The Center for Risk and Reliability

Overview of Reliability Engineering and My Current Research

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Outline

PART 1:

– A Quick Overview of Reliability Engineering

– Current Leading Researches in Reliability Engineering

PART 2:

– My Current Research:

- Reliability Based on Entropy
- Damage Precursors and Uses in Prognosis and Health Management (PHM)

– Conclusions

Reliability Engineering Overview

- Reliability engineering measures and improves resistance to failure of an item over time
- Two Overlapping Frameworks for Modeling Life and Performance of Engineered Systems Have Emerged:
  - Data or Evidence View: Statistical / Probabilistic
  - Physics-View
    - Empirical: Physics of Failure
    - Physical Laws
- Areas of Applications
  - Design (Assuring Reliability, Testing, Safety, Human-Software-Machine, Warranty)
  - Operation (Repair, Maintenance, Risks, Obsolescence, Root Cause Evaluations)

Data or Evidence View: Statistical / Probabilistic Metric

- Post WWII Initiatives due to unreliability of electronics and fatigue issues
  - Inspired by the weakest link, statistical process control, insurance and demographic mortality data analysis methods
  - Defined reliability on an item as the likelihood of failures based on life distribution models $\boxed{R(t) = Pr(T \geq t)}$
  - Systems analysis methods
    - Based on the topology of components of the system
    - Based on the logical connections of the components (fault trees, etc.)
- Common Assumptions
  - Use of historical failure data or reliability test data are the truth and every items have the same resistance to failure as the historical failures indicate
  - Maintenance and repair contribute to renewal of the item
  - Degradation trend can be measured by the hazard rate . In this case $R_i(t) = e^{-H(t)},\ \ where\ \mathrm{H(.)} = \mathrm{cumulative\ hazard, and\ h(.)} = \mathrm{hazard\ rate}$
- Issues
  - Results rarely match field experience

Physics-Based View of Reliability

– Failures occur due to failure mechanisms

– This view started in the 1960's and revived in the 1990's.

– Referred to physics-of-failure, time to failures are empirically modeled: $t_f = f(S_o, S_e, g, d_i, \vec{\boldsymbol{\theta}})$

S_o = Operational Stresses
S_e = Environmental Stresses
g = Geometry related factors
$\vec{\boldsymbol{\theta}}$ = material properties
d = defects, flaws, etc.

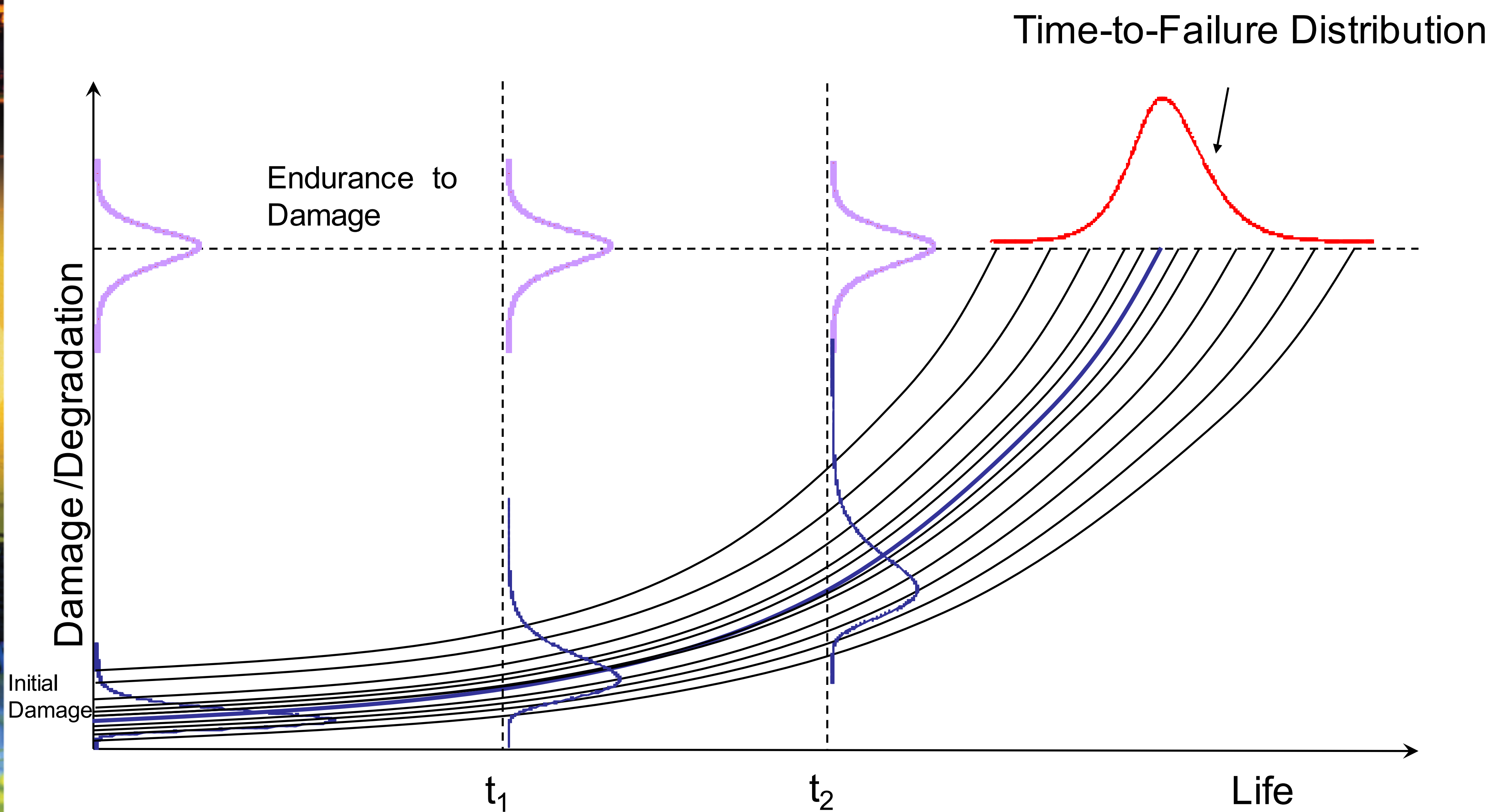
- Inspired by advances in fracture mechanics
- Accelerated life and degradation testing provide data
- Probabilistic empirical models of time to failure (PPoF models) developed and simulations

