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Importance sampling-based system reliability analysis of corroding pipelines considering multiple failure modes

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A B S T R A C T

The importance sampling (IS) technique is employed to evaluate the time-dependent system reliability of corroding pipeline segments containing multiple active corrosion defects by considering two competing failure modes, small leak and burst. The IS density functions in the standard normal space for incremental probabilities of small leak and burst of the pipe segment over a short time period are established as the weighted averages of the IS density functions for small leak and burst, respectively, at individual corrosion defects. The IS density functions for incremental probabilities of small leak and burst of individual defects are centred at the design points in the corresponding failure domains. Four numerical examples that are representative of the onshore gas transmission pipelines in the US are used to illustrate the application of the proposed methodology. The results demonstrate the excellent accuracy and efficiency of the methodology.

1. Introduction

The metal-loss corrosion is a common threat to the structural integrity of oil and natural gas pipelines: it accounts for 35% of failures on oil and gas transmission pipelines in Canada between 2010 and 2014 [1] and 32% of reportable incidents on gas transmission pipelines in the US between 2002 and 2013 [2]. A metal-loss corrosion defect, on either the external or internal surface of a pipeline, can be characterized as a three-dimensional part through-wall defect. The defect causes thinning of the pipe wall and compromises the pipe's capacity to contain its internal pressure. If sufficiently large, the defect will cause the pipeline to fail by one of two distinctive failure modes, i.e. small leak and burst [3]. A small leak occurs once the defect penetrates the pipe wall, whereas a burst occurs if the remaining ligament of the pipe wall at the defect is severed (i.e. undergoing plastic collapse) due to the internal pressure prior to the defect penetrating the pipe wall. The failure consequences of bursts are in general much more severe than those of small leaks [4].

Pipeline operators conduct inline inspections (ILI) of pipelines using high-resolution inspection tools (e.g. based on the magnetic flux leakage technology) to detect, locate and size corrosion defects on a regular basis [4–6]. Given the ILI results, either the deterministic or reliability-based corrosion defect assessment can be carried out [7]. The reliability-based corrosion assessment is gaining popularity in the pipeline industry for its ability to deal with relevant uncertainties, such as the inherent randomness of the corrosion growth process and measurement errors involved in ILI, within a consistent framework [5,6]. Central to such an assessment is the evaluation of the time-dependent reliability of corroding pipelines as it provides the basis for developing corrosion mitigation measures that minimize the risk with limited resources. More often than not, multiple active corrosion defects exist on a pipeline; in this case, the pipeline is a series system since failure at any defect implies failure of the pipeline. Therefore, the reliability analysis of the pipeline should be carried out using methodologies that are appropriate for evaluating the system reliability of series systems. Due to the marked differences in the consequences associated with small leaks and bursts, it is important to distinguish these two failure modes in the reliability analysis [3,8]. Note that once a corroded pipeline segment fails, by small leak or burst, it is usually detected and repaired within a short time frame such as several days. It follows that the occurrence of a small leak eliminates the potential occurrence of a burst, and vice versa. Therefore, the small leak and burst should be considered as two competing failure modes in the system reliability analysis of corroding pipelines. Note further that the potential stochastic dependence among failures at different defects should also be accounted for in the reliability analysis. Such a dependence may result from that the pipe properties and internal pressure at different defects are similar and that growths of different defects are driven by similar corrosion environments.

The simple Monte Carol simulation (MC) is the most straightforward approach to evaluate the time-dependent system reliability of corroding pipelines considering the small leak and burst failure modes [3,9]. However, this approach is in general time-consuming, especially if the failure probability is small (e.g. $\leq 10^{-6}$) and/or the number of pipelines to be analysed is large. A first order reliability method (FORM)-based methodology for evaluating the system reliability of corroding pipelines was recently developed [10]. Although computationally efficient and shown to be generally accurate, this methodology requires combining different limit states into an equivalent limit state, the implementation of which is somewhat involved and may not be amenable for practical application. Furthermore, the verification of the actual accuracy of this

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methodology still requires using simulation-based methods. Leira et al. [11] proposed an enhanced MC simulation technique to evaluate the probability of burst of a corroding pipeline containing multiple defects. The enhancement results from fitting a parametric probability function at moderately high failure levels and extrapolating the tail probability, thus improving the efficiency of the simulation. However, this approach is potentially subjected to tail sensitivity issues.

