Entropic Damage: A New Physics-of-Failure and Prognosis Perspective

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Presented at
Mechanical Engineering Department
University of Chile
Santiago, Chile
30 March 3017

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Acknowledgments

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9. Prof. Mohammad Modarres (PI)

Funding and oversight:

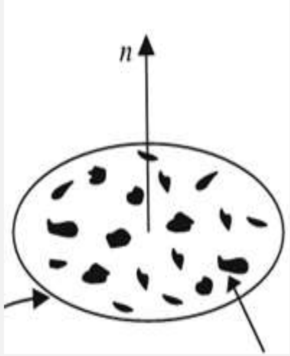
Office of Naval Research

Objectives

- Describe damage resulted from failure mechanisms within the irreversible thermodynamics framework
- Improve understanding of the coupled failure mechanisms
- Develop an example: entropic corrosion-fatigue damage model including confirmatory tests
- Define reliability in the context of the 2nd law of thermodynamics
- Extend the framework to statistical mechanics and information theory definitions of entropy
- Search for applications to Prognosis and Health Management (PHM) of structures

Motivation

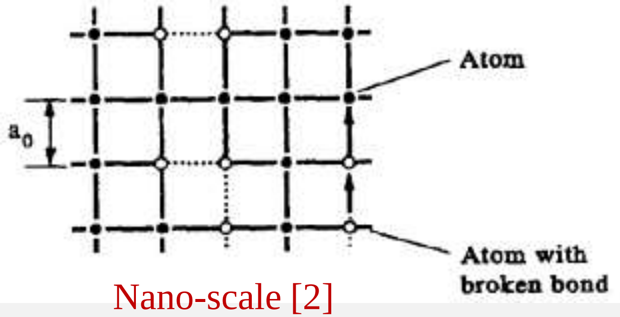
- Common definitions of damage are based on observable markers of damage which vary at different geometries and scales
  - Macroscopic Markers of Damage (e.g. crack size, pit densities, weight loss)
  - Example: Macroscopic Fatigues Markers include: crack length, reduction of modulus, reduction of load carrying capacity
  - Issue: When markers of damage observed 80%-90% of life has been expended



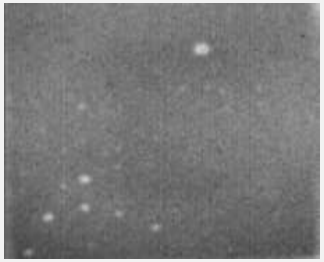
$$D(\mathbf{n}) = \frac{A_0 - A_e}{A_0}$$

Continuum damage mechanics [1]

Micro-scale



Nano-scale [2]