- **Benefits**
  - No or very little dependence on historical failure data
  - Easily connected to all physical models
  - Address the underlying causes of failure (failure mechanisms)
  - Specific to the items and the condition of operation of that item
- **Drawbacks**
  - Hard to model interacting failure mechanisms
  - Models markers of degradation not the total damage
  - Based of small experimental evidences and more on subjective judgments

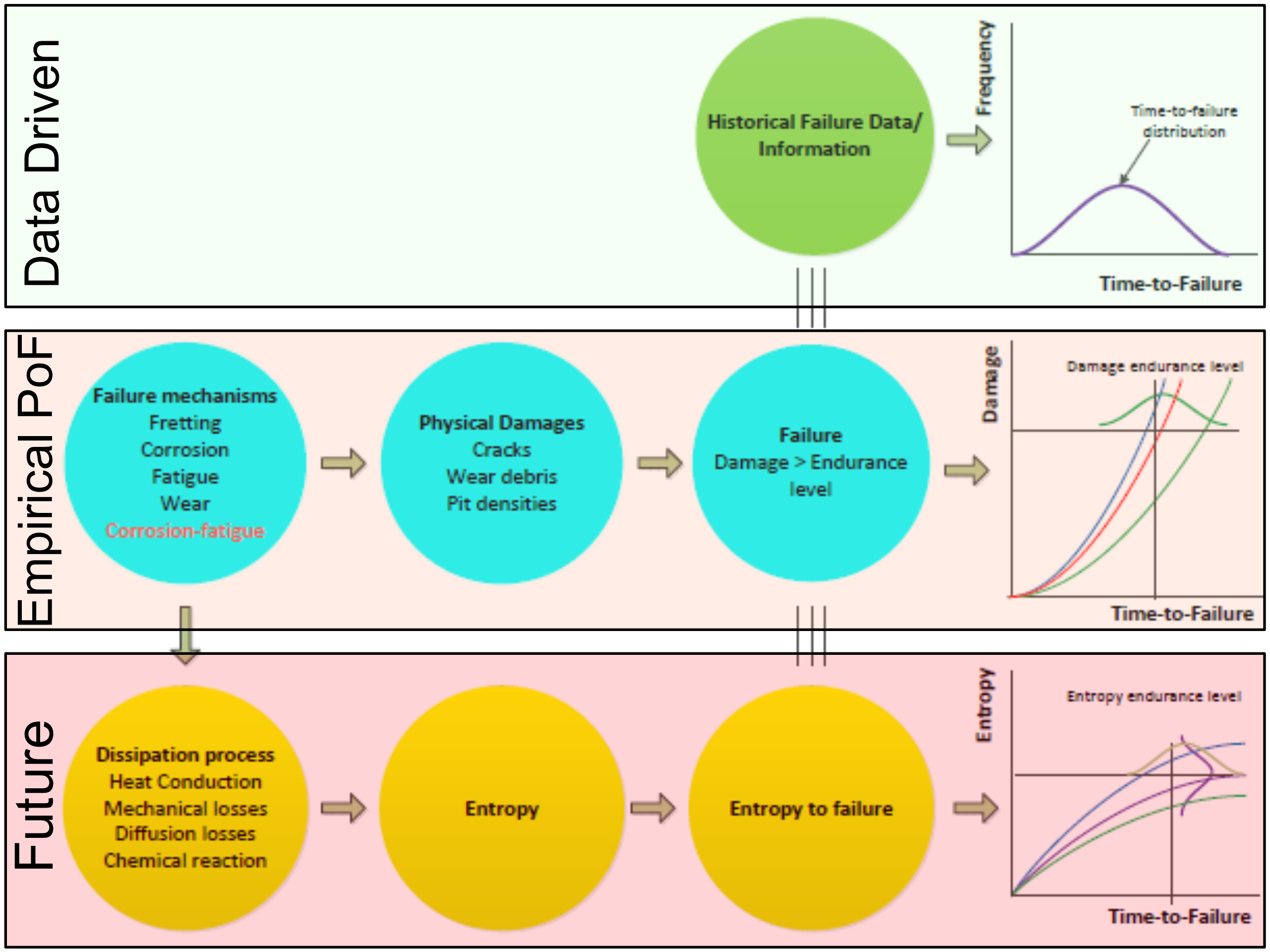
Physics-Based View (Cont.)

- Modern Areas of Research
  - Hybrid Models Combined Logic Models, Physical Models (PoF) and Probabilistic Models
    - Tremendous emphasis on
      - PHM methods in support of resilience, replacement, repair and maintenance
      - Reliability of autonomous systems and cyber-physical safety security
    - Applications of Data science
      - Sensors
      - Data / information fusion
      - Simulation tools (MCMC, Recursive Bayes and Bayesian filtering)
      - Machine learning
  - Search for fundamental sciences of reliability
    - Thermodynamics
    - Information theory
    - Statistical mechanics

Reliability Summary



Summary of Reliability Overview



Why Entropy?

- ✓ Entropy can model multiple competing degradation processes leading to damage
- ✓ Entropy is independent of the path to failure ending at similar total entropy at failure
- ✓ Entropy accounts for complex synergistic effects of interacting degradation processes
- ✓ Entropy is scale independent

- My Recent Research on Damage, Degradation and Failure

An Entropic Theory of Damage

- Failure mechanisms are irreversible processes leading to degradation and share a common feature at a deeper level: ***Dissipation of Energy***
- Dissipation (or equivalently entropy generation)≅Damage

Degradation mechanisms → Damage → Dissipation energies → Entropy generation

Failure[1] occurs when the accumulated total entropy generated exceeds the entropic-endurance of the unit

- Entropic-endurance describes the capacity of the unit to withstand entropy
- Entropic-endurance of identical units is equal
- Entropic-endurance of different units is different
- Entropic-endurance to failure can be measured (experimentally) and involves stochastic variability

1. Defined as the state or condition of not meeting a requirement, desirable behavior or intended function

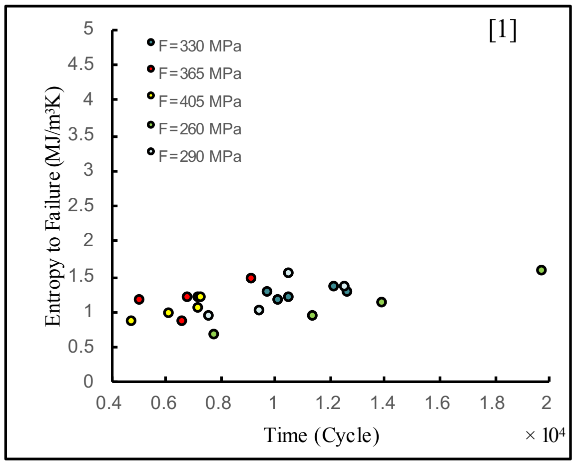
An Entropic Theory of Damage(Cont.)