The efficiency of the simple MC simulation can be improved by using the importance sampling (IS) technique. The theory of the IS technique is well described in the literature [12–14]. By using an appropriately selected IS density function, the IS-based simulation samples the failure domain more frequently and therefore achieves a higher efficiency in estimating the failure probability than the simple MC simulation. Studies on selecting the appropriate IS density functions for evaluating the system reliability of series and parallel systems have been reported in the literature [12,14–17]. More recently, the kriging method has been successfully combined with IS [18] to deal with systems that have low failure probabilities and are associated with computationally-intensive (e.g. requiring finite element analyses) limit state functions. However, the application of the IS technique to evaluate the time-dependent system reliability of corroding pipelines by considering the small leak and burst failure modes has, to our best knowledge, not been reported in the literature.

The objective of the work reported in this paper is to explore the use of the IS technique to evaluate the time-dependent system reliability of corroding pipelines containing multiple active, stochastically dependent corrosion defects by considering the small leak and burst failure modes. The remainder of the paper is organized as follows. Section 2 describes the limit state functions relevant to the small leak and burst failure modes for a corroding pipeline; Section 3 presents the methodologies for evaluating the system reliability of corroding pipelines based on the IS technique and selecting the IS density function; numerical examples are given in Section 4 to demonstrate the accuracy of the proposed methodology, followed by conclusions.

2. Formulations for limit state functions and failure probabilities

Consider a pipeline segment containing m ($m \geq 1$) active corrosion defects. The limit state function, $g_j^s(t)$, for the jth ($i = 1, 2, \ldots, m$) defect to penetrate the pipe wall as a function of time t is given by Zhou [3]

$$g_j^s(t) = \varphi wt_j - d_j(t) \tag{1}$$

where wt_j denotes the pipe wall thickness at the jth defect; $d_j(t)$ is the depth (i.e. in the through-pipe wall thickness direction) of the jth defect at time t; $\varphi(\varphi \leq 1)$ is a professional factor to account for that the remaining ligament of the pip wall may develop cracks that result in leaks for relatively deep corrosion defects [19], and φ is typically assumed to equal 0.8 [19,20]. The time-dependent limit state function, $g_j^c(t)$, for the severance of the remaining ligament at the jth defect is given by Zhou [3]

$$g_j^c(t) = p_{cj}(t) - p_j \tag{2}$$

where $p_{cj}(t)$ is the burst capacity pressure at the jth defect at time t and p_j is the internal pressure at the jth defect. In this study, p_j is considered a random variable as opposed to a stochastic process. Many empirical and semi-empirical models have been developed to evaluate the burst capacity pressure at a corrosion defect; a summary of these models can be found in Zhou and Huang [21]. In this study, the model proposed by Leis and Stephens [20,22] is adopted to calculate p_{ci} as follows:

$$p_{cj} = \xi_j \frac{2wt_j\sigma_{uj}}{D_j}\left[1 - \frac{d_j}{wt_j}\left(1 - exp\left(\frac{-0.157l_j}{\sqrt{\frac{D_j(wt_j - d_j)}{2}}}\right)\right)\right] \tag{3}$$

where σ_u denotes the pipe ultimate tensile strength; ξ is the associated model error; D is the pipe outside diameter, and l denotes the length (i.e. in the longitudinal direction of the pipeline) of the defect. The subscript j for a given symbol indicates its association with the jth defect. Similar to the defect depth, the defect length can also grow with time. For brevity, $p_{cj}(t)$, $d_j(t)$ and $l_j(t)$ are simply written as p_{cj}, d_j and l_j, respectively, in Eq. (3).

Let $P_l(t)$ and $P_b(t)$ denote the cumulative probabilities of small leak and burst of the pipeline segment, respectively, within a time interval [0, t]. Further let t_j^s denote the time at which the jth defect just penetrates the pipe wall, and t_j^c denote the time at which plastic collapse takes place at the jth defect due to the internal pressure. Because of the competing characteristics of the small leak and burst failure modes, $P_l(t)$ and $P_b(t)$ can be expressed in terms of t_j^s and t_j^c as follows:

$$P_l(t) = \text{Prob}\left[\left(0 \leq \min_j\left\{t_j^s\right\} \leq t\right) \cap \left(\min_j\left\{t_j^s\right\} < \min_j\left\{t_j^c\right\}\right)\right] \tag{4a}$$

$$P_b(t) = \text{Prob}\left[\left(0 \leq \min_j\left\{t_j^c\right\} \leq t\right) \cap \left(\min_j\left\{t_j^c\right\} < \min_j\left\{t_j^s\right\}\right)\right] \tag{4b}$$

where Prob[•] denotes the probability of an event, and the symbol "∩" denotes the intersection of two events.

