KSME International Journal, Vol. 16 No. 7, pp. 889~895, 2002

Failure Probability of Corrosion Pipeline with Varying Boundary Condition

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This paper presents the effect of external corrosion, material properties, operation condition and design thickness in pipeline on failure prediction using a failure probability model. The predicted failure assessment for the simulated corrosion defects discovered in corroded pipeline is compared with that determined by ANSI/ASME B31G code and a modified B31G method. The effects of environmental, operational, and random design variables such as defect depth, pipe diameter, defect length, fluid pressure, corrosion rate, material yield stress and pipe thickness on the failure probability are systematically studied using a failure probability model for the corrosion pipeline.

Key Words : Corrosion, Pipeline, Failure Probability, Reliability, Failure Assessment

1. Introduction

The maintenance and management skill of the industrial equipments has been emerged as a very important technique to be properly dealt with since the industrial apparatus becomes more complicated and diversified throughout all kinds of industries according to the development of various mechanical techniques. It has been often reported as an industrial example in that a catastrophic disaster has been caused by the defect like corrosion arisen by aging and/or environmental effect in pipeline transporting gas and oil (Kim, 1997, Choi, 2000).

The technique to predict pipeline failure due to corrosion damage is necessary to determine the corrosion tolerance for the pipeline design. Especially, it could be the inevitable technical information to assess the safety life of aging pipeline. Therefore, systematic investigation which deals with the damage and the failure of pipelines corresponding to varying boundary conditions is needed.

It is generally known that the occurrence of corrosion in pipelines reduces the strength of pipeline material. Thus, the development of reference and/or standard has been required to prevent failure accidents in advance by predicting the stress condition and failure life corresponding to the shape and location of corrosion (Lee and Kim, 1998, 1999, Lee and Choi, 1999, Lee and Cho, 1992).

The codes such as ANSI/ASME B31G dealt with the reference and/or standard for the corrosion pipeline in detail (ANSI/ASME B31-1985, 1985). An assessment procedure in a modified version of existing one, ASME MB31G code, was widely utilized in the oil and gas industries (Hopkins and Jones, 1992, Mohammdi et al, 1985).

The objective of this study is to present an approach to quantify the reduction in safety and hence the remaining life for deteriorating corroded steel pressurised buried pipelines during its

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operation period. A failure probability model proposed by Mohammdi *et. al.* (1985) has been used. The effect of varying boundary condition on the failure probability of the buried pipelines is studied systematically using this model.

2. Fundamentals for the Failure Probability Model

The major causes of the failure of pipelines transporting high pressure gas are known as the mechanical damage and the corrosion.

The standards for regular hydrostatic test and corrosion assessment are generally used to assess the effect of mechanical damage and corrosion on the integrity of the pipelines. In ordr to assess the integrity of corrodeel pipeline, we need to simplify the geometry in the vicinity of corrosive part.

Figure 1 shows a corrosion model, and which is further simplified as shown in Fig. 2 to analyse easily the given geometric configuration.

2.1 ANSI/ASME B31G code

A failure formula for corrosion pipelines was based on data from the explosion experiment, suggested as follows(Kiefner, 1974):

