DETERMINATION OF EXTENSION OF LIFE OF CORRODED OFFSHORE PIPELINES USING FORM AND MONTE CARLO STRUCTURAL RELIABILITY

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ABSTRACT

The evaluation of the structural strength of an offshore pipeline after 25 years of service is an important issue for extending its lifespan. This is an important environmental and economic issue, especially when the pipeline is related to the oil and gas industry. Remaining strength after corrosion effects are included in the performance equation and can be determined by using maximum operating pressure and capacity equations. The results are then compared from burst test results. In this study, Bayesian updating of probability of failure is used to evaluate the updated probability of failure. The performance equations from the two main codes on corrosion used in this study are B31G and DNV-RP-F101 and they are used validate the results. The sensitivity analysis of the variables such as defect depth and thickness is considered in the analysis. This method could be adopted for evaluating the service life extension and evaluation of pipelines working under extreme environments. FORM and Monte Carlo simulations will be used to determine the updated probability of failure. The method could be used for many engineering structures where either practical approaches are not feasible to determine the remaining life of the structure or the uncertainty of the expected results is too high. The evidence concluded in this study could be used by industry to enhance our understanding of the mechanisms for pipeline failure and processes necessary for its preservation.

KEYWORDS

Corrosion, subsea pipeline, Structural assessment, Bayesian updating, Burst test, Structural reliability.

INTRODUCTION

Pipeline is a popular and significant mode of transporting liquids for the onshore and offshore oil and gas industry. This is due to many reasons such as economics, easy to lay, and long design life of approximately 20-30 years, which are necessary criteria for offshore pipelines due to undersea work environments. Oil pipelines require continuous assessment for their structural integrity. Pipelines commonly deteriorate due to external or internal corrosion. Though cathodic protection and corrosion resistant paints are used at the time of installation, due to decay, with time their effect decreases significantly to withhold corrosion. This is due to sea environment in which these pipelines are placed and the oil and gas these pipelines transport. This paper refers a pipeline that has already completed its design life and is under constant investigation given that it is severely affected by internal corrosion. The rate of corrosion in sea water is 0.3 to 1 mm / year. External corrosion is protected by cathodic protection and a coat of concrete. Malaysia is an offshore oil producing country. There are approximately three hundred Jacket platforms in operation for more than 30 years. Many of its pipelines networks have already completed their design life, and offshore Jacket platforms continue to produce and temporarily store oil and gas to be transported onshore or to another platform.

Offshore oil and gas pipelines are a complex infrastructure system with a significant impact on the economy, environment, and society. The world is moving towards adopting more proactive and optimised approaches to manage underground pipeline systems for their short and long term renewal planning in a more sustainable way (Tee, Khan et al. 2014). The main causes of their damage are stress corrosion cracking, wall thickness reduction, and the presence of stress concentrators (Amirat, Mohamed-Chateauneuf et al. 2006). Pipelines, like other structures in nature, deteriorate over time. The deterioration of pipelines in the form of corrosion is found to be a major problem for pipeline operators that worsen as pipelines age. The annual direct cost of corrosion, in the U.S. oil industry exceeds $5.1 billion per year (Nuhi, Abu Seer et al. 2011). Corrosion was a major cause of 18% of significant incidents from 1988-2008 (Fessler 2008). Structural engineers and naval architects are becoming increasingly interested in rate of loss of strength of steel and thus in loss of material for offshore and onshore
METHODOLOGY

