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Probabilistic Reliability Assessment of an Insulated Piping in the Presence of Corrosion Defects

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Abstract: Corrosion Under Insulation (CUI) is found to be a major problem for insulated pipes as it becomes even worse as the pipes age increases. Gradual metal loss due to CUI may cause the pipe to leak or in the worst scenario, the pipe may rupture. The presence of small leak or rupture in lines may lead to a hazardous situation since the piping systems carry hydrocarbons or other process fluids. Hence, a proper inspection and maintenance program of these piping systems is crucial to maintain a safe and continuous operation. Corrosion and inspection engineers mostly are confronted with the problem of optimizing the inspection schedule for insulated piping systems due to the fact that most inspection/maintenance optimization models are based on the reliability models to predict the failure probability of the system. However, no reliability model was found within the literature that has currently been applied to insulated piping systems. This study presents a methodology for the estimation of the reliability of insulated piping systems containing corrosion defects. A probabilistic approach is adopted to this methodology and the associated variables are represented by normal probability distributions. First-order reliability method is employed for carrying out the reliability analysis due to the presence of nonlinearity in the limit-state function and also in the possible presence of non-normal variables. The methodology is applied to a real case study and the remaining useful life of the insulated pipe is assessed.

Key words: Structural reliability, corrosion under insulation, reliability assessment

INTRODUCTION

Process piping are insulated to reduce energy loss and its associated costs in applications involving heating and cooling. However, insulation poses another problem where it allows corrosion to take place beneath the insulation. This corrosion process proceed in an insidious manner which unfortunately, in many occasions, result in serious consequences. This degradation damage mechanism is known as Corrosion Under Insulation (CUI) and is a major problem for insulated pipes as it becomes even worse as the pipes age. CUI results in material thinning, which may be localized or can spread over a large surface area. In the former, material degradation is seen in the form of pitting, while in the latter, a general thickness loss occurs. Carbon steels are usually more susceptible to general thinning, while stainless steels are usually more prone to stress corrosion cracking.

Gradual metal loss can cause the pipe to leak or in the worst scenario, the pipe may rupture. Since, the piping systems carry hydrocarbons or other process fluids, the presence of small leak or rupture in lines may lead to a hazardous situation. Hence, to maintain a safe and continuous operation, proper inspection and maintenance of these piping systems is crucial.

Corrosion and inspection engineers mostly are confronted with the problem of optimizing the inspection schedule for insulated piping systems. This is due to the fact that most inspection/maintenance optimization models are based on the reliability models to predict the failure probability of the system. However, no reliability model was found within the literature that has currently been applied to insulated piping systems.

Consequently, inspection/maintenance programs for CUI are typically being developed based on the guideline by American Petroleum Institute, API 581, to assess the failure probability for CUI (API, 2000). However, the assessment is deterministic as the model implicitly assumed that the associated parameters are free of any uncertainties. Unfortunately this is not true in actual cases. Uncertainties can be found in most of the parameters, if not all. For an insulated pipe that contains live corrosion defects, the major concern is the need to have a simple technique which can be used to evaluate

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the current reliability of the insulated pipe and also the time-dependent change in reliability. (Note that reliability = 1 – probability of failure).

Corrosion under an insulated pipe can be detected by the use of several techniques such as profile radiography and ultrasonic thickness measurement, which can be used to measure the size of a corrosion defect. Through periodic inspections, the growth of a corrosion defect can be monitored. The problem then is to determine how a corrosion defect affects the integrity of the insulated pipe. Also of interest is an estimate of when an affected insulated pipe is likely to fail from the growth of a corrosion defect.

To assess the integrity of a corroded pipe, a test known as a hydrostatic test is occasionally used. However, serious drawbacks have been found with this test as mentioned by Ahammed (1998). As such this test cannot be reliably used to predict when a pipe containing active corrosion defect is going to fail. Theoretically, it is possible to estimate the remaining strength of a corroded insulated pipe using the techniques specified in B31G (Ahammed, 1998). However, the approach is deterministic where it cannot estimate the probability of failure with time. To tackle this problem, a reliability analysis is proposed to assess the safety and integrity and also to predict the remaining life of a corroded pipe with active corrosion growth. The resulting information can be used to prepare an effective and economic inspection/maintenance schedule.

The study explores the possibility of using the structural reliability analysis technique to assess the failure probability for insulated piping systems subject to CUI and to be further used in establishing the inspection interval for insulated piping system. First Order Reliability Method (FORM) model which is based on the reliability index will be employed to estimate the failure probability where the model requires data such as material properties and physical geometric of the piping system. To illustrate the approach, the reliability analysis is carried out for a real case study where the calculations are performed for various corrosion rates.

