Reliability Assessment of Oil and Gas Pipeline Systems at Burst Limit State Under Active Corrosion

Ram K. Mazumder, Abdullahi M. Salman, and Yue Li

Abstract Civil infrastructures such as oil and gas transportation systems play a vital role in industrial and public energy distribution and consumption. A large number of existing oil and gas transportation pipelines in many cities in the USA are running at the end of their design life and are at risk. Failure in these systems can potentially cause adverse effects to the society, economy, and environment. Asset managers often need to prioritize the critical segments based on the risk of failure, available budget, and resources. In this paper, the fitness for service of oil and gas pipelines and network integrity are evaluated probabilistically using various burst pressure models to prioritize the riskiest segments to support asset management. The current state-of-the-art practice of burst failure models for pressurized metallic pipelines is compared using a physical probabilistic approach. Since metallic pipelines for oil and gas transportation are typically designed for a long lifespan and experience localized corrosion deterioration throughout their lifetime, a steady-state corrosion model was assumed for accounting for the effect of external corrosion deterioration on the burst pressure of pipelines. A Monte Carlo Simulation technique is utilized to generate the fragility curves of pipelines considering corrosion deterioration over time. Uncertainties involved in various parameters related to burst failure and fragility estimation are modelled based on the knowledge gained from past research. A comparative analysis is presented for various fragility models of pipelines. Also, system reliability was evaluated using a minimum cut sets approach. The proposed approach is illustrated for a simple hypothetical oil/gas transmission system. Outcomes of the study show a consistent trend of failure for various models over time. The results of the probabilistic models of burst failures are analyzed, and recommendations are provided to support asset management planning.

Keywords Burst failure · Corrosion · Pipelines · Reliability · Risk

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1 Introduction

Civil infrastructure systems such as oil and gas transportation systems are essential for a country's economic growth and smooth functionality of societies [1]. Unfortunately, the reliability of aging oil and gas pipelines has significantly decreased over the years. As pipelines age, the growth of corrosion on the pipeline wall significantly weakens their strength and often results in failure and severe consequences [2]. Burst failure is a common type of failure that causes severe destruction to pipelines and causes huge economic and environmental consequences. Various guidelines have been developed to determine the burst failure pressure of pipelines [3–8]. Burst failure pressure estimated using these guidelines is usually estimated using a deterministic approach. The factors associated with the bursting failure estimation model involve large uncertainties. The deterministic approach is unable to predict the failure probability of the pipeline accurately [9]. Moreover, the use of different guidelines provides different outcomes in burst failure prediction and may lead to varying decisions on the design and management of pipelines.

In this study, the current state-of-the-art burst failure estimation models are used to estimate the burst failure probability of oil/gas pipelines [10]. Since metallic pipelines for oil and gas transportation are typically designed for a long lifespan and sustain corrosion deterioration during the course of its life, a steady-state corrosion model is assumed to account for the effect of corrosion deterioration on the burst pressure of pipelines. The burst limit state is evaluated by comparing the burst failure pressure and the internal pressure of the pipeline. Uncertainties involved in various parameters associated with fragility calculation are modeled based on the knowledge gained from past research. A Monte Carlo Simulation technique is used to generate the fragility curves of pipelines subjected to active corrosion defects. A comparative analysis is presented for various fragility models of pipelines. Also, system reliability is evaluated using the minimum cut sets approach. The proposed approach is illustrated for a simple hypothetical oil/gas transmission system.

2 Methodology

2.1 Burst Limit State

The burst failure probability of a pipeline can be estimated by comparing the failure pressure and pipeline internal operating pressure. The following limit state function is generated for burst failure estimation [2, 9]:

$$g(X) = P_b - P_i \tag{1}$$

where P_b is the burst failure pressure of the pipeline, P_i is the internal oil/gas pressure of the pipeline, g(X) is the burst limit function where x is the vector of random variables. Burst failure occurs when the internal pressure exceeds the burst failure pressure of the pipeline. In other words, a negative value of g(X) indicates the failure of the pipeline. Failure pressure is estimated based on the various standards and guidelines as described below. The internal operating pressure of the pipeline is estimated based on current practice.