Failure analysis of X52 pipeline and its background

The sampled pipeline is located in peninsular Malaysia with a diameter of 273.05 mm, nominal wall thickness of 11.1 mm, and total length of 6.9 km. It transports wet and semi processed crude oil between two Jacket platforms with a flow rate of 168 m³/day. The design code is ASME B31G and material grade is API 5L X52. The design pressure was 10.35 MPa at the time of design and maximum allowable operating pressure (MAOP) was set to 9.3 MPa which was subsequently decreased to 4.0 MPa and at the time of last inspection the average operating pressure was 2.8 MPa. It was put into operation in 1982 for a design life of 20 years. The defect assessment was performed using ultra sonic non-destructive scan tests named as the intelligent pigging method of Magnetic Flux Leakage tool to evaluate its internal and external corrosion with confidence level of 80%. This assessment was performed using ultra sonic non-destructive scan tests named as the intelligent pigging method of Magnetic Flux Leakage tool to evaluate its internal and external corrosion with confidence level of 80%. This process started in 1984 and subsequently repeated in 1993, 1997, 1998, 1999, 2002, 2003, 2005 and 2006. The main corrosion enhancing elements in hydrocarbon carrying pipeline are acid gases like CO₂ and H₂S both of which dissolve in water and separate to cause carbonate acid corrosion and hydrogen sulphide cracking respectively. The presence of water is a prerequisite for corrosion. Other elements of corrosion include salts, carbonates, bicarbonates, and organic acids such as Ferric chloride, ferrous sulfide, ferric chloride, sand, coating failure, and anode depletion. The operating temperature is 55°C and it is located below mean sea level of 67.2 m. There were 6000 defects between 10-50% of material loss with the maximum corroded depth recorded as 5.11 mm out of a total depth of 11.1 mm. The most significant defect recorded in 1991 was 2.33 mm and the inspection carried in 2003 reported 5mm. Total number of defects identified in inspection reports of 1993, 1997, 2003 and 2006 are 944, 2186 and 10896 respectively. Out of these, 60% of defects reported were pit defects. The majority of these defects were in one segment of a 250 meters section of the pipeline. In 2008, it was recommended that a segment of 1000 meters should be replaced with a new one due to corrosion between long distances of 93-850 m because single and interacting defects gave (corroded pressure) \( p_{corr} = 0 \) bar containing the highest density of defects of 88%. Table 1 shows some significant corroded defect lengths and depths of the pipeline section. The data is taken from a section of the pipeline. The absolute distance shown in the first column is based on a 500 meter section of pipe sampled in this study. The distance is mentioned here to show the nearness of corrosion pits. The length and width shows defected length and width of a pit. Depth of pit is shown in terms of percentage of original wall thickness which is 11.1 mm. Some of these defects are in close proximity and there is likelihood that they will grow and become one significant defect.
Table 1: Corrosion defect resistance and load variables.

<table>
<thead>
<tr>
<th>Absolute distance (m)</th>
<th>Length (mm)</th>
<th>Width (m)</th>
<th>Depth (%)</th>
<th>ERF</th>
</tr>
</thead>
<tbody>
<tr>
<td>113.54</td>
<td>247</td>
<td>10</td>
<td>33</td>
<td>1.219</td>
</tr>
<tr>
<td>122.73</td>
<td>265</td>
<td>35</td>
<td>40</td>
<td>1.361</td>
</tr>
<tr>
<td>134.92</td>
<td>400</td>
<td>80</td>
<td>24</td>
<td>1.075</td>
</tr>
<tr>
<td>147.88</td>
<td>374</td>
<td>45</td>
<td>33</td>
<td>1.219</td>
</tr>
<tr>
<td>184.71</td>
<td>370</td>
<td>130</td>
<td>26</td>
<td>1.104</td>
</tr>
<tr>
<td>197.00</td>
<td>290</td>
<td>130</td>
<td>25</td>
<td>1.089</td>
</tr>
<tr>
<td>200.33</td>
<td>310</td>
<td>180</td>
<td>38</td>
<td>1.318</td>
</tr>
<tr>
<td>215.11</td>
<td>303</td>
<td>120</td>
<td>39</td>
<td>1.339</td>
</tr>
<tr>
<td>230.05</td>
<td>493</td>
<td>37</td>
<td>31</td>
<td>1.184</td>
</tr>
<tr>
<td>486.83</td>
<td>250</td>
<td>40</td>
<td>41</td>
<td>1.385</td>
</tr>
</tbody>
</table>

Estimated repair factor (ERF) is used to rank the abnormalities in the pipeline based on their severity. ERF is shown in terms of maximum allowable operating pressure MAOP and safe pressure ($P_{safe}$) by Eq. (1).

$$ERF = \frac{MAOP}{P_{safe}}$$  (1)

**Pipeline Burst test analysis**

Two meters of pipeline was cut and used for burst pressure test analysis. The water was inserted until a burst in the pipe occurred with water capacity of 100 MPa. The burst pressure is shown in Table 2 with average value of 33.5 MPa. Maximum hoop stress predicted by equation (2) is 36.5 MPa. This burst test which showed confidence in the remaining strength of pipeline was considered necessary to recheck the reliability of the pipeline. The burst test provided a reserve strength which is incorporated into the limit state equation to get the new updated reliability.

