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Pressure Capacity Reduction of X52 Pipeline Steel Damaged by a Semi-Elliptical Pitting Corrosion

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***Abstract*—**Steel made pipelines with different diameters are used for transmitting oil and gas which in many cases are buried in soil under the sea bed or immersed in sea water. External corrosion of pipes is an important form of deterioration due to the aggressive environment of sea water. Corrosion normally results in pits. Hence, using the finite element method, namely ABAQUS software, this paper estimates the amount of pressure capacity reduction of a pipe-containing a semi-elliptical pitting corrosion and the rate of corrosion during the pipeline life of 25 years.

***Keywords*—**Petroleum Transmission, Pipeline, Pressure Capacity, Semi-Elliptical Pitting Corrosion.

I.INTRODUCTION

THE mechanical characteristics of transit petroleum pipelines made up of thermomechanically processed steels do not essentially change during the life-time of the pipe. However, the pressurized pipelines are subject to the harmful effects both of the surrounding environments, such as the sea water, and of the materials conveyed in them. One of these effects is corrosion. There exist different types of corrosive defects among which localized, such as pitting, and general ones are those which attract the greatest interest among pipeline operators and research institutes all over the world.

Predicting the failure pressure of corroded pipelines with pitting corrosion, and particularly the semi-elliptical one, has been the subject of considerable research in the last decades. For instance, applying burst testing and finite element modeling, Chouchaoui and Pick [1] undertook a study on the behavior of circumferentially aligned elliptical corrosion pits. As a result of the comparison of the burst pressures of pipes affected by such pits, namely experimental results, with finite element predictions, they concluded that the defect depth followed by the defect length are the main geometric parameters controlling burst in the case of single corrosion pits. Furthermore, they inferred that finite element predictions of burst pressures of open-ended pipes are in great agreement with experimental results while in the case of closed-ended pipes, predicted burst pressures are somewhat below the measured burst pressures.

Applying numerical solutions, Valenta et al. estimated the remaining load carrying capacity of pipelines with quasispherical corrosive defects of the same widths but different depths and lengths. They also compared the experimental results with failure pressure results recommended in ASME B31G code. In sum, they observed that load carrying capacity decreases as the depth and length of the corrosive defect increase [2].

A series of burst tests on line pipe samples containing longitudinally aligned elliptical corrosion pits was performed by Chouchaoui and Pick. They considered both single and closely spaced corrosion pits and used the finite element method to analyze the test data and to investigate geometric parameters not considered experimentally. Consequently, they interpreted that the finite element results were in excellent agreement with experimental results [3].

To assess the remaining strength of corroded gas pipelines with semi-elliptical pits, Kim et al. [4] proposed limit load solutions through comparing experimental results and finite element analyses. As a result, they found that with R/t increasing, the maximum allowable pressure is decreased (where R and t are the radius and wall thickness, respectively).

Melchers investigated the effect of pitting corrosion on the structural reliability of steel offshore structures and showed the trend increase in failure probability with exposure time. As a consequence, he found that the modeling of longer-term behavior of pit depth growth is particularly important for probability estimates, and short-term laboratory observations are of limited usefulness [5]. In the same vein, Netto et al. studied the effect of external corrosion defects on the burst pressure of pipelines using a series of small-scale experiments and a nonlinear numerical model based on the finite element method, namely the ABAQUS software. They tested sample pipelines with semi-elliptical corrosive defects of various lengths and depths. Finally, the experimental results were compared with those of the numerical and they presented good correlation [6].

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Using probabilistic models, Tiexeira et al. [7] assessed the reliability of pipelines with corrosion defects subjected to internal pressure. They defined the limit-state (or failure) function based on the results of a series of small-scale experiments and three-dimensional non-linear finite element analysis of the burst pressure of intact and corroded pipelines conducted by Netto et al. [6]. An interesting result they got was that the deterministic predictions of the B31G code have been shown to be over-conservative when compared with the estimates of the failure equation proposed by Netto et al. [6]. Furthermore, they found it evident that the depth of corrosion, the internal operating pressure, and the yield stress are the most important variables in the failure function.

Through the application of ABAQUS software, a numerical model based on the finite element method, this research estimates pressure capacity reduction of X52 pipeline steel damaged by a semi-elliptical pitting corrosion on the external surface. To obtain failure pressure, due to the existence of hydrostatic pressure on the external pipe surface in water depth of 40 meters and through the application of high internal pressure to attain the ultimate tensile strength, we are lead to pressure capacity (load carrying capacity) of intact and corroded pipes for 25 years life of the pipe and determine the relationship between the amount of pressure capacity decrease and the rate of corrosion (RC) during the life of pipe.

