Prognostics and Health Management in Petroleum Structures

Mohammad Modarres
Nicole Y. Kim Eminent Professor
Director, Center for Risk and Reliability
University of Maryland-College Park

Invited Talk at the
2015 Plant Maintenance & Reliability 6th Global Praxis Interactive Technology Workshop

17 February 2015
Outline of the Talk

- Center for Risk and Reliability, University of Maryland
- Important Failure Mechanisms
- Examples of PHM
- Applications to the Petroleum Industry
- Conclusions
Areas of Recent Focus at Center for Risk and Reliability (CRR)

- Probabilistic Physics of failure (PPoF, PHM, ADT, ALT)
  - Corrosion
  - Fatigue
  - Wear
  - Creep
  - Combinations

- PPoF Based Modeling of Structures and Systems
  - Agent-Based Computing
  - Simulations-Based Computing
  - Common Cause Failures

- Probabilistic Risk Assessment and Reliability Analysis
  - Risk Assessment and Management
  - Transportation Risk (CNGs and Pipelines)
  - Small Modular Reactors
  - Failure Data Collection and Analysis (small and large data, machine learning)
  - Modeling Reliability of complex components (Compressors, pumps, MOVs, etc.)
Overview of Failure Mechanisms

Physical Phenomena
- Thermal damage
- Fatigue and fracture
- Wear
- Creep
- Radio-activity: neutron bombardment

Chemical Phenomena
- Aqueous corrosion
- Solvation by liquid metal
- Reaction with organic solvents
- High-temperature corrosion
- Corrosion-fatigue
- Corrosion-wear
- Accelerated wear and fracture of metals inside human body
- Bacterial corrosion of cements and metals

Biological Phenomena
- Consumption of wood by termites and marine worms
- Consumption of polymers by rats

According to the National Bureau of Standards, the costs associated with material fractures for 1978 in the United States was $119 billion or 4% of the Gross National Product.

Aloha Airlines accident, 1988

According to the NACE, 2001, the direct cost of corrosion in the U.S. is $276 billion or 3.1% of the Gross Domestic Product.

Silver Bridge collapse, 1967
### Important Failure Mechanisms in the Petroleum Industry

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Failure inducing agents</th>
<th>Sub-categories</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue</td>
<td>Fluctuating stress/strain Assisted by environment: temperature, humidity, oxidation, corrosion</td>
<td>High-cycle fatigue Low-cycle fatigue Thermal fatigue Impact fatigue Surface fatigue Fretting fatigue Corrosion fatigue Creep fatigue</td>
<td>Airframes, pipelines, bridges, railroad structures, rotating shafts, turbine blades, pumps, bolts, gears, hip joint, welded structures, solder in electronic devices</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Chemical or electrochemical reaction with environment Assisted by stress, deformation, abrasion, wear</td>
<td>Direct chemical attack Galvanic corrosion Uniform corrosion Pitting corrosion Erosion corrosion Crevice corrosion Intergranular corrosion Stress corrosion Biological corrosion Hydrogen damage Corrosion fatigue Dealloying corrosion</td>
<td>Pressure vessels, boiler tubes, pumps, compressors, bridges, crude oil storage tanks, airframes, marine structures, bolts, medical devices</td>
</tr>
<tr>
<td>Wear</td>
<td>Relative motion between mating surfaces Plastic deformation Assisted by environment: humidity, oxidation, temperature, corrosion</td>
<td>Adhesive wear Abrasive wear Fretting wear Corrosive wear Fatigue wear Impact wear Deformation wear</td>
<td>Pipe bends, seals, bearings, gears, disks and tapes, piston rings, nuclear machinery, drills, pump impellers, human teeth and joints</td>
</tr>
<tr>
<td>Creep</td>
<td>Plastic deformation due to stress and elevated temperature Assisted by fluctuating stress/strain, corrosion</td>
<td>Creep fatigue Creep corrosion</td>
<td>Boiler super-heaters, petro-chemical furnaces, reactor vessel components, gas turbine blades, aeroengines</td>
</tr>
</tbody>
</table>
Fact About Corrosion in Industries

- Corrosion is considered a significant factor in the failure and damage of metals
- Annual direct cost of corrosion in U.S. oil and petrochemical industry = $6.8 billion
- Mechanistic loads increase damage in the presence of Corrosion
- Pipelines are subject to mechanical stresses and harsh corrosive environments
Fact About Corrosion in Industries (Cont.)

