] code, the estimation of the maximum strain in a dent is performed by first evaluating each strain component separately; then, assuming that each component occurs coincidently at the dent apex, the components are accordingly combined to determine the total strain. The following equations are presented for the evaluation of the bending strain in the circumferential direction (ε_1), and the bending and membrane strains in the longitudinal direction (ε_2 and ε ε_3):

$$\varepsilon_1 = (\frac{t}{2})(\frac{1}{R_0} - \frac{1}{R_1}) \tag{1}$$

$$\varepsilon_2 = -(\frac{t}{2})(\frac{1}{R_2}) \tag{2}$$

$$\varepsilon_3 = (\frac{1}{2})(\frac{d}{L})^2 \tag{3}$$

where R_0 is the radius of curvature of the undeformed pipe surface (equal to half of the nominal pipe outside diameter), and t, d and L correspond, respectively, to the wall thickness, dent depth and dent length in the longitudinal direction.

The external surface radii of curvature R_1 and R_2 are measured in the transverse and longitudinal planes through the dent, respectively. Radii are positive if measured from the direction of the centre of the pipe, that is, radius R_1 would be positive if the denting only results in flattening of the pipe. The radius would be negative if the dent is actually reentrant (i.e., the curvature of the pipe has been reversed). Therefore, R_1 is positive when the dent partially flattens the pipe, in which case the curvature of the pipe surface in the transverse plane is in the same direction as the original surface radius of curvature R_0. Otherwise, if the dent is re-entrant, R_1 is negative. The curvature R_2 as used in the code is generally a negative value.

The total strain acting on the inside and outside pipe surfaces (respectively ε_i and ε_o) are then given by the following expressions:

$$\varepsilon_i = \sqrt{\varepsilon_1^2 - \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2} \tag{4}$$

$$\varepsilon_o = \sqrt{\varepsilon_1^2 + \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2} \tag{5}$$

The dent is considered as acceptable when the larger of the values ε_i and ε_o is lower than the allowable strain limit. Equations (4) and (5) are employed to combine the strain components to obtain a scalar that can be compared to the acceptance criterion. However, these equations were derived considering incorrect plane strain assumptions, and therefore their use can lead to inaccurate results.

More appropriate expressions to the equivalent strain was presented by Noronha et al. [10] considering the hypothesis that the strains in this region are mainly in the plastic range, where the incompressibility condition may be applied. Hence:

$$\varepsilon_i = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_1^2 + \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2} \tag{6}$$

$$\varepsilon_o = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_1^2 - \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2} \tag{7}$$

III. Finite Element Simulation

The pipe deformation process induced by plain dents in a pipe submitted to internal pressure is studied by finite element simulations. A three-dimensional finite element model was developed through the mainframe ABAQUS release 6.12 for these purposes. The FE analysis comprised an elastic–plastic simulation of the denting process and the determination of the strain distribution in the steel pipe. In all simulations a pipe longitudinal length of 2.6 times the external diameter is adopted and the ratio between the outside diameter and the wall thickness is 90. The pipe specimen has 762mm outer diameter; 8.5mm wall thickness and 2000mm length. To minimize computational time, half of the pipe is simulated due to symmetry.

The FE mesh is generated using C3D8R element which is an 8-node linear brick with reduced integration and hourglass control. The internal pressure is applied as a function of yield pressure, p_y. Yield pressure causes the stress in the hoop direction to reach material's yield stress level, σ_y. The following equation can be used to relate p_y and σ_y.

$$p_y = \frac{\sigma_y t}{r_i} \tag{8}$$

where t is the pipe wall thickness and r_i is the inner radius of the pipe. In the FE modeling, the internal pressure is applied to the inner surface of the pipe to simulate the field condition. The level of internal pressure and the indentation depth are varied in FE simulations to investigate their effect on the denting load-displacement curves and the strain distributions in the dented region of the pipe.

