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Chapter 28

# Developments in Reliability-Based Assessment of Corrosion

Zahiraniza Mustaffa

Additional information is available at the end of the chapter

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## 1. Introduction

The title of this book, *Developments in Corrosion Protection*, portrays one of the important issues addressed by the industries in the present world. This theme covers a wide range of topics with regards to corrosions which can be further expanded in different contexts. This chapter proposes the theme to be addressed based on the assessment aspects of managing corrosions, for which it is very much applicable to a structure that is already in operation. The discussion presented in this chapter is generally applicable to corrosions in general but special attention is given to corrosions in offshore pipelines. Thus this chapter attempts to brief readers on the development of the approaches used in assessing the reliability of corroded pipelines.

## 2. Disputes on the significance of corrosion parameters

A corrosion defect that forms in a pipeline is represented by several length scale parameters, namely *depth* (*d*), *longitudinal length* (*l*) and *circumferential width* (*w*), as shown in Table 1. Typically, it will have an irregular depth profile and extend in irregular pattern in both longitudinal and circumferential directions (Cosham et al., 2007). A defect will spread and develop in size with time. Its growth is described by the *d*, *l* and *w* dimensions. Therefore, one of the earliest concerns related to corrosion assessment in pipelines is about understanding the importance of these parameters with respect to the reliability of the pipe. Only the most governing parameters will be included in the design codes and standards.

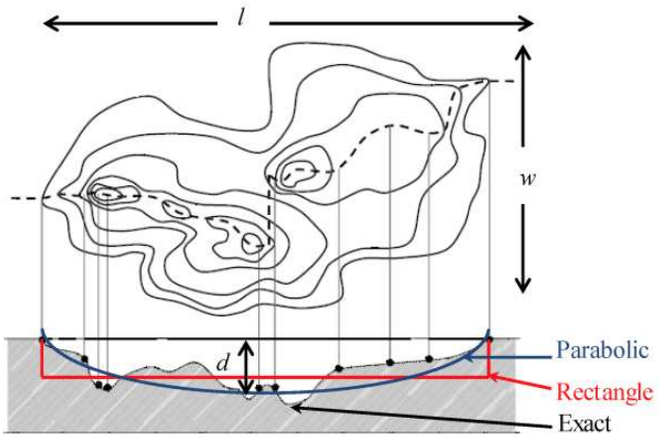
Extensive experimental and numerical works have been dedicated to determine the best governing parameters to represent a corrosion shape. The current assessment practices use a single simple corrosion geometry and the corrosion circumferential width (*w*) is not considered

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(Fu and Kirkwood, 1995). The longitudinal extent of a corroded area is the most important length parameter for the burst strength under internal pressure loading (Cosham et al., 2007). Defects in this orientation have been reported to be the most severe since it alters the hoop stress distribution and promotes bulging. Concurrently, Chouchaoui and Pick (1994), Fu and Kirkwood (1995) and Batte et al. (1997) have shown that the influence of corrosion circumferential width ($w$) to failures was not that significant.

There have been many arguments on the corrosion shapes assumed by the design standards. Corroded area has been argued from as simple shape as a rectangle to parabolic and average of rectangular and parabolic shapes, summary of which as shown in Table 1. The most conservative idealisation is a rectangular profile (Cosham et al., 2007). Even until today, one can never be too sure of the assumptions made in those standards.

| Corrosion Shape | Calculation of Area, A | Corrosion Illustration |
|---|---|---|
| Rectangle | $dl$ |  |
| Parabolic | $2/3dl$ | |
| Average of rectangle and parabolic | $0.85dl$ | |
| 'Exact' shape | 'Exact' calculation | |



Note = Corrosion parameters: depth ($d$), longitudinal length ($l$) and circumferential width ($w$)

**Table 1.** Disputes on corrosion shapes

## 3. Mechanics of corrosion models

The assessment models used to describe the reliability of corrosions in pipelines were originated from the mechanics of the circumferential stress or hoop stress ($\sigma_h$) acting on a pipeline. For this, consider a unit length (1 m long) pipeline containing fluids with external diameter ($D_o$), internal diameter ($D_i$), wall thickness ($t$), internal pressure ($p_i$), and external pressure ($p_o$), as shown in Fig.1(a). The idea is to determine the force that the internal pressure induces in the wall by considering the equilibrium of everything within the circumscribing rectangle drawn in Fig. 1(b). Half the pipe and half the contents are redrawn in Fig.1(b) as a free body diagram. The rectangle is bounded by the diameter, two tangents at the point where the diameter intersects the outside surface, and a tangent parallel to the diameter. The stress

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components that act across the boundaries of different parts of the rectangle are known as the hoop stress.

