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CONTENTS

VOLUME II

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Determination of failure pressure of corroded linepipes using the nonlinear finite element method

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ABSTRACT

This paper describes an analytical study of the failure behaviour of corroded linepipe. The study is based on an elastic-plastic, large-deformation finite element (FE) analysis of simulated pipeline corrosion shapes (corrosion pits and corrosion grooves). A failure criterion, based on the local Mises stress state in the corroded region and failure due to plastic collapse, is proposed. Failure predictions obtained using the FE method are compared with published test results. The comparisons show that the proposed method gives accurate failure predictions.

1. INTRODUCTION

Predicting the failure of damaged oil and gas pipelines is essential for the determination of design tolerances, post inspection integrity assessment and effective maintenance action. An aged transmission pipeline may experience significant internal or external corrosion defects which reduce its strength and resistance to fatigue cracking, local buckling, leakage and bursting. The existing criterion for assessing corroded linepipe, as detailed in ANSI/ASME B31G [1], was developed on an empirical basis over 20 years ago. The code was based on a fracture mechanism calibrated by extensive testing of pipe vessels with narrow machined slots and a series of corroded pipe burst tests. The majority of pipe materials were lower grade steels, from API 5L Grade A25 to 5LX Grade X52 [2,3]. A simple failure equation was derived which includes the following considerations: (i) limiting the maximum hoop stress by the material's yield strength and (ii) characterising a corrosion geometry by a projected parabolic shape for relatively short corrosion and a rectangular shape for long corrosion. The corrosion assessment methods in the B31G code have been successfully used in the oil and gas industries but it has been recognised that they may be over-conservative [4]. This is mainly due to the simplifications embodied in the methods and through its application to a complex variety of corrosion defect shapes which have an inherently different failure mechanism. For example, linepipe corrosion often have anomalous shapes, such as an array of pitting or a group of pits which spread over a wide circumferential extent on the pipe wall. Many burst tests of corroded pipe vessels have showed failure of plastic collapse. However, the B31G code use a single simple corrosion geometry, i.e. either a parabolic or a rectangular shape and the corrosion width is not considered. Additionally, the accuracy of the method in corroded pipeline with higher grade steels has not been fully justified.

High-resolution on-line inspection techniques developed during the last decade have enabled the accurate location and sizing of pipe wall corrosion. In parallel, modern numerical analysis methods have enabled the modelling of realistic defect shapes and nonlinear material behaviour. Backed by experimental validation, these are proving a powerful and accurate tool in predicting critical condition against failure. In order to reduce unnecessary repair or replacement actions and optimise pipeline design, research aimed at developing new failure criteria and guidelines, is being undertaken worldwide. Limited numerical studies using thin shell models [5,6], plane strain and plane stress models [7,8] and general 3D models [9] have been published, in which failure pressures are predicted by either the elastic limit state, the plastic limit state, the maximum pressure point, the maximum plastic strain or equivalent stresses. Fu and Kirkwood [10] recently published a 3D nonlinear finite element (FE) analysis of internally corroded linepipes and suggested a critical condition criterion for predicting failure pressure using the non-linear FE method. The critical condition was based on a local stress state at the corrosion defect.

This paper presents a further numerical study of the failure behaviour of corroded linepipe. The study is based on an elastic-plastic, large-deformation FE analysis of simulated pipeline corrosion shapes (corrosion pits and corrosion grooves). A failure criterion, based on the local Mises stress state in the corroded region and failure due to plastic collapse, is proposed. Failure predictions obtained using the FE method and the proposed criterion are compared with published burst test results.

2. ANALYTICAL STUDY OF FAILURE BEHAVIOUR

2.1. Corrosion Models

Two types of corrosions, isolated pits and narrow band grooves, are studied using the FE method. The pit models have a semi-spherical shape and the groove models have a semi-cylindrical shape. Figure 1 shows typical 3D FE meshes used for local regions around the corrosion defects.

The present study includes the corrosion models in 762mm (30 inch) diameter (D) and 15.9mm (0.625 inch) wall thickness (t) API Grade X60 linepipe. The corrosion groove models have a length of 190.5mm (25% of the pipe diameter). Three corrosion depths, d/t=0.25, 0.50 and 0.75 are considered, which represent shallow, intermediate and deep corrosions respectively. FE models of the pipe sections have a length of 7620mm (10XD). A longitudinal restraint is applied to the pipe ends to simulate the boundary condition of long pipeline.