2.2 Burst Failure Pressure Estimation

Extensive research has been performed on burst failure analysis of corroded pipelines [2, 9, 11, 12]. Several standards and guidelines are established for estimating the failure pressure of corroded pipelines. Among the existing methods, B31G, Modified B31G, DNV RP F101, Battelle, Shell-92, Battelle and Netto et al. (2005) models are used to develop and compare the failure probability of pipelines [3–8]. Although previous studies determine the reliability of pipelines using these approaches, however, comparison between the failure probability estimations for pipelines and corresponding system reliability estimation under active corrosion is rare [e.g., 13]. Table 1 shows various failure pressure estimation models used in this study.

In Table 1, P_b is the failure pressure, UTS is the ultimate tensile strength, YS is yield strength, M is folias factor, D is diameter of pipe, t is the initial thickness of pipe wall, d(T) and L(T) are defect depth and defect length, respectively, as a function of time; T is the time in year.

2.3 Corrosion Model

Corrosion is the most influential parameter for metallic pipeline deterioration. It occurs due to an aggressive environment and becomes serious with aging [11]. Pipeline maintenance requires regular inspection and rehabilitation of the corroded pipeline. The corrosion growth overtime depends on the surrounding environmental conditions (soil characteristics, chemical attacks on pipeline materials, etc.). The corrosion growth on a pipeline surface can be modelled by the defect depth and defect length of corrosion as expressed by the following equation;

$$d(T) = d_0 + V_r(T - T_0) \quad (2)$$

$$L(T) = L_0 + V_a(T - T_0) \quad (3)$$

where d(T) is the defect depth, L(T) is the defect length, d_0 is the initial defect depth, L_0 is the initial defect length, V_a is the axial corrosion rate and V_r is the radial corrosion rate. T_0 is the time to initiate corrosion.

Table 1 Failure pressure models

Sl	Model name	Burst failure pressure, P_b		Ref.
1	B31G	$P_b = \begin{cases} \frac{1.11 \cdot 2YSt}{D}\left(\frac{1-\frac{2d(T)}{3t}}{1-\frac{2d(T)}{3t}M^{-1}}\right); G < 4 \\ \frac{1.11 \cdot 2YSt}{D}\left(1-\frac{d(T)}{t}\right); G \geq 4 \end{cases}$	$\mathrm{M} = \sqrt{1 + 0.893\frac{\mathrm{L(T)}^2}{\mathrm{Dt}}};\ \mathrm{G} = 0.893\frac{\mathrm{L(T)}^2}{\sqrt{\mathrm{Dt}}}$	[3]
2	Modified B31G	$P_b = \frac{2.0(YS+68.95MPa)t}{D}\left(\frac{1-0.85\frac{d(T)}{t}}{1-0.85\frac{d(T)}{t}M^{-1}}\right)$	$\mathrm{M} = \begin{cases} \sqrt{1 + 0.6275\frac{\mathrm{L(T)}^2}{\mathrm{Dt}} - 0.003375\frac{\mathrm{L(T)}^4}{\mathrm{D^2t^2}}}\, if\, \frac{\mathrm{L}^2}{\mathrm{Dt}} \leq 50 \\ 0.032\frac{\mathrm{L(T)}^2}{\mathrm{Dt}} + 3.3 if\, \frac{\mathrm{L}^2}{\mathrm{Dt}} \leq 50 \end{cases}$	[4]
3	DNV-RP-F101	$P_b = \frac{2UTS}{D-t}\left(\frac{1-\frac{d(T)}{t}}{1-\frac{d(T)}{t}M^{-1}}\right)$	$\mathrm{M} = \sqrt{1 + 0.31\frac{\mathrm{L(T)}^2}{\mathrm{Dt}}}$	[5]
4	Shell-92	$P_b = \frac{1.8UTS}{D}\left(\frac{1-\frac{d(T)}{t}}{1-\frac{d(T)}{t}M^{-1}}\right)$	$\mathrm{M} = \sqrt{1 + 0.805\frac{\mathrm{L(T)}^2}{\mathrm{Dt}}}$	[6]
5	Battelle	$P_b = \frac{2UTSt}{D}\left(1 - \frac{d(T)}{t}M\right)$	$\mathrm{M} = 1 - \exp\left(-0.157\frac{\mathrm{L(T)}}{\sqrt{\mathrm{D(t-d(T))/2}}}\right)$	[7]
6	Netto et al. (2005)	$P_b = \frac{1.1 \cdot UTS \cdot 2t}{D} \cdot \left[1 - 0.9435\left(\frac{d}{t}\right)^{1.6}\left(\frac{L(T)}{D}\right)^{0.4}\right]$		[8]

