Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 13 (2018) 1670–1675

Structural Integrity Procedia

www.elsevier.com/locate/procedia

ECF22 - Loading and Environmental effects on Structural Integrity

Structural Reliability Analysis of Corroded Pipeline made in X60 Steel Based on M5 Model Tree Algorithm and Monte Carlo Simulation

Mohamed Seghier[a,c], Behrooz Keshtegar[b], José Correia[c], Abílio De Jesus[c], G. Lesiuk[d]

[a] *Laboratory of Petroleum Equipment's Reliability and Materials, University M'hamed Bougara of Boumerdes, Boumerdes 3500, Algeria*
[b] *Department of Civil Engineering, University of Zabol, P.B. 9861335856, Zabol, Iran*
[c] *Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.*
[d] *Wroclaw University of Technology, Faculty of Mechanical Engineering, Department of Mechanics and Materials Engineering, Smoluchowskiego 25, PL50370 Wroclaw, Poland*

Abstract

Accurate determination of the failure probability of oil and gas pipeline is very important in integrity assessment and work conditions of such structure. In this paper, the failure probability of the corroded pipelines which is made by X60 steel grade is evaluated. The burst corroded performance function is developed using the M5 model tree for this complex real engineering failure problem. The structural reliability of a the pressurized gas pipeline containing external corrosion defects has been evaluated using hybrid reliability method combined by the M5 model tree and Monte Carlo simulation. The results indicated that increasing the defects depth are strongly reduced the safety levels of this problem.

Peer-review under responsibility of the ECF22 organizers.

Keywords: Reliability analysis; Corroded pipeline; M5 model tree algorithm; X60 steel, External corrosion, Monte Carlo method

1. Introduction

Oil and gas pipelines are considered are vital infrastructures in the petroleum industry. Pipes are made from metallic steels in which they are in most time buried in aggressive soil environments. This abnormal condition leads to the formation of corrosion defects on the external surface of the pipe wall. As pipelines, transportation capacity needs to be sufficient to ensure oil and gas increasing demand, the safety of such structures is important issue must be precisely determinate to avoid any failure that can cause environmental damages or economies losses for pipelines' owners. For that estimating the failure probability of pipelines with external corrosion defects is considered as an important cause of pipes damages [1][2][3].

Peer-review under responsibility of the ECF22 organizers.
10.1016/j.prostr.2018.12.349

Evaluation of failure probability of corroded pipelines is one of the core contents of quantitative risk assessment in the oil and gas field. Several approaches are conducted by researchers to model and analyze the failure probability oil and gas pipelines. The main efforts in reliability methods are to estimate the failure probability using the limit state function (LSF; i.e. $g(X)=0$). The LSF is separated the design domain into the failure ($g(X)\leqslant 0$) and safety ($g(X)>0$) regains [4]. To address the problem, several efficient approximate techniques such as the first/second-order reliability method (FORM/SORM) and the advanced Monte Carlo simulation (MCS) have been widely adopted to achieve efficient reliability evaluations [5]. Although the widely used of the methods they contain various drawbacks. The FORM/SORM methods may provide unstable or unreasonable failure probabilities for highly nonlinear limit function as the case in corroded pipelines [6][7]. The MCS the most straightforward and used method for its simplicity suffer from tremendous computational cost especially for low failure probabilities. Therefore more robust and efficacy method should be used to estimate the failure probability of corroded pipelines

In this paper, a combined M5Tree meta-model with MCS reliability method is applied to evaluate the failure probabilities of a corroded pipe made by X60 grade steel. The inspection of this pipe reveals various corrosion defects in the external wall. Therefore, the inspection data were used in the calculation to show the efficacy of the proposed method. The complex performance function in the simulation of Monte Carlo technique was enhanced by the M5Tree model to pass the drawback of MCS time consuming for an accurate evaluating the corroded limit state function.

1.1. Reliability analysis of corroded pipes-based M5Tree and MCS

The MCS is used to approximate the failure probability, which is used to compute the below integration:

$$P_f = \int \ldots \int f_X(x_1, \ldots, x_n)dx_1 \ldots dx_n \quad (1)$$

where, P_f is the joint probability density function of n-dimensional random variables X [6,8], and f_X is the performance function of corroded pipe based on burst failure mode, which is evaluated using the M5Tree model. Thus, the approximation of performance function is a vital important issue in this problem.