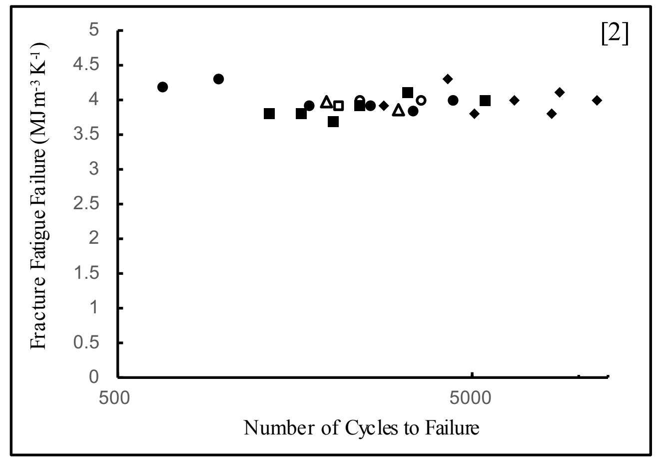
[1, 3,4]

$$\sigma = \underbrace{\frac{1}{T^2} J_q \cdot \nabla T}_{\text{Thermal}} - \underbrace{\sum_{k=1}^{n} \left(\nabla \frac{\mu_k}{T}\right)}_{\text{Diffusion}} + \underbrace{\frac{1}{T} \tau : \dot{\epsilon}_p}_{\text{Mechanical}} + \underbrace{\frac{1}{T} \sum_{j=1}^{r} v_j A_j}_{\text{Chemical}} + \underbrace{\frac{1}{T} \sum_{m=1}^{h} c_m J_m (-\nabla \psi)}_{\text{External field energy}}$$

$$\sigma = \sum_{i=1}^{m} X_i J_i$$

Product of thermodynamic forces and fluxes





[1] Anahita Imanian and Mohammad Modarres, A Thermodynamic Entropy Approach to Reliability Assessment with Application to Corrosion Fatigue, Entropy 17.10 (2015): 6995-7020

[2] M. Naderi et al., On the Thermodynamic Entropy of Fatigue Fracture, Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 466.2114 (2009): 1-16

[3] D. Kondepudi and I. Prigogine, *"Modern Thermodynamics: From Heat Engines to Dissipative Structures,"* Wiley, England, 1998.

[4] J. Lemaitre and J. L. Chaboche, "*Mechanics of Solid Materials,*" 3rd edition; Cambridge University Press: Cambridge, UK, 2000.

$\boldsymbol{J}_n$ $(n = q, k, and\ m)$ = thermodynamic fluxes due to heat conduction, diffusion and external fields, T = temperature, μ_k = chemical potential, v_i = chemical reaction rate, $\boldsymbol{\tau}$ = stress tensor, $\dot{\epsilon_p}$ = plastic strain rate, A_j = chemical affinity, ψ = potential of the external field , and c_m = coupling constant [3, 4].

Entropy as an Index of Damage

- The evolution trend of the damage, D, according to our theory is dominated by the entropy generated:

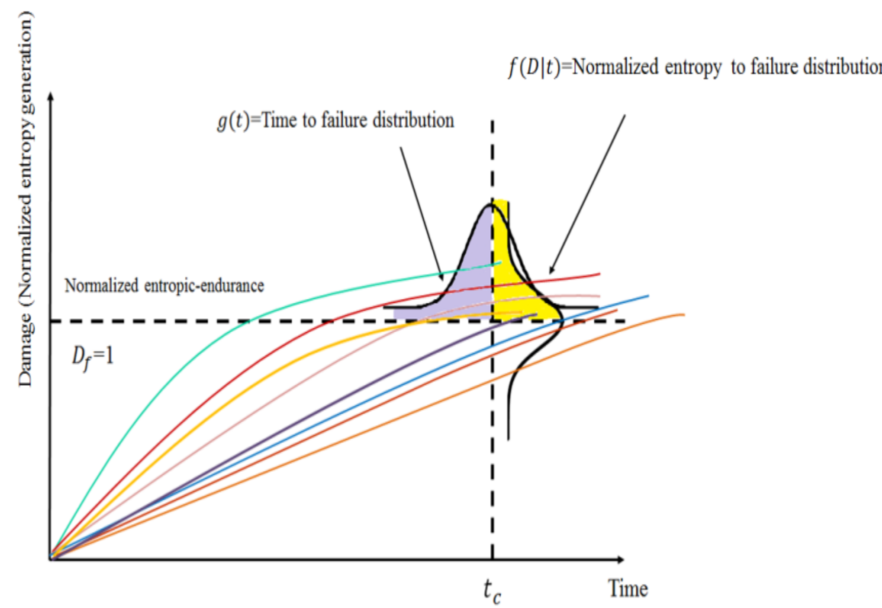
$$D \sim \gamma_d | t \sim \int_0^t [\sigma | X_i(u), \boldsymbol{J}_i(u)] du$$

$$D = \frac{\gamma_d - \gamma_{d_0}}{\gamma_{d_E} - \gamma_{d_0}} ,$$

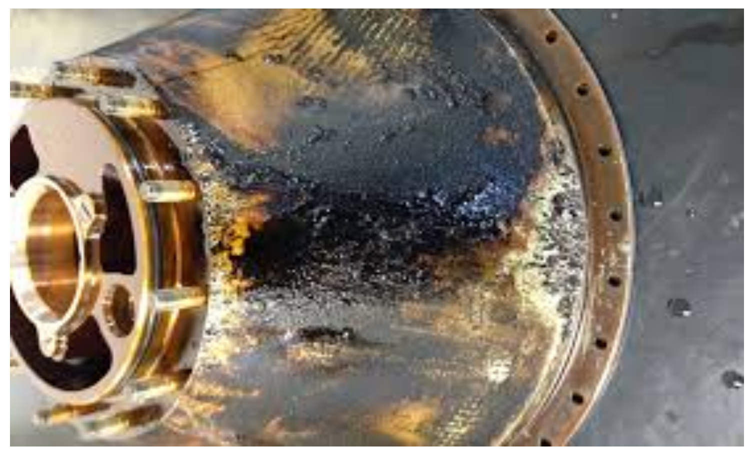
$\gamma=\rho s$ *volumetric entropy generation*