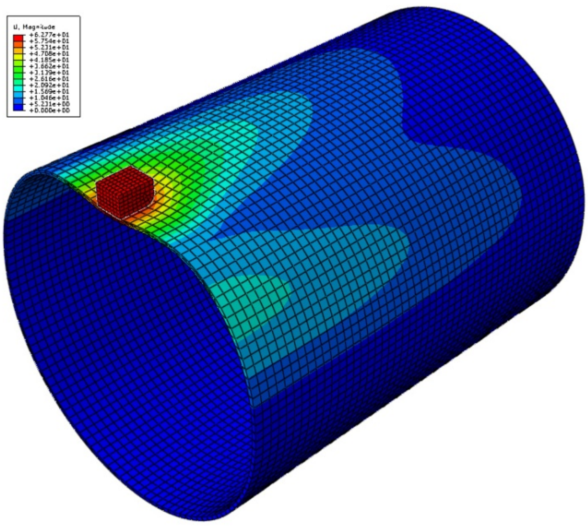

Fig. 2 Spatial displacements at nodes

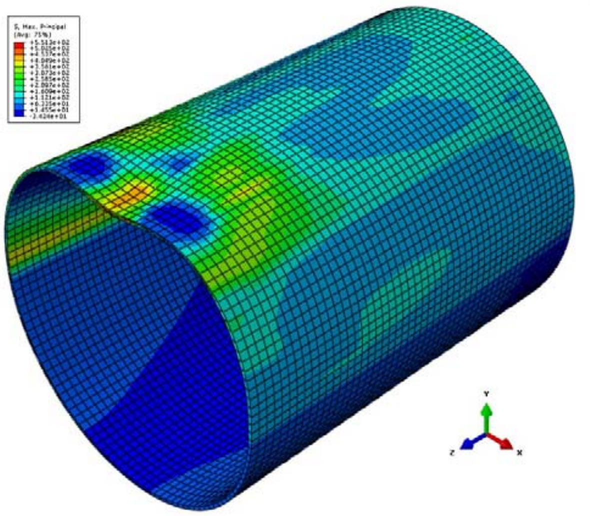

Fig. 3 Maximum principal stress

The change in thickness with deformation is ignored in the analysis and a parametric study was carried out to determine the influence of internal pressure and dent depth on strain distribution. The denting of the pipe is simulated with the aid of rectangular rigid surfaces (denting tools) punching plastically the pipe’s external surface. The material properties are determined through tensile tests of the steel specimen. A plastic potential flow rule together with the von Mises yield function and combined isotropic and kinematic hardening is assumed. The surface to surface contact between the indenter and the tube is modeled through the master-slave algorithm and load step simulating the application of internal pressure is performed, followed by loading and unloading with the denting tool. Figs. 2 and 3 show the FE results of the magnitude of spatial displacements at nodes and the maximum principal stress on the external surface of the dented region.

IV. Results and Discussions

The indentation load-displacement curve of the steel pipe at (p/p_y)=0.30 and (d/D_o)=0.04 is shown in Fig. 4. The general shape of the force-deflection curve depends on the magnitude of the internal pressure. It can be seen that the magnitude of the denting force increases nearly linearly with denting depth. A permanent, non-zero indentation depth is obtained after complete unloading and the indenter separates from the pipe.

The distribution of the circumferential and the longitudinal strains at (p/p_y)=0.30 and (d/D_o)=0.04 are illustrated in Figs. 5 and 6. It can be seen that the maximum compressive strains occur close to the centre of the indentation point.