Structural reliability analysis: Theory and methods for structural reliability have been developed significantly in the last few years. They are in fact a useful means for evaluating rationally the safety of complex structures or structures with unusual designs (Cardoso *et al*., 2008; Caleyo *et al*., 2002, 2009; Guohua and Shuho, 1996; Li, 2004; Low, 2005). In structural reliability analysis, the concept of a 'limit state' is used to help define failure in the context of structural reliability analyses. A limit state is a boundary between desired and undesired performance of a structure (Santosh *et al*., 2006). This boundary is often represented mathematically by a limit state function or performance function, also known as a failure function. A traditional definition of the 'safety margin' or 'margin of safety' is associated with the ultimate limit states.

For corrosion failure, the failure function proposed by Khan *et al*. (2006) will be used in this study. A failure function needs to be defined where this function expresses the criterion for failure of the pipe. The failure function g(x) in this case is the difference between the material resistance and the applied stress. It can be defined as:

$$g(x)=R-St=(1-\frac{c\Delta t}{d})-\frac{PD}{2d} \tag{1}$$

where, R is material resistance, St is the applied stress, S is material strength, C is corrosion rate, P is operating pressure, D is the diameter of the component, d is the material thickness, and Δt is a time increment. Operating pressure P is the pressure in the internal fluid that is being transmitted. The state function g(x), is a measure of the ability of the material to resist failure. By definition, failure will occur when $g(x) < 0$, whereas no failure occurs with $g(x) > 0$. $g(x) = 0$ defines the so-called failure surface, a hyper-surface in the n-dimensional space of the basic variables. The failure surface separates the failure domain F (with $g(x) < 0$) and the safe domain ($g(x) > 0$).

For structural reliability analysis, the parameters in Eq. 1 are to be treated as random variables having normal distributions. The mean and standard deviation are assumed to be known for each. The failure behavior depending on basic random variables $x = (x_1.....x_n)$ which denote applied loads and structural resistance parameters such as dimensions and material properties. The failure probability P_1 can be calculated as the probability content of the failure domain F:

$$pf=\int_F f_1(x_1)...f_n(x_n)dx_1...dx_n \tag{2}$$

where, f_i (x_i) represents the probability densities of the respective basic variables, which for the sake of simplicity are assumed to be stochastically independent (Melchers, 1999).

It is evident that the above failure function is a function of many basic variables. These basic variables are considered to be random and statistically distributed. It may also happen that the distribution of some of the variables is not normal. First Order Reliability Method (FORM) is well equipped to handle this type of problem and hence will be employed here (Melchers, 1999). For this approach, the variables need to be characterized only by their means and standard deviations or Coefficient Of Variation (COV). It will be assumed, for simplicity, that these variables are mutually independent. This method involves linearising the failure function at the design point and then determining the value of the reliability index, β which satisfies the failure function, corresponding to the linearized failure function (Melchers, 1999). This method is based on an iterative technique and the iteration is continued until a desired convergence is obtained. It should be noted here that β is a measure of pipe safety. For more information on the reliability index and its determination (Melchers, 1999; Low and Tang, 2007; Zhao and Ono, 1999). This method can also handle situations such as where the distribution of some or all of the variables is not normal. Once β is found, the pipe failure probability corresponding to the corrosion defect can be determined from:

$$pf = \text{Prob}\,(g(x) < 0) = \Phi\,(-\beta) \qquad (3)$$

where $\Phi\,(-\beta)$ is a distribution function of a variable and this function is assumed to be distributed normally with zero mean and unit standard deviation.

FORM has been applied to assess the system reliability with corrosion defects (Juang *et al*., 2006; Teixeira *et al*., 2008; Low and Tang, 2004). FORM model was built using Microsoft Excel and Visual Basic for Application (Low and Tang, 2004, 2007; Zhao and Ono, 1999). The reliability index was obtained by calling Excel's built-in optimization program, Solver, with the objective function to minimize the reliability index subject to the constraint that the limit-state function, $g(x) = 0$. The probability of failure is then calculated.

In the case where a pipe has more than one corrosion defect and these defects are assumed to be designated at locations 1,2,3...n, then the corresponding failure probabilities are by $p_1, p_2, p_3, \ldots, p_n$, respectively. If it is assumed that the individual failures are mutually independent (which implies that the failure of any one of them is sufficient to cause pipeline failure) then the failure probability of the pipe can be approximated from:

$$pf\,(\text{pipe failure}) = 1 - (1 - p_1)(1 - p_2)(1 - p_3) \ldots (1 - p_n) \qquad (4)$$

Illustrative example: In order to demonstrate the applicability and usefulness of the above methodology to an insulated pipe, a real case study from a local petrochemical plant with a known CUI defect were analyzed. The defects and their characteristics became known through a periodic inspection (after opening the insulation). All basic random variables are assumed to follow a normal distribution.