- The reliability expressed in terms of entropic damage :

$$R(t) = \int_{t_c}^{\infty} g(t)\, dt = 1 - \int_{D_f}^{\infty} f(D|t) dD$$



Reliability of Structures Subject to Corrosion-Fatigue (CF)



Entropy Generation in CF

- Contribution from corrosion activation over-potential, diffusion over-potential, corrosion reaction chemical potential, plastic and elastic deformation and hydrogen embrittlement to the rate of entropy generation:

$$
\begin{aligned}
\sigma = &\frac{1}{T}\left(\boldsymbol{J}_{M,a} z_M F E_{M_{act,a}} + \boldsymbol{J}_{M,c} z_M F E_{M_{act,c}} + \boldsymbol{J}_{O,a} z_O F E_{O_{act,a}} + \boldsymbol{J}_{O,c} z_O F E_{O_{act,c}}\right) \\
&+ \frac{1}{T}\left(\boldsymbol{J}_{M,c} z_M F E_{M_{conc,c}} + z_O F \boldsymbol{J}_{O,c} E_{O_{conc,c}}\right) \\
&+ \frac{1}{T}\left(\boldsymbol{J}_{M,a} \alpha_M A_M + J_{M,c}(1-\alpha_M) A_M + \boldsymbol{J}_{O,a} \alpha_O A_O + \boldsymbol{J}_{M,a}(1-\alpha_O) A_O\right) \\
&+ \frac{1}{T}\dot{\boldsymbol{\epsilon}}_p : \boldsymbol{\tau} + \frac{1}{T} Y \dot{\boldsymbol{D}} \\
&+ \sigma_H
\end{aligned}
$$

Diffusion dissipations

Chemical reaction dissipations

Mechanical dissipations

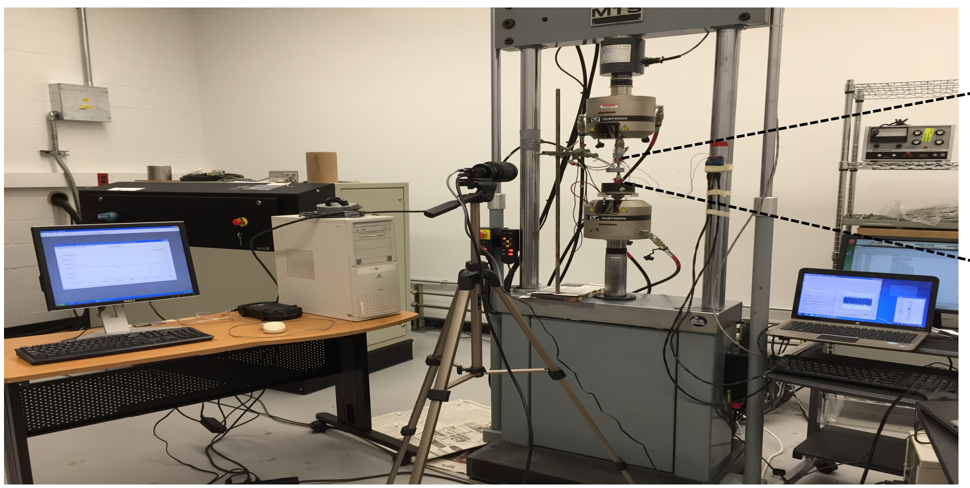
Hydrogen embrittlement dissipation

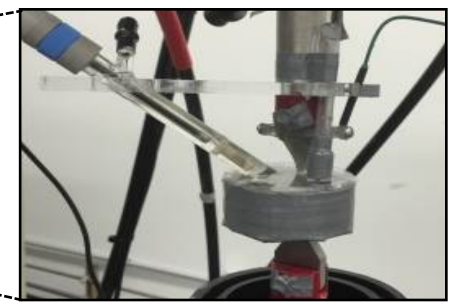
T = temperature, z_M =number of moles of electrons exchanged in the oxidation process, F =Farady number, $J_{M,a}$ and $J_{M,c}$ = irreversible anodic and cathodic activation currents for oxidation reaction, $J_{O,a}$ and $J_{O,c}$ =anodic and cathodic activation currents for reduction reaction, $E_{M_{act,a}}$ and $E_{M_{act,c}}$ =anodic and cathodic over-potentials for oxidation reaction, $E_{O_{act,a}}$ and $E_{O_{act,c}}$ =anodic and cathodic over-potentials for reduction reaction, $E_{M_{conc,c}}$ and $E_{O_{conc,c}}$ =concentration over-potentials for the cathodic oxidation and cathodic reduction reactions, α_M and α_O =charge transport coefficient for the oxidation and reduction reactions, A_M and A_O = chemical affinity for the oxidation and reductions, $\dot{\epsilon}_p$ =plastic deformation rate, τ =plastic stress, $\dot{D}$ =dimensionless damage flux, Y the elastic energy, and σ_H =entropy generation due to hydrogen embrittlement.

[1] Imanian, A. and Modarres. M, "*A Thermodynamic Entropy Based Approach for Prognosis and Health Management with Application to Corrosion-Fatigue*," 2015 IEEE International Conference on Prognostics and Health Management, 22-25 June, 2015, Austin, USA.