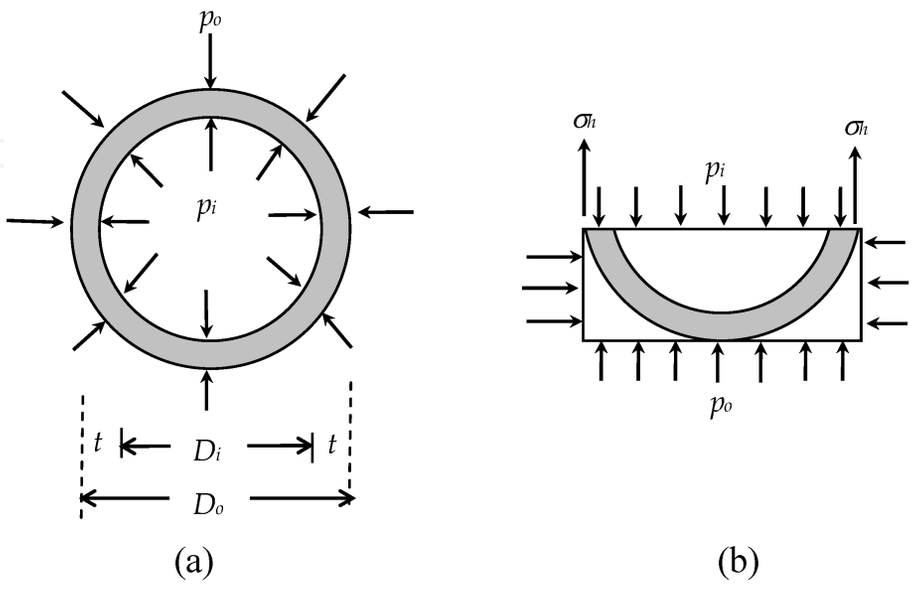



**Figure 1.** Circumferential stress in a pipeline pressurized internally and externally

The resultant force in the vertical direction must be zero, thus the equilibrium equation becomes,

$$p_o D_o + 2\sigma_h t = p_i D_i \tag{1}$$

Arranging Eq. (1),

$$\sigma_h = \frac{p_i D_i - p_o D_o}{2t} \tag{2}$$

Eq. (2) gives the mean circumferential stress exactly, whatever the diameter-to-thickness ($D/t$) ratio. There are various versions of Eq. (2) and the most widely used is the Barlow formula, given by,

$$\sigma_h = \frac{p_i D}{2t} \tag{3}$$

The above formula was derived by neglecting the external pressure term $p_o D_o$ in Eq. (2). Internal pressure from the contained fluid is the most important loading a pipeline has to carry (Palmer and King, 2008). $D$ is normally taken as the outside diameter which is obviously larger than the inside parameter. This can be interpreted as a round-and-ready way of allowing for the

small variation of hoop stress through the wall thickness (Palmer and King, 2008). Rearranging Eq. (3),

$$p_i = \frac{2\sigma_h t}{D} \tag{4}$$

It can be said that that,

$$p_i = f\left(\frac{t}{D}, \sigma_h\right) \tag{5}$$

The above equation implies that the internal pressure of an intact (no defect) pipe can withstand is a function of a wall thickness-to-diameter ($t/D$) ratio and its strength (or stress).

For the case of a pipeline with corrosion defects, Eq. (5) can be modified by incorporating the defect projected area ($A$) term into the equation. The same principle was applied when developing the failure pressure (PF) model; a model used for the assessment of remaining strength in a pipeline subjected to corrosions. Generally, the basic PF model can be expressed as,

$$p_i = PF = f\left(\frac{t}{D}, \sigma_h, A\right) \tag{6}$$

Batelle developed a semi-empirical equation for the remaining strength of corroded pipelines in early 1970 (Maxey et al., 1971; Kiefner and Duffy, 1971; Kiefner, 1974). The equation has been called the NG-18 equation and is given by,

$$PF = \frac{\sigma_{flow}.2.t}{D}\left[\frac{1-\frac{A}{A_o}}{1-\frac{A}{A_o}\frac{1}{M}}\right] \tag{7}$$

where, $A_o$=$dt$, $M$ is Folias bulging factor, $\sigma_{flow}$ is flow stress, and $d$ is maximum corrosion depth. Note that the $\sigma_h$ term has been replaced by $\sigma_{flow}$ here. Several modifications have been made to the above parameters depending on the available test data sets and study techniques. These includes (i) flow stress, $\sigma_{flow}$, (ii) defect profile or projected corrosion area, $A$, and (iii) geometry correction factor (also referred to as the Folias factor, or the bulging correction factor, $M$).

The flow stress (strength), $\sigma_{flow}$ is a concept proposed in the 1960s to measure the strength of steel in the presence of a defect. The NG-18 equation here assumes that failure is due to a flow stress dependent mechanism and can, therefore be described by the tensile properties like yield

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strength or ultimate tensile strength (Cosham et al., 2007). The $\sigma_{flow}$ has been proposed for several modifications, as listed below,

$\sigma_{flow}$ = 1.1 SMYS

$\sigma_{flow}$ = 1.15 SMYS

$\sigma_{flow}$ = 0.5 (SMYS+SMTS)

$\sigma_{flow}$ = *SMYS* + 68.95 MPa (or 10 ksi)

$\sigma_{flow}$ = $x$.*SMYS*, where $x$ = 0.90, 1.0 or 1.1

where, *SMYS* and *SMTS* is Specified Minimum Yield Stress and Specified Minimum Tensile Strength, respectively. The projected corrosion area, A has also undergone several propositions, namely,

$A = dl$ (rectangle)

$A = 2/3dl$ (parabolic)

$A = 0.85dl$ (approximate average of rectangle and parabolic)

$A$ = 'exact' calculation

with $l$ as the defect longitudinal length (refer Table 1).

The geometry correction factor which is also referred to as the Folias factor, or the bulging correction factor, $M$ developed by Folias (1964) to account for the stress concentration that is caused by radial deflection of the pipe surrounding a defect.