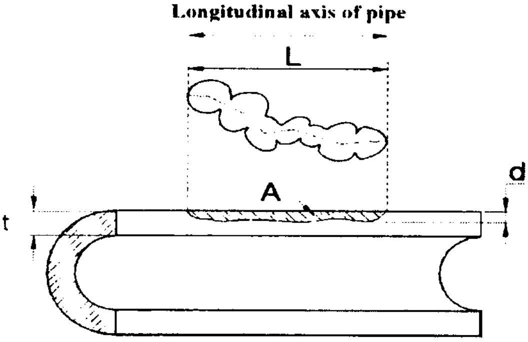

Fig. 1 A simplification of a corroded surface flaw in pipeline

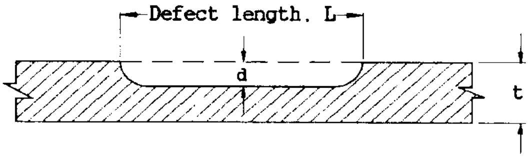

Fig. 2 Section with an idealized corrosion defect

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

Figure 2 shows the cross-section of the external corrosion pipeline(Ahammed and Melchers, 1996) and equation (1) is necessary to determine the failure stresses in corrosion pipeline. Where σ_f is the failure stress(MPa), $\bar{\sigma}$ is the flow stress (MPa), A is the projected cross-section area of corrosion pipeline(mm^2), A_0 is $L\times t$(mm^2), L is the projected corrosion length(mm), t is the wall thickness(mm), d is the maximum corrosion depth(mm), and M is the Folias bulging factor (ANSI/ASME B31-1985, 1985).

Equation (1) has been modified by considering the two conditions: 1) the hoop stresses may not be larger than the yield strength of the pipeline material(Kiefner et al, 1992), 2) the relatively short corrosion is assumed to be projected as a parabola by asseening the long corrosion as a rectangular shape. The modified failure formula for parabola and rectangular shape are given, respectively, as follows(ANSI/ASME B31-1985, 1985):

i) Parabola

$$\sigma_f=1.1\sigma_{\min}\left[\frac{1-(2/3)(d/t)}{1-(2/3)(d/t)M^{-1}}\right] \qquad (2)$$

$$\left(\text{if, } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}\leq 4\right)$$

ii) Rectangular

$$\sigma_f=1.1\sigma_{\min}[1-(d/t)] \qquad (3)$$

$$\left(\text{if, } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}>4\right)$$

Where D is the outer diameter of the pipeline (mm), $\sigma_{\min}$ is the minimum yielding stresses (MPa) and M is defined as follows(ANSI/ASME B31-1985, 1985):

$$M=\sqrt{1+0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \qquad (4)$$

$$\left(\text{if, } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}\leq 4\right)$$

$$M=\infty$$

$$\left(\text{if, } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}>4\right)$$

2.2 MB31G(Modified B31G) code

It was noted by Kiefner and Vieth that the flow stresses ($\bar{\sigma}=1.1\sigma_{\min}$) and the bulging factor of ANSI/ASME B31G have some problems. They proposed a new flow stresses of $\bar{\sigma}=1.1\sigma_{\min}+69$ (*MPa*) and a new bulging factor such that (Kiefner et al, 1992)

$$M=\sqrt{1+0.63\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)-0.0034\left(\frac{L}{D}\right)^4\left(\frac{D}{t}\right)^2} \quad (5)$$

$$\left(\text{if, } \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)\leq 50\right)$$

$$M=3.3+0.032\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right) \quad (6)$$

$$\left(\text{if, } \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)> 50\right)$$

Bubenik has investigated and clarified that the modified flow stresses and bulging factors improve the effect on the failure pressure while the concept of the effective area improved the conservative design consideration greatly when compared to the failure pressures obtained by B31G and MB31G. The corrosion configurations in pipelines of various shapes commonly classified as corrosion pit, corrosion groove and general corrosion. (Bubenik *et al*, 1992).

The corrosion bands are formed by the row of pits and the general corrosion is composed of the crowd of pits widely spreaded in the circumferential direction. However, it is noted that the width of the corrosion has not been considered in the B31G and MB31G codes.

2.3 Failure probability of corrosion pipeline

It should be necessary to define a failure function when the failure probability analysis is carried out. The failure function may be expressed as a reference for the pipeline failure and must include the failure pressure and the operation service pressure. The operation service pressure is just the pressure of the fluid which flows inside the pipeline. A failure function can be postulated as the difference between the failure pressure p_f which is appeared in Sec 2.1 and 2.2 and the operation service pressure p_a. In other words,

$$\begin{aligned} z&=p_f-p_a \\ &=2(\sigma_y+68.95)\frac{t}{D}\frac{1-[d_o+R_d(T-T_o)]/t}{1-[d_o+R_d(T-T_o)]/tM}-p_a \end{aligned} \quad (7)$$

where σ_y is the yield stress, t is the thickness of pipeline, D is the diameter of pipeline, d_o is the depth of corrosion, R_d is the corrosion rate, T is the inspection year, T_o is the former inspection year and M is the bulging factor, respectively.