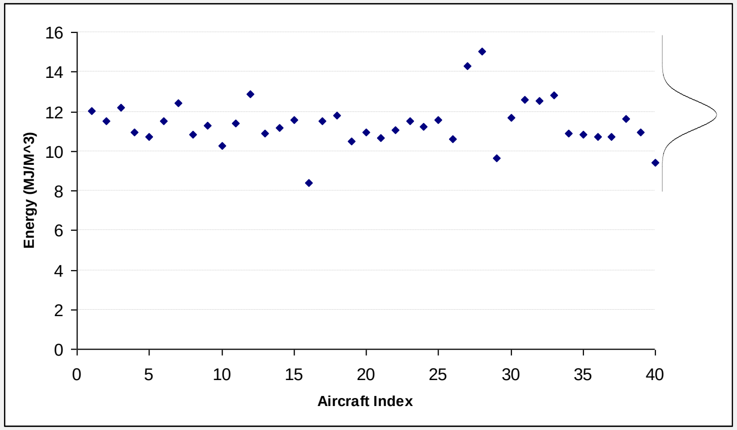


Meso-scale

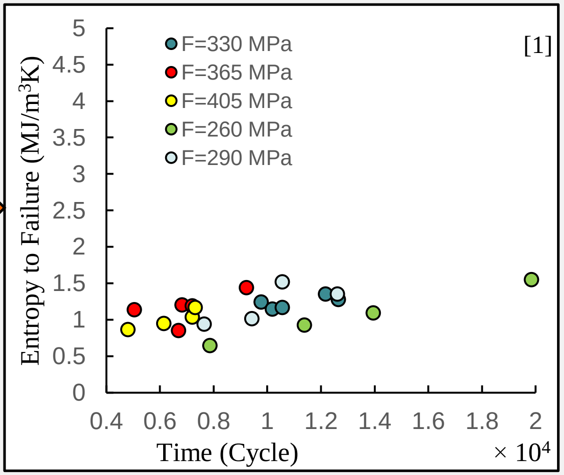
[1] J. Lemaitre, "*A Course on Damage Mechanics*", Springer, France, 1996.
[2] C. Woo & D. Li, "*A Universal Physically Consistent Definition of Material Damage",* Int. J. Solids Structure, V30, 1993

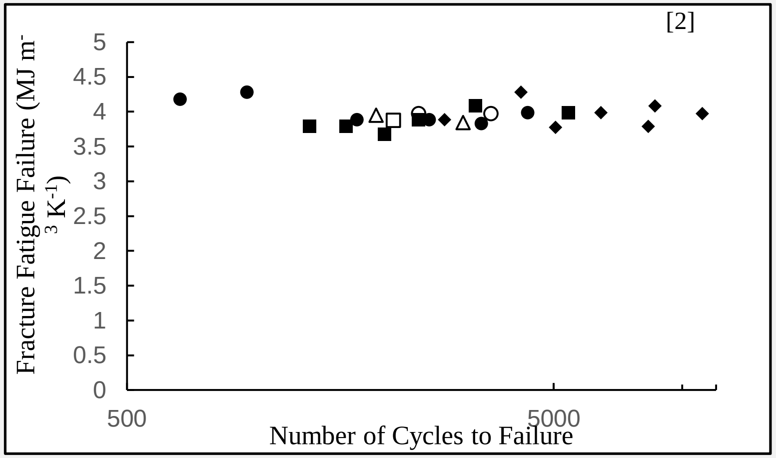
Motivation (Cont.)

Total Strain Energy Expended in 40 P-3 Aircraft with vastly Different Loading Histories when the Miner's Cumulative Damage Reaches 0.5



Entropy to crack initiation





Entropy to Fracture

[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

Thermodynamics Approach to Damage

Second Law of Thermodynamics: In an isolated system, entropy will always increase until it reaches a maximum value.

Second Law of Thermodynamics (Statistical Mechanics Version): In an isolated system, the system will always progress to a macrostate that corresponds to the maximum number of microstates.

All damages resulting from failure mechanisms share a common feature: Dissipation of Energy.

Dissipation: a fundamental determinant of irreversibility can be described well within the context of non-equilibrium thermodynamics.

Approaches to derive and quantify entropy

Entropy

Statistical mechanics

$S = K_B \ln W$

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

Classical Thermodynamics and Continuum mechanics

$$\sigma = \frac{1}{T^2}\boldsymbol{J}_q . \nabla T - \Sigma_{k=1}^{n}\boldsymbol{J}_k\left(\nabla\frac{\mu_k}{T}\right) + \frac{1}{T}\boldsymbol{\tau}{:}\,\dot{\boldsymbol{\epsilon}}_p + \frac{1}{T}\Sigma_{j=1}^{r} v_j\, A_j + \frac{1}{T}\Sigma_{m=1}^{h} c_m \boldsymbol{J}_m(-\nabla\psi)$$

Information Theory

$S = \sum p_i \log p_i$

Approaches to derive and quantify entropy

Entropy

Statistical mechanics

- Obtained by repetition of the experiments of the same conditions to form the distribution of the work
- Performed on the same sample in the forward and backward protocol

Classical Thermodynamics and continuum mechanics

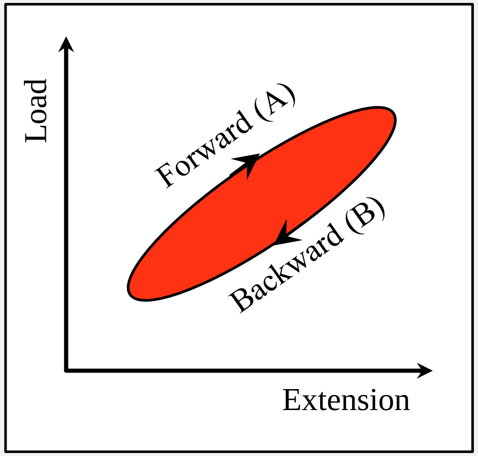
- Obtained by measurement of the thermodynamic forces and fluxes for a specific problem.
- The forces and fluxes are defined according to the physics of the problem