## 4. Reliability assessment of corrosion in pipelines

### 4.1. Deterministic vs. probabilistic method

The offshore technology is evolving and growing rapidly. As offshore knowledge continues to evolve, the recommended design practice gets revised accordingly as well. The basic approaches to structural reliability and design codes can be historically described based on three approaches, namely,

- Deterministic
- Semi-probabilistic
- Probabilistic

The *deterministic (traditional)* method originated from the knowledge of allowable stress design and plastic design while the *semi-probabilistic* method progresses from the ideology of partial factors design. The *probabilistic* method on the other hand, is based on the analytical methods and simulation. The difference between the early and recent practice in the design of structures can be summarized in Table 2.

| Early Practice | Recent Practice |
|---|---|
| Design Margin | Probability of Failure |
| Factor of safety | Partial safety factors |
| Experience based | Probabilistic calculation |
| Natural scatter ignored | Statistical distributions used in practical engineering |

**Table 2.** Comparison between the early and recent practice in the design concept of structures

In the deterministic method, the safety aspect of structures was expressed in terms of *safety margins* and *safety factors* to consider the effect for uncertainties in loading and material properties and inaccuracies in geometry and theory. The use of precisely defined point design (single) values represents not what an engineer needs to accomplish, but rather what is convenient to numerically solve, assuming inputs that are known precisely (Singh et al., 2007). It considers the *worse-case scenarios* to determine the load and capacity of a system. In most cases, such safety margins and factors are seldom based on any mathematical rigor or true knowledge of the underlying risk and results in an overdesign (Singh et al., 2007). Consequently, this leads to designs that are more 'heavy' and costly and even result in greater safety or reliability.

The probabilistic method deals with many uncertainties that are common to the data (random variables) employed. Both the strength ($R$) and load ($S$) can take on a wide range of values by explicitly incorporating uncertainty in system parameters. Note that the deterministic method does not give any idea of *probability of failure* ($P_f$) or *reliability*. The $P_f$ is a rational measure of safety. The key to probabilistic method is the interference between load and strength to evaluate $P_f$. The approach treats both random variables in the form of probability density functions (with statistical parameters mean, $\mu$ and standard deviation, $\sigma$) rather than considering each input parameter as an average value, as what has been assumed in the deterministic approach. Fig. 2 illustrates the contradiction on these definitions. Measuring the safety of a structure by its reliability makes the reliability a useful decision parameter.

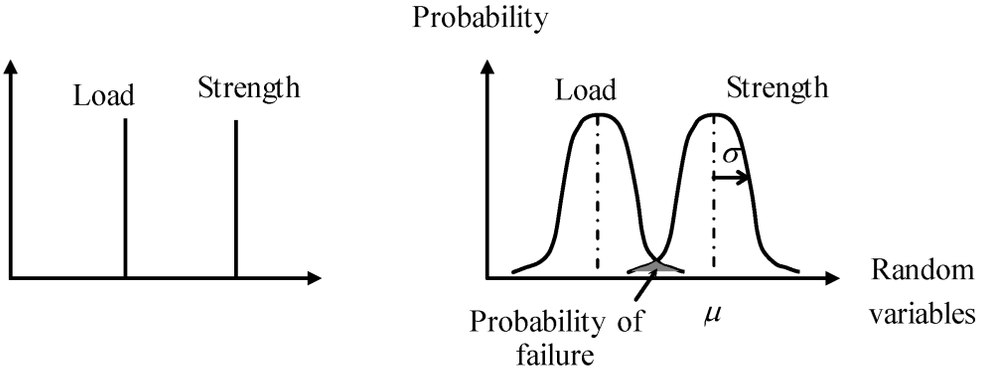



**Figure 2.** Comparison in load and strength from two different methods, (a) Deterministic (b) Probabilistic

The probability theory is considered to be more suitable since all design parameters used in engineering calculations have a degree of uncertainty. The uncertainties associated with these quantities arise because of many factors related to the measurement, calibration equipment, operator's error etc. Therefore, statistics and probability provides conventional means of reducing observed data to a form in which it can be interpreted, evaluated and effectively measured.

### 4.2. Design codes and standards

Several design codes and standards have been widely used to estimate the reliability assessment of corroded pipelines, namely ASME B31G, Modified ASME B31G, DNV 99, Shell 92, RSTRENG and PCORRC. Note that these codes take into account only the corrosion *depth* (*d*) and *longitudinal length* (*l*) parameters in their equations. The assessment in these codes is in the form of a *failure pressure* (PF) model, which is originated from the NG-18 criterion. Detailed discussions and comparison on the theories and development of the PF models have been carried out by Cosham et al. (2007), Bjørnøy and Marley (2001) and Cronin (2000), for instance while a summary of the equations are presented in Table 3.