Table 2: Pipeline Burst test results

<table>
<thead>
<tr>
<th>Average measured wall thickness (mm)</th>
<th>Defect Dimensions (mm)</th>
<th>Burst Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Defect depth (d)</td>
<td>Defect length (L)</td>
</tr>
<tr>
<td>10.87</td>
<td>4.0</td>
<td>200</td>
</tr>
<tr>
<td>10.58</td>
<td>Not available</td>
<td>Not available</td>
</tr>
<tr>
<td>12.11</td>
<td>6.0</td>
<td>200</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$P_{max} = \frac{2t F_t}{(D - t)}$$  (2)

**Limit state function**

The remaining strength limit state equations are taken from DNV RP-F101 and B31G. When a structure completes its design life, it might have changed in many ways such as with additions or alterations inside the structure, deterioration of its components i.e. change in geometrical dimensions as well as a decrease in the strength due to environment or passage of time. This makes the re-evaluation of strength compulsory if we want to extend its lifespan. Equations (3-4) are the limit state function used in this study for the determination of reliability. The B31G code provides limit state function as shown in Equation (3). $P_a$ is the allowable pressure which is a variable in this study.

$$P = F \left(\text{SMYS} + 69 \text{ MPa}\right) \frac{2t}{D} \left[ 1 - 0.85 \frac{d}{D} \left(1 + 0.03 \frac{1}{M_{ij}}\right) - P_a \right]$$  (3)
Where, \( Z = \frac{L^2}{D \cdot t} \)

If \( Z \leq 50 \), \( M_3 = \sqrt{1 + 0.6275 \cdot Z - 0.003375 \cdot Z^2} \)

If \( Z > 50 \), \( M_3 = 3.3 + 0.032 \cdot Z \)

For DNV code the limit state function is shown by Equation (4), which shows the capacity of the pipe pressure.

\[
P_{\text{cap}} = 1.05 \frac{2t \sigma_t}{(D - t)} \left(1 - \frac{(d/t)}{Q}\right) - P_a
\]

Where

\[
Q = \sqrt{1 + 0.31 \left(\frac{L}{\sqrt{D \cdot t}}\right)^2}
\]

Model uncertainties of basic random variables:

Uncertainties in capacity or member strength occur due to material or geometric variability named generally as epistemic uncertainty i.e. uncertainty based on imperfection of information about the variable. Material uncertainties are used to measure statistical spread, evaluated by using the data from fabrication yard and mill test reports. Structural reliability depends on probabilistic nature of material and load uncertainties. Once this data is determined we need to update the structural reliability. For uncertainty analysis, nominal bias values were taken from Zimmerman and Cosham et al. (1998), as shown in Table 3. These nominal bias values were then used to get the actual mean and standard deviation based on the data shown in Table 1.

Table 3: Uncertainty variables.

<table>
<thead>
<tr>
<th>Random variable</th>
<th>Type of distribution</th>
<th>Bias mean</th>
<th>Bias COV%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>Normal</td>
<td>1.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>Normal</td>
<td>1.01</td>
<td>1.0</td>
</tr>
<tr>
<td>Yield strength</td>
<td>Normal</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>Normal</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Damaged depth</td>
<td>Normal</td>
<td>1.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Damaged length</td>
<td>Normal</td>
<td>1.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Model uncertainty (DNV)</td>
<td>Normal</td>
<td>1.05</td>
<td>9.5</td>
</tr>
<tr>
<td>Pressure</td>
<td>Normal</td>
<td>1.07</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Pipeline reliability: FORM and MC