Material properties of the FE models were calibrated from a database of standard tensile tests of API Grade X60 linepipe material. A true stress-strain relationship of the X60 linepipe material is used.

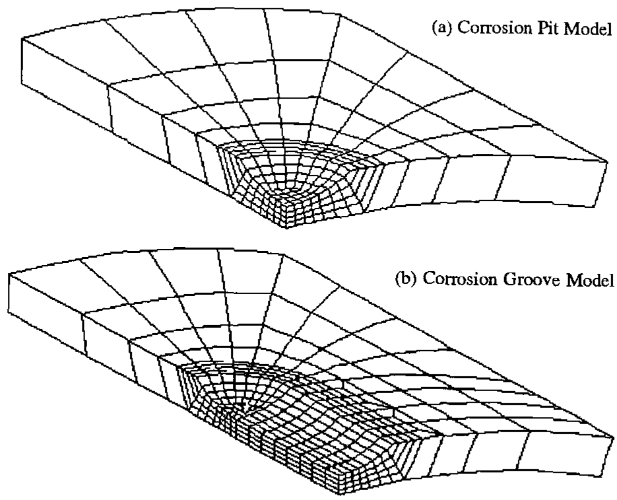

Figure 1. 3D FE models of corrosion defects.

2.2. Stress Analysis

The FE analysis uses both the ABAQUS v5.3[11] and the PATRAN v2.5[12] software. The FE solution incorporates both material non-linearity and large displacement theory by means of a geometrically non-linear static analysis procedure. Internal pressure is modelled as a static condition in which the pressure load increases to a level at which the required load increment is less than a specified minimum value of 10^{-5} of the total applied load.

Results of linear elastic stress analyses of the corrosion models show approximately linear hoop stress distributions through the remaining ligaments. This type of stress distributions indicates that the local stress states are controlled by a membrane stress and a bending moment, instead of a stress concentration. Both the membrane stress and the bending stress in the hoop direction increase as the corrosion depth and the corrosion length increase. Such stress states result in a localised bulging deformation and failure will occur in the manner of plastic collapse as the pressure load exceeds a critical level.

2.3. Critical Stress State

Since the physical models used in the FE analysis are based on continuum mechanics, which cannot represent material failure, such as rupture after local ligament necking, a critical state, at which plastic collapse will occur, must be defined.

Figure 2 and 3 show variations of local Mises stress with pressure, at the corrosion surface, an intermediate point and at the inner wall surface, of a corrosion pit (d/t=0.25) and a corrosion groove (d/t=0.25, l/D=0.25) respectively. Both figures highlight a similar local structural behaviour. Before numerical instability remaining ligaments at the corrosion base exhibit three phases, elastic deformation, plasticity spreading and post yield hardening.

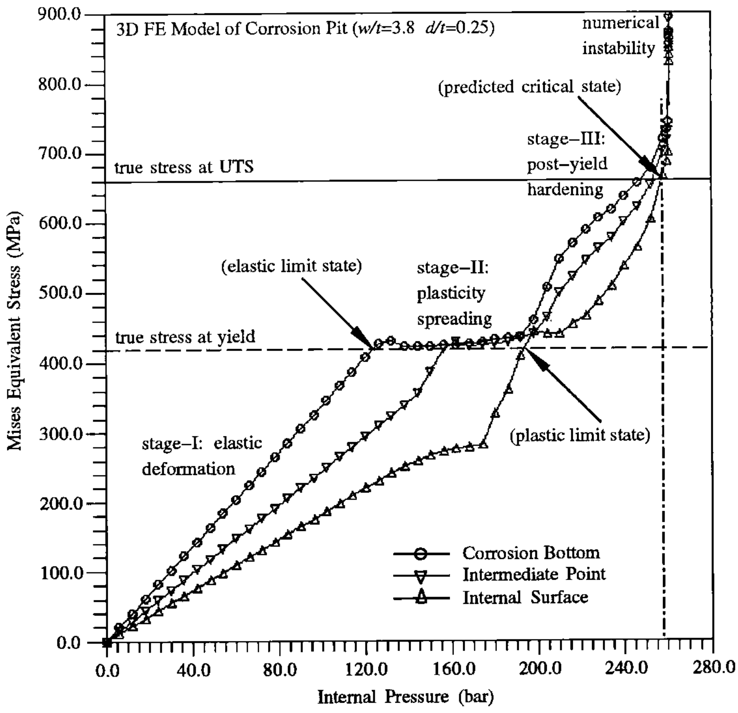

Figure 2. Variations of stress state at different positions in the corrosion pit.