1.1.1 M5 Tree model

The M5 Tree model is a one of the popular nondramatic data-driven to predict the performance function. This meta-model for evaluating the limit state function is proposed in structural reliability analysis by Keshtegar and Kisi [9]. Recently, the radial M5Tree is applied to calibrate the nonlinear performance function in structural reliability analysis using radial sapling set [10][11]. Two stages are involved to build a model in M5Tree as:

i) Dividing input space into sub regions (Fig. 1a);

ii) Building the trees using data of each sub region (Fig. 1b) that these stages are plotted in Fig. 1.

This model is calibrated using two input data of x_1 and x_2 that each sub data points are used to evaluate a linear model (LM1-LM4).

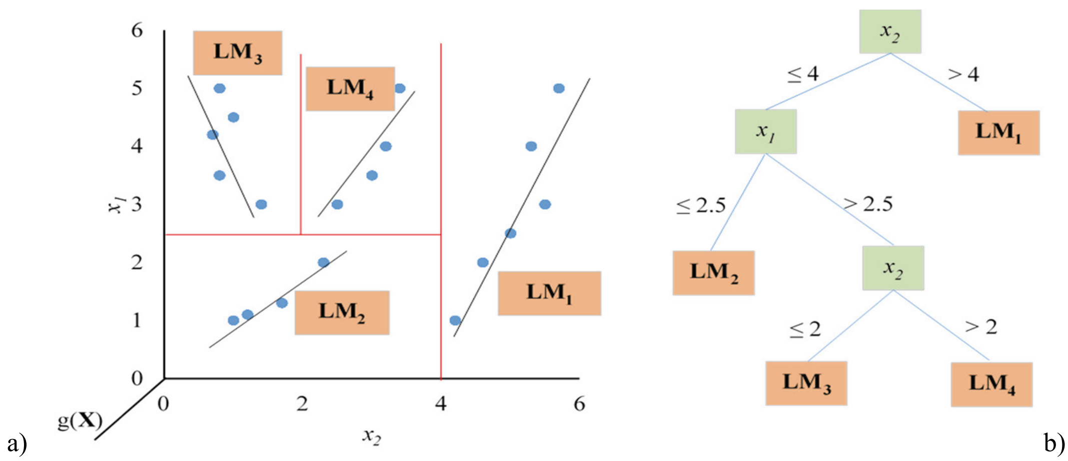

Fig. 1. The M5 model tree structure: a) data in sub regions; b) linear model for sub regions.

The M5Tree is calibrated based on the data of the experimental corroded pipes which is made by X60 which are extracted from reference [2]. This data include 28 full-scale experimental burst data point that the mid-strength X60 steel grade varied from 73 to 720 mm for diameter, 3-14.8mm for wall-thickness, 430 - 478MPa for yield strength, 620.9 – 673.5MPa for ultimate strength, 1.5 – 10.5mm for the maximum corroded depth and 25.5-1016 mm for length of corrosion defects with corroded burst test ranged between 7.55 and 36.33MPa.

1.1.2 Monte Carlo simulation

The Monte Carlo method is the most straightforward method used in the reliability of corroded pipelines. Basically the simulation is based on the generation of a large number of random variables used in the limit state function calculation, then the failure probability is expressed using the following expression:

$$P_f = \frac{1}{N}\sum_{i=1}^{N} I\left[g\left(P_{Burst} \leq P_{Op}\right)\right] = \frac{n}{N} \tag{2}$$

where, I represent an indicator equal to 1 if the statement is true or 0 otherwise, n is the number of the failure scenarios, while N is the total number of simulations. The convergence condition taken in this study to attend sufficient precision is the variation coefficient, this latter should satisfy the following condition:

$$CoV = \sqrt{\frac{(1-P_f)}{P_f(N-1)}} \leq 0.05 \tag{3}$$

where, CoV is the variation coefficient, and P_f is the failure probability provided by the MC technique.