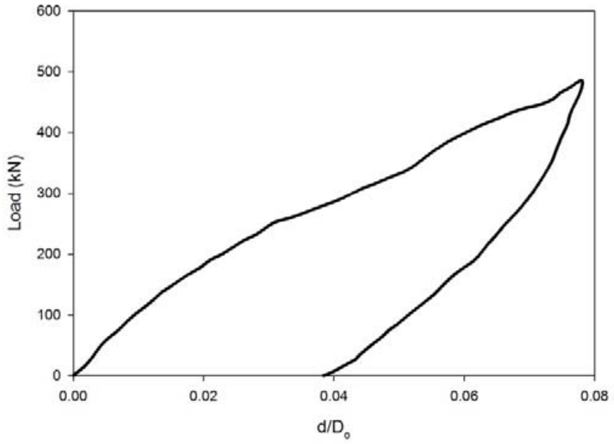

Fig. 4 Denting load-displacement curve for (p/p_y)=0.30 and (d/D_o)=0.04

The effect of the internal pressure and the depth of the dent on the maximum circumferential and longitudinal strains are depicted in Figs. 7 and 8. In general, the load carrying capacity increases with increasing pressure and the deformation caused by a given load reduces with increasing internal pressure. Results obtained from the FE analyses show that the circumferential and the longitudinal strains strongly depend on the internal pressure and the indentation depth. For deep indentation depths, the strain changes are large, and therefore, the fatigue life of the indented pipe would be relatively short. Increasing the internal pressure of the pipe can also greatly increase the value and place of the maximum strain.

