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Reliability-based lifecycle management for corroding pipelines

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ABSTRACT

Corrosion-induced damage is a major source of deterioration in infrastructure and industrial systems such as bridges, offshore and onshore structures, and underground oil and gas pipelines. The uncertainty is pervasive in the parameters affecting the evolution of corrosion process. Risk assessment and management of these systems require a suitable dynamic description of the corrosion process that sufficiently accounts for the underlying uncertainty and subsequently propagates it into the lifecycle reliability assessment of these systems. In this paper, we present a novel approach for reliability-based life cycle management of buried pipelines subjected to corrosion damage. We view our main contributions as twofold. First, a probabilistic model for time evolution of corrosion growth is constructed from available data using polynomial chaos formalism. The model is used to systematically propagate the underlying uncertainty into the limit state functions and the lifecycle reliability analysis. Second, we propose a computationally efficient and accurate optimization strategy using polynomial surrogate in order to solve the stochastic optimization associated with the lifecycle management of buried pipelines. The proposed method facilitates the optimization of maintenance scheduling to achieve minimum expected lifecycle cost by allowing implementation of a gradient-based optimization scheme. This is generally a challenging task due to the discontinuous nature of the objective function with respect to design variables. We examine the sensitivity of the optimum maintenance scheduling with respect to the different measures related to failure probability representing different risk strategies. The proposed development provides an uncertainty-aware decision support tool for making more informed decision regarding the lifecycle management of corroding pipelines. This formalism can also be adapted to other deterioration mechanisms that result in damage-induced structural failure over the lifetime.

1. Introduction

Addressing the performance of deteriorating structural systems has constantly motivated efforts pertaining to their repair, rehabilitation and overall lifecycle management. These efforts have led to a growing body of literature aiming to address different aspects of improving safety and cost-effectiveness of deteriorating systems. These include physical condition investigations, constructing empirical models to predict and estimate the state of decay, analyzing the remaining lifetime of systems, and finally suggesting feasible strategies to restore them to their initial state, either nearly or completely [1,2]. Considerable research has dealt with identifying inspection and maintenance schedules to prevent premature failure in a variety of structures and applications. Examples include mechanical components subjected to fatigue-induced deterioration [3–6], general civil engineering systems [7–10], and in particular bridges [11–15]. Corrosion-induced damage, in particular, has evoked considerable attention as one of the main sources of deterioration in many infrastructure and industrial systems such as bridges, offshore and onshore structures. Corrosion leads to the loss in the performance and durability that eventually reduces the safety, serviceability, and service life of systems. Significant efforts related to corrosion mitigation have been directed towards concrete structures [16,17] and underground pipelines [18–20].

The corrosion process is a complex physico-chemical phenomenon, which is influenced by multitude of factors including environmental and climatic conditions, as well as material characteristics and compositions. Modeling corrosion evolution has always been challenging, mainly due to large degree of uncertainty in the parameters and processes that describe the initiation and growth [21,22]. Ignoring the uncertainty leads to either overestimating the capacity and remaining life of corroded structures, which in turn threatens the safety and serviceability of the system, or overestimating the probability of failure which increases the system lifecycle cost. In studying corrosion-induced deterioration, a significant amount of literature has dedicated to

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pipeline integrity management, specifically incorporating long-term damage due to external corrosion. A gradual reduction in resistance and loss of material by corrosive processes often leads to higher risks, due to an increased probability of failure. Degrading pipelines require regular inspections, repair to cover existing damage, or complete replacement in case of failure. This, in turn, significantly increases the cost of operating and maintaining the pipeline. Hence, to mitigate the adverse effects associated with failure, effective maintenance strategies need to be implemented [23]. The method of lifecycle assessment and reliability analysis provide the ingredients for the systematic formulation of integrity management of pipelines. Accordingly, reliability-based management programs with the aim of mitigating corrosion-induced failure and minimizing the lifetime cost have been adopted to address this problem [24–26]. In this context, there are noteworthy recent examples of research that have addressed multiple aspects related to improving strategies for corrosion mitigation of pipelines. Hong [27] evaluated the remaining pipeline strength based on corrosion defects, by incorporating the probability of defect detection and uncertainty in defect size. Zhou [28] studied the optimal design of pipelines focusing on comparing different wall thicknesses with the American [29] and Canadian pipeline standards [30]. This was followed by studying the effect of spatial variability of corrosion defects on system reliability [31]. The results showed a strong impact of initial defect size and growth rate on pipeline failure, implying that it might be overly conservative to ignore the effect of correlation between multiple corrosion defects, and system reliability. However, this study incorporated a conservative linear corrosion growth model where the rates at which the defect depth and length grew were random but constant with time. Additionally, inspections were periodic and at a fixed interval. Gomes et al. [32] considered a different non-linear growth model and allowed the time interval between inspections to be a design variable, subject to optimization. Further attempts by the same authors [33] involved modeling the uncertainty in pitting corrosion depth by polynomial chaos method and incorporate it into the limit state functions associated with pipeline failures. A global optimization strategy based on multi-start simplex optimization technique was employed to deal with the discontinuous nature of the objective function. Tee et al. [25] presented a reliability-based lifecycle optimization for the network of pipelines using first-order reliability method, where the corrosion growth was assumed to follow a power-law model. A global optimization scheme based on the genetic algorithm was then used to find the optimum solution.