Information Theory

- Applied to acoustic dissipation of the materials by signal processing of the acoustic emission signals
- Its relation to thermodynamic entropy is on debate for a long time

Thermodynamic entropy

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



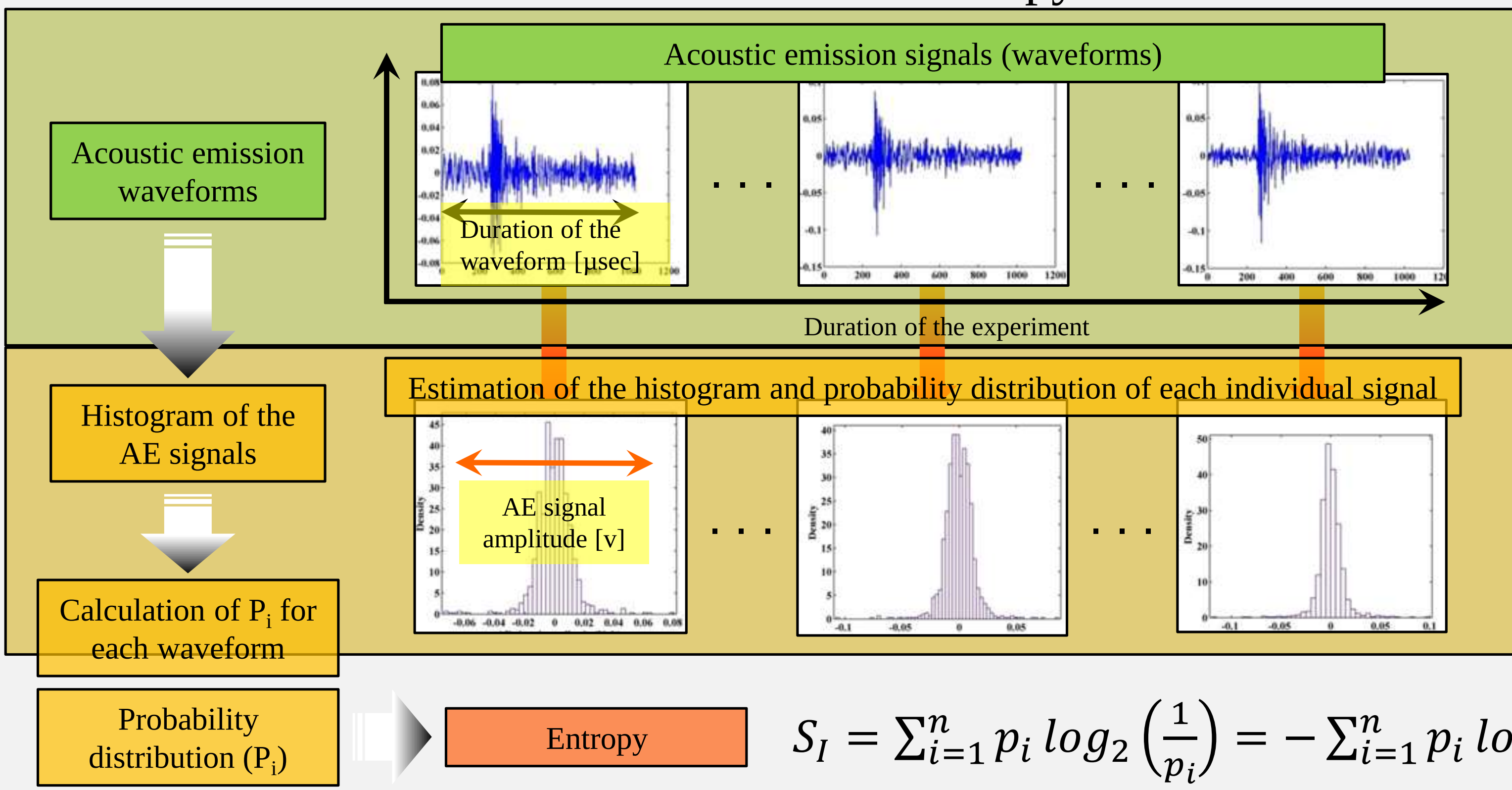
$$\Delta S_{total} = \frac{W^{diss}}{T} = \frac{Hysteresis\ Area}{T}$$