CF Experimental Set up

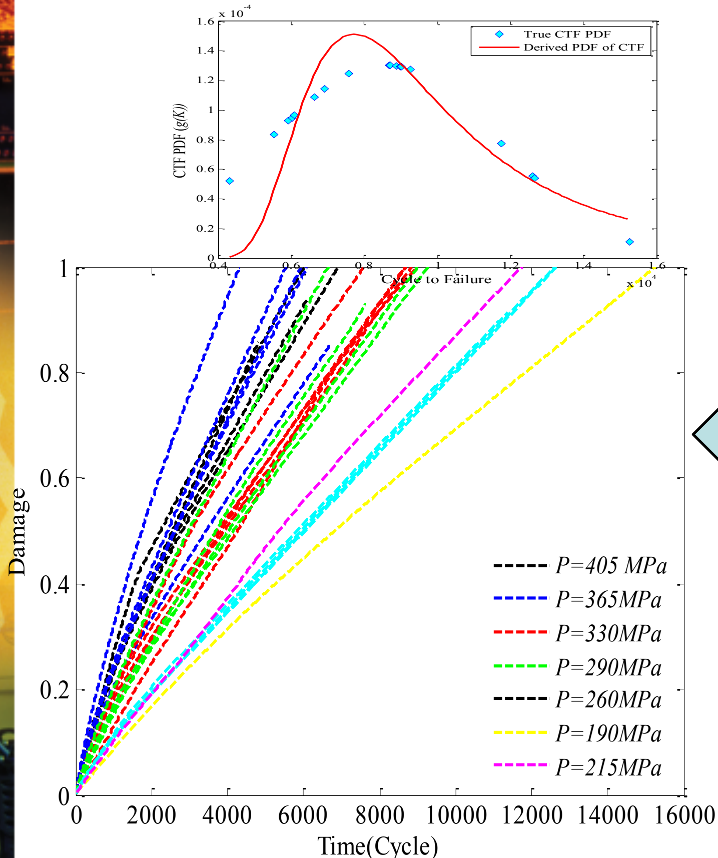
- Fatigue tests of Al 7075-T651 performed in 3.5% wt. NaCl aqueous solution acidified with a 1 molar solution of HCl, with the pH of about 3, under axial load controlled and free corrosion potential
- Specimens electrochemically monitored via a potentiostat using Ag/AgCl reference electrode maintained at a constant distance (2 mm) from the specimen, a platinum counter electrode, and specimen as the working electrode
- Digital image correlation (DIC) technique used to measure strain

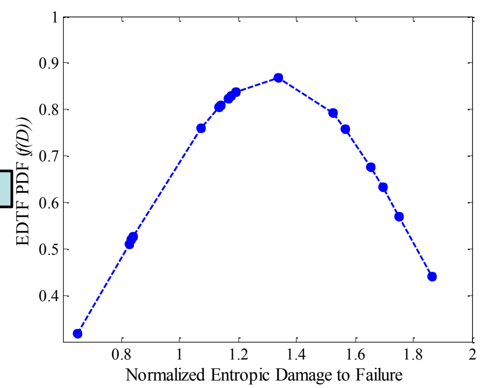




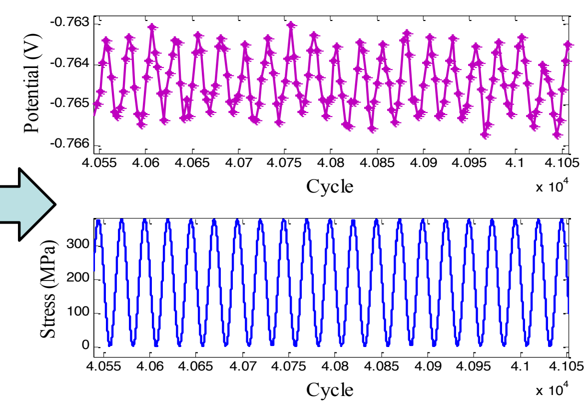
Electrochemical corrosion cell made of plexiglass

Entropic-Based Reliability Results for CF





- In a mechano-chemical effect in CF, an enhanced anodic dissolution flux is induced by the dynamic surface deformation



1. Imanian, A. and Modarres, M, “A Thermodynamic Entropy Approach to Reliability Assessment with Applications to Corrosion-Fatigue”, vol., 17. 10, 6995-7020, **Journal of Entropy**.

Statistical Mechanics Entropy Measure of Damage

- **First law of thermodynamics**

Internal energy — Flow of energy into the system — Applied work on the system

$$\Delta U = Q + W$$

by the work protocol

$$U_B - U_A = Q + W$$

- **From Helmholtz free energy**

$$F = U - ST \;\rightarrow\; \Delta F = F_B - F_A = U_B - U_A - (S_B - S_A)T$$

$$\Delta F = \Delta U - T\Delta S \;\rightarrow\; \Delta F = W + Q - T\Delta S$$

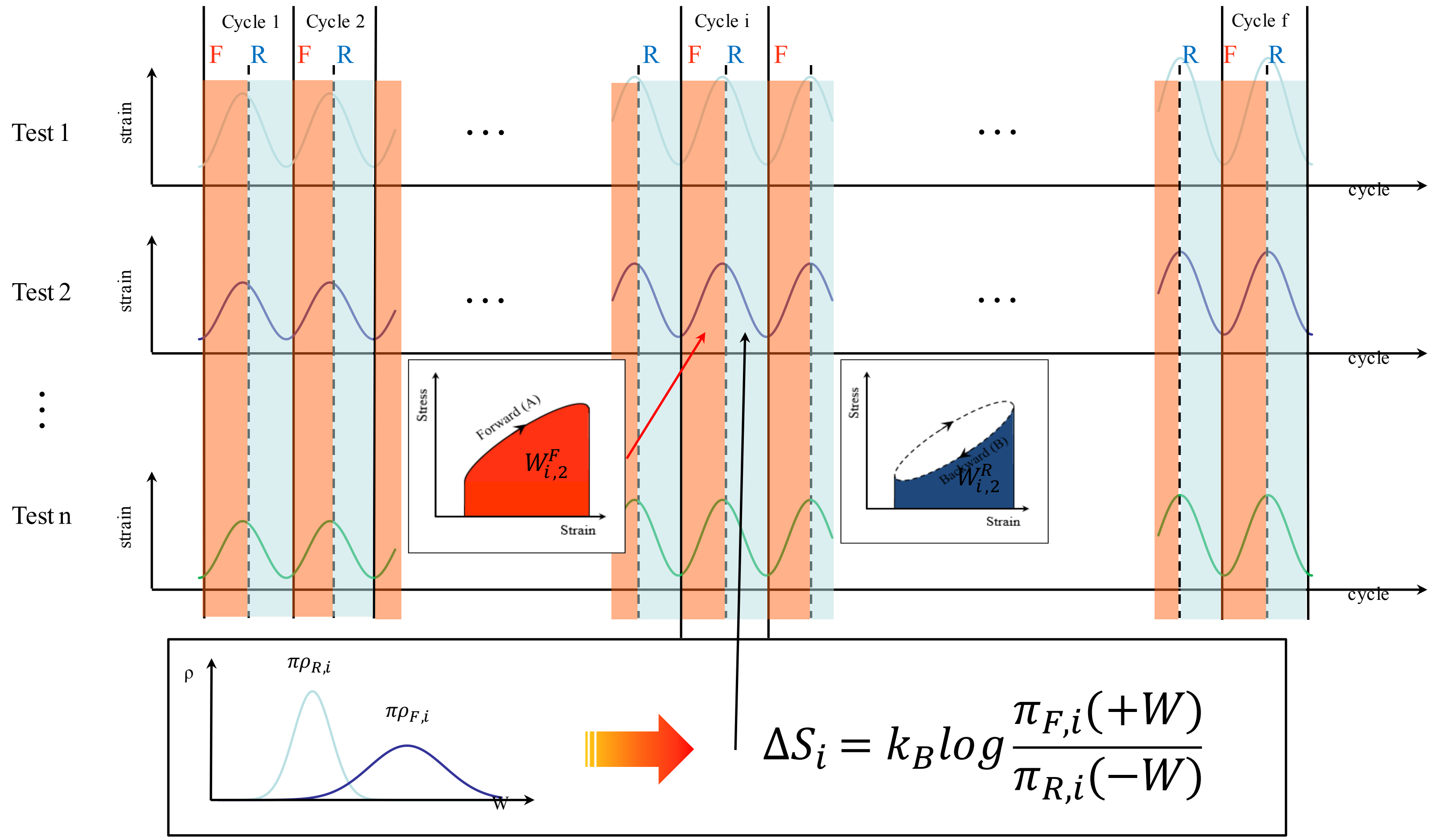
$$\boxed{\frac{W-\Delta F}{T} = \Delta S - \frac{Q}{T} = \Delta S_{tot}}$$