| Method | Basic equation | Flow stress | Defect shape | Bulging factor |
|---|---|---|---|---|
| NG-18 | NG-18a | SMYS + 68.95 MPa | Rectangle (*dl*) | $\sqrt{1+0.6275\left(\frac{l}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{l}{\sqrt{Dt}}\right)^4}$ |
| ASME B31G | NG-18 | 1.1 SMYS | parabolic (2/3*dl*) | $\sqrt{1+0.8\left(\frac{l}{\sqrt{Dt}}\right)^2}$ |
| Modified B31G | NG-18 | SMYS + 68.95 MPa | arbitrary (0.85*dl*) | $\sqrt{1+0.6275\left(\frac{l}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{l}{\sqrt{Dt}}\right)^4}$ |
| RSTRENG | NG-18 | SMYS + 68.95 MPa | river bottom profile | $\sqrt{1+0.6275\left(\frac{l}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{l}{\sqrt{Dt}}\right)^4}$ |
| SHELL 92 | NG-18 | SMTS | rectangle(*dl*) | $\sqrt{1+0.8\left(\frac{l}{\sqrt{Dt}}\right)^2}$ |
| LPC | NG-18 | SMTS | rectangle(*dl*) | $\sqrt{1+0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$ |
| DNV-RP-F101 | NG-18 | SMTS | rectangle (*dl*) and river bottom profile | $\sqrt{1+0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$ |
| PCORRC | Newb | SMTS | rectangle (*dl*) | c |

**Table 3.** Design standards on the assessment of corrosion in pipelines (Adapted from Cosham et al., 2007)

[b]The basic equation of the PCORRC part-wall NG-18 failure criterion is,

$\sigma_\theta = \bar{\sigma}\left[\frac{1-\left(\frac{A}{A_0}\right)}{1-\left(\frac{A}{A_0}\right)^{1/M}}\right] = \bar{\sigma}\left[\frac{1-\left(\frac{d}{t}\right)}{1-\left(\frac{d}{t}\right)^{1/M}}\right]$, where, M is bulging factor and $\bar{\sigma}$ is flow stress.

[c] The basic equation for PCORRC failure criterion is,

$$\sigma_\theta = \bar{\sigma}\left[1-\left(\frac{d}{t}\right)\left(1-\exp\left[-0.16\left(\frac{l}{\sqrt{Rt}}\right)\left(1-\frac{d}{t}\right)^{-0.5}\right]\right)\right].$$

These design codes and standards have been critically discussed by Stephens and Francini (2000) and Cosham et al. (2007) for instance, and have further classified them into two categories, namely the 'old' and 'new' methods. Descriptions pertaining to these methods are summarized in Table 4.

| Category | Description |
|---|---|
| 'Old' Method | • Example: ASME B31G (or modified B31G and RSTRENG).<br>• Predominantly developed and validated through full scale tests on older line pipe steels.<br>• Empirically calibrated criteria that have been adjusted to be conservative for almost all corrosion defects, irrespective of the toughness of the line pipe (these criteria are variously based on the yield strength, the flow stress, or ultimate tensile strength). |
| 'New' Method | • Example: DNV RP-F101 and PCORR.<br>• Developed through tests on modern, high toughness, line pipe steels.<br>• Developed based on plastic collapse criteria that are only appropriate for blunt defects in moderate to high toughness line pipe (these criteria are based on the ultimate tensile strength). |

**Table 4.** Classification of the design standards on the assessment of corrosion in pipelines according to Stephens and Francini (2000) and Cosham et al. (2007)

The 'old' and 'new' methods were biased towards the type and toughness of the steels. Then, the difference between the behaviour of both categories can largely be attributed to the general increase in the toughness of line pipe, due to improvement in steel production and technological advances. Because of the 'old' methods demonstrate greater scatter than the 'new' methods when compared to the (relevant) published full-scale test data, the 'new' methods are more accurate (Cosham et al., 2007).

### 4.3. Limit state function models

With time, the *probabilistic* approaches have been identified as a more suitable approach to be used in the assessment of corrosions as compared to the deterministic method due to the conservatism of the latter (Mustaffa, 2011). The assessment of corroded pipelines has then been modified with the integration of probabilistic approaches into the existing failure pressure (PF) models. One of the common ways to represent probabilistic assessment is through the use of *limit state function* (LSF) equations. The LSF model is able to check the remaining strength of the pipe, for which its response towards operational loads can then be predicted.

A general limit state function, $Z$ model can be written as,

$$Z = R - S \tag{8}$$

where $R$ is the strength or more generally the resistance to failure and $S$ is the load or that which is conducive to failure. The limit state is described by $Z$=0. Failures takes place when the failure surface falls in the region of $Z < 0$ while $Z > 0$ is a survival region. The probability of failure, $P_f$ is then given by,

$$P_f = \mathrm{P_r}\left(\mathrm{Z} \le 0\right) = \mathrm{P_r}\left(R \ge S\right) \tag{9}$$

The reliability is the probability $\mathrm{P_r}$ ($Z \ge 0$), and is therefore when described in term of probability of failure becomes,

$$\mathrm{P_r}\left(\mathrm{Z} > 0\right) = 1 - P_f \tag{10}$$

The past limit state function models as given in Table 5 were mostly modified from the PF models originated from the NG-18 criterion. In these models, the strength/resistance ($R$) term of Eq. 8 has been aggressively studied by Ahammed and Melchers (1996), Pandey (1998), Ahammed (1998), De Leon and Macías (2005) and Teixeira et al. (2008), for instance. All models, however, assumed the same parameter for the load ($S$) term, represented by the *operational loading* ($P_o$) exerted by the transported hydrocarbon in the pipeline.