1.1.3 M5 tree model algorithm with Monte Carlo

The M5Tree model is used for approximating the performance function of the corroded pipes under burst pressure failure mode. The ten million random sample data points-based MCS is applied for the evaluating the LSF to approximate the failure probability in the next process. The failure probability by hybrid M5Tree and MCS can be approximated by the following steps:

Step 1: *Define initial parameters*

1- Sample points to calibrate the M5Tree model, number of random samples in MCS (*N*).
2- Give statistical properties of random variables ($\boldsymbol{\mu}$ and $\boldsymbol{\sigma}$) and their distributions.

Step 2: *Generate the performance function by using M5Tree model.*

Step 3: *Generate N random samples –based MCS using statistical properties of random variables*

Step 4: *Approximate the performance function for N- random samples using M5Tree model*

Step 5: *Approximate the failure probability using M5Tree based on the predicted values of performance function for burst pressure of corroded pipe in Step 4.*

2. Case of Study

To show the robust and the applicability of the proposed method (M5tree model combined with Monte Carlo Simulation) a candidate gas pipeline carries made from medium grade steel, X60. The pipe is 40 inches in diameter, was inspected to determine the corrosion defects on pipe-wall-thickness, 100 km was the inspected part of the pipe which reveal a huge number of defects. A statistical analysis of corrosion defects in the external wall of the pipeline was carried out using the Anderson Darling test for the purpose of finding the best fitting distortion of the input parameters based on the inspection data. The chosen distribution are Normal, Log-Normal, Weibull, Frechet and Gumbel distributions while the tested variables are the length and the depth of corrosion defects. The diameter and wall thickness distribution were taken as the nominal values with a slightly CoV. The operating pressure is characterized by a Gumbel distribution. Table 1 presents the input variables used in the reliability analysis.

Table 1. Description of statistical data of the X60 corroded pipeline.

Random variables	Description	Mean	CoV	Distribution
D	Outer diameter of the pipe (mm)	1016	0.03	Normal
t	Wall thickness of the pipe (mm)	12.7	0.06	Normal
σ_y	Yield stress (MPa)	467	0.07	Normal
σ_u	Ultimate tensile strength (MPa)	576	0.08	Lognormal
P_0	Pipeline operating pressure (MPa)	5, 8, 10, 15	0.1	Normal
d^a	Depth of the defect (mm)	2.44	0.51	Frechet
L^b	Length of the defect at time T_0 (mm)	38.72	1.14	Frechet

[a] Based on the results obtained by Andersing Darling test, the probability distribution function of the defects depth is Frechet with the shape parameter of α=2.827 and scale parameter of α=1.954.
[b] Based on the results obtained by Andersing Darling test, the probability distribution function of defects length is Frechet with the shape parameter α=1.942 of and scale parameter of β=28.731.

3. Results and discussions

To investigate the applicability and the performances of the new reliability analysis method based on combining the M5 tree meta-model with the known MCS, the reliability analysis of a corroded pipeline made of mid-strength steel X60 was calculated in term of reliability index and failure probability in which the relationship between both is expressed by the following expression:

$$P_f = \phi(-\beta) \tag{4}$$

First is worthy to mention that the relationship between reliability index and failure probabilities is inversely proportional, that mean an increasing in reliability index is a decrease in failure probability. Results are performed based on the influence of failure probabilities and the reliability on three parameters, which are the operating pressure, corrosion defects depth and length.

In Figure 2 were plotted the reliability index (a) and failure probabilities (b) of the X60 pipeline for four cases of operating pressure regime such as 5, 8, 10 and 15 MPa. The effect of corrosion depth was investigated based on the reliability index and the failure probabilities, in which corrosion depths to wall thickness ratios *(d/t)* are represented in range of 0.05 to 0.8 . It is obvious from results that the reliability indexes decrease with the increasing of the defects depth and/or the increasing in operating pressure while the failure probabilities are increasing in the other hand.

Some worthy result should be denoted such that the ratio d/t=0.8 has the smallest reliability index (highest failure probability) compared to the other ratios for all P_0 cases. The result is logical due to the decreasing of remaining strength of the pipe caused by defects depth (10.16mm as mean). In the case of d/t=0.2 that represent our real case with 2.44 mm of corrosion defects as depth, a threshold should be noted to better know the operating pressure applicable for the operating X60 gas pipeline. Based on reference [6], a reliability index threshold was taken equal to 3 (which mean a failure probability equal to 10^{-3}). Therefore for the ratio d/t=0.2, the operating pressure valid of the candidate pipeline are the one less or equal to 8 MPa. These results are logical for a pipeline made of X60 which confirm the applicability of the developed model.