- The 2010 Enbridge Spill in Michigan-U.S. was due to **Corrosion-Fatigue** (~$1B cost of clean up so far!).

- **Why Mechanistic Failures are Important?**
  - Preexisting cracks (pits, dents, weld flaws, cracks initiation due SCC, etc.)
  - Mechanical loads (tensile and cyclic)

---

**Significant Incident Cause Breakdown**
National, Hazardous Liquid, 1992-2011

- **CORROSION**: 23.6%
- **EXCAVATION DAMAGE**: 18.8%
- **INCOMPLETE CONSTRUCTION**: 7.9%
- **MAT’L/WELD/EQUIP FAILURE**: 4.9%
- **NATURAL FORCE DAMAGE**: 4.9%
- **OTHER OUTSIDE FORCE DAMAGE**: 18.8%
- **ALL OTHER CAUSES**: 1.9%

*Source: PHMSA Significant Incidents Files, December 31, 2012*
UMD Approach to the Petroleum Industry PHM Application

**Define Conditions:**
- Understand needs and interests in the oil industry facility integrity management
- Define accelerated test conditions that matches the operating field environment of the targeted facility

**Perform Experiments and Data Gathering:**
- Experiments to accelerate damage on representative materials
- Analysis of data and associated uncertainties
- Gather field data

**Develop Models:**
- Select Mathematical Model
- Model Validation

---

**Step 1**
- Problem Definition
- Test Conditions Determination

**Step 2**
- Conduct the Experiments
- Field Data Gathering

**Step 3**
- Modeling & Validation
- Conclusions
- Recommendations
Types of Corrosion

- **Stress corrosion**
  Stress & corrosion work together at crack tips.

- **Uniform Attack**
  Oxidation & reduction occur uniformly over surface.

- **Selective Leaching**
  Preferred corrosion of one element/constituent (e.g., Zn from brass (Cu-Zn)).

- **Intergranular**
  Corrosion along grain boundaries, often where special phases exist.

- **Erosion-corrosion**
  Break down of passivating layer by erosion (pipe elbows).

- **Pitting**
  Downward propagation of small pits & holes.

- **Galvanic**
  Dissimilar metals are physically joined. The more anodic one corrodes. Zn & Mg very anodic.

- **Crevice**
  Between two pieces of the same metal. due to concentration difference

(Corrosion and Corrosion Control, H. Uhlig, et. al. 1997)
Importance of Corrosion in PHM

- Waste of Material and Energy
- Economical Loss
  - Direct Loss
  - Indirect Loss
    - Shutdown
    - Loss of product
    - Loss of efficiency
    - Product contamination
    - Overdesign
- Environmental Impact/Health

Different Types of Corrosion in a petrochemical Plant

- Pitting
- SCC
- Crevice
- Erosion
- Fatigue
- Embrittlement
- Intergranular
- General
- Stress corrosion crack

Data from major companies in France
(www.corrosion-doctors.org)
By common usage: "Fatigue" refers to the behavior of materials under the action of repeated stresses or strains, as distinguished from their behavior under monotonic or static stresses or strains.
Examples Fatigue Test & Specimens

Accelerated Testing
PHM in Oil Industry Considering NDT

Assessment of Real Damage /Degradation

g(ρ)=Real Damage Density Distribution?
f(a)=Real Damage Size Distribution?