The first phase is an elastic stage which progresses to a point where the elastic limit is reached, at this point a second phase is evident, a plasticity spreading phase where plasticity spreads through the remaining ligament while the Mises stress remains approximately constant. The third phase is dominated by material hardening and begins when the loading reaches the plastic limit. Once the third stage is reached the whole ligament deforms plastically but failure does not occur immediately due to constraint from the surrounding pipe wall.

At a stress level (true stress) corresponding to the material's ultimate tensile strength (engineering stress), the through ligament stress distribution becomes near uniform and a steep increase in the stress level occurs. With only a small increment in the pressure load the stress level corresponding to the material's final elongation (in a standard tensile test) is reached. Results of burst tests indicate that failure (rupture) occurs when the minimum stress, i.e. at inner wall surface, exceeds the material's ultimate tensile strength. Unpublished British Gas burst test results show that, before bursting, hoop strains measured at the inner wall surface exceeded the strain level at the material's UTS in standard tensile tests.

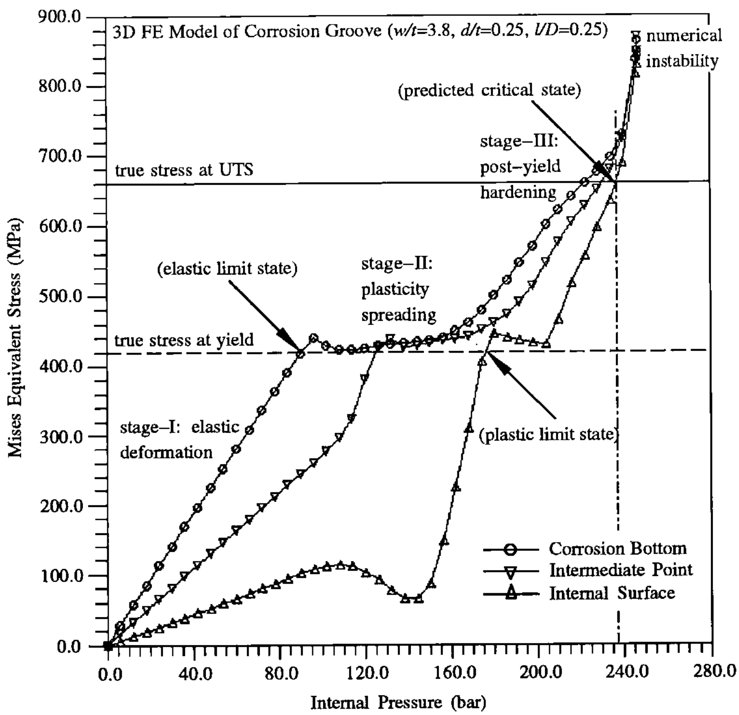

Figure 3. Variations of stress state at different positions in the corrosion groove.

FE analyses of various corrosion models show that, for corrosions with higher local bending, e.g. deeper and longer corrosions, the first and the second phases reduce and failure pressure levels reduce. Figure 4 shows variations of the predicted failure pressures. These results demonstrate that changes in corrosion depth and in corrosion length affect failure pressure level but the failure behaviour, which can be characterised by the three phases, is not affected.

Figures 2 and 3 show that the elastic limit state criterion is over-conservative and the plastic limit state, which excludes the post-yield hardening stage, also considerably under-estimates the remaining strength of corroded linepipe. But, comparisons of the FE results and burst test data indicate that the maximum pressure level corresponding to a numerical instability point may over-estimate remaining strength of corroded linepipe. It is then suggested that a failure pressure, or a critical condition, can be equivalently determined by the stress state, of which the variations starts to exhibit acceleration and the minimum Mises stress at the corrosion exceeds the true stress level corresponding to the material's UTS calibrated by uniaxial tensile tests.