It is generally accepted to represent the average failure probability as

$$P_f=P(z<0)=\Phi(-\beta) \quad (8)$$

where $\Phi(\cdots)$ is the distribution function of variables. And, β is the reliability index expressed in terms of u_z and the average variation σ_z as

$$\beta=\frac{u_z}{\sigma_z} \quad (9)$$

where

$$\begin{aligned} u_z=&z(d_o{}^*, T^*, D^*, p_a^*, R_d^*, \sigma_y^*, t^*, L^*) \\ &+(\bar{d}_o-d_o^*)\frac{\partial z}{\partial d_o}+(\bar{T}-T^*)\frac{\partial z}{\partial T}+(\bar{D}-D^*)\frac{\partial z}{\partial D} \\ &+(\bar{p}_a-p_a^*)\frac{\partial z}{\partial P_a}+(\bar{R}_d-R_d^*)\frac{\partial z}{\partial R_d}+(\bar{\sigma}_y-\sigma_y{}^*)\frac{\partial z}{\partial \sigma_y} \\ &+(\bar{t}-t^*)\frac{\partial z}{\partial t}+(\bar{L}-L^*)\frac{\partial z}{\partial L} \end{aligned} \quad (10)$$

$$\begin{aligned} \sigma_z^2=&\left(\sigma_{d_o}^N\frac{\partial z}{\partial d_o}\right)^2+\left(\sigma_T^N\frac{\partial z}{\partial T}\right)^2+\left(\sigma_D^N\frac{\partial z}{\partial D}\right)^2 \\ &+\left(\sigma_{p_a}^N\frac{\partial z}{\partial p_a}\right)^2+\left(\sigma_{R_d}^N\frac{\partial z}{\partial R_d}\right)^2+\left(\sigma_{\sigma_y}^N\frac{\partial z}{\partial \sigma_y}\right)^2 \\ &+\left(\sigma_t^N\frac{\partial z}{\partial t}\right)^2+\left(\sigma_L^N\frac{\partial z}{\partial L}\right)^2 \end{aligned} \quad (11)$$

In which $\bar{d}_o$, $\bar{T}$, $\bar{D}$, $\bar{p}_a$, $\bar{R}_d$, $\bar{\sigma}_y$, $\bar{t}$ and $\bar{L}$ are the average values and d_o^*, T^*, D^*, p_a^*, R_d^*, σ_y^*, t^*, L^* are the values at the inspection time. And, σ_z, σ_{do}, σ_{rT}, σ_D, σ_{pa}, σ_{Rd}, $\sigma_{\sigma y}$, σ_t and σ_L are the average variations for each variable in ferms of d_o, T, D, p_a, R_d, σ_y, t and L.

The failure probability at the N$^{\text{th}}$ check point can be represented as

$$P_f=1-(1-P_{f_1})(1-P_{f_2})(1-P_{f_3})\cdots(1-P_{f_N}) \quad (12)$$

The average variance for each variable is the multiplication of the average of each variable to the coefficient of variation (Ahammed and Melchers, 1997, Ahammed, 1998).

3. Case Study of Corrosion Pipeline

The variables, the means and the coefficients of the variation listed in Table 1 have been utilized to investigate the effect of each variable on the

Table 1 Random variables and their parameters used in experiments

Variable	Mean	COV
d_o	3mm	0.10
D	600mm	0.03
L	200mm	0.05
p_a	5MPa	0.10
R_d	0.1mm/yr	0.20
σ_y	423MPa	0.067
t	10mm	0.05

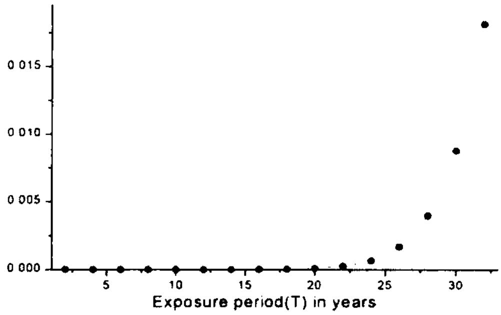

Fig. 3 A relationship between the failure probability (P_f) and exposure period(T) in year