| **Limit State Function** | **Remarks** |
|---|---|
| Ahammed and Melchers (1996):<br>$Z = \left[2\, m_f\, s_y \frac{t}{D} \frac{1-d/t}{1-d/(tM)}\right] - p_a$ | A multiplying factor, $m_f$ was introduced into the equation which is usually taken as between 1.10[10] and 1.15[10] |
| Pandey (1998):<br>$Z = \left[2.3\, s_y \frac{t}{D} \frac{1-d/t}{1-d/(tM)}\right] - p_a$ | Flow stress, $\sigma_{flow}$ coefficient of 1.15 |
| Ahammed (1998) and De Leon and Macias (2005):<br>$Z = \left\{2(s_y + 68.95)\frac{t}{D} \frac{1-\left[d_0 + R_d(T-T_0)\right]/t}{1-\left[d_0 + R_d(T-T_0)\right]/tM}\right\} - p_a$<br>with, $d=d_o+R_d(T-T_o)$ and $l=l_o+R_L(T-T_o)$ | Revision in the $\sigma_{flow}$ coefficient. |
| Teixeira *et. al.* (2008):<br>$Z = \left(\frac{1.1\, s_y 2\, t}{D}\right)\left[1 - 0.9435(d/t)^{1.6}(l/D)^{0.4}\right] - p_a$ | Applied the Buckingham-π theorem and multivariate regression analysis techniques. |

**Table 5.** Different limit state function models applied in the reliability assessment of corrosions in pipelines

For all expressions, the $M$ term is given by,

$$M = \left(1 + 0.6275\frac{l^2}{Dt} - 0.003375\frac{l^4}{D^2 t^2}\right)^{1/2} \text{for } l^2/Dt \le 50 \text{ or}$$

$$M = 0.032\frac{l^2}{Dt} + 3.3 \text{for } l^2/Dt > 50$$

with
$s_y$ = yield stress
$d$ = defect depth
$l$ = defect longitudinal length
$t$ = wall thickness
$D$ = pipe outer diameter
$M$ = Folias/bulging factor
$p_a$ = applied/operating pressure
$d_o$ = defect depth measured at time $T_o$
$l_o$ = defect longitudinal length measured at time $T_o$
$T$ = any future time
$T_o$ = time of last inspection
$R_d$ = radial corrosion rate (=$\Delta d/\Delta T$)
$R_L$ = longitudinal corrosion rate (=$\Delta l/\Delta T$)

The Folias factor, $M$ is a measure of stress concentration that is caused by radial deflection of the pipe surrounding a defect.

The performance of these models can be visualized in a plot as shown in Fig. 3. The figure illustrates the behaviour of $P_f$ under varying pipeline operating pressures ($P_o$); a term that has been made dimensionless by dividing it with the specified minimum tensile strength (*SMTS*) term. The $P_f$ increases as loads increases. Results from the figure showed the model developed by Ahammed and Melchers (1996) tends to fail first while those developed by Ahammed (1998) and De Leon and Macias (2005) seems to be the last to fail.

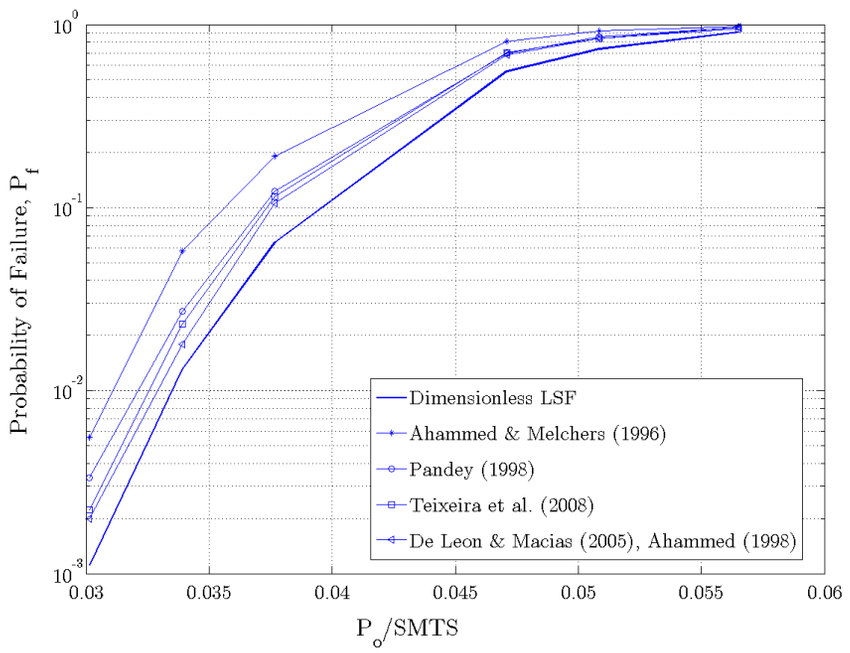



**Figure 3.** Probability of failure ($P_f$) computed for all limit state functions under varying operating pressures

This section has provided discussion on different methods and approaches used to estimate the reliability assessment of corrosion in pipelines, part of which can be summarized in Table 6 below.

