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Effect of External Corrosion in Pipeline on Failure Prediction

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ABSTRACT

This paper presents the effect of shape of external corrosion in pipeline on failure prediction by using a numerical simulation. The numerical study for the pipeline failure analysis is based on the FEM (Finite Element Method) with an elastic-plastic and large-deformation analysis. Corrosion pits and narrow corrosion grooves in pressurized pipeline were analysed. A failure criterion, based on the local stress state at the corrosion and a plastic collapse failure mechanism, is proposed. The predicted failure stress assessed for the simulated corrosion defects having different corroded shapes along the pipeline axis are compared with those by methods specified in ANSI/ASME B31G code and a modified B31G code. It is concluded that corrosion geometry significantly affects the failure behavior of corroded pipeline and categorisation of pipeline corrosion should be considered in the development of new guidance for integrity assessment.

Keywords : External corrosion, pipeline, failure prediction, FEM, elastic-plastic, integrity assessment

1. Introduction

Predicting the failure of damaged oil and gas pipeline is essential for the determination of design tolerance. A pipeline may experience significant internal and external corrosion defects by chemical and environmental effects that reduce its strength and resistance to fatigue, local buckling, leakage and bursting. In particular, crack occurrence in the corroded surface reaches critical stage. The existing criterion, detailed in ANSI/ASME B31G[1], was developed on an empirical basis over 20 years ago. The code was based on an extensive testing of pipeline with narrow machined slots in the external surface. The corrosion assessment methods in the B31G code have been successfully used in the oil and gas industries but it has been recognized that they can be over-conservative. This is mainly due to the simplifications embodied in the methods and through its application to a complex variety of defect shapes which have an inherently different failure mechanism.

Prediction techniques of failure pressure developed during the last decade have enabled the accurate location and sizing of pipeline wall corrosion. In parallel, modern numerical analysis methods have enabled the modeling of realistic defect shapes and nonlinear material behavior. Limited numerical studies using solid models, plane strain models and general 3D models have recently been published[2,3,4], in which failure pressures are predicted using either an elastic limit stage criterion, plastic limit stage criterion or allowable plastic strain criterion. These studies have improved failure predictions for the defect groups considered.

This paper described the limitations in the using of the existing code and presents a numerical study of the behavior of corroded pipeline. The study is based on an elastic-plastic, large-deformation finite element method(FEM) of simulated pipeline corrosion shapes, external corrosion pits and grooves. A failure criterion, based on the local stress stage in the corroded region and failure due to plastic collapse, is proposed.

2. Theory

The original B31G criterion for predicting the failure of corrosion was derived from an extensive database of flawed pipe burst tests, resulted in the following failure equation[5]:

$$\sigma_f = \bar{\sigma}\left[\frac{1-(A/A_0)}{1-(A/A_0)M^{-1}}\right] \qquad (1)$$

This failure equation was modified by two conditions[6]. First, limiting the maximum hoop stress by the material's yield strength. Second, characterizing corrosion geometry by a projected parabolic shape for relatively short corrosion and a rectangular shape for long corrosion. Fig. 1 shows the section through an idealized external corroded pipeline[7].

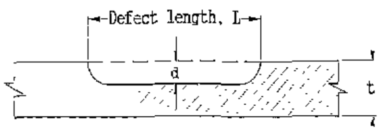

Fig. 1 Section through an idealized corrosion defect

Simple failure equations are embodied in the B31G code as below: Where, σ_f is failure stress (MPa), $\bar{\sigma}$ is flow stress of the pipeline material (MPa), A is projected cross-sectional area of corrosion (mm^2), A_0 is $L \times t$ (mm^2), L is longitudinal length of corrosion (mm), t is corrosion thickness (mm), M is Folias bulging factor[8].