$$\boxed{\frac{\pi_F(+W)}{\pi_R(-W)} = e^{\frac{W-\Delta F}{k_B T}}} \text{ [1,2]}$$

$$\boxed{\Delta S_{total} = k_B \log \frac{\pi_F(+W)}{\pi_R(-W)}}$$

[1] Crooks, Gavin E. "Entropy production fluctuation theorem and the nonequilibrium work relation for free energy differences." *Physical Review E* 60.3 (1999): 2721.
[2] Jarzynski, C., Nonequilibrium Equality for Free Energy Differences, Phys. Rev. Lett. (1997), 78, 2690-2693.

Entropy Computation in Fatigue Degradation / Damage



$$\Delta S_i = k_B log \frac{\pi_{F,i}(+W)}{\pi_{R,i}(-W)}$$

Information Entropy: Acoustic Emission As a Damage Signal

- Discrete approaches

Acoustic emission waveforms

↓

Histogram of the AE signals

↓

Calculation of p_i each waveform

↓

Probability distribution (p_i)

↓

Shannon Entropy

$$S_E = -\sum_{i=1}^{n} p_i \, log_2(p_i)$$

- Parametric approach

Acoustic emission waveforms

↓

Assigning a set of trial probability density function to the acoustic waveform

↓

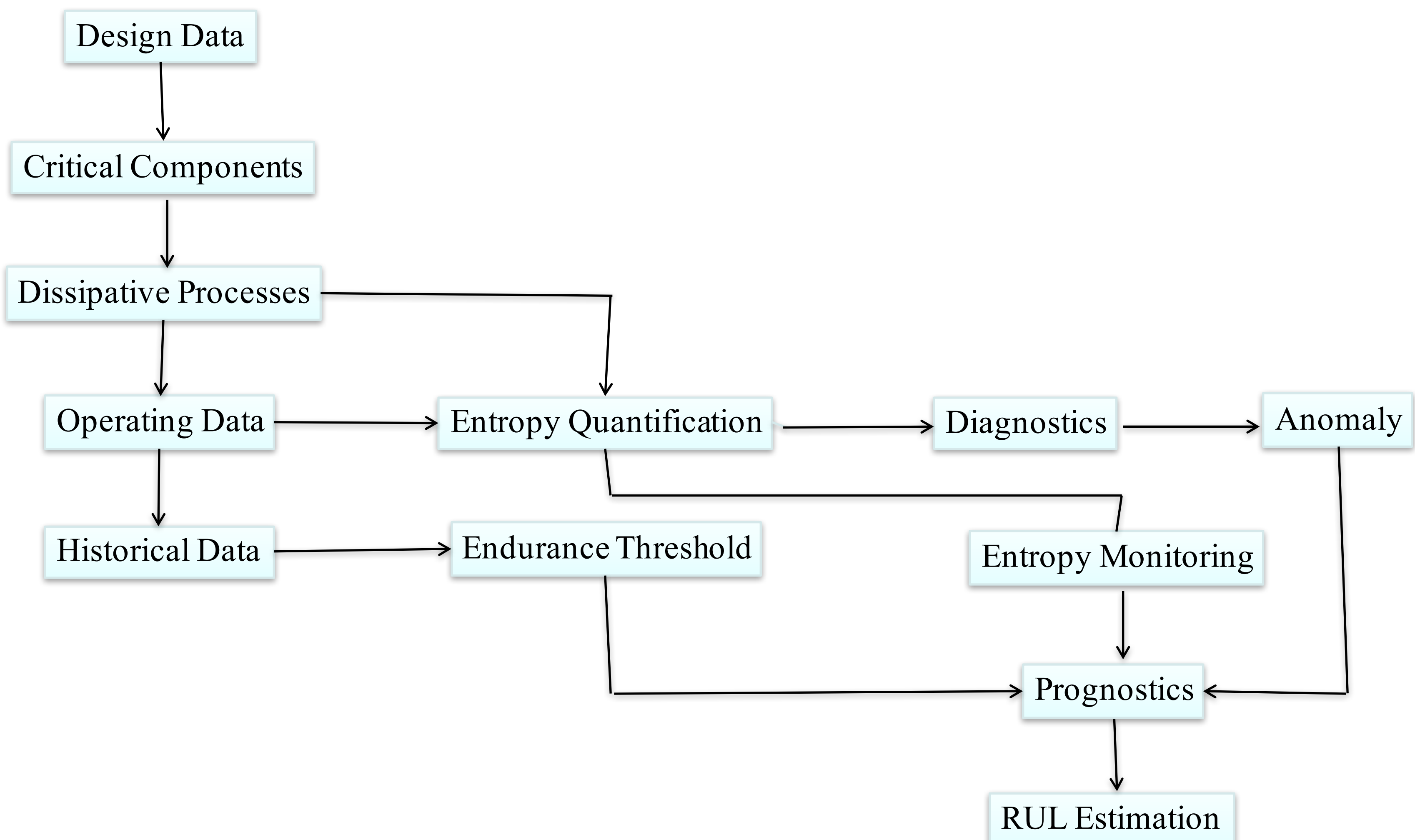
Model selection based on the Maximum Entropy obtained