| Approach | Research | Related Literature |
|---|---|---|
| **Deterministic approach:**<br>• Semi-empirical fracture-mechanical formula<br>Finite element analysis | • Ambiguities in corrosion parameters and shapes.<br>• Development of NG-18 criterion.<br>• Development of *failure pressure* (PF) models design codes and standard criterion such as ASME B31G, Modified ASME B31G, DNV 99, Shell 92, RSTRENG and PCORRC. | *Critical summary prepared by:* Cronin (2000), BjØrnØy and Marley (2001) and Cosham et al. (2007) etc. |
| **Probabilistic approach** | • Corrosion assessment for *single pipeline*: Integration of *failure pressure* models into *limit state function* (LSF) models. | Ahammed and Melchers (1996), Pandey (1998), Ahammed (1998), De Leon and Macías (2005) and Teixeira et al. (2008) etc. |
| | • Corrosion assessment for *pipeline system*. | Li et al. (2009), De Leon and Macías (2005), Zhou (2010), and Mustaffa (2011). |

**Table 6.** Brief summary on the development of reliability assessment of corrosions in pipelines

## 5. System reliability assessment of corrosions in pipelines

### 5.1. Reliability of pipeline in series

Several attempts have been made by previous researchers in understanding the response of corrosions towards the reliability of pipelines when acting as a *system*. A system can be defined as a group of elements connected either in *series* or *parallel*, having the same function or objective. Many structures are designed to be composed of multi components and the reliability/failure of a component may be triggered by other components as well. This is true as these components are sharing similar loads, thus their performance may be redundant.

A pipeline acts a system connected in series, as shown in Fig. 4. Therefore, the failure of any one or more of these components constitutes the failure of the system. In other words, the reliability or safety of the system requires that none of the components fail. From Fig. 4 for instance, the probability of failure, $P_f$ of a corroded pipeline acting as a unit is not the same with those separated into different segments. Each small segment portrays smaller probability of failures (*i.e.* ~$10^{-3}$) as compared to the whole structure (*i.e.*~$10^{-2}$).

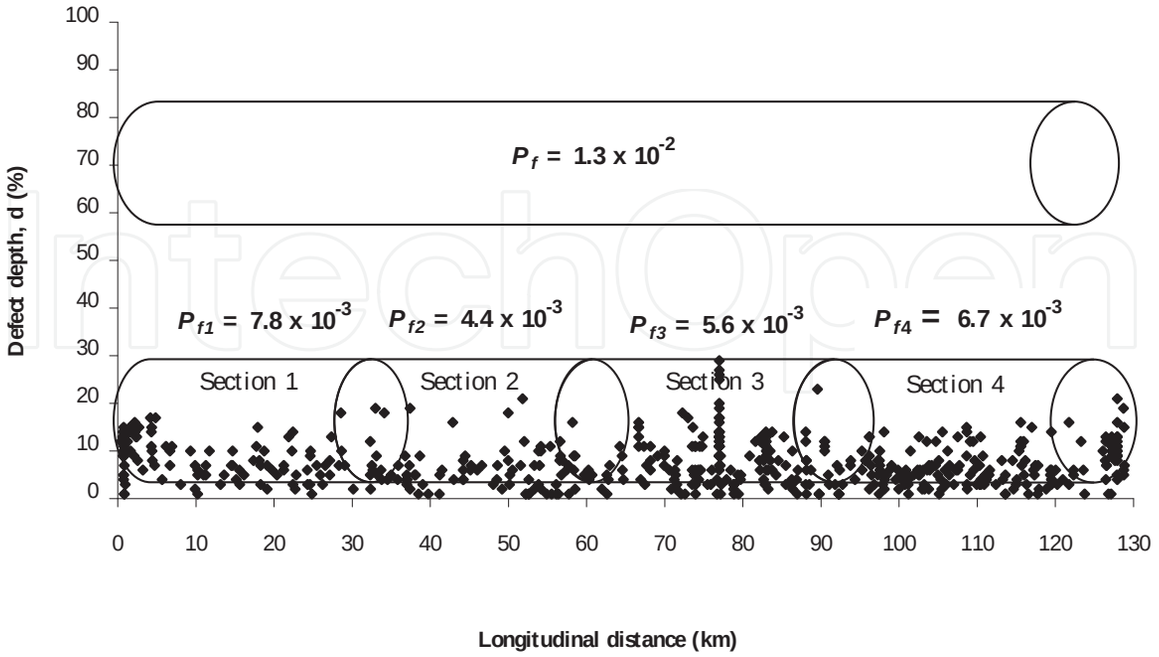



**Figure 4.** Comparison in probability of failure ($P_f$) between sectional and individual pipeline of corroded pipeline

Better understanding on pipelines acting as a system has paved the knowledge to interpret the correlation and characteristics among corrosion defects in the pipe. The interaction among multiple corrosion defects can best be assessed by assuming the pipeline operating as a series system. The interaction among defects is still not well defined. When it is conservative to assume that all of a cluster of adjacent defects interact (Cosham et al., 2007), Bjørnøy and Marley (2001) concluded that there are unlimited combinations of interaction of defects. Li et al. (2009) has studied the effect of correlation of corrosion defects and it was revealed that the assumption of independent corrosions defects lead to conservative results. Literatures on this, however, are still limited. To the author best knowledge, the reliability of corroded pipelines acting in a system has been reported by De Leon and Macías (2005), Zhou (2010) and Mustaffa (2011). A summary on their works are presented in Table 7.

| Research on: | Related Literature |
|---|---|
| Spatial correlation between multiple defects on a pipeline system reliability under burst failure mode. | De Leon and Macías (2005) |
| Reliability of a corroding pipeline segment as a series system under three potential failure models (small leak, large leak and rupture). | Zhou (2010) |
| Length scale effect of a pipeline in series. | Mustaffa (2011) |

**Table 7.** Literatures on corrosion assessment in pipeline systems

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### 5.2. reliability-based maintenance approach

Most of the discussions on reliability assessment of pipelines presented in earlier sections of this chapter are those closely developed based on the mechanics of corrosions. The parameters addressed in the equations are very much depending on the design parameters of the pipe as well as the corrosion inspection data reported by the inspection tool *i.e.* intelligent pigging tool. Apparently, these are the important two factors required to carry out the assessment.