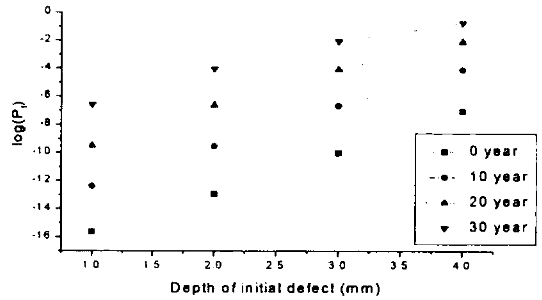

Fig. 4 Relationship between failure probability and defect depth for varying exposure period in year

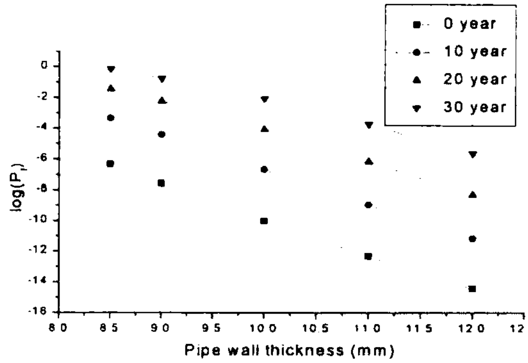

Fig. 5 Relationship between failure probability and pipe wall thickness for varying exposure period in year

failure probability of the corrosion pipeline (Ahammed, 1998). The applied forces at boundaries except for the inner pressure of the pipeline are assumed to be negligible.

4. Results and Discussion

Figure 3 shows the relationship between the failure probability of the corrosion pipeline and the exposed period in year using practical data listed in Table 1. It is noted from Fig. 3, that the failure probability increases slowly during the period between 20 and 25 years and the increasing rate of the failure probability becomes steeper after 25 years of the exposure period. Furthermore, it is noted that a certain size of corrosion does not affect the failure probability within a certain exposed period and a rapid increase of the failure probability occurs after a certain exposed period is elapsed.

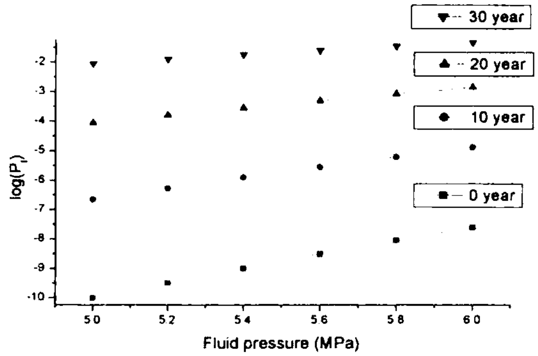

Fig. 6 Relationship between failure probability and fluid pressure for varying exposure period in year

Figures 4~10 show the aspects of change in the failure probability corresponding to each variable appeared in Table 1. The deeper the initial depth of the corrosion defect, the more rapid increase of the failure probability is shown in Fig. 4. The thicker the pipe wall thickness, the decrease of the failure probability is pronounced as shown in

Fig. 5. Figures 6 and 7 show the increase of failure probability to the increase of operation service inner gas pressure and the corrosion rate.

It is noted that the failure probability of the pipeline with the smaller diameter, is lower than that of the larger diameter as shown in Fig. 8. Figures 9 and 10 show the variation of the failure probability corresponding to the yield stresses of the pipeline and the length of the corrosion. It is found through Figs 9 and 10 that the variation of the failure probability gets lower according to the change of the corrosion length. The corrosion rate is known to be highly affected by the environment in which the pipeline is set. However, the change of the corrosion rate is found to be dependent on the exposed period even under the same environmental condition. Figure 11 shows the variation of the failure probability corresponding to the variation of the corrosion rate for varying exposure periods. The larger the variation ratio, the increase of failure probability becomes more pronounced.