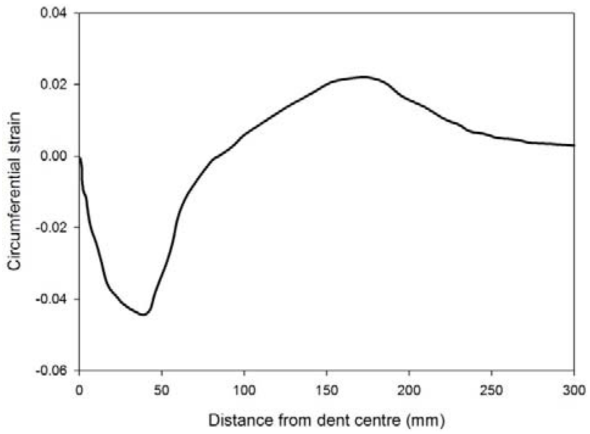

Fig. 5 Circumferential strain at (p/p_y)=0.30 and (d/D_o)=0.04

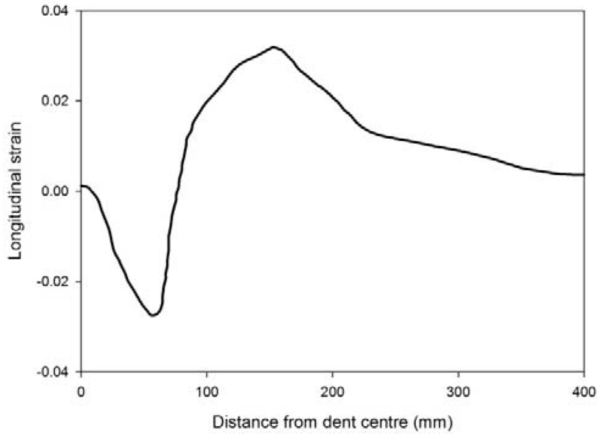

Fig. 6 Longitudinal strain at (p/p_y)=0.30 and (d/D_o)=0.04

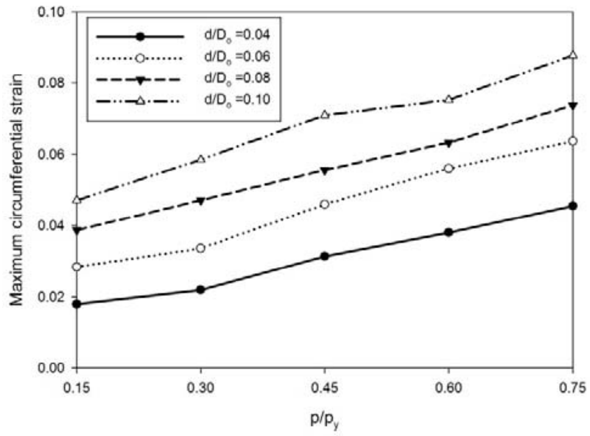

Fig. 7 Effect of internal pressure and dent depth on circumferential strain

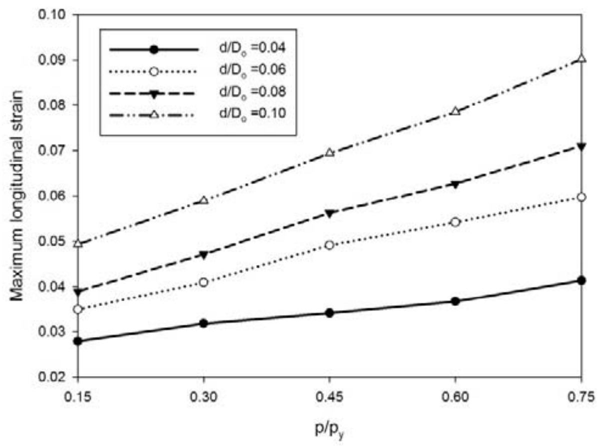

Fig. 8 Effect of internal pressure and dent depth on longitudinal strain

The different formulas presented in the previous section for estimating the combined strains will now be compared and verified against results of finite element analyses, in order to show how important the differences are in practice. For the inner surface of the dent, Table I compares the combined strain ε_i obtained with the two different formulas (4) and (6) to the corresponding maximum von Mises strain determined by the FE simulation. Similarly, for the outer surface of the dent, Table II compares the results provided by (5) and (7) with the corresponding FE result. In both tables it can be observed that the combined strains obtained considering the radial components ((6) and (7)) provide the best results, closer to the FE results. It is noteworthy that the ASME formulas (4) and (5) provided rather unconservative results.

TABLE I
COMPARISON OF COMBINED STRAIN VS. FE VON MISES STRAIN IN THE INNER SURFACE AT P/P$_Y$=0.3

d/D_o	ε_i ASME B31.8 (4)	ε_i (6)	ε_i FE simulation
0.04	0.0527	0.0597	0.0713
0.06	0.0531	0.0603	0.0714
0.08	0.0534	0.0604	0.0719
0.10	0.0540	0.0609	0.0723

TABLE II
COMPARISON OF COMBINED STRAIN VS. FE VON MISES STRAIN IN THE OUTER SURFACE AT P/P$_Y$=0.3

d/D_o	ε_o ASME B31.8 (5)	ε_o (7)	ε_o FE simulation
0.04	0.0514	0.0577	0.0721
0.06	0.0517	0.0585	0.0729
0.08	0.0519	0.0590	0.0737
0.10	0.0525	0.0592	0.0744

In another study, pipes of the same dimension were dented with zero internal pressure and then pressurized. Maxey [13] presented the following empirical equation for the variation of the central dent displacement with internal pressure.

$$\frac{p}{p_y} = 1.213\,(1-\frac{w}{d}) \tag{9}$$

where w is the inward radial displacement at the centre of the dent, measured from the original cylindrical pipe surface. It can be seen from Fig. 9 that the dent depth is reduced significantly upon pressurization and a good agreement can be seen between the theoretical and FE simulation results. For example, according to (9), an operating pressure of (p/p_y)=0.5, reduces the central dent depth up to 60% of the initial depth and same trend observed in FE analysis. This indicates an immediate permanent plastic deformation from the earliest dent movement. Although (9) was developed for aluminum pipes, Fig. 9 shows that the FE results of indentation of steel pipes correlate very well with (9).