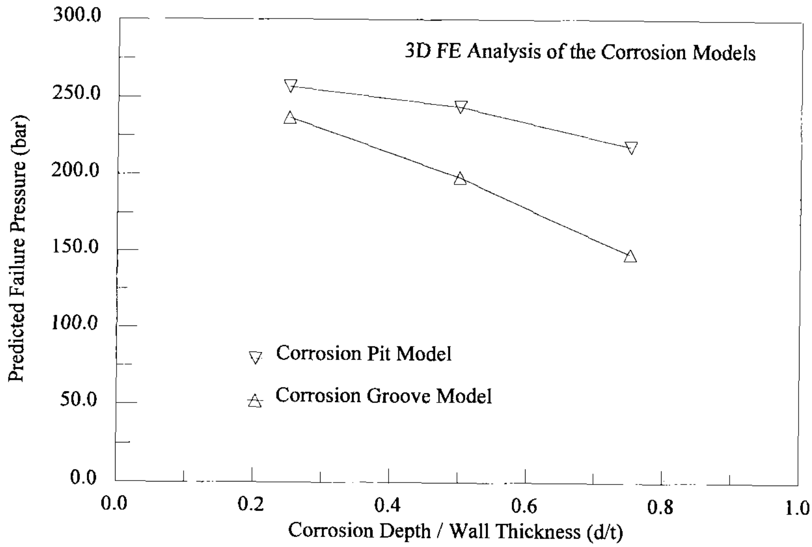

Figure 4. Variations of failure pressure levels.

3. BURST TESTS OF CORROSION PITS

Chouchaoui and Pick [13] published a series of burst tests on linepipe containing internal corrosion pits. The corroded pipes, removed from crude oil service, had API Grade X46 steel and 304.8mm (12 inch) outside diameter and 6.35mm (0.25 inch) nominal wall thickness. Actual wall thickness and corrosion shapes were measured and the stress-stain relationships of the material were calibrated by tensile tests. The corroded pipe sections, in an open end condition, were pressurised to failure and 12 test results were obtained. Three of these test models were also analysed using the FE method [9]. In their FE study, critical conditions, determined by fixed maximum values of the Mises stress, the Tresca stress and the equivalent plastic strain and that marked by numerical instability, were discussed.

These test results are used in the present study. Non-linear FE analysis of these corrosion pit models are conducted. Details of the corrosion models are listed in Table 1. The values given in Table 1 are the maximum measurements of the corrosions, which have anomalous shapes [14]. In the present FE analysis, semi-ellipsoidal corrosion shapes are assumed and these values have been used as the maximum dimensions. Material properties for each of the pipe sections are applied. It is noted that the stress-strain relationship reported for the pipe section with the pit, No.F07, has considerably lower yield strength, which is 20% lower than the API specified value, i.e. SMYS.

Failure pressures are predicted using the proposed criterion. The FE predictions obtained are then compared with the test results and predictions using the B31G method, as summarised in Table 2. The comparison shows that the proposed criterion gives consistent, conservative and accurate predictions while the predictions by the B31G method include larger margin of conservatism. The predicted failure pressure value for the test pipe, No.F07, is 7.9% lower than the measured failure pressure. This is mainly due to the use of the stress-strain relationship with lower yield strength and ultimate tensile strength.

Table 1
Geometry of the corrosion pit models

Pit No.	Pipe diameter D (mm)	Wall thickness t (mm)	Corrosion depth d (mm)	Corrosion length l (mm)	Corrosion width w (mm)
F05	304.8	5.84	3.91	33.0	21.0
F07	304.8	5.99	4.67	26.0	20.0
F25	304.8	6.16	4.50	37.0	30.0

Table 2
Failure pressures of the corrosion pit models

Pit No.	Failure pressure (bar)			P / P^*
	Measured, P^*	FE prediction, P	B31G prediction, P^{**}	
F05	162.9	160.0	127.8	0.994
F07	153.6	141.5	129.1	0.921
F25	142.9	142.0	122.1	0.994

Additional FE analyses of the other test models give failure predictions with similar accuracy. Those results are not included in the present paper.

4. BURST TESTS OF LONG CORROSION GROOVES

Mok et al [14] and Coulson and Worthingham [4] published a series of burst tests of linepipe with machined long corrosion defects, which include 5 single longitudinal corrosion groove models. The test vessels were made of 508mm (20 inch) diameter and 6.35mm (0.25 inch) nominal wall thickness API Grade X60 linepipe. Details of the 5 corrosion models are listed in Table 3. In the present FE analysis, three corrosion depths, d/t=0.34, 0.40 and 0.54, have been considered. The FE model of the 40% depth corrosion has the same length (75% OD) as in the test vessel. The FE models of the 34% depth and 54% depth corrosions have various lengths ranging from 25% OD to 125% OD. The 3D FE models include end caps.