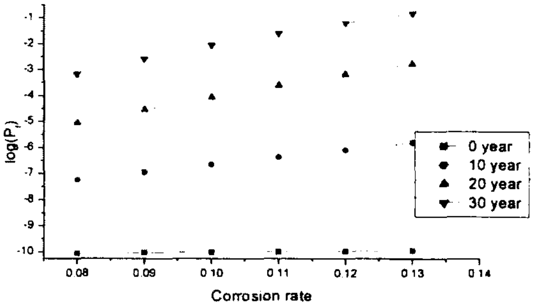

Fig. 7 Relationship between failure probability and corrosion rate for varying exposure period in year

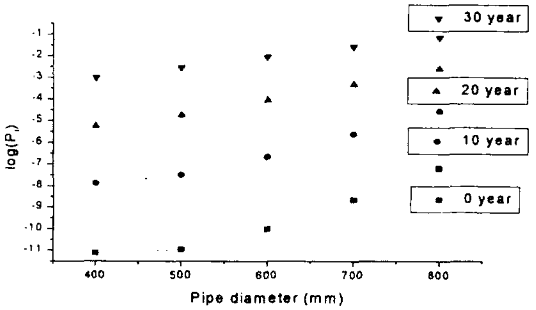

Fig. 8 Relationship between failure probability and pipe diameter for varying exposure period in year

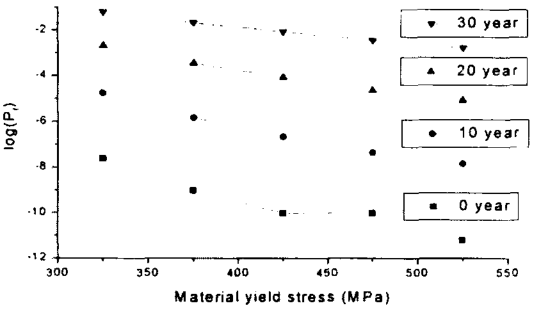

Fig. 9 Relationship between failure probability and material yield stress for varying exposure period in year

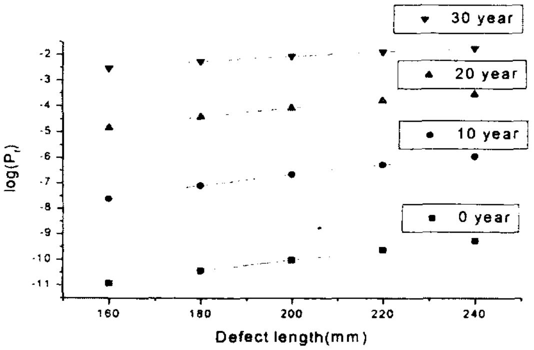

Fig. 10 Relationship between failure probability and defect length for varying exposure periods in year

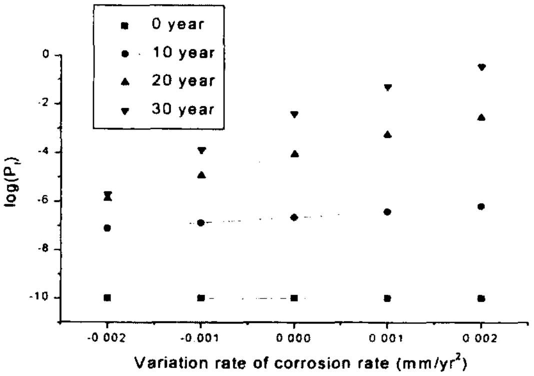

Fig. 11 Relationship between failure probability and variation rate of corrosion rate for varying exposure period in year

5. Results

In this study, a failure probability model is utilized to carry out the effective failure control for the corrosion pipeline. Using the failure probability model, the effect of the corrosion depth and length, the thickness, the diameter, the inner fluid pressure, the yield stress and the corrosion rate of pipeline on the failure probability is systematically studied, frean which the following results are obtained;

(1) It is found that the thickness, diameter and the yield stress of pipeline highly affect the FP (Failure Probability) and especially the effect of the variation of thickness, among others is found to be more pronounced than any other parameters. Therefore, it is recommended that a different corrosion tolerance corresponding to the appropriate environment should be taken.