II. RATE OF CORROSION

Calculating the rate of corrosion is a prerequisite for indicating the effect of corrosion on the pressure capacity. In this research, we have used a polarization method, which is custom in corrosion engineering, to estimate the rate of corrosion. It has results nearly similar to those ones of the immersion test, in which (the immersion test) the corrosion rate is estimated through immersing a sample pipeline segment in a natural environment, such as the sea water, and calculating the weight loss after the corrosion occurred. However, in the polarization method, corrosion studies can be performed using an electrochemical instrumentation and the rate of corrosion is investigated based on the current density. When corrosion occurs, after determining the corrosion current density, we estimate the rate of corrosion per year by inserting it (the current density) into the following equation based on Faraday's low [11].

$$\text{Rate of Corrosion} = K\frac{ai}{nD} \qquad (1)$$

Where a is the atomic weight of metal, i is the current density ($\mu A/cm^2$), n is the number of lost electrons, D is the density of metal (g/cm^3), and K is a constant value which equals 0.00327.

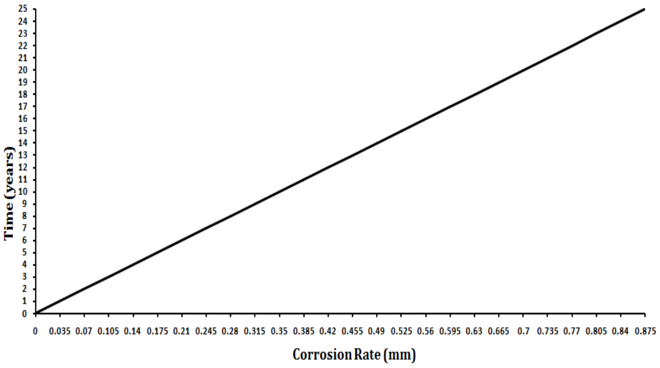

Fig. 1 The growth of corrosion rate with time

In the present experiment, a segment of 5L X52 pipe is used and the rate of corrosion in Persian Gulf is estimated to be 0.035 mm/y in depth of 40 meters. This corrosion rate is revealed through the reduction of the pipeline thickness. Following Caleyo et al. [8] and Ahammed [9]–[10], we have assumed a linear growth rate for corrosion with the increase of the time period, as is shown in Fig. 1. In addition, two pipeline segments are shown in Figs. 2 and 3 before and after corrosion through magnifying them by means of a microscope.

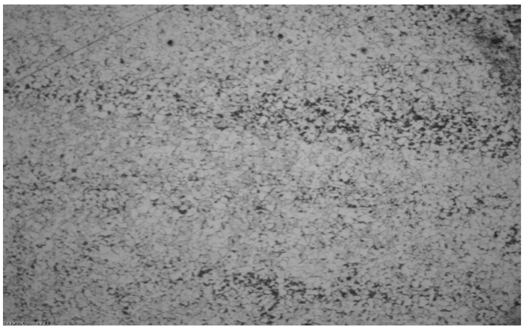

Fig. 2 The intact segment of pipe

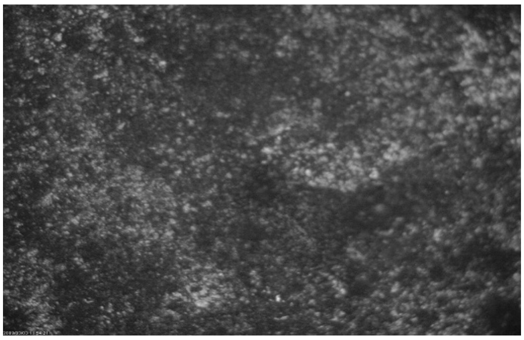

Fig. 3 The same segment after corrosion

III. NUMERICAL MODEL

Using a finite element model, ABAQUS software (version 6.8-1), we simulated the failure of an intact and externally corroded pipe with a semi-elliptical pit (with a major diameter of 0.02 m, a minor diameter of 0.01 m, and a depth dependent on the growth of corrosion rate with time) under both internal and external (hydrostatic) pressure (P_o= 401408 Pa). A structured mesh was used in the analyses of corroded pipeline and the mesh was made uniform in each direction in the intact area, in comparison with which, the size of elements is smaller in the corroded section and the section next to it, in a way that the length and width of elements are closer to each other in the latter-mentioned areas.

In order to mesh the intact pipeline, 3840 numbers of elements were used; the pipeline was represented by a hundred and twenty elements in the axial direction, thirty two in the circumferential direction and one through the thickness, as is shown in Figure 4. To mesh the corroded pipeline, 13440 numbers of elements were used; the intact area (including the area close to the corroded one, too) was represented by 13056 elements, namely a hundred and thirty six elements in the axial direction, forty eight in the circumferential direction and two through the thickness, and the corroded area was represented by 384 elements, as is shown in Fig. 5. Other geometric and material properties used in modeling are illustrated in Table 1.