In reality, the development of corrosions in the pipe cannot be explicitly described. Not only corrosion growth is based on the science of corrosion, but other external factors are also believed to contribute to this development as well. These external factors can be further described in the aspects of operation and maintenance of the pipeline. Corrosions are mainly controlled by the use of *corrosion inhibitors*. A corrosion inhibitor is a chemical compound that, when added to a liquid or gas, decreases the corrosion rates of a material, typically a metal or an alloy. A pipeline is dosed continually with an inhibitor in order to mitigate against any corrosion that could occur. It acts as a film on a metal surface that provides physical protection against corrosive attack.

Describing the effect of corrosion inhibitors, however, is not a straightforward task (Nešić, 2007). The inhibitor is said to be only efficient when it could present in the water phase and reach the pipe wall. If the inhibitor residual concentration in the water phase exiting the pipeline is above a certain target level, then the whole pipeline is assumed to be protected by the inhibitor (Rippon, 2003). It is essential to keep the inhibitor concentration as close as to and above the minimum required at all time in order to effectively control corrosion in the pipeline in the most cost-effective ways. Longer exposure time may allow the inhibitor to perform better as suggested by Hong et al. (2002). In addition, Valor et al. (2010) have experimentally proven that corrosions do grow on a daily basis even though the increment is considered to be very small. The fact that corrosion grows every day, this then reflects the argument to also allow the presence of corrosion inhibitor in the pipe at the same time. Leaving a pipeline without inhibition within a period of time might cause the corrosion to grow rapidly. The inhibitor performance is the key for day to day assessment of the inhibitor system availability. Therefore the probability of an inhibitor to present and retain at the internal pipe circumference wall are something that should be addressed in a corrosion assessment model.

It has been assumed that the corrosion inhibitor will be injected into the system of pipeline at the correct dosage, without interruption during the lifetime of the system (Hedges et al., 2000), but experience has shown that these assumptions are not applicable for a variety of reasons for example pumps failure and interruption on inhibitor supplies. Also note that the practice of releasing inhibitor inside a pipe is mainly controlled by the pipeline operators. The inhibitor may not be injected accordingly to its dosage and schedule which can cause corrosion to happen rapidly in the pipelines. Consequently, the aspect of human intervention may then become an additional factor that indirectly contributes to the reliability assessment of corrosions in a pipeline (Mustaffa, 2011).

The practice of releasing inhibitor in a pipe is then considered as another source of uncertainty to the system. A reliability of a system that is exposed to such uncertainties can best be analysed

using probabilistic approaches. This section illustrates an approach for which the effect of human intervention can be considered in a reliability model. This example portrays the inconsistency of releasing corrosion inhibitor in the pipeline, as shown in Fig. 5.