2.1 Parabolic shape

$$\sigma_f = \bar{\sigma}\left[\frac{1-(2/3)(d/t)}{1-(2/3)(d/t)M^{-1}}\right]$$

$$\left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \le 4\right)$$

$$M = \sqrt{1+0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}$$

$$\left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \le 4\right)$$

$$M = \infty \quad \left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} > 4\right) \qquad (2\text{-}1)$$

Where, D is outside diameter of pipeline (mm), d is maximum corrosion depth (mm), σ_{SMYS} is the specified minimum yield strength (MPa)

2.2 Rectangular shape

$$\sigma_f = 1.1\sigma_{SMYS}[1-(d/t)]$$

$$\left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \ge 4\right)$$

$$M = \sqrt{1+0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}$$

$$\left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \le 4\right)$$

$$M = \infty \quad \left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} > 4\right) \qquad (2\text{-}2)$$

Kiefner and Vieth argued that the B31G code is over conservative due to the flow stress and bulging factor. So they proposed a new flow stress value ($\bar{\sigma} = 1.1 \times \sigma_{SMYS}$), an "effective area" for projected corrosion shape, that is A/A_0, and a new bulging factor[9]:

$$M = \sqrt{1+0.63\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right) - 0.0034\left(\frac{L}{D}\right)^4\left(\frac{D}{t}\right)^2}$$

$$\left(\text{for } \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right) \le 50\right)$$

$$M = 3.3 + 0.032\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)$$

$$\left(\text{for } \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right) > 50\right) \qquad (3)$$

Bubenik et al compared the failure prediction obtained using the original and modified B31G code and showed that the change the flow stress definition and bulging factor do not give significant improvement, but the use of effective area considerably reduces the conservatism[10].

Pipeline corrosion often has anomalous shapes that are normally classified by corrosion pitting, corrosion groove and general corrosion. A corrosion groove is usually formed by an array of pitting, and a general corrosion may be group pits, which spread over a wide circumferential extent on the pipeline wall. However, the existing codes use a single simple corrosion geometry, either a parabolic or a rectangular shape and the corrosion width is not considered.

3. Stress Analysis using FEM

Two types of external corrosions, isolated pits and narrow band grooves, have been studied using the Finite Element Method (FEM). Failure stresses of these two models are predicted according to their width and length. The pit model has semi-spherical shape with 60mm and 80mm diameter and the groove model has semi-cylindrical shape with width of 60mm, 80mm and length of 250.5mm(L/D=0.33mm). Three corrosion depths, d/t=0.25, 0.50 and 0.75 have been considered. The change of corrosion direction is considered every 15 degrees from 0 to 90 degree along the pipeline axis. The geometry of the pipe, which is considered in this study, is of 762mm outer diameter and 15.9mm wall thickness Material used for modeling is API grade X60(yield stress, $\sigma_{YS} = 400\,MPa$, Elastic modulus, $E = 193.2\,GPa$), and the relationship between the true stress-strain of this material was used in the Finite Element analysis.

Fig. 2.1 shows 3D Finite Element(FE) meshes for local regions around the pit and the groove models. Fig. 2.2 shows the groove models having different corroded shapes along the pipeline axis[11]. Where, l is actual corroded length.

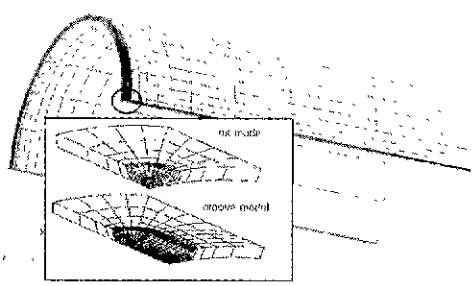

Fig. 2.1 Finite-element model on external corroded pipeline

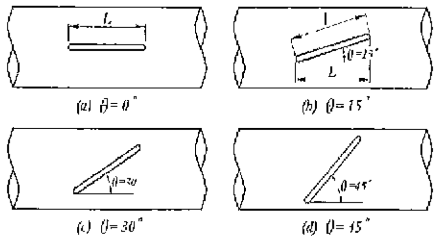

Fig. 2.2 Groove models having different corroded direction to the pipeline axis

4. Result and Discussion

The FE analysis was carried out using ABAQUS v5.7 FE software[12]. Failure was predicted by calculating the von Mises stress at the external surface of the corroded pipe.

