Engineering Failure Analysis 90 (2018) 245–261

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Reliability analysis of low, mid and high-grade strength corroded pipes based on plastic flow theory using adaptive nonlinear conjugate map

Mohamed El Amine Ben Seghier[a], Behrooz Keshtegar[b,*], Bouali Elahmoune[a]

[a] Laboratory of Petroleum Equipment's Reliability and Materials, University M'hamed Bougara of Boumerdes Boumerdes, Algeria
[b] Department of Civil Engineering, University of Zabol, P.B. 9861335856, Zabol, Iran

ARTICLE INFO

Keywords:
Probabilist burst pressure model
Corroded low
Mid
High-grade pipelines
Reliability analysis
Adaptive conjugate map
Model error

ABSTRACT

Generally, the safety levels of corroded pipes are evaluated using the nonlinear probabilistic model thus, an accurate probabilistic model is the important step in the structural reliability analysis of corroded pipelines. In this paper, three novel probabilistic models are developed for describing the burst pressure in low, mid and high-strength grades steels. The developed probabilistic models for corroded pipelines include three terms as 1) model errors, 2) burst pressure of intact pipes based on stress criteria improved by the plastic flow theory and 3) different remaining corroded strength factors. The best models for each steel grades category of corroded pipeline are selected using the confidence index based on three burst experimental database tests of pipes. The best distributions of model error for different probabilistic burst corroded models are given based on Anderson-Darling statistic from the Normal, Lognormal, Frechet, Gumbel, and Weibull distribution functions. An adaptive conjugate map-based first order reliability method is developed to assess the structural failure analysis of corroded pipelines. Six corroded pipelines with different grades strength steels are selected to demonstrate the applicability of the proposed probabilistic models in structural reliability analysis. It conducted that the average shear stress yield criterion is the best plastic flow theory for modeling the burst pressure of intact pipes, where the Gumbel, Frechet and Lognormal are respectively the best distributions for model errors of low, mid and high-strength grade steels. The reliability results of corroded pipelines demonstrated that the depth of corrosion defects is a sensitive variable, which reduce the safety levels of all corroded pipe examples compared to the length of defect and operating pressure. The safety levels of corroded pipelines reduce about twice less than un-corroded pipes for corrosion defect depth to pipe thickness (d/t) in the range from 0.4–0.5 for almost pipes grades.

1. Introduction

Oil and Gas production facilities are often very far from the treatments and consumption centers. Hydrocarbon products are then transported using steel pipelines over distances of several hundred kilometers. At the present, transporting pipelines of oil and gas are constructed from high variety of strength steels (i.e. X46, X60, X65, X70, X80 and X100), that these pipelines operate under severe conditions by different loads and stresses including internal pressure, mechanical stresses, soil pressure, temperature drops and others. All these factors favor the development and the growth of corrosion defects on the pipes-walls, leading to the leaks and/or the

* Corresponding author.
E-mail addresses: benseghier.ma@univ-boumerdes.dz (M. El Amine Ben Seghier), bkeshtegar@uoz.ac.ir (B. Keshtegar).

https://doi.org/10.1016/j.engfailanal.2018.03.029
Received 12 February 2018; Received in revised form 18 March 2018; Accepted 19 March 2018
Available online 30 March 2018
1350-6307/

ruptures of these structures, which constitute a potential danger to the personnel and the environment. Consequently, it is a great importance to evaluate the reliable levels and the safe operation of oil and gas pipelines, especially in probabilistic modeling the burst pressure of corroded pipelines. The accurate prediction of the burst pressure for high-verity of corroded steel pipes is a vital factor to approximate the safety domains of different steel-pipeline grades.

Available predictive models for the burst pressure of corroded pipelines can be decomposed into the products of two terms: the failure pressure of intact (free-defect) pipe and the remaining corroded strength factor. The first term is a function of pipelines material properties (yield and ultimate tensile strength), and their design parameters such as diameter and wall-thickness, where the second is function of corrosion defect geometries. Both terms have been developed based on full-scale burst test experiments and empirical fitting through regression analyses or Finite Element Analysis (FEA). As an example, the B31G model [1] was developed using full-scale burst test of low strength pipes (X52) for longitudinal oriented defects. The DNV RP F101 model [2] was extended based on medium strength pipelines (X65) for rectangular shaped defects. The PCORRC [3] model was also developed using medium strength full-scale burst test (X65 and X70) based on the finite element method, Ma et al. [4] used high-strength pipe (X70 and X80) with a single rectangular corrosion defect in FEA. According to comparative studies of some existing predictive burst pressure models, most of these models do not give a good result when it is come to grade-strength pipelines not included in the model development. Zhou et al. [5] have been investigated the accuracy of eight models (namely: ASME B31G, Modified B31G, DNV, PCORRC, CPS, the CSA model, RSTRENG and SHELL92) by comparing the results with a full-scale database of burst test. Consequently, it is advisable to develop the accurate probabilistic models for the burst pressure of corroded pipelines with different steel grades.