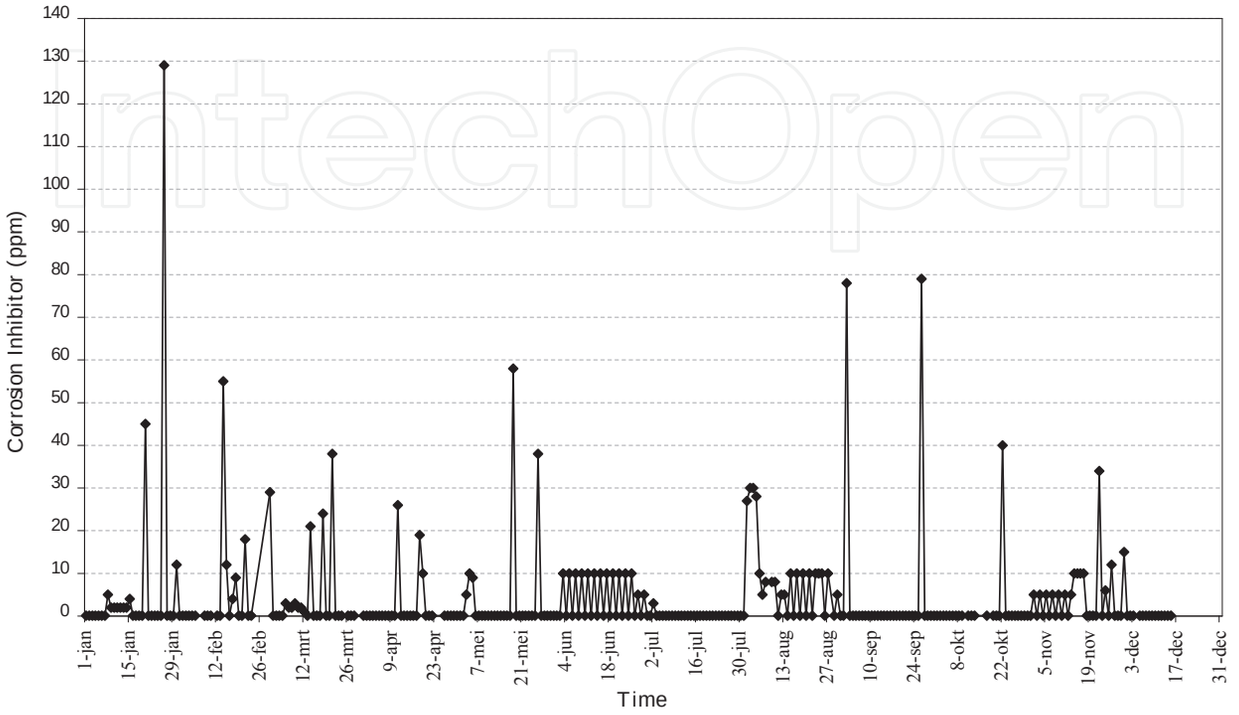



**Figure 5.** An illustration on the unavailability of corrosion inhibitor in pipeline in a year

In can be seen from Fig. 5 that the inhibitors were absent in the pipe for most of the days from a sample period of one year *i.e.* when inhibitor is 0 ppm. Such practice is believed to have direct impact towards corrosion growth in the pipe. It is proposed that the reliability for this scenario to be translated into the form of a limit state function model as well, part of which has been introduced in the earlier section. Therefore, the limit state function in Eq. 8 can be expanded to an equation described by,

$$\mathrm{g}(\mathrm{x}) = Z = d - \left(CR \times t_{abs}\right) \tag{11}$$

where $d$ = allowable corrosion depth (mm), $CR$ = corrosion rate (mm/yr), $t_{abs}$= time (days) when the corrosion inhibitor is absent in the pipeline. Eq. 11 translates the ideology of predicting corrosion in a particular pipeline given the amount of present corrosion, its expectation to evolve with time and the likelihood of having inhibitor in the pipeline. Eq. 11 also implicitly states that corrosions are allowed to grow based on the given rate, but their growth could be controlled by the practice of releasing inhibitor in the pipe.

In this model the availability of inhibitor is described as its time of absence per month. Herein, the corrosion parameters $d$ and $CR$ are identified based on the inspection and assessment

reports while the time $t_{abs}$ is entirely influenced by human intervention. The parameter $t_{abs}$ on the other hand, is proposed to be treated as a variable so as to simulate its response towards the availability of inhibitor monitored in a month. The number of days of corrosion inhibitor absence in the pipeline decreased from 30 to 0 days and the effect on the pipeline integrity was investigated. Table 8 provides descriptive statistics of the random variables applied into the model.

| Variables | Distribution | Mean, μ | Standard deviation, σ |
|---|---|---|---|
| Defect depth, *d* | Normal | 15.69 | 0.76 |
| Corrosion rate, *CR* | Normal | 0.25 | 0.50 |
| $t_{absence}$ @ 30 days | Normal | 30.42 | 0.90 |
| $t_{absence}$ @ 0 day | Normal | 0.42 | 0.90 |

**Table 8.** Descriptive statistics of random variables

The probability of failures were computed using Eq. (11) based on the random tabulated in Table 8, with results as shown in Table 9.

| t absence (day/month) | Probability of Failure ($P_f$) |
|---|---|
| 30 | 0.312 |
| 28 | 0.278 |
| 26 | 0.247 |
| 24 | 0.231 |
| 22 | 0.188 |
| 20 | 0.149 |
| 18 | 0.109 |
| 16 | 0.087 |
| 14 | 0.081 |
| 12 | 0.032 |
| 10 | 0.009 |
| 8 | 0.003 |
| 6 | 0.002 |
| 4 | 0.000 |
| 2 | 0.000 |
| 0 | 0.000 |

**Table 9.** Probability of failure ($P_f$) reported according to $t_{absence}$

From the table, it can be seen that when the number of days of corrosion inhibitor absence in the pipeline decreases, the probability of failure also decreases. Results from the table portray the impact of corrosion failure as a result of the absence of corrosion inhibitor (in days per month) in a particular pipeline. It can be seen from the table that the probability of failure increases with the increase in the days of inhibitor absence. This is true because no continuous protection is given to the pipe giving more chance for the corrosions to grow rapidly. Thus it is important for the corrosion inhibitor to be present in the pipeline on a daily basis in order to keep the probability of failure lower.

## 6. Conclusions

This chapter discusses the development of reliability assessment models used for the offshore pipelines subjected to corrosion. It has been shown that the models were mostly developed based on the mechanics of corrosions acting on a pipe. Comparisons have also been made on different design codes and standards by the industry to estimate the reliability of corroded pipelines. Most of these standards, however, are deterministic in nature. Corrosions cannot be explicitly determined as there are so many uncertainties involved, thus probabilistic method seems to be more realistic to be applied instead. In the probabilistic approaches, literatures have integrated the failure pressure (PF) models into the limit state function (LSF) equation. Comparisons on the performance of these LSF models have been briefly discussed.

It is proposed that human intervention to be addressed when assessing the reliability of corroded pipelines. This is true as the growth of corrosions is very much depending on the effectiveness practice of releasing corrosion inhibitor in the pipe. Herein, a model has been proposed to the consider the aspect of human intervention in the assessment, and the simulation seems to provide favorable results.

## Author details

Zahiraniza Mustaffa*

Civil Engineering Department, Universiti Teknologi PETRONAS, Tronoh, Perak, Malaysia

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