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Effect of correlated input parameters on the failure probability of pipelines with corrosion defects by using FITNET FFS procedure

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ABSTRACT

The paper presents a probabilistic methodology considering the correlations between the input variables for the failure probability evaluation of corroding pipelines based on the corrosion module of the FITNET FFS procedure. A computer program based on this method is developed to calculate the failure probability of pipelines by considering different numbers of defects and different elapsed times. In case of one defect, the correlation between the initial defect depth and the initial defect length has the most significant impact on the failure probability of the pipeline. If the correlations between these two parameters for an individual defect are not considered, the prediction results are nonconservative when the failure probability is below 40% and conservative when it is above 40%. In case of multiple defects, the independent assumption of variables generally leads to a conservative estimate of the failure probability. The conservatism increases if the elapsed time and/or the actual correlation coefficients of the variables increase. The correlation of the operating pressure, the initial defect depth and material ultimate tensile strength at the location of different defects has a larger impact on the failure probability than the correlation of other parameters at different defects. The upper bound failure probability calculated by engineering method corresponds to that calculated using the presented method without considering the correlation between input parameters. This confirms the validity of the presented model.

1. Introduction

With the development of the industry, more and more piping systems are being used in the field of nuclear power generation and petrochemical industry. The mechanical integrity of the nuclear reactor piping and gas pipeline is a matter of great importance for both economical and safety reasons. Corrosion is recognized as one of the most important degradation mechanisms that affect the long-term reliability and integrity of metallic pipelines. The prediction of the remaining strength of pipelines containing active corrosion defects is frequently carried out by using deterministic methods such as the ASME B31G [1], the Modified B31G [2,3], the Battelle [4], the DNV-99 [5] and the Shell-92 [6] models. The practical application of the deterministic approach is easier from an engineering point of view, and consequently has received the most attention for the pipeline safety assessment. However, there are some inevitable variations in parameters due to numerous objective and subjective factors, such as the measurement of the dimensions, the manufacturing and the operating conditions of pipelines, which can have an effect on the remaining life of pipelines. The traditional deterministic approaches are unable to consider the significance of random variables. It is generally accepted that, by using deterministic methods, the safety margin will be large when the variability of variables is small. On the other hand, it is pointed out in Ref. [7] that the deterministic methods could lead to nonconservative results. Therefore, in order to make a rational prediction, it is especially advantageous to resort to a probabilistic approach to estimate the remaining life and the failure probability of pipelines. Furthermore, the outcomes from probabilistic methods are useful as a decision making tool for the maintenance optimization and repair of pipelines. Over the years, lots of studies have been devoted to the probabilistic analysis of the pipelines containing defects by considering independent random variables [7–21].

For a pressurized piping or vessel containing multiple defects, it is noted that failures at different defects are correlated events. This means the same parameter at different defects is correlated. The correlation stems from the fact that the defects are subjected to the same operation environment, e.g. temperature and internal pressure loading and the same pipe properties, e.g. wall thickness, yield

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Nomenclature

D	outer diameter of the pipeline, mm
$d(T)$	time-dependent depth of the defect, mm
d_0	measured depth of the defect at time T_0, mm
$F_{Xi}(X_i)$	cumulative distribution function of X_i
L_0	measured surface length of the defect at time T_0, mm
$L(T)$	time-dependent surface length of the defect, mm
L_{SF}	limit state function, MPa
L_{SFi}	limit state function for the ith defect, MPa
n	number of simulation cycles when $L_{SF} \leq 0$
N	total number of simulation cycles
p_f	failure pressure of the corroded pipeline, MPa
p_{op}	pipeline operating pressure, MPa
P_F	failure probability of the pipeline
PF_l	lower bound of failure probability
PF_u	upper bound of failure probability
PF_i	failure probability for the ith defect
Q	length correction factor
t	wall thickness of the pipeline, mm
T	elapsed time, years
T_0	time of last inspection, year
ΔT_e	pipeline elapsed time since the last inspection date, years
T_{ij}	function of ρ_{ij} and the distributions of the variables
u_1, u_2, u_3, u_4	independent variables following the uniform distribution $U(0,1)$
V_r	radial corrosion defect growth rate, mm/year
V_a	axial corrosion defect growth rate, mm/year
X	random variable
X_i	correlated variable following non-standard normal distributions
Y	random variable
Y_i	random variable following the standard normal distribution
Z_i	correlated variable following standard normal distribution
ρ_{ij}	correlation coefficient matrix of the input variables
ρ'	correlation matrix
ρ''	Cholosky decomposition matrix of ρ'
ρ_{XY}	correlation coefficient between X and Y
σ	standard deviation of random variable
σ_X, σ_Y	standard deviation of X and Y
σ_{ys}	yield stress, MPa
σ_{uts}	ultimate tensile strength, MPa
μ	mean value of random variable
μ_X, μ_Y	mean value of X and Y
Φ	cumulative distribution function of the standard normal variable