2.4 System Reliability

The reliability of the oil/gas network is estimated based on the concept of minimum cut sets (MCSs). In this case, the reliability is defined based on whether a specific demand node is connected to at least one source at any time. An oil/gas network can be modelled using graph theory. In a graph, nodes and pipelines of oil/gas network are defined by vertices and edges, respectively. The number of MCS is determined using an adjacent matrix. A subset of the pipelines is defined as an MCS if the failure of all components in the subset leads to a failure of the system. The failure probability of an MCS is determined by Eq. (4) [14].

$$P(MC_i) = \prod_{j=1}^{n_p} P_j \tag{4}$$

where $P(MC_i)$ denotes the failure probability of the i-th MCS that contains n_p number of pipelines; P_j is the failure probability of pipeline j. The failure probability of the system (P_S) is evaluated using Eq. (5).

$$P_S = P\left(MC_1 \cup MC_2 \cup \ldots \cup MC_{n_{mc}}\right) \tag{5}$$

where n_{mc} is the number of MCS in a system. Assuming that the failure events are statistically independent, the failure probability of the system is estimated by Eq. (6):

$$P_s = \sum_{i=1}^{n_{mc}} P(MC_i) \tag{6}$$

The reliability of the system (R_S) is then the complement of the failure probability of the system.

3 Case Study

A simple hypothetical oil/gas transmission network consisting of 5 nodes, 1 source and 8 pipes is assumed, as shown in Fig. 1. The reliability of the system is estimated for a scenario that node-5 will remain in-service and connected to the source node-S. For the simplicity of the calculation, it is assumed that all the pipelines in the system are made of the same section and pipe type (diameter: 610 mm, thickness: 20 mm).

The failure probability of the pipelines is determined from fragility curves obtained using a burst limit state expressed in Sect. 2.1. Time-dependent corrosion models, as shown by Eqs. (2) and (3), are accounted for generating the fragility curves for the pipelines. Axial corrosion rate and radial corrosion rate are assumed equal to L0/15 and V0/15, respectively. Initial defect length and defect depth are

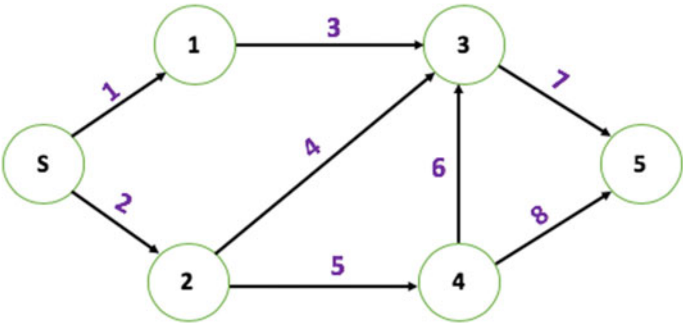

Fig. 1 Hypothetical network

assumed equal to 50 mm and 0.3 t. It is also assumed that 15 years is long enough for the defect growth to reach a steady-state [9]. To develop the fragility curves, six different models are used to determine the failure pressure as expressed in Table 1. Failure pressure is then compared with the internal pressure of the pipeline to determine the failure probability of the pipeline. Table 2 shows the statistical distribution of random variables for estimating the fragility curves. The statistical distribution of random variables is taken based on the Refs. [2, 9]. Monte Carlo Simulation is performed with 1-year time step to estimate the failure probability of the pipeline over time. At each time step, 100,000 simulation points are generated to determine the failure probability of the pipeline. Fragility curves developed utilizing six different models are shown in Fig. 2. Although there is very little difference in failure probabilities estimated using different models at the early stage of the pipeline, the failure probability varies significantly at the later stage of the pipeline.