The FE analysis indicates a critical condition that can be approximately determined by a point, which indicates the end of the post-yield hardening state, i.e. the beginning of the acceleration in stress variation leading to an instability, in the plot of von Mises stress versus pressure load[13].

Figs. 3 and 4 show the variation of local von Mises stresses at the inner wall, mid section and corrosion surface, with an increase in the pressure load for the corrosion pit model and the corrosion groove model, respectively. Variations of the stress states indicate that, before structural failure occurs, the remaining ligaments under the corrosions experience three distinct loading stages.

In the first stage, the local ligament deforms elastically. As the pressure increases, the corrosion surface reaches material's yield strength. In the second stage, the plasticity spreads through the remaining ligament while the Mises stress level remains approximately constant until the plasticity reaches the opposite wall surface. The third stage shows the ultimate capacity of the corroded pipe at which point the whole ligament deforms plastically.

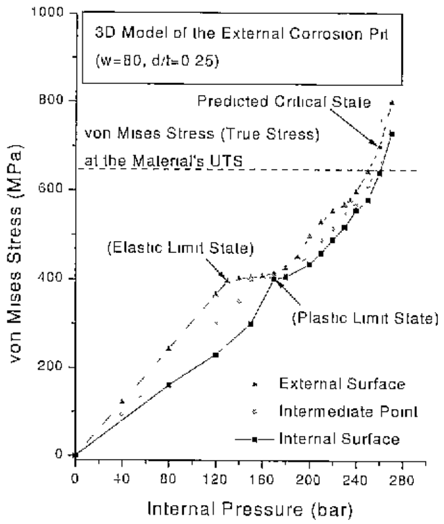

Fig. 3 Variation of von Mises stress at external corrosion pit (w=80 mm, d/t=0.25)

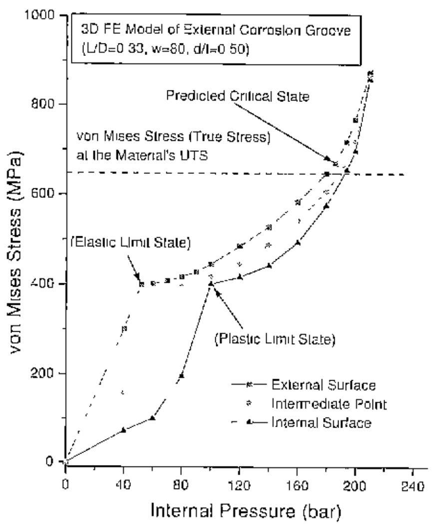

Fig. 4 Variation of von Mises stress an external corrosion groove (w=80 mm, L/D=0.33)

A failure criterion based on the elastic limit state, at which the maximum stress at the corrosion bottom reaches the material's yield strength is over-conservative and a failure criterion based on plastic limit state, at which the minimum stress at the opposite wall surface reaches the material's yield strength, may also considerably under estimates the ultimate strength of corroded pipe.

Figs. 5 and 6 show the effect of the variation of corrosion length and depth on local stress state of pit and groove models with 80mm width. According to this result, the variation of corrosion depth and length has considerable effect on the failure pressure.

Specially, the groove model has been more effected by the variation of the corrosion depth than the pit model.