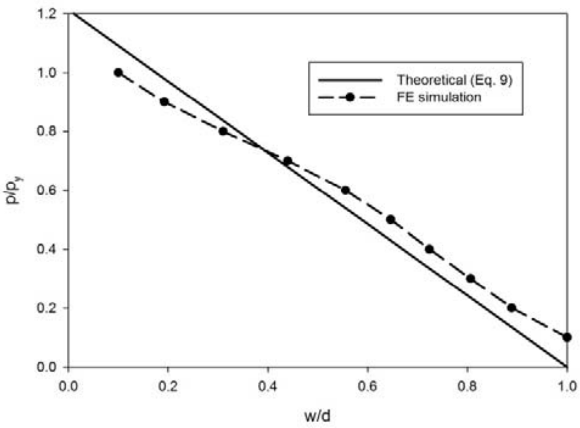

Fig. 9 Internal pressure vs. dent depth

V. CONCLUSIONS

Underground pressurized gas pipes can suffer damage due to earth movement, corrosion, fatigue, or indentations caused by contact with mechanical diggers. The strain distributions which occur in pressurized indented pipes are investigated using the results of finite element analysis and theoretical equations. The insertion and subsequent withdrawal of an indenter result in plastic deformation. The indenter force vs. deflection characteristics of pressurised pipes is also investigated using finite element method. An empirical formulation for predicting the variation of the central dent displacement with internal pressure is used to validate the FE results and a very close correlation is obtained.

REFERENCES

[1] Jiao, Z.-L., Shuai, J. (2011) Integrity assessment of pipeline with dents. *Xinan Shiyou Daxue Xuebao/Journal of Southwest Petroleum University* 33 (4) , pp. 157-164.
[2] Yang, Q., Shuai, J. (2010) Engineering evaluation method for dented pipeline. *Shiyou Xuebao/Acta Petrolei Sinica* 31 (4) , pp. 649-653.
[3] Macdonald, K.A., Cosham, A. (2005) Best practice for the assessment of defects in pipelines - Gouges and dents. *Engineering Failure Analysis* 12 (5 SPEC. ISS.) , pp. 720-745.
[4] Orynyak, I.V., Shlapak, L.S. (2001) Estimation of ultimate pressure for a pipe with a dent. *Problemy Prochnosti* (5) , pp. 101-110.
[5] Liu, J.H., Francis, A. (2004) Theoretical analysis of local indentation on pressured pipes. *International Journal of Pressure Vessels and Piping* 81 (12) , pp. 931-939.
[6] Iflefel, I.B., Moffat, D.G., Mistry, J. (2005) The interaction of pressure and bending on a dented pipe. *International Journal of Pressure Vessels and Piping* 82 (10) , pp. 761-769.
[7] Hyde, T.H., Luo, R., Becker, A.A. (2005) Elastic-plastic response of unpressurised pipes subjected to axially-long radial indentation. *International Journal of Mechanical Sciences* 47 (12) , pp. 1949-1971.
[8] Hyde, T.H., Luo, R., Becker, A.A. (2007) Elastic-plastic analysis of offset indentations on unpressurised pipes. *International Journal of Solids and Structures* 44 (2) , pp. 399-418.
[9] Błachut, J., Iflefel, I.B. (2011) Analysis of pipes containing plain and gouged dents. *Strain* 47 (SUPPL. 1) , pp. e34-e51.
[10] Noronha, D.B., Martins, R.R., Jacob, B.P., de Souza, E. (2010) Procedures for the strain based assessment of pipeline dents. *International Journal of Pressure Vessels and Piping* 87 (5) , pp. 254-265.
[11] ASME B31.8 (2007) gas transmission and distribution piping systems.
[12] Baek, J.-H., Kim, Y.-P., Kim, W.-S., Koo, J.-M., Seok, C.-S. (2012) Load bearing capacity of API X65 pipe with dent defect under internal

pressure and in-plane bending. *Materials Science and Engineering A* 540 , pp. 70-82.
[13] Maxey, W.A. (1986) Outside force defect behaviour. *Seventh Symposium on Linepipe research*, paper 14 (American Gas Association, Houston, Texas).