After estimating the failure probability of the pipelines, the system failure probability, and system reliability are estimated using the MCS approach. Table 3 shows the number of MCSs found for the system reliability analysis that node-5 will remain in-service. It is very unlikely that more than three pipelines fail at a time. Hence, the MCSs consisting of more than three pipelines are ignored. As it can be seen from Table 3, it is found that a single pipeline failure alone will not disconnect node-5 to a source. If all the components in any of these MCSs in Table 3 fail, then node-5 would be out of service.

Table 2 Statistical distribution of random variables

Parameters	Mean	Coefficient of variation	Unit	Distribution type
Wall thickness, t	20	0.05	mm	Normal
Pipe diameter, D	610	0.03	mm	Normal
Yield stress, YS	356	0.08	MPa	Normal
Tensile stress, UTS	455	0.08	MPa	Normal
Operating pressure, P_O	7.8	0.10	MPa	Normal

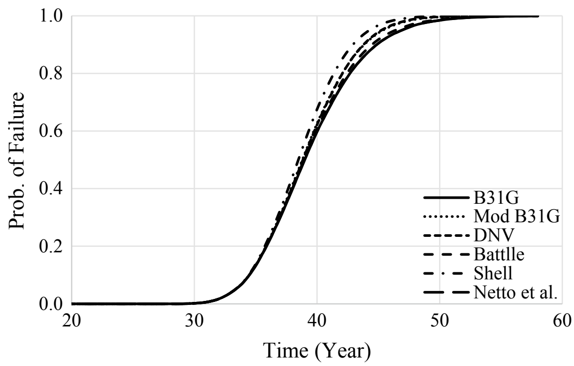

Fig. 2 Fragility curves

Table 3 Minimum cut sets

No. of pipe breaks	Minimum cut sets {pipe #}	No. of set(s)
1	–	0
2	{1–2} {2–3} {7–8}	3
3	{1–4–5} {3–4–5} {5–6–7}	3

The failure probability of the system is estimated based on Eq. (6). Figure 2 compares the system reliabilities (complement of system failure probabilities) estimated based on various models. Among these models, reliability results obtained using B31G and Modified B31G are the highest. On the other hand, reliability is the lowest using the Battelle model. The system failure probabilities from 35 years stage to 40 years stage increased significantly as the failure probability of each pipeline also increase significantly between 35 and 40 years, as shown in Table 4.

Table 4 System reliability

Reliability approach	Age 0 years (%)	30 years (%)	35 years (%)	40 years (%)	50 years (%)
B31G	100.0	100.0	94.0	33.3	0.0
Modified B31G	100.0	100.0	93.9	27.7	0.0
DNV-RP-F101	100.0	100.0	94.0	29.8	0.0
Shell-92	100.0	100.0	94.0	32.0	0.0
Battelle	100.0	100.0	93.5	15.7	0.0
Netto et al. (2005)	100.0	100.0	94.0	33.3	0.0

4 Conclusions

This study represents a comparative analysis of various fragility models of pipelines. Also, subsequent system reliabilities are estimated and compared using various approaches. Time-dependent reliability is analyzed by incorporating the time-dependent corrosion growth on the pipeline wall. The proposed approach is illustrated for a simple hypothetical oil/gas transmission system. Analysis outcomes show a consistent trend of failure for various models overtime. It is found that the selection of a specific model may lead to obtaining a higher or lower reliability result, especially during the later stage of a pipeline lifespan. Such deviation from selecting a specific model should be considered while identifying the riskiest pipelines in the asset management plan.

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