(2) The depth of corrosion shows more pronounced effect on the PF than the length of the corrosion.

(3) The rate of the corrosion is generally known to be dependent on the environmental condition such as the location of pipeline setting. It is noted that the increase of the rate of corrosion makes the PF rapidly increase. Therefore, the increase of PF can be more effectively controlled by the suppression of the corrosion rate than the decrease of the corrosion rate.

Acknowledgment

The authors are grateful for the support provided by a grant from the KOSEF and Safety and Structural Integrity Research Center at the SungKyunKwan University. The authors wish to thank all the members concerned.

References

Ahammed, M., 1998, "Probabilistic Estimation of Remaining Life of a Pipeline in the Presence of Active Corrosion Defects," *International Journal of Pressure Vessels and Piping* 75, pp. 321~329.

Ahammed, M. and Melchers, R. E., 1996, "Reliability Estimation of Pressurised Pipelines Subject to Localized Corrosion Defects," *Int. J. Pres. Ves and Piping*, 69, pp. 267~272.

Ahammed, M. and Melchers, R. E., 1997, "Probabilistic Analysis of Underground Pipelines Subject to Combined Stresses and Corrosion," *Engineering Structures*, Vol. 19, No. 12, pp. 988~994.

ANSI/ASME B31-1985, 1985, "Manual for Determining the Remaining Strength of Corroded Pipeline," *Supplement to ANSI/ASME B31G Code for Pressure Piping. The American Society of Mechanical Engineers*, New York.

Bubenik, T. A., Olson, R. J., Stephens, D. R. and Francini, R. B, 1992, "Analyzing the Pressure Strength of Corroded Linepipe," *Proc., 11th Int, Conf. Offshore Mech and Arctic Eng.*, Vol V, pp. 225~232.

Choi, S. C., 2000, "Coating Flaw Prevention of Underground Buried Pipeline," *Gas Safety Journal*, Vol. 26, No. 5, pp. 25~33.

Hopkins P. and Jones D. G., 1992, "A study of the Behaviourof Long and Complexshaped Corrosion in Transmission Pipelines," *In Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering*, ASME, Volume V, Part A, pp. 211~217.

Kiefner, J. F., 1974, "Corroded Pipe Strength and Repair Methods," *Symposium on Line Pipe Research, Houston*, Texas.

Kiefner, J. F., Hisey, D. T. and O'Grady, T. J., 1992, "Pressure Calculation for Corroded Pipe Developed," *Oil and Gas Journal*, pp. 84~89.

Kim, S. H, Kim, J. W. and Kim, K. J., 1997, "Three-Dimensional Dynamic Analysis of Underground Openings Subjected to Explosive Loadings," *Journal of the Computational Structural Engineering Institute of Korea*, Vol. 10, No. 2, pp. 171~178.

Lee, O. S. and Kim, H. J., 1998, "Criterion for Predicting Failure External Corroded Pipeline," *Proceeding of Korea Institute of Industrial Safety*, pp. 261~266.

Lee, O. S. and Kim, H. J., 1999, "Effect of External Corrosion in Pipeline on Failure Prediction," *Proceeding of Korean Society of Mechan-*

ical Engineering, Vol. 23, No. 11, pp. 2096~2101.

Lee, O. S. and Choi, S. S., 1999, "Effect of Circular Cavity on Maximum Equivalent Stress and Stress Intensity Factor at a Crack in Buried Pipeline," *KSME International Journal*, Vol. 13, No. 4, pp. 350~357.

Lee, O. S. and Cho J. U., 1992, "Computer Simulation of the Dynamic Behavior of Three Point Bend Specimen," *KSME International Journal*, Vol. 6, No. 1, pp. 58~62.

Mohammdi, J., Saxena, S. K. and Wong, Y. T., 1985, "Modeling Failure Probability Underground Pipes," *Underground Pipeline Engineering*, pp. 193~205.