Incomplete and Uncertain Evidence of Damage

Evidence-Based
(NDT-Based Defect/Damage size and density)
Methodology USED

• Hybrid PHM consisting of the following modules:
  – Physics-of-Failure (PoF) Model
  – NDT-based structural integrity assessment
  – Knowledge Fusion Module
Hybrid PHM Approach

Damage size \( a_{\text{crit}} \)

0.01\" Day One

\( t_1 \) \( t_2 \) Prediction

Prediction for \( \Delta T \)

Meta model

\[ a = f(RUL | _) \]

\[ \Pr(a > a_{\text{critical}}) \]

\[ \pi(\theta | \text{Evidence}) = \frac{L(\text{Evidence} | \theta)p(\theta)}{p(\text{Evidence})} \]

Damage Growth PoF Model

Field NDT

Field Inspection

The Center for Risk and Reliability
Acoustic Emission Monitoring
AE for Fatigue Prediction

Deconvolution of the measured voltage signal from the sensor to evaluate the properties of the source event is extremely difficult.

AE Features
- Amplitude
- Energy
- Rise time
- Counts (Threshold crossing)
- Frequency content
- Waveform shape
AE for Fatigue Prediction (Cont.)

Acoustic Emission
- Amplitude
- Energy
- Rise time
- Counts
- Frequency
- Waveform

Fatigue
Crack Growth Rate
\( \Delta K = f(\text{stress, crack size}) \)

\[
\log \left( \frac{da}{dN} \right) = \beta_1 \log \left( \frac{dc}{dN} \right) + \beta_2
\]

One can estimate \( \frac{da}{dN} \), given \( \beta_1, \beta_2 \) and AE count rate

Elements of Model Development: Bayesian Approach

- POD model
- Sizing Error model
- Observed NDT Data

Prior data and model parameters used in mechanistic models for assessing damage size and density

Likelihood of damage size and density distribution parameters given observed data corrected for sizing error and POD

Bayesian Inference

Posterior probability distribution of parameters of damage size depth and density
Machine Learning and NDT Data Fusion in PHM

- Periodic Inspection
- Bayesian Fusion
  - Corrosion and other Mechanistic PPoF Models
  - Updated Crack and Defect Size
  - Updated Crack Growth Rate
  - Updated PPoF Model Parameters
- Observations
  - $z_{k-2}$
  - $z_{k-1}$
  - $z_k$
- Inspection times
  - $r_{k-2}$
  - $r_{k-1}$
  - $r_k$
- Prognosis
  - $r_{k+1}$
  - $r_{k+2}$

- Formal framework
- Recursive (online fusion)
- Computationally feasible
- Multiple source
- Quantitative
- Probabilistic

Current time

Prognosis

The Center for Risk and Reliability
Probabilistic Modeling of Failure Mechanisms

➢ MTS Uniaxial Fatigue Testing Machines
  • Two-post and Four-post machines rating at ±100kN in tension or compression under static and cyclic conditions.
  • Fatigue Life Assessment Based on Energy Release
  • Fatigue Crack Initiation Based on Entropy Generation

➢ Optical Microscopy for Short Fatigue Crack
  • 25 to 10X Microscope with C-mount adaptor for the video port. Magnification of 25X to 100X, can be increased to as high as 200X. Simultaneous visual and video viewing.
  • Short crack detection in fatigue
  • Visualization of crack growth

➢ Acoustic Emission Technique for Crack Initiation and Growth
  • Sensors and amplifiers to collect and amplify the signals, a data acquisition module to perform front-end filtration and record the signals, and a software module to visualize the data and to perform the required analysis such as feature extraction and source location.
  • Assessment of crack initiation
  • Large crack growth modeling
  • Information entropy analysis of AE signals for crack initiation

➢ Heating Chamber for Creep Testing
  • Exposure of specimen under controlled heat up to 700°C
  • Probabilistic modeling of creep
  • Fatigue-creep testing capability

➢ Corrosive Medium Chamber
  • Probabilistic corrosion-fatigue model development in piping
  • Probabilistic pitting corrosion in pipes
  • Probabilistic stress corrosion in piping
Conclusions

• CRR Provides Most Up to Date Methods for PHM in the Petroleum Industry
• Strong Experimental, Model Development and Simulation Approaches to PHM
• Investments in PHM Corresponds to Multiples of Direct and Indirect Returns
Thank you for listening

Question?