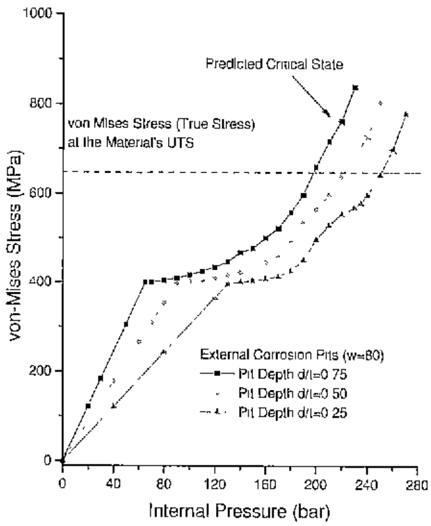

Fig. 5 Variation of the local stresses at external surface of the corrosion pit models

Figs. 7 and 8 show the effect of the variation of corrosion length and depth on local stress of pit model with 60mm corrosion width. Comparing to the Fig. 5, the difference of the failure pressure with the change of width 60mm to 80mm has small effects.

Fig. 9 shows the effect of corrosion direction on failure pressure in the groove model with 60mm width and 250.5mm corrosion length. The corrosion direction is considered every 15 degrees from 0 to 90 degree. This result says that even the real

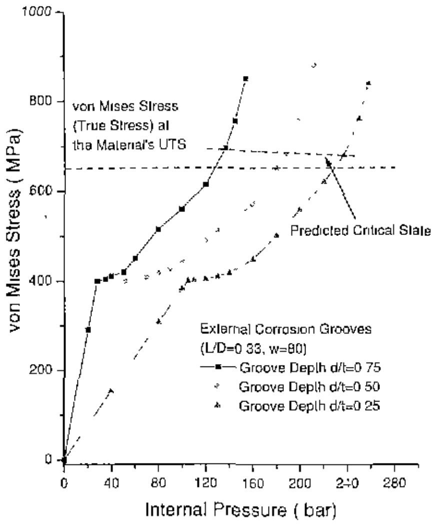

Fig. 6 Variation of the local stresses at external surface of the corrosion groove models

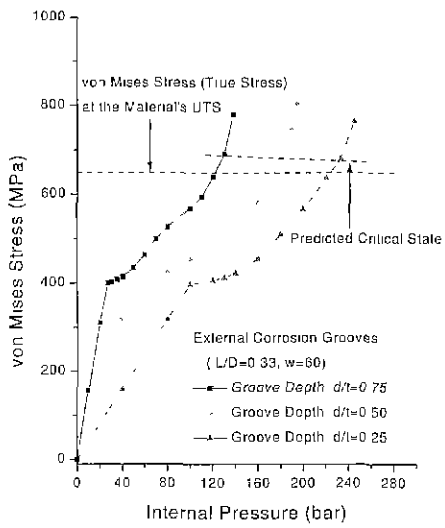

Fig. 8 Variation of the local stresses at external surface of the corrosion groove models

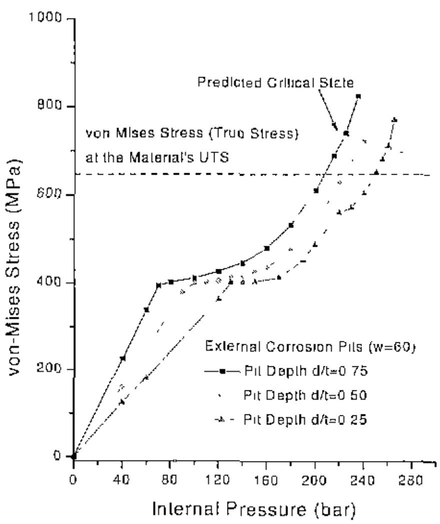

Fig. 7 Variation of the local stresses at external surface of the corrosion pit models

corrosion length is the same, the corrosion direction has effect on the magnitude of failure pressure because the projected area varies according to the angle with axis.

Fig. 10 shows the predicted failure pressure with corrosion direction calculated by FE analysis, B31G and MB31G code. The results obtained from these method shows that the failure stress increases with the increase of the angle between axis and external corrosion. In other words, the change of corrosion direction effects on the magnitude of failure pressure by changing the projected area.