Table 1: Relationship between corrosion rate and operating temperature and type of environment (API, 2000)

	Type of environment (mm year^{-1})		
Temperature (°C)	Marine	Temperature	Dry
<-12	0	0	0
-12 to 16	0.127	0.076	0.025
16 to 49	0.051	0.025	0
49 to 93	0.254	0.127	0.051
93 to 121	0.051	0.025	0
>121	0	0	0

Table 2: Parameter for limit-state function with mean and coefficient of variance

Symbol	Parameters	Mean	Variance
S	Material yield strength (Mpa)	240	25
d	Thickness of the pipe (mm)	6.35	0.148
D	Outer diameter of the pipe (mm)	273.1	1.5
C	Corrosion rate (mm year^{-1})	0.067	0.015
P	Operating pressure (Mpa)	0.03	0.9

The following insulated pipe is taken as a case study. The 273 mm diameter pipe is made of carbon steel A333 Class 6 and are subjected to CUI. The pipe is operating at-44°C where according to API 581; the corrosion rate is negligible in any type of environment (API, 2000). Refer to (Table 1) for the relationship between the corrosion rate, the operating temperature and the type of environment. However, after 15 years of service life, the pipe was found to be badly corroded with 1 mm wall loss giving a calculated corrosion rate of 0.067 mm year^{-1}. This corrosion rate is very significant compared to the assumed value by API 581.

To assess the failure probability using the structural reliability analysis, the following parameters as tabulated in Table 2 are used. All parameters are assumed to follow normal distribution.

RESULTS AND DISCUSSION

The results of the analysis of the above-insulated pipe are presented in this section. The plots of the failure probability and the reliability index against year in service are presented, as shown in Fig. 1 and 2, to draw the inferences. It is observed that the failure probability generated for the first 10 years are almost the same. However, after the first 10 years, the probability of failure increases exponentially. It can be seen from Fig. 1, after 15 years of service, the failure probability of the pipe is 0.014 with the reliability index of 2.196. Comparing the probability value with the failure probability categories by API (API, 2000) in Table 3, the pipe is now in the likelihood category 5 which is very high failure probability.

It can be seen from the reliability index plotting in Fig. 2 that as the year in service increases, the reliability index decreases exponentially. This is as expected and may be explained in the following way. With increased

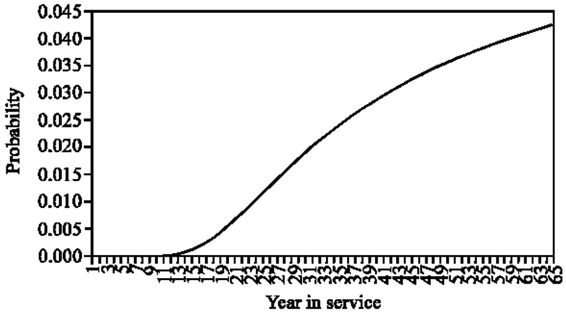

Fig. 1: Failure probability plot

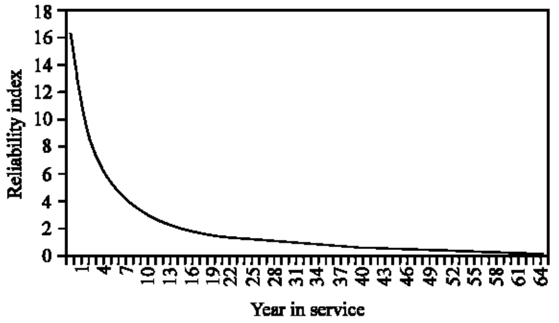

Fig. 2: Reliability index vs. year in service

Table 3: Failure probability categories (1)

Range of failure probability	Likelihood category0	Category
1×10^{-4} to 1.0	5	Very high
1×10^{-5} to 1×10^{-4}	4	High
1×10^{-6} to 1×10^{-5}	3	Medium
1×10^{-8} to 1×10^{-6}	2	Low
$< 1 \times 10^{-8}$	1	Very low

year in service, the corrosion defect increases, and hence the pipe capability to resist the effect of stresses generated by the loads is also reduced. In other words, this increases the severity of the circumferential stress leading to an increase in the pipe failure probability.

The graph in Fig. 2 can be used to plan effective and economic inspection, repair and replacement programs. Not only that, this graph can be used to set effective remaining service life. For example, if the hypothetical minimum acceptable value of reliability index is set at 1, then it can be said that the remaining service life of this pipeline is (28 - 15) years, i.e., 13 years. After the period of the remaining life, even if it appears that the pipeline has not failed, it would not be safe to use it. For safety reasons, it would be wise for the pipe to be abandoned, repaired or replaced, in order to decrease its failure probability if further service is required.

CONCLUSIONS

In this study, the failure probability assessment models based on structural reliability analysis was developed and applied to estimate the failure probability of insulated piping systems. This probabilistic methodology allows calculation of the reliability index and the failure probability. This study is required to establish inspection program for insulated piping systems based on the quantitative risk assessment. The following key findings have been derived:

- Structural reliability analysis can be applied to estimate the failure probability of carbon steel piping systems subject to CUI. The insulated pipe reliability decreases with increased time in service
- The results generated by the proposed method are well comparable with the results available in the literature

Further works need to be done on the proposed model as follows:

- To identify the random variables that give significant contribution to the pipe failure
- To conduct the sensitivity analysis of the pipe reliability using different values of coefficient of variation
- To identify the distribution for each parameter

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