↓

Shannon Entropy

$$S = -\int_{-\infty}^{+\infty} f(x)\log[f(x)]dx$$

Entropic-based PHM Framework

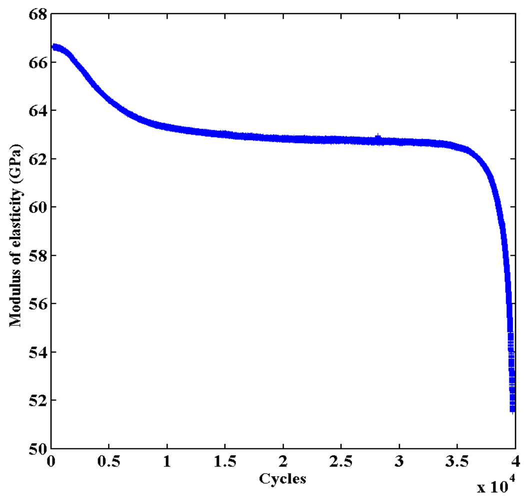


Intersection of Data Science and Reliability: PHM Applications

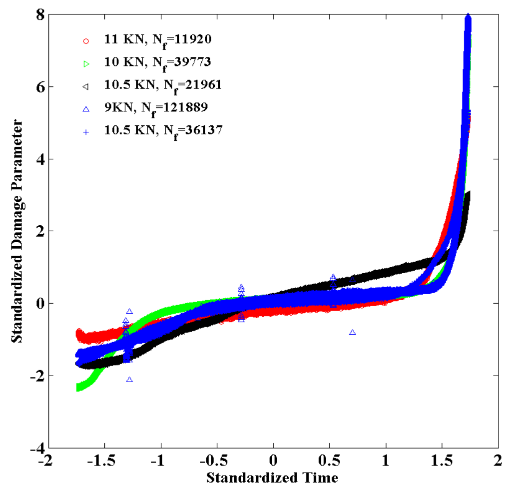
– Damage Precursors: Any recognizable variation of materials/physical properties influenced by the evolution of the hidden/ inaccessible/ unmeasurable damage during the degradation process
– Heterogeneous Big Data / Information Sources
  - Online and Offline Sensor Values
  - Human Inspections
  - Physical Model Predictions / Simulations

Information Entropy: Parametric Results

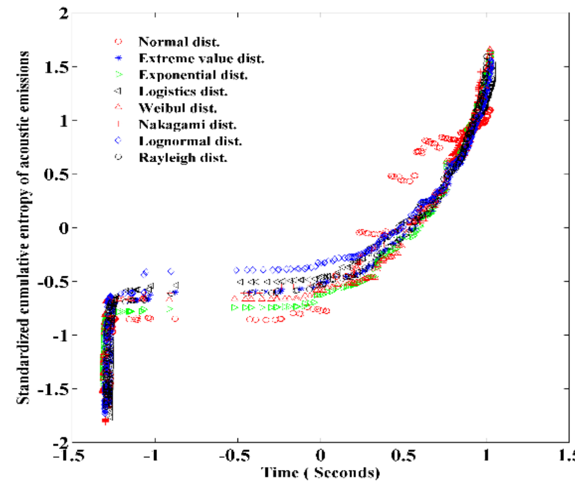
Trend of Degradation of the modulus of elasticity in the course of the fatigue



Damage parameter based on the degradation of the modulus of elasticity

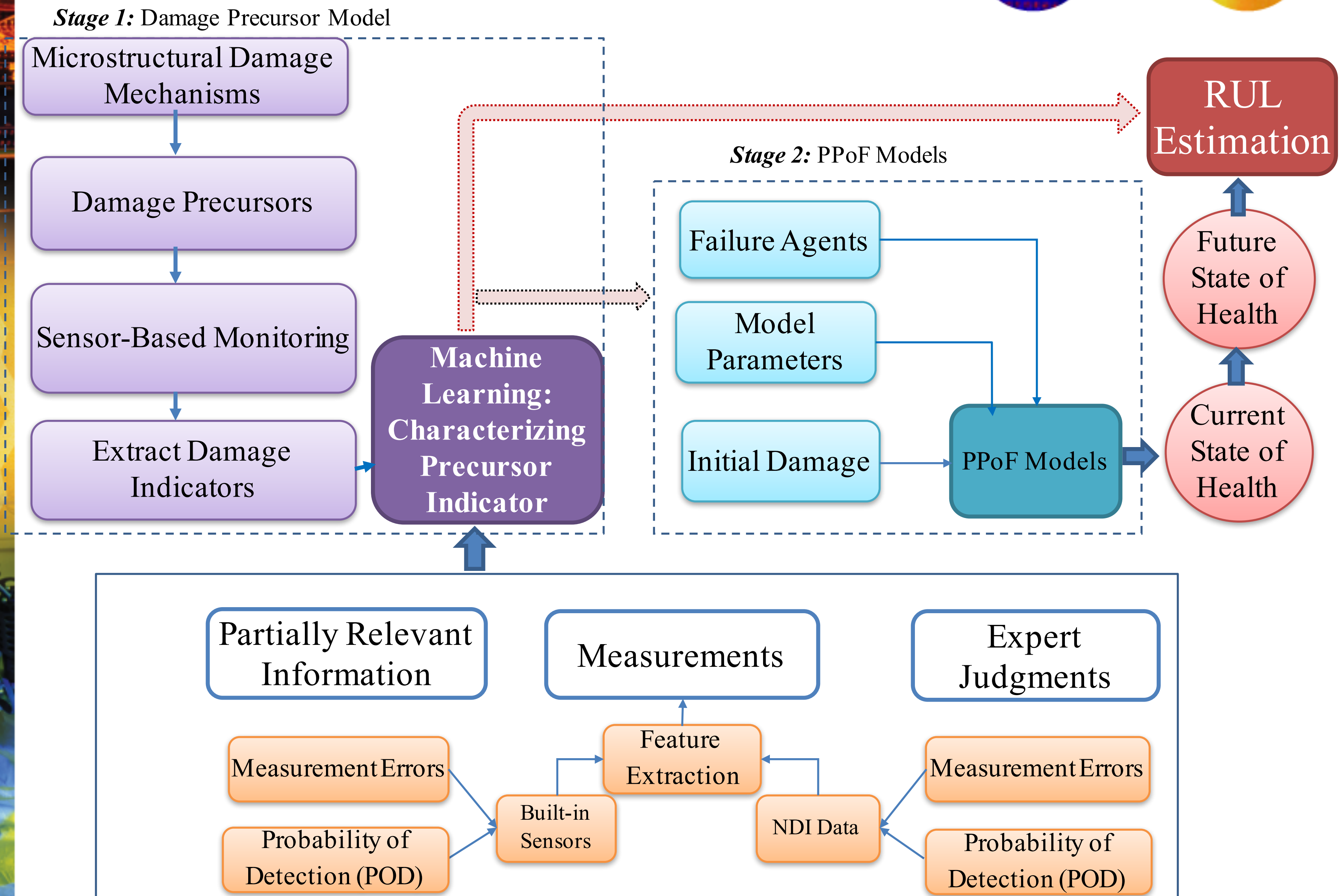


Trend of evolution of the cumulative entropy of the acoustic signals (parametric approach)