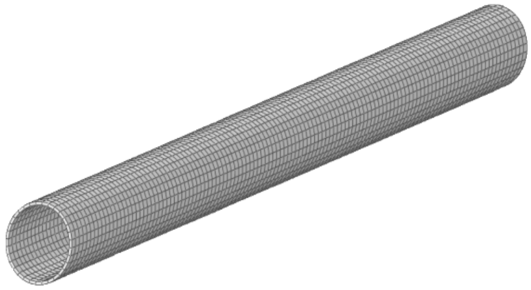

Fig. 4 Structured finite element mesh of the intact pipeline

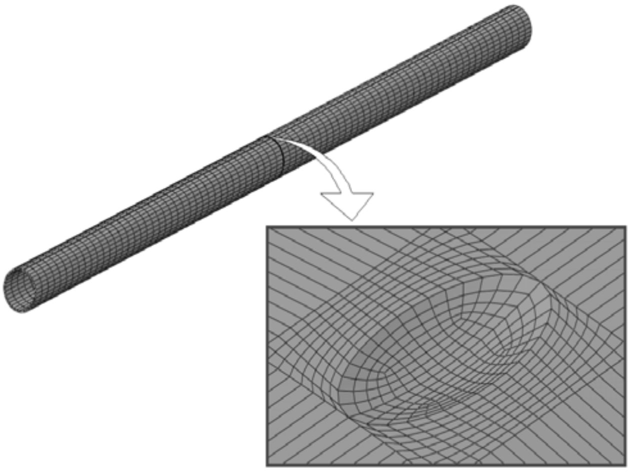

Fig. 5 Structured finite element mesh of the same pipeline after being corroded with a semi-elliptical pit

TABLE I
GEOMETRIC AND MATERIAL PROPERTIES OF X52 PIPELINE MODEL

Geometric properties		Material properties	
wall thickness (m)	0.0127	yield strength (MPa)	358
length (m)	12	ultimate tensile strength (MPa)	455
outer diameter (m)	0.3048	young's modulus (GPa)	210
inner diameter (m)	0.2794	mass density (kg/m^3)	7850

At the end, considering fixed boundary conditions at the two edges of the pipe, we modeled the sample. To obtain failure pressure, due to the existence of hydrostatic pressure on the external pipe surface in water depth of 40 meters and through the application of high internal pressure to attain the ultimate tensile strength, we were lead to pressure capacity of intact and corroded pipes for 25 years life of the pipe.

IV. RESULTS

In the case of pitting corrosion, in comparison with the initial wall thickness of the intact pipe, the external surface of the pipe is corroded locally according to the rate of the corrosion. This corrosion growth is extended to the 1st, 3rd, 5th, 6th, 7th, 10th, 15th, 20th, and 25th years. As is shown in Fig. 6, the pressure capacity of the pressurized pipeline with a semi-elliptical pitting corrosion is calculated against the time, mentioned years.

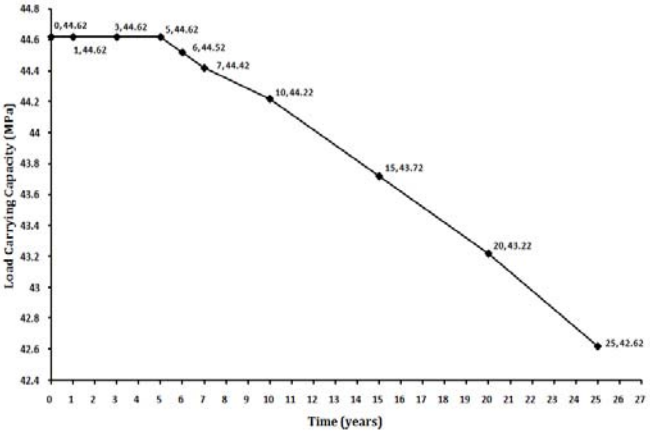

Fig. 6 Pressure capacity of sample pipeline for T=0-25 years

As is illustrated in Fig. 6, two different conditions are observed before and after the 5th year. The first condition is related to the 5th year and the years before it, i.e. the 1st and the 3rd ones. During these years, the increase of corrosion rate has no effect on the pressure capacity; hence its value is constant and equals the value of the intact pipe's load carrying capacity, i.e. it equals 44.62 MPa. The results show that the size of corrosion is considered as an important parameter when the rate of corrosion increases. In other words, in the first 5th year, the size of corrosion is so small that it doesn't influence the carrying capacity.

The second condition includes time intervals after the 5th year. During this time interval, the pressure capacity decreases from 44.62 MPa in the 5th year to 44.42 MPa in the 7th year with a linear slope. After that, with a decrease in slope, it reaches 44.22 MPa and then, with a slope similar to the one of the 5th to 7th years, it equals 43.22 MPa in the 20th year. At the end, with the increase of slope, the carrying capacity equals 42.62 MPa.

V. CONCLUSION

Pipeline managers and operators frequently encounter the need to repair or replace corroded pipeline sections. Therefore, the major concern of operators is whether the integrity of the pipeline is affected by corrosion defects. Aiming to answer this question, we used a numerical model based on a finite element method and estimated the pressure capacity of X52 intact pipeline and corroded pipeline with a semi-elliptical pitting corrosion. In addition, rate of corrosion was obtained using the Polarization experiment during 25 years life of pipe. It has been observed that corrosion rate increases linearly with time and its effect is revealed in the form of pitting corrosion on the external surface of the pipe. The increase of corrosion rate influences wall thickness and based on the analyses done, we concluded that pressure capacity of the corroded pipe does not change due to the shallow corrosion, but in long period, it became evident that pressure capacity decreases with time due to the more localized decrease of wall thickness. This result helps us in selecting the type and amount of necessitated optimized coating of the pipeline and avoiding costly accidents caused by corrosion.

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