A failure pressure, 109.0 bar, is predicted using the proposed criterion for the corrosion model of 40% depth. The measured failure pressure for this corrosion model is 112.45 bar and the failure pressure predicted by the B31G method is 68.97 bar. The FE prediction is 3% lower than the measured failure pressure while the prediction by the B31G method is 38.7% lower.

Table 3
Geometry and measured failure pressures of the corrosion groove models

Test No.	Pipe diameter D (mm)	Wall thickness t (mm)	Corrosion depth d (mm)	Corrosion length l (mm)	Corrosion width w (mm)	Failure pressure p^* (bar)
1-5	508.0	6.35	2.54	381.0	25.4	112.45
1-6	508.0	6.35	2.54	1016.0	25.4	115.45
2-3	508.0	6.40	2.18	900.0	25.5	118.0
2-2	508.0	6.40	3.46	900.0	25.5	80.0
2-7	508.0	6.40	3.20	1000.0	25.5	84.0

Table 4
Failure pressures of the long corrosion models

l/D	Failure pressure (bar) for corrosions d/t=0.34			Failure pressure (bar) for corrosions d/t=0.54		
	Test result	FE prediction	B31G prediction	Test result	FE prediction	B31G prediction
0.25	-	126.0	98.9	-	107.5	87.7
0.50	-	121.2	94.1	-	88.7	80.6
0.75	-	118.0	75.9	-	83.3	52.9
1.00	-	117.0	75.9	-	81.8	52.9
1.25	-	116.0	75.9	-	80.5	52.9
1.77	118.0	-	75.9	80.0	-	52.9

Because of difficulty in modelling the long corrosion length by 3D FE mesh, the corrosion models with the length of 900mm are not analysed. However, the FE predictions show clear trends that the failure pressure levels predicted converge to constant values slightly below the test results. The B31G method again gives considerably lower failure predictions, which are approximately 30-35% lower than the measured failure pressures.

All the above comparisons support the proposed method. These provide experimental validations from extreme short corrosion models (pits) to very long corrosion models (longer than the pipe diameter).

5. CONCLUSIONS

This paper has described a rigorous analytical study of the failure behaviour of corroded linepipe. A new failure criterion, based on plastic collapse mechanism, is proposed. Failure pressure for various simulated corrosion pit and long corrosion groove models are predicted using the proposed criterion, which show very good agreement. The criterion can be applied to advanced numerical analysis of realistic corrosion models for the development of guidelines on corrosion in transmission pipelines.

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Full scale testing and numerical simulation of corroded line pipe under combined loading

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1. ABSTRACT

This paper discusses testing and analysis procedures employed during a three phase study of the integrity of corroded oil transmission pipelines under combined load conditions. The study was necessary for two reasons. First, the current and potential modified ANSI/ASME B31G criteria for corroded pipe are empirically drawn from experimentations on pipes much smaller in diameter and lower in grade of steel than those used in the oil transmission pipelines. Second, the current criterion does not account for the effects of axial bending that could occur in buried pipes due to settlement, and for the axial compression that could occur because of differences in installation and service temperature. To address these deficiencies, an elastic shell engineering model was developed and calibrated against full-scale burst tests and numerical simulations of pipes with artificial corrosion subjected to combined loading. In general, the dimensions of the simulated corroded region and the axial stresses due to constrained thermal expansion were specified at the start of a test. A combination of internal pressure, bending moment, and axial load was then applied to the test section until failure occurred. In order to gain insight into the different failure mechanisms, each of the burst tests was simulated using a three-dimensional elastic-plastic large deformation finite element analysis.

2. INTRODUCTION

When corrosion damage in the form of wall loss is discovered by a pigging or excavation operation, a replace/repair/ignore decision must be made. This decision hinges crucially on a prediction of the failure pressure of the corroded pipe. Above all else, because environmental safety is paramount, the failure pressure that is predicted for the observed damage must be reliable and readily obtainable. But at the same time, unnecessary field maintenance operations should not be performed—not only to avoid unnecessary expenses and curtailment of service, but also to prevent the possibility of additional damage that sometimes occurs in field operations. Thus, the prediction must be accurate without being grossly conservative, and should not require a time consuming analysis procedure.

The current and potential new ASME B31G guidelines satisfy these requirements for most existing pipelines. However, because the present guidelines are drawn from methods that are both empirically based and have a somewhat limited range of applicability, there are pipeline service conditions for which they may not be entirely appropriate. These include damage regions having a large circumferential dimension, multiple nearby interacting discrete damage zones, damage zones at or near weldments, and combined loading conditions.

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