The acoustic entropy evolution trend reveals the trend of evolution of the fatigue damage

A Two-Stage Hybrid-Model PHM Approach



Conclusions

- Reliability engineering traditionally relied on historical evidences of failures which provide limited and often inaccurate perspective on aging
- Physics of failure and simulation methods offer improvement in reliability assessment, but the models are judgmental or at based on limited empirical evidence.
- Entropic damage provides a more fundamental approach to degradation, damage and aging assessment in reliability engineering
- Applications to reliability and PHM are explored
- The proposed theory offers a consistent framework to account for the underlying dissipative processes
- Entropic fatigue and corrosion-fatigue degradation model experimentally studied and supported the proposed theory
- Expansions to statistical mechanics definition of entropy and applications to the information theory is underway
- Applications of the entropic-damage in reliability assessment in PHM is promising

Thank you for your attention!

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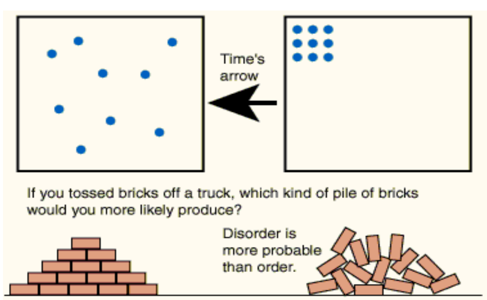
Literature: Entropy for Damage Characterization

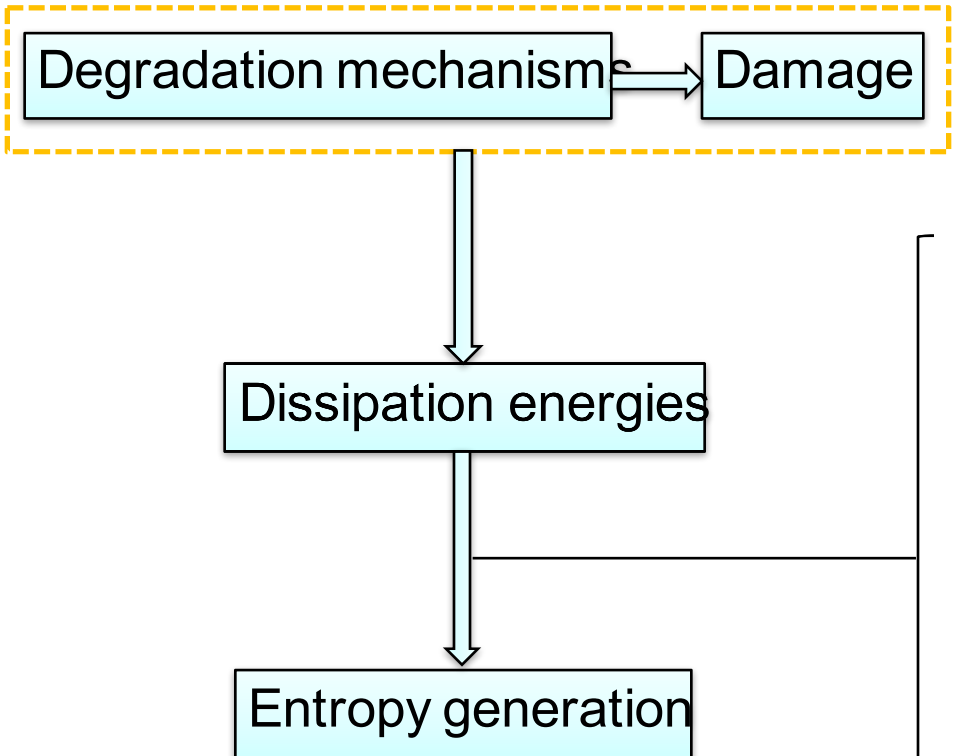
Entropy $\boxed{S = K_B \ln W}$ Damage

Entropy for damage characterization

- **Statistical mechanics microscopic interpretation**
  - Basaran et al. (1998, 2002, 2004, 2007)
  - Tucker et al. (2012)
  - Chen et al. (2012)
  - Temfeck et al. (2015)
- **Macroscopic interpretation within the second law of thermodynamics**
  - Feinberg and Widom (1996, 2000)
  - Bryant et al.(2008)



Entropy Generation for Damage Characterization



- Fatigue
  - Whaley et al. (1983)
  - Ital'yantsev (1984)
  - Naderi et al. (2010)
  - Amiri et al. (2012)
  - Ontiveros (2013)
- Wear
  - Klamecki et al. (1984)
  - Doelling (2000)
- Corrosion
  - Gutman (1998)

Examples of Thermodynamic Forces and Fluxes

Primary mechanism	Thermodynamic force, X	Thermodynamic flow, J	Examples
Heat conduction	Temperature gradient, $\nabla(1/T)$	Heat flux, q	Fatigue, creep, wear
Plastic deformation of solids	Stress, τ/T	Plastic strain, $\dot{\epsilon}_p$	Fatigue, creep, wear
Chemical reaction	Reaction affinity, A_k/T	Reaction rate, ν_k	Corrosion, wear
Mass diffusion	Chemical potential, $-\nabla(\frac{\mu_k}{T})$	Diffusion flux, j_k	Wear, creep
Electrochemical reaction	Electrochemical potential, $\tilde{A}/T$	Corrosion current density, i_{corr}	Corrosion
Irradiation	Particle flux density, A_r/T	Velocity of target atoms after collision, $\dot{v}_r$	Irradiation damage
Annihilation of lattice sites	Creep driving force, $(\tau - \omega_I)/T$	Creep deformation rate, R	Creep