ASSESSMENT OF THE INTEGRITY OF PIPELINES SUBJECT TO CORROSION-FATIGUE AND PITTNG CORROSION
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Objectives

Why Physics based probabilistic model?

PoF (Physics of Failure) models capture material degradation and failure mechanism and can be extrapolated to different levels.

Probabilistic models can adequately represent all of the factors that contribute to variability (e.g. material properties, Inspection devices accuracy, human errors, etc.)

Uncertainty is Certain!
Problem Statement

Event:
- Degradation of pipeline due to corrosion and fatigue
  - Leaks & ruptures
  - Unwanted plant shutdowns

Consequences:
- Cost due to inspection & repair
- Cost due to loss of production
- Cost due to impact on environment

Solution: Predictive maintenance

Problem: Cost of corrective maintenance
Corrosion-Fatigue in Pipes

\[ \sigma = \frac{PD}{2t} \] 
\( t \ll 1; D = \text{diameter}; t = \text{thickness} \)

\[ P \]

\[ P_{\text{mean}} \quad P_{\text{max}} \]

\[ \sigma \]

\[ \sigma_{\text{mean}} \quad \sigma_{\text{max}} \]

\[ t \]

\[ \sigma_{\text{min}} \]
Modeling Approach

Pit Nucleation -> Pit Growth -> Crack Nucleation (Pit to crack transition) -> Crack Growth

Corrosion is Dominant
Fatigue is Dominant

The criterion for transition:
\[
\left( \frac{da}{dt} \right)_{\text{crack}} \geq \left( \frac{da}{dt} \right)_{\text{pit}}
\]
Stress-Strength Interference Reliability Models

\[ P(\text{Stress} > \text{Strength}) = \int_0^\infty \left( \int_0^s g(x)dx \right) f(s)ds \]

Examples:
- Damage-Endurance Model
- Challenge-Tolerance Model
- Performance-Requirement Model
Probabilistic Fracture Mechanics Approach to Fatigue

Critical Crack size

ALT

N_{ALT} N_1 N_2 Life (Cycles)

TTF Distribution

Crack Size

Initial Crack size

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Modeling Outline

Critical Crack size

Transition

Corrosion fatigue crack growth

CTF Distribution

\[
\left( \frac{da}{dN} \right) = C_r \left( F \Delta \sigma \sqrt{R} \right)^n (1-\theta) + C_e \left( F \Delta \sigma \sqrt{R} \right)^n \theta
\]

\[
\frac{da}{dN} = \frac{MI_e}{2\pi n} \frac{1}{a^3}
\]

\( a_{tr} \)

\( N_{tr} \)

Life (Cycles)
Simulation Results

These are the \((N_{tr}, a_{tr})\) Coordinates
Empirical Model Development

Find the correlation of A & B with the physical parameters of the pipeline:

- Loading Stress “σ”
- Loading Frequency “ν”
- Temperature “T”
- Flow Characteristic “C” (e.g., \( I_p, [Cl^-], pH, \ldots \))

\[ Damage, D = f(ν_i, t_i|\Theta) \]

\( D \approx \) e.g. crack size, \( a \)

\( ν_i \approx \) variables (e.g. \( T, σ, ν, [Cl^-] \), \ldots \)

\( t_i \approx \) index of time (e.g. \( N, \ldots \))

\( θ \approx \) vector of model constants (e.g. \( ε, A, B, \ldots \))
The Proposed crack size vs. stress, cycle, etc.

\[ L(a_i) = LN(\mu_i, \sigma_i) \]
\[ \mu_i = ln[f(s_i, T_i, v_i, Ip_i, N_i)] \]

\[ q = \left[ A \cdot s_i^{0.182} \cdot v_i^{-0.288} \cdot Ip_i^{0.248} \cdot N_i^{1/3} + B \cdot s_i^{3.24} \cdot v_i^{-0.377} \cdot Ip_i^{0.421} \cdot N_i^2 \cdot e^{(4 \times 10^{-10} \cdot s_i^{2.062} \cdot v_i^{0.024} \cdot N_i)} \right] \]

where: \( a = \text{crack size} \), \( v = \text{load frequency} \), \( s = \text{stress amplitude} \), \( f_i = \text{Current intensity} \), \( N = \text{cycle Na} \)

\[ L(a) = f(a) = \frac{1}{\sigma \cdot \sqrt{2 \pi} a} \exp \left[ -\frac{1}{2\sigma^2} (\ln a - \ln(\sqrt{A \cdot s_i^{0.182} \cdot v_i^{-0.288} \cdot Ip_i^{0.248} \cdot N_i^{1/3} + B \cdot s_i^{3.24} \cdot v_i^{-0.377} \cdot Ip_i^{0.421} \cdot N_i^2 \cdot e^{(4 \times 10^{-10} \cdot s_i^{2.062} \cdot v_i^{0.024} \cdot N_i)})))^2 \right] \]
Data Collection

Corrosion-Fatigue Testing

Set-Up (In-House, Corest)

- Autoclave
- Data Acquisition Tower
- Recirculating Fluid Tank
- Motor Assembly
Data Collection

Corrosion-Fatigue Testing

Data (In-House, Cortest)
Parameter Estimation

A, B, σ
Prior Dist. (Uniform Non Informative)

Evidence Ni & ai From Experiment

Likelihood function L(ai) = LN (μi, σi)

WinBUGS Program

Posterior Dist. A, B, σ

Marginal A & B Longnormal Distribution

\[
\begin{align*}
\mu_A &= -9.34 \\
\sigma_A &= 7.41 \times 10^{-3} \\
\mu_B &= -34.524 \\
\sigma_B &= 0.4686 \\
\mu_{s2} &= 4.468 \\
\sigma_{s2} &= 1188
\end{align*}
\]
Probability Risk Assessment Application

Run simulation

Using proposed Empirical Model

- $a_i$ Lognormal distribution:
  $\mu = -5.47$, $\sigma = 0.06$
Probability Risk Assessment Application

A harsh pipeline environment:
- Higher Loading Stress

Frequency of Exceedance for Each Observed Number of Pits in the Refinery Pipeline.

The new frequency of exceedance for the bulk pipeline is estimated to be 548 pits/25 yrs life of pipeline!!!! → Drastically Increased
Conclusions

- A simple physics based empirical model has been proposed that could be globally applied to wide range of applications in pipes.

- The proposed model captured two main degradation processes: firstly the pitting initiation site for cracking and secondly the dominating fatigue crack growth part.

- The physical parameters in the proposed model reflect corrosion under aquatic environment.

- Generic data helped in model development, and Experimental data validated the proposed empirical model through a Bayesian approach.