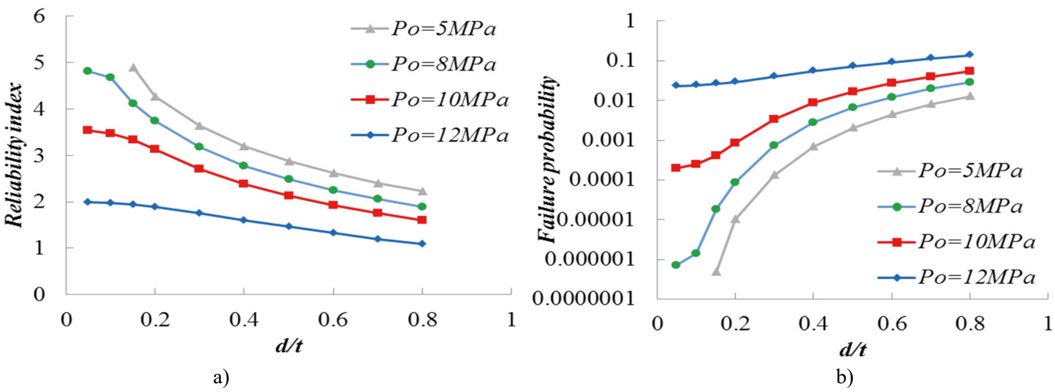

Fig. 2. Structural reliability results of the X60 gas pipeline corresponding to various ratio of corrosion defect depth -to- pipes-wall thickness under different operating pressures cases: a) Reliability index results; b) Failure probabilities results.

The effects of corrosion defect length on the reliability index and failure probability are investigated and presented in Figures 3 (a) and (b), respectively. This latter show the reliability index and failure probability of the X60 studied pipeline corresponding to various ratios $\frac{L}{\sqrt{Dt}}$ in the range from 0.05 to 15 under four cases of operating pressure as 5, 8, 10 and 12 MPa as mean. The results of the calculation show that the influence of $\frac{L}{\sqrt{Dt}}$ ratio increasing on reliability index and failure probability for the four curves-based different cases of P_0, i.e. 5, 8, 10, 12 MPa, are different then Figure 2. The results are more sensitive to the variation of $\frac{L}{\sqrt{Dt}}$ in the beginning then reliability index and/or failure probabilities results became insensitive to the ration variation after $\frac{L}{\sqrt{Dt}}$ >3. These results confirm the ones obtained in reference [6]. The results of the reliability index and failure probability in Figures 2 based on the proposed threshold (β=3 / P_f =10^{-3}) with $\frac{L}{\sqrt{Dt}}$ =0.34 indicated that the allowed pressure for X60 pipeline are the ones less than 8MPa , same as the first results obtained from corrosion to wall-thickness ratio.

Generally, for case under consideration, the gas pipeline could work under operating pressure equal or less than 8Mpa for the mentioned corrosion defects depth and length (see Table 1). Moreover, if the depth to wall-thickness ration exceed 0.4 the operating pressure should decreased to 5 MPa while the reliability index and failure probability are insensitively changed from narrow corrosions $\frac{L}{\sqrt{Dt}}$ <1, otherwise it should be work with the regime of 5MPa.