Analytical and simulation methods of reliability analysis are used to determine the reliability index. Analytical methods include moment based methods such as First Order Reliability Method (FORM) and Second Order Reliability Methods (SORM). The FORM method is based on the first-order Taylor series approximation of a limit state function. The limit state function must be defined to formulate the FORM and estimate the reliability. The curvature of the limit state around the minimum distance point determines the accuracy of the first-order approximation in the FORM (Lee, Kim et al. 2005). A major simulation method is the Monte Carlo simulation. It is easy to use, robust, and accurate by using a large number of samples, though it requires considerable analysis to achieve a good quality approximation of low probability of failure. The problem with this simulation technique is that it produces noisy approximation of probability. Monte Carlos simulation method involves sampling and estimation to determine structure reliability. Reliability based structures are designed so that their reliability is always higher than the target reliability specified by the codes of design. The main methods for evaluating the remaining strength are based on codes DNV-RP-F101, B31G by ASME based on NG 18 Equation, RSTRENG by Shell. The safety margin between load and resistance is indicated by the limit state function \((g)\) in Equations (5),
\[ g = R_i - Q_i \leq 0 \]  
Equation (5)

Probability of failure is given by Equation (6),

\[ P_f = P(g < Q) \]  
Equation (6)

The reliability index can be found by Equation (7),

\[ \beta = \Phi^{-1}(P_f) \]  
Equation (7)

The probability of failure can be evaluated by Monte Carlo simulation as shown in Equation (8),

\[ P_f = \frac{N_f}{N} \]  
Equation (8)

**Target reliability**

The reliability based structures are designed so that their reliability is always higher than the target reliability i.e., minimum specified by the well-established standards. Target reliability is required for calibration in order to make sure that certain safety levels are maintained. There is an agreement among researchers that if annual probability of failure due to some cause is less than 1 in 10,000, then it is small in relation to major risks (Efthymiou and Graham 1990). DNV reports acceptable annual target reliability for redundant Jackets as 3.09 or probability of failure of \(10^{-4}\) (Pradnyana, Surahman et al. 2000). In this paper, target reliability of 3.0 is used.

**Failure / reliability assessment framework or life extension scenarios**

In this study, two types of analysis are used to find the updated reliability or probability of failure. The first is by using FORM analysis and the second by using Monte Carlo simulation.

**i) Updating of Probability of Failure using FORM analysis**

For FORM, the updated reliability of the strength of the pipe based on the Burst test was included in the limit state equation for the respective code. The new reliability is calculated and shows its reserve strength. In this study, MATLAB code is formed to solve the limit state equations from each code separately. FERUM open source compiler is used to perform the FORM analysis. The results are shown in Figures (1-8).

**ii) Bayesian Updating of Probability of Failure using Monte Carlo Simulation**

Epistemic uncertainty is due to shortage of confidence for evaluated probability. This type of uncertainty can systematically updated when more information and data for that random variables becomes available. This method is used to get the updated probability of failure using Monte Carlo simulation (Ang and Tang 2007). The probability of failure is determined using Eq. (8). Probability of survival can be evaluated using number of survival to total number of simulations. The reassessment of the pipeline and its survival probability of \((P_s)\) is incorporated in the reliability analysis, as shown in Equation (9),

\[ P_s = \frac{\text{Number of Survival}}{\text{Total Number of Simulations}} \]  
Equation (9)

Equation (9) provides us the probability of survival depending upon the limit state equation and its variables. When \(P_s\) is evaluated given that \(P_s\) is also known, then we can find the updated probability of failure \((P_{uf})\). Failure probability has already been found using Equation (8). The new updated probability of failure is shown by Equation (10),

\[ P_{uf} = P(g < 0|S > 0) \]  
Equation (10)

Equation (10) provides information of probability of occurrence of an event. Thus when given limit state equation is having failure what is the survival chance at that particular probability level.

\[ P(g < 0) = \text{Probability of failure of limit state function}, \]
\[ P(S > 0) = \text{Probability of survival of limit state function} \]

Now using Equations (9-10) updated probability of failure (\( P_{uf} \)) can be determined as shown by Equations (11-12). Equation (11) provides us a tool to calculate the probability of survival in the presence of probability of failures.

\[
P_{uf} = \frac{P(g(x) < 0 \cap S > 0)}{P[S > 0]} \quad (11)
\]

\[
P_{uf} = P(g|S)P(S) \quad (12)
\]

In this study, MATLAB code is formed to solve the limit state equations from each code separately. The results are shown in Figures (9-16).