3. IS-based system reliability analysis of corroding pipelines

3.1. Overview of IS technique

The failure probability, P_f, of an engineering system can be calculated as

$$P_f = \int_{\Omega(\boldsymbol{x})} f_{\boldsymbol{X}}(\boldsymbol{x})d\boldsymbol{x} \tag{5}$$

where $\boldsymbol{X}$ is a vector of random variables involved in the system; $f_{\boldsymbol{X}}(\boldsymbol{x})$ is the joint probability density function (PDF) of $\boldsymbol{X}$, and $\Omega(\boldsymbol{x})$ denotes the failure domain with $\boldsymbol{x}$ being the value of $\boldsymbol{X}$. It is generally more advantageous to evaluate P_f in the standard normal space than in the original (i.e. $\boldsymbol{X}$) space due to the rotational symmetry of the joint standard normal PDF [23,24]. To this end, $\boldsymbol{X}$ is transformed to a vector of independent standard normal variate $\boldsymbol{U}$ that has the same dimension as $\boldsymbol{X}$, and P_f is then given by

$$P_f = \int_{\Omega'(\boldsymbol{u})} f_{\boldsymbol{U}}(\boldsymbol{u})d\boldsymbol{u} \tag{6}$$

where $\boldsymbol{u}$ is the value of $\boldsymbol{U}$; $\Omega'(\boldsymbol{u})$ is the failure domain in the standard normal space, and $f_{\boldsymbol{U}}(\boldsymbol{u})$ is the joint (standard normal) PDF of $\boldsymbol{U}$. The techniques for transforming $\boldsymbol{X}$ to $\boldsymbol{U}$ are described in many well-known references on the structural reliability theory [14,23,24]. By applying the IS technique, P_f expressed by Eq. (6) can be evaluated as [14]

$$P_f \approx \frac{1}{N}\sum_{i=1}^{N}\frac{I(\boldsymbol{u}_i)f_{\boldsymbol{U}}(\boldsymbol{u}_i)}{h_{\boldsymbol{U}}(\boldsymbol{u}_i)} \tag{7}$$

where N is the total number of IS simulation trials; $h_{\boldsymbol{U}}(\boldsymbol{u})$ is the so-called importance sample density function; $\boldsymbol{u}_i$ is the ith random ($i = 1, 2, \ldots, N$) sample generated from $h_{\boldsymbol{U}}(\boldsymbol{u})$, and $I(\boldsymbol{u}_i)$ is an index function that equals unity if $\boldsymbol{u}_i$ falls in the failure domain and zero otherwise.

To define $h_{\boldsymbol{U}}(\boldsymbol{u})$, first consider the case where the failure domain of the system is characterized by a single limit state function, $g(\boldsymbol{x})$, with $g(\boldsymbol{x}) < 0$ and $g(\boldsymbol{x}) > 0$ representing the failure and safe domains, respectively. Let $G(\boldsymbol{u})$ denote the mapping of $g(\boldsymbol{x})$ in the standard normal (i.e. $\boldsymbol{U}$) space, with $G(\boldsymbol{u}) < 0$ and $G(\boldsymbol{u}) > 0$ representing the failure and safe domains, respectively in the $\boldsymbol{U}$ space; $g(\boldsymbol{x}) = 0$ and $G(\boldsymbol{u}) = 0$ are known as the limit state surfaces in the $\boldsymbol{X}$ and $\boldsymbol{U}$ spaces, respectively. The importance sampling function $h_{\boldsymbol{U}}(\boldsymbol{u})$ for the single limit state function case can be determined by simply shifting $f_{\boldsymbol{U}}(\boldsymbol{u})$ to the so-called design point $\boldsymbol{u}^*$ [14,25], i.e. $h_{\boldsymbol{U}}(\boldsymbol{u}) = f_{\boldsymbol{U}}(\boldsymbol{u} - \boldsymbol{u}^*)$, where $\boldsymbol{u}^*$ is located on the limit state surface and has the shortest distance to the origin [23]. Making $h_{\boldsymbol{U}}(\boldsymbol{u})$ centred at $\boldsymbol{u}^*$ is justified by the fact that $\boldsymbol{u}^*$ is the point in the failure domain that has the highest probability density [23]. The value of $\boldsymbol{u}^*$