The estimation of oil and gas corroded pipelines failure probability needs high fidelity by using appropriate methods. Nowadays, two main groups of reliability methods are used as solutions for the reliability analyses of corroded pipelines including analytical approaches (e.g. first order second moment (FOSM) [6] and first/second order reliability method (FORM/ SORM) [7–9] and simulation methods [10]. The main efforts of FORM approaches are to find the most probable failure point (MPP) on the limit state surface. In general, for highly nonlinear problems with non-Normal basic variables [10] as the case in corroded pipeline reliability, the traditional FORM algorithms may provide the unstable results to estimate the failure probability. Recently, the inverse modified FORM approaches are utilized to improve the robustness and efficiency of the reliability loop using enhanced chaos control [11], enriched self-adjusted mean value [12], hybrid descent mean value [13] and enhanced chaos control-based adaptive loop [14] in reliability-based design optimization of applicable complex aircraft panel problems. In the simulation methods, the Monte Carlo simulation (MCS) method [3,7,15] are widely used to solve corroded pipeline reliability problems due to its simplicity. The MCS generates a large sample set to evaluate the limit state function for low failure probabilities ($P_f < 10^{-6}$), thus the MCS is time-consuming to approximate the accurate reliability analysis [16]. Moreover, the corroded pipes with multiple corrosion defects are a series reliability system. Using MCS to evaluate the failure probability of each defect at different time may lead to huge computational costs. To overcome these problems, the development of efficient approach with stable result is critical issue for reliability analyses of corroded pipes. The accuracy of reliability analysis is also dependent on the predictions of probabilistic model for different corroded pipe grades. Consequently, the stable and accurate reliability results for applicable complex reliability problem of corroded pipes can be improved based on the robust and efficient FORM algorithm with an accurate probabilistic corroded model.

This paper develops three probabilistic models to predict the burst pressure of corroded pipelines using three categories of full-scale burst database test for low, mid and high-grade strength steels. The probabilistic models for reliability analysis are developed based on three terms including 1) model errors, which show the differences between the experimental pressures and predicted data, 2) the burst pressure of intact pipes, which computes by using plastic flow theory and 3) remaining strength factors subjected to corrosion defects, which select from B31G [1], PCORRC [3], Ma et al. [4] and Oryniak et al. [17]. The best model combined with the burst pressure of intact pipes and remaining strength factor is chosen using the confidence index statistic for each category of grade steel. The Anderson-Darling statistic is used to obtain the best distribution of model error for each category. Finally, three-grade steel probabilistic models for corroded pipes are presented for reliability analysis. The FORM using an adaptive conjugate map is applied for reliability analysis of six applicable corroded pipes with different grades. The effects of corrosion defects and operating pressure are investigated based on three novel probabilistic models and proposed adaptive conjugate FORM.

2. Reliability method using adaptive nonlinear conjugate map

The vital computational effort of structural reliability analysis is to approximate the failure probability (P_f) by the following integration [18]:

$$P_f = \int_{g(\boldsymbol{X})\le 0} \dots \int f_{\boldsymbol{X}}(x_1,\dots,x_n)dx_1\dots dx_n \approx \Phi(-\beta) \tag{1}$$

where $g(\boldsymbol{X})$ is limit state function, $g(\boldsymbol{X}) < 0$ represents the failure region. $f_{\boldsymbol{X}}$ is joint probability density function (PDF). Φ and β are respectively the standard normal cumulative distribution function (CDF) and reliability index. Generally, the HL-RF formula is widely applied to search the reliability index using FORM, but the traditional analytical FORM formula (i.e. HL-RF) may produce unstable periodic and chaotic solutions [19–21]. The modified visions of the FORM formula using the steepest descent direction have been formulated by chaos feedback control (CC) with step size < 1 [22,23]. The step size (chaos control factor) < 1 in CC methods is determined in terms of the Armijo [24,25], Wolfe condition [26], angle condition [27], convex criterion [28] or merit function [18,29]. Therefore, the improved versions of FORM are computationally more inefficient to determine the reliability index for some convex problems due to applied the step size < 1. The efficient and robust convergence characteristics of a modified iterative