**Burst Test**

From the Burst test, the reserve strength of the pipe was determined to be 33.5 MPa. This deterministic value is incorporated in the limit state equations. Thus, an updated reliability can be evaluated based on information provided by the Burst test.

**RESULTS AND DISCUSSIONS**

The overall results for FORM and Monte Carlo simulation for codes DNV and B31G respectively are discussed below.

**FORM analysis**

This paper uses FERUM as an open source MATLAB code to generate FORM analysis. Figure 1 shows when the DNV code is used and defect length is fixed up to 200 mm and FORM analysis is made. Figure 1 shows that at defect depth of 4 mm, the reliability index reaches 2.8 for MAOP of 9.3 and 3.2 for MAOP of 4.0 and 2.8. Thus, we can say that the limit for safe running of the pipeline is reached when the defect depth is 4 mm. If the Burst test results are incorporated in resistance of the limit state equation with fixed defect length of 200 mm and using DNV code, Figure 2 shows that it is 4.2 mm where the target reliability is reached and the pipe becomes unsafe. However, in this case, all MAOP values have the same reliability due to the significant increase in resistance.

Figure 3 shows the reliability index values for the DNV code using a constant damaged depth of 4 mm with different Maximum allowable operating pressure (MAOP) values. The reliability decreases up to damage length of 500 mm and remains almost constant for respective MAOP. The reliability indices are 3.0 for MAOP of 4.0 and 2.8, but against a load of MAOP of 9.3, the reliability index decreases to 2.5 which is lower than the target reliability. The pipeline cannot withstand that pressure. Using the DNV code and fixed damaged depth of 4 mm, and if the results from the Burst test is included in the resistance for the limit state equation, then the reliability indices increases significantly. In Figure 4, all the reliability indices show significant increase and the minimum value is 3.47, which is higher than the target reliability.

If the FORM analysis is made with B31G and fixed defect length of 200 mm, then Figure 5 shows that with a design load of MAOP of 9.3, a reliability index of 3.0 is achieved with defect depth of 4.0 mm, and for MAOP of 4.0 and 2.8, the defect depth could reach 5.0 mm. If the Burst test results are also incorporated in the resistance of limit state equation and using B31G with defect length fixed at 200 mm, the FORM results are shown in Figure 6, which shows that all three loads are on the same line and minimum target reliability is reached at defect depth 5 mm. Figures 7 and 8 shows reliability indices for B31G using FORM analysis with fixed defect depth of 4 mm. The Figures show little influence of length on reliability but with load of MAOP of 9.3, target reliability becomes less than 3.0 below defect length of 500 mm. If the resistance also incorporates Burst test results, then reliability indices remain higher than 4.0 even for a load of 9.3 MPa.
Monte Carlo Simulation:

When the Monte Carlo simulation is used to determine the reliability index using DNV code and with fixed
defect length of 200 mm, Figure 9 shows that target reliability decreases below defect depth of 4 mm but for
other loads, it reaches defect depth of 4.4 mm. Figure 10, which uses Bayesian updating, shows that target
reliability, is still safe for defect depth of 5 mm. All loads have no difference for reliability index.
Figure 11 shows the reliability index for DNV using Monte Carlo simulation for fixed depth of 4 mm. The load
of 9.3 MPa has reliability of 3.0 and less throughout the length, thus it is not safe. Figure 12 shows that with
Bayesian updating, the reliability index for all loads is above the target reliability. The variability is due to
nuisance in Monte Carlo simulation. Figure 13 shows the updated reliability using Bayesian updating and that reliability is higher than the target with defect
depth of 5 mm for all loads. Figure 15 shows the reliability index for B31G using Monte Carlo simulation for
constant defect depth of 4 mm. The Figure shows that a load of 9.3 MPa has reliability higher than the target at
defect length of 300 mm but it decreases below that after 300 mm. All other loads are safe for all defect depths.
Using Bayesian updating, all loads’ reliability index is well above the target reliability.

Sensitivity analysis

Table 4 shows sensitivity analysis results from FORM analysis for B31G and DNV. The Table shows that
damaged depth is more sensitive than other variables. It has the same sensitivity in both codes. As compared to
B31G, Model uncertainty, wall thickness, and damaged length are also sensitive in DNV.