Table 1 shows the predicted failure pressure for pit and groove models with 80mm corrosion width. From these results it is found that the failure pressure by FE analysis is 5% to 25% higher than those obtained by using B31G and MB31G without considering the corrosion width.

Table 2 shows the predicted failure pressure for the pit model with 60mm and 80mm width. The results show that the predicted failure pressures obtained by FE analysis and theoretical method agree well. It means that small change of corrosion width in pit model does not have considerable effect on failure pressure.

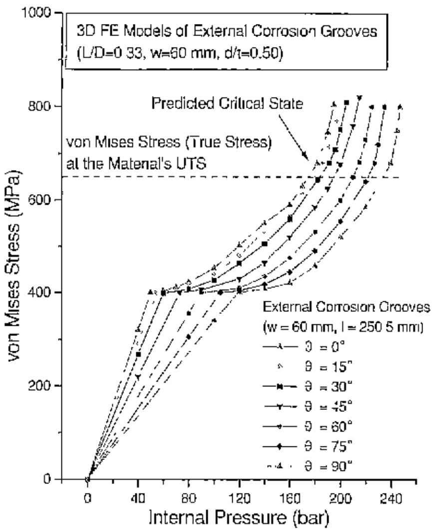

Fig. 9 Variation of the local stresses at external surface of the corrosion groove models having different corrosion directions

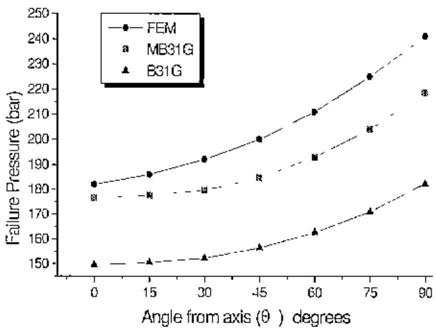

Fig. 10 Predicted failure pressure for the groove models having different corrosion directions

It is found that the failure pressures obtained by using FE analysis are 5% to 32% higher than those by MB31G and B31G with respect to the angles between axis and external corrosion. We have noted that the projected area affect the failure pressure significantly even corrosion width and length are the same. We found that the difference increases with the increasing angle.

Table 1 Comparison of the predicted failure pressure for the pit models and groove models.

d/t	Predicted failure pressure(bar)					
	Pit model(w=60mm)			Groove model(w=60mm)		
	FEM	MB31G	B31G	FEM	MB31G	B31G
0.25	262	218.7	187.8	232	201.1	172
0.5	238	212.9	182.4	182	176.6	149.8

Table 2 Comparison of the predicted failure pressure for the pit models.

d/t	Predicted failure pressure(bar)					
	Pit model(w=80mm)			Groove model(w=60mm)		
	FEM	MB31G	B31G	FEM	MB31G	B31G
0.25	260	215.9	185.6	262	218.7	187.8
0.5	230	207.8	177.3	238	212.9	182.4
0.75	220	195.6	164.1	225	204.8	174

Table 3 Comparison of the predicted failure pressures for the pit models having different wall thickness.

Degrees	Predicted failure pressure(bar)		
	Groove models(w=60mm, d/t=0.5)		
	FEM	MB31G	B31G
0	182	176.6	149.8
30	192	179.6	152.2
60	211	193.1	162.6
90	240	218.7	182.4

5. Conclusions

The following results have been obtained from the numerical investigation for the varying failure behavior of corroded pipelines.

1. It is found that FE analysis may cover more detailed range for the prediction of the failure pressure than that from existing theoretical methods which do not include corrosion width.
2. It is demonstrated that the corrosion depth and length have considerable effects on failure pressure.
3. An 30% change of corrosion width shows little effects on failure pressure.
4. The variation of the corrosion direction with respect to the pipeline axis reveals significant effects on the actual failure pressure even though

the real corrosion length are identical.

5. It is confirmed that the projected area is appropriate to check the integrity and safety of the corroded pipelines.

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