Despite recent valuable efforts and contributions in advancing optimal maintenance planning of corroding pipelines, challenges still remain in developing efficient and accurate uncertainty-aware approaches that support more informed decision for lifecycle optimization and management. One of the challenges is related to the construction of a suitable dynamic stochastic description of corrosion process directly from available measurements without making prior assumptions that may either overestimating the capacity and remaining life of corroded structures, or overestimating the probability of failure which increases the lifecycle cost of the system. Another challenge lies in enhancing the robustness and efficiency of the stochastic optimization problem associated with reliability-based maintenance planing of pipelines, thus enabling improved evaluation of the optimum management strategies and their implications on lifecycle cost of the systems under different parameters and uncertainty scenarios.

In order to improve the current state of corrosion mitigation for underground pipelines, in this paper we address the two challenges identified above. We first present the construction of a polynomial chaos (PC) random field to model the uncertainty in time evolution of corrosion depth, which allows characterizing the probabilistic description and temporal correlation of corrosion depth directly form measurements. This representation provides a flexible mathematical structure that enables propagating the uncertainty in the limits state functions and lifecycle reliability analysis. An efficient optimization strategy based on polynomial surrogate is also presented that facilitates solving the stochastic optimization problem associated with the optimal maintenance and repair strategy of buried pipelines. Using this formalism, the expected lifecycle cost can be minimized while constraining probability of failures to prescribed desired values. These prescribed thresholds represent the level of risk or the margin of safety thus allowing identification of an optimal maintenance schedule that minimizes the cost for a desired level of risk. Moreover, the proposed framework provides promising toolset that can be adapted to other applications within the context of reliability-based lifecycle management, which involves other modes of deterioration.

The paper is organized into three main parts. Following this introduction, Section 2 describes the methodology used for stochastic modeling of corrosion evolution based on the polynomial chaos formalism. Section 3 outlines the main ingredients of the reliability-based lifecycle assessment framework for identifying the optimum scheduling of maintenance under the uncertainty. This includes presenting the formulation of the stochastic optimization problem and the strategy to solve it accurately and efficiently as the basis for adopting the maintenance strategy. Finally, in Section 4 the implementation and the results of the proposed methods are presented using a case study consisting of corrosion growth measurements.

2. Stochastic modeling of corrosion evolution

2.1. An overview of corrosion growth models

Modeling and predicting the time evolution of corrosion growth is a challenging task. One of the important challenges lies in the stochastic nature of this phenomenon. Several sources of uncertainty exist within the process and its defining parameters, which can often be difficult to identify. Thus, recognizing them is crucial, in order to improve the accuracy of predicting corrosion evolution. Also, corrosion occurs in many forms and often propagates differently for each structural system because it highly depends on environmental factors, further complicating the modeling aspect.

Several models have been used in the past, to represent the evolution of corrosion over time, in pipelines. The National Association of Corrosion Engineers (NACE) prescribed a deterministic model which used a constant corrosion growth rate of 0.4 mm/year [34]. This was a preliminary model, limited in its scope, as it did not account for the age of the system, or the defect depth. Also, having a predefined growth rate limits its applicability to other corrosive environments. Linear growth models have also been proposed as an improvement, in which the defect depth over time is estimated by assuming a linear behavior of corrosion growth, measured from at least two sets of data [35,36]. An advantage of these models is that, as they depend on the data provided, they can be applied to different corrosive processes, to generate a uniform rate of growth of the defect under consideration. The linear growth models have been used in a deterministic way and calibrated using measurements in time. Both of these models, whether relying on a given dataset, or with an assumed rate of defect growth, do not account for uncertainties in the evolution of corrosion process. A non-linear corrosion growth model was proposed by [18], which depends on the soil and pipe material properties. This could capture the rate of growth far more accurately. Additionally, by considering its parameters as random variables, it can be utilized as a probabilistic model to predict corrosion growth over time, while also including the possible random behavior of the corrosive process. However, most of these models depend on predefined parameters, and often fail to identify certain sources of uncertainty within the system, which leads to results that are more conservative. The presence of significant uncertainty in modeling corrosion-induced deterioration and the challenges in properly accommodating this uncertainty in the system reliability have motivated many researchers to explore and adopt stochastic approaches to address this problem. Gabrielli et al. [37] presented a review of the probabilistic