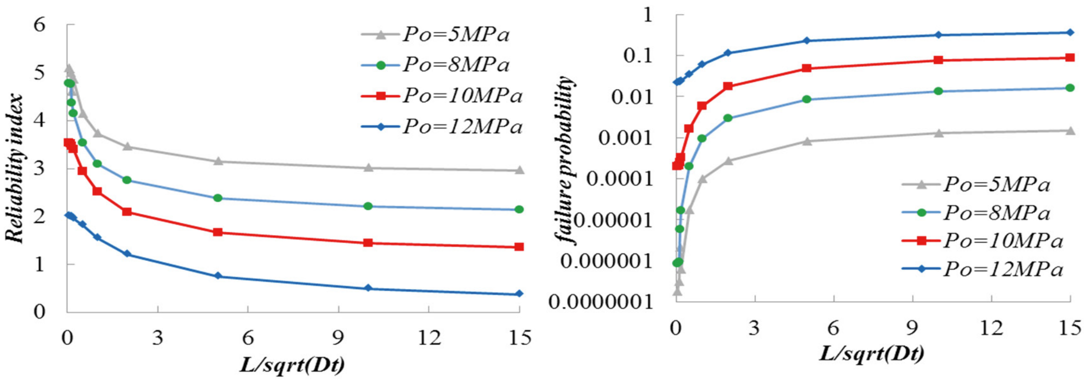

Fig 3. Structural reliability results of the X60 gas pipeline corresponding to various values $\frac{L}{\sqrt{Dt}}$ ratio under different operating pressures cases: a) Reliability index results; b) Failure probabilities results.

4. Conclusion

A new structural reliability method based on meta-model combined with Monte Carlo simulation is proposed for probabilistic reliably levels assessment of operating corroded gas pipeline. The proposed approach, termed as M5tree algorithm-MCS, improves the efficiency of the simulation-based MCS to pass the drawback of the latter that take an enormous computational cost in estimating the failure probabilities of corroded pipelines. The estimated reliability levels are presented on terms of reliability index and failure probability, where the effect of operating pressure and defects geometries on those terms were investigated. For the studied case, gas pipeline made of X60 steel the effect of corrosion defect length on the reliability levels (indicated by the calculation of the reliability index/ failure probability) is insignificant. In the other hand, the maximum operating pressure of the pipe should not exceed 8MPa for the obtained defects depths using Darling Anderson test and real inspection data. Based on the study results it is important to define the regime of the operating pressure and well identify the corrosion defects depth, due to theirs great influence on the failure probability of the pipe.

References

[1] M. El Amine Ben Seghier, B. Mourad, B.Elahmoune, M. Gaceb, Probabilistic approach evaluates reliability of pipelines with corrosion defects, OIL GAS J. 115 (2017) 64–68.
[2] M. Witek, Validation of in-line inspection data quality and impact on steel pipeline diagnostic intervals, J. Nat. Gas Sci. Eng. (2018).

[3] B. Keshtegara, M. El Amine Ben Seghier, Modified response surface method basis harmony search to predict the burst pressure of corroded pipelines, Eng. Fail. Anal. 89 (2018) 177–199. doi:10.1016/j.engfailanal.2018.02.016.
[4] B. Keshtegar, M. Miri, Reliability analysis of corroded pipes using conjugate HL-RF algorithm based on average shear stress yield criterion, Eng. Fail. Anal. 46 (2014) 104–117. doi:10.1016/j.engfailanal.2014.08.005.
[5] M. El Amine Ben Seghier, M. Bettayeb, J. Correia, A. De Jesus, R. Calçada, Structural reliability of corroded pipeline using the so-called Separable Monte Carlo method, J. Strain Anal. Eng. Des. (2018).
[6] M. El Amine Ben Seghier, B. Keshtegar, B. Elahmoune, Reliability analysis of low, mid and high-grade strength corroded pipes based on plastic flow theory using adaptive nonlinear conjugate map, Eng. Fail. Anal. 90 (2018) 245-261. doi:10.1016/j.engfailanal.2018.03.029.
[7] M. Witek, Anatolii Batura, I. Orynyak, M. Borodii, An integrated risk assessment of onshore gas transmission pipelines based on defect population, Eng. Struct. (2018) 150–165.
[8] B. Keshtegar, S. Chakraborty, A hybrid self-adaptive conjugate first order reliability method for robust structural reliability analysis, Appl. Math. Model. 53 (2018) 319–332. doi:10.1016/j.apm.2017.09.017.
[9] B. Keshtegar, A hybrid conjugate finite-step length method for robust and efficient reliability analysis, Appl. Math. Model. 45 (2016) 226–237. doi:10.1016/j.apm.2016.12.027.
[10] B. Keshtegar, O. Kisi, RM5Tree: Radial basis M5 model tree for accurate structural reliability analysis, Reliab. Eng. Syst. Saf. (2018).
[11] B. Keshtegar, O. Kisi, M5 model tree and Monte Carlo simulation for efficient structural reliability analysis, Appl. Math. Model. 48 (2017) 899–910.