<table>
<thead>
<tr>
<th>Random variable</th>
<th>Sensitivity analysis index DNV</th>
<th>Sensitivity analysis index B31G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness</td>
<td>0.13</td>
<td>0.2</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.9e-4</td>
<td>1.5e-5</td>
</tr>
<tr>
<td>Yield strength</td>
<td>-</td>
<td>7.8e-4</td>
</tr>
<tr>
<td>Damaged depth</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Damaged length</td>
<td>0.06</td>
<td>3.1e-4</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.008</td>
<td>4.7e-4</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>0.008</td>
<td>-</td>
</tr>
<tr>
<td>Model uncertainty</td>
<td>0.02</td>
<td>-</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This research used data from an actively corroded pipeline to determine pipeline reliability. The results showed
that with pressure of 9.3 MPa and the defect size of 5 mm, it is not possible to extend the life of a pipe if target
reliably is set as 3.0. By using Burst test results and Bayesian updating techniques, the reliability index increases
compared to reliability index based on design values. Thus, if we include probability of survival and reserve
strength, then the pipeline can withstand pressure as high as 9.3 MPa. The DNV code showed more reserve
strength compared to B31G. This may be due to the inclusion of model uncertainty in the limit state equation of
DNV whereas not model uncertainty is included in B31G. The sensitivity analysis shows that defect depth is a
significant factor for the reliability analysis for DNV and B31G codes. Besides that, DNV shows that original
wall thickness is sensitive to the reliability index. This method provides good judgement on assessing the
pipeline for its life extension. This method could be applied to major structures such as nuclear power plants,
dams, and bridges.

ACKNOWLEDGMENTS

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Universiti Teknologi PETRONAS.
Figure 1: Reliability index against defect depth using DNV code (FORM)

Figure 2: Updated reliability index against defect depth using DNV code (FORM)

Figure 3: Reliability index against defect length using DNV code (FORM)

Figure 4: Updated reliability index against defect length using DNV code (FORM)

Figure 5: Reliability index against defect depth using B31G code (FORM)

Figure 6: Updated reliability index against defect depth for B31G code (FORM)
Figure 7 Reliability index against defect length for B31G code (FORM)

Figure 8 Updated reliability index against defect length for B31G code (FORM)

Figure 9 Reliability index against defect depth for DNV code (MC)

Figure 10 Updated reliability index against defect depth for B31G code (MC)

Figure 11 Reliability index against defect length for DNV code (MC)

Figure 12 Updated reliability index against defect length for DNV code (MC)
Notations:

- $t$: Uncorroded pipe wall thickness
- $p_{\text{corr}}$: Corroded pressure
- $P_{\text{max}}$: Maximum hoop stress
- $P_{\text{SMYS}}$: Specific minimum yield strength
- $P_a$: Safe pressure (random variable)
- $F$: Folias factor used for bulging
- $P_{\text{cap}}$: Capacity pressure
- $Q_i$: Load variable
- $\Phi^{-1}$: Inverse normal random variables
- $P_s$: Probability of survival
- $D$: Outside diameter of pipe
- $F_t$: Ultimate tensile strength
- $\text{ERF}$: Estimated repair factor
- $\text{MAOP}$: Maximum allowable operating pressure
- $\text{ILI}$: Inline inspection tools
- $M$: Folias factor or bulging factor (B31G code 1991)
- $\sigma_t$: Tensile strength
- $P_{\text{safe}}$: Safe operating pressure
- $d$: Depth of corroded region
- $P_{\text{maop}}$: MAOP
- $P_{\text{uf}}$: Updated probability of failure
- $R_f$: Resistance variable
- $\beta$: Reliability index
- $N$: Total number of simulations
- $\beta$: Reliability index
- $\Phi^{-1}$: Inverse normal random variables
- $N_f$: Number of Failures
- $\text{MAOP}=9.3$
- $\text{MAOP}=4$
- $\text{MAOP}=2.8$

**Figure 13** Reliability index against defect depth using B31G code (MC)

**Figure 14** Updated reliability index against defect depth using B31G code (MC)

**Figure 15** Reliability index against defect length using B31G code (MC)

**Figure 16** Updated reliability index against defect length for B31G code (MC)
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