stress, tensile strength and defect geometry at different defect locations are similar. Meanwhile, even for the same defect, some of the parameters, like material properties, defect geometry could be mutually correlated. Because a pipeline containing multiple defects is a series system, ignoring the correlation between the defects when evaluating the structural reliability will lead to imprecise results.

So far, there are only a few studies about the correlation of multiple defects for the probabilistic analysis of structures [22–24]. We [22] performed a probabilistic leak-before-break analysis by considering correlated random variables. De Leon and Macia [23] studied the effect of the spatial correlation between the initial depths of defects on the burst probability of pipelines with different segments. The results showed that when the coefficient of correlation is greater than 0.6 and the number of pipeline segments is greater than 5 the correlation between the initial defect depths has a significant impact on the system reliability. Zhou [24] presented a methodology to evaluate the pipeline reliability containing multiple defects by considering three potential failures due to corrosion. The results showed that the correlations of the internal pressures, initial defect sizes and defect growth rates have a significant effect on the system reliability whereas the effect of the correlation of pipe properties can be neglected. The effect of the correlated input parameters on the failure probability of pipelines containing multiple defects still needs more studies.

In 2008 the FITNET FFS procedure [25], which was developed as a unified European procedure for the structural integrity assessment, provides a new failure pressure model in the corrosion module to analyze the plastic collapse failure of pipelines. In Ref. [7], a probabilistic method using the Monte Carlo (MC) simulation based on the FITNET FFS procedure is presented by the authors to predict the failure probability of pipelines containing corrosion defects by assuming the random variables to be independent. However, the impact of correlation between multiple defects and the correlation between different parameters for the same defect on the structural integrity of pipelines based on FITNET procedure has not been studied yet.

Therefore, in this paper, a probabilistic method is presented to analyze the failure probability of pipelines by considering the correlated input parameters. It is based on the MC simulation with the Nataf transformation to generate correlated random variables. An example is used to illustrate the proposed method. The impact of the correlation of the parameters such as initial defect sizes, material properties for different defects as well as the correlation between these parameters for the same defect on the failure probability of pipelines is studied. The role of multiple defects and the correlation coefficient of the defects on the failure probability of pipelines are also presented.

2. Probabilistic model of corroded pipelines in the FITNET FFS procedure

In the FITNET FFS procedure, the plastic collapse pressure for a pipeline containing an axial corrosion defect (Fig. 1) is expressed as [7,25]:

$$p_f = \frac{2\sigma_{uts} t (1/2)^{(65\ \mathrm{MPa}/\sigma_{ys})}}{(D-t)} \left[\frac{1 - \dfrac{d(T)}{t}}{1 - \dfrac{d(T)}{t} Q^{-1}} \right], \tag{1}$$

where

$$Q = \sqrt{1 + 0.8 \frac{L(T)^2}{Dt}}. \tag{2}$$

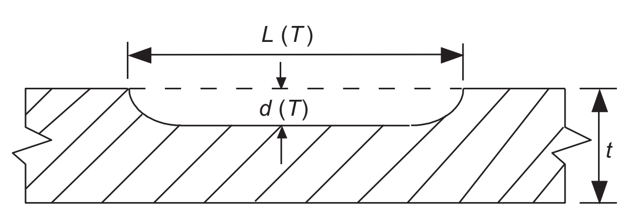

Fig. 1. Pipeline wall section with an idealized corrosion defect.