Hysteresis Area: From load-extension analysis
T: From surface temperature measured by infrared camera

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

Information Entropy

- Acoustic emission waveform information entropy



[2]

$$S_I = \sum_{i=1}^{n} p_i \, log_2\left(\frac{1}{p_i}\right) = -\sum_{i=1}^{n} p_i \, log_2(p_i)$$

[2] Ali Kahirdeh et al., Acoustic Emission Entropy as a Measure of Damage in Materials, Bayesian Inference and Maximum Entropy Methods in Science and Engineering AIP Conf. Proc. 1757 (2016): 060007-1-7

Approaches to Estimate from AE Signals

- 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

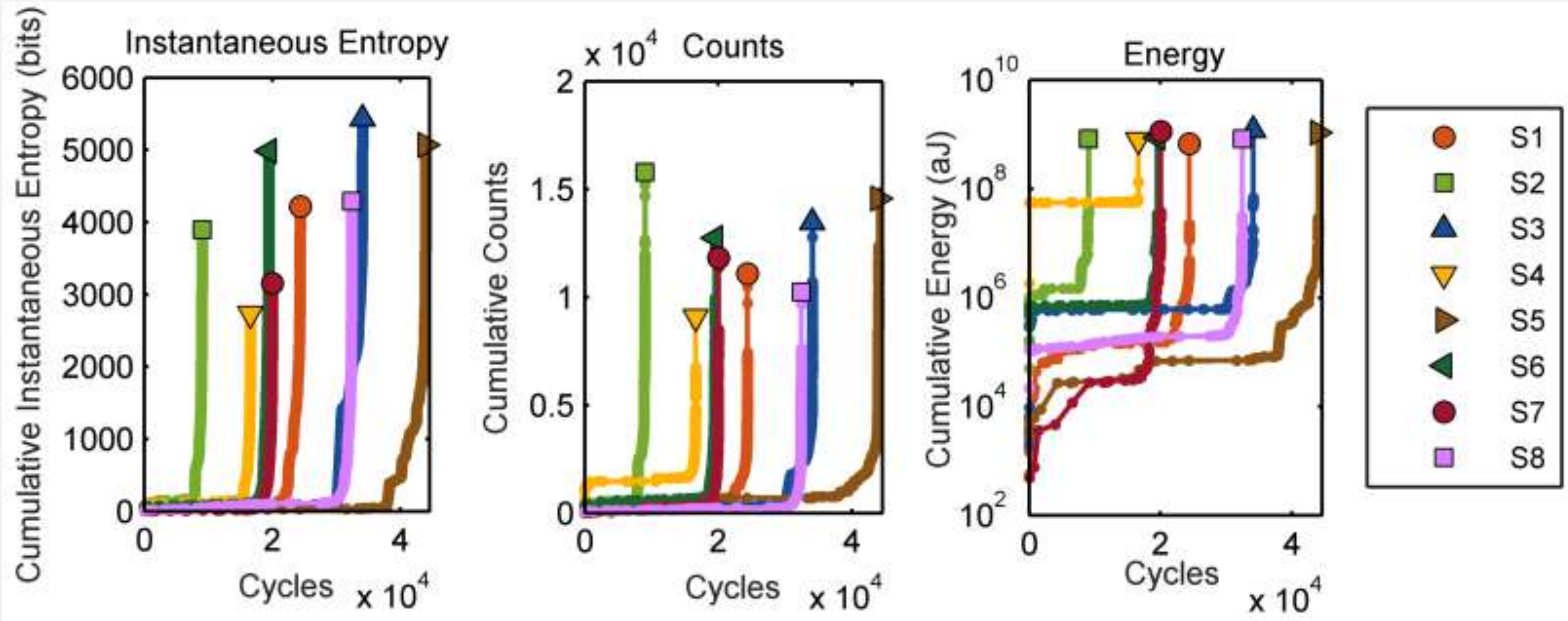
↓

Shannon Entropy

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

► **Includes feature, updated, relative, and Bayesian entropy approaches**

Information Entropy

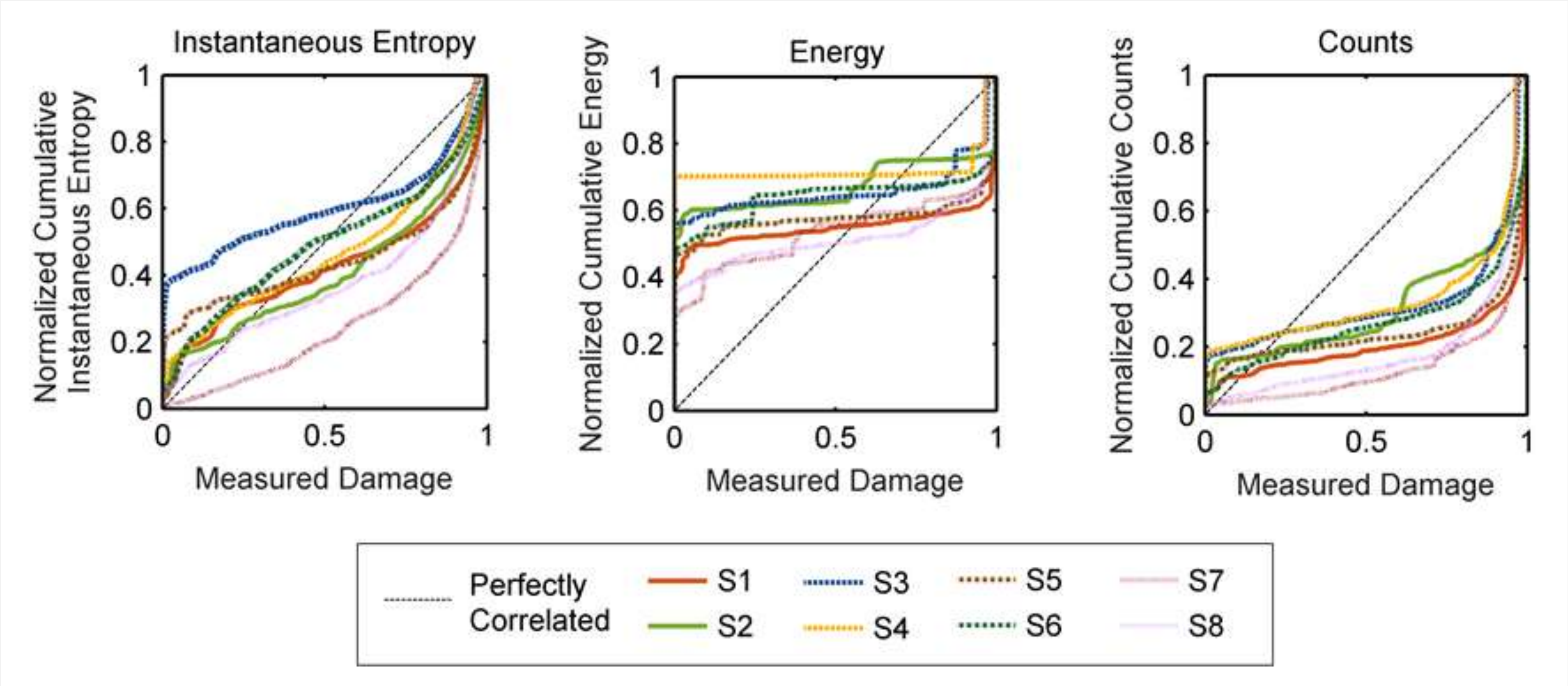


(a) (b) (c)

Figure 5. Cumulative trend for 3 parameters versus fatigue cycles: (**a**) Cumulative instantaneous entropy; (**b**) Cumulative counts; (**c**) Cumulative energy.

Sauerbrunn, Christine Marie. Evaluation of Information Entropy from Acoustic Emission Waveforms as a Fatigue Damage Metric for Al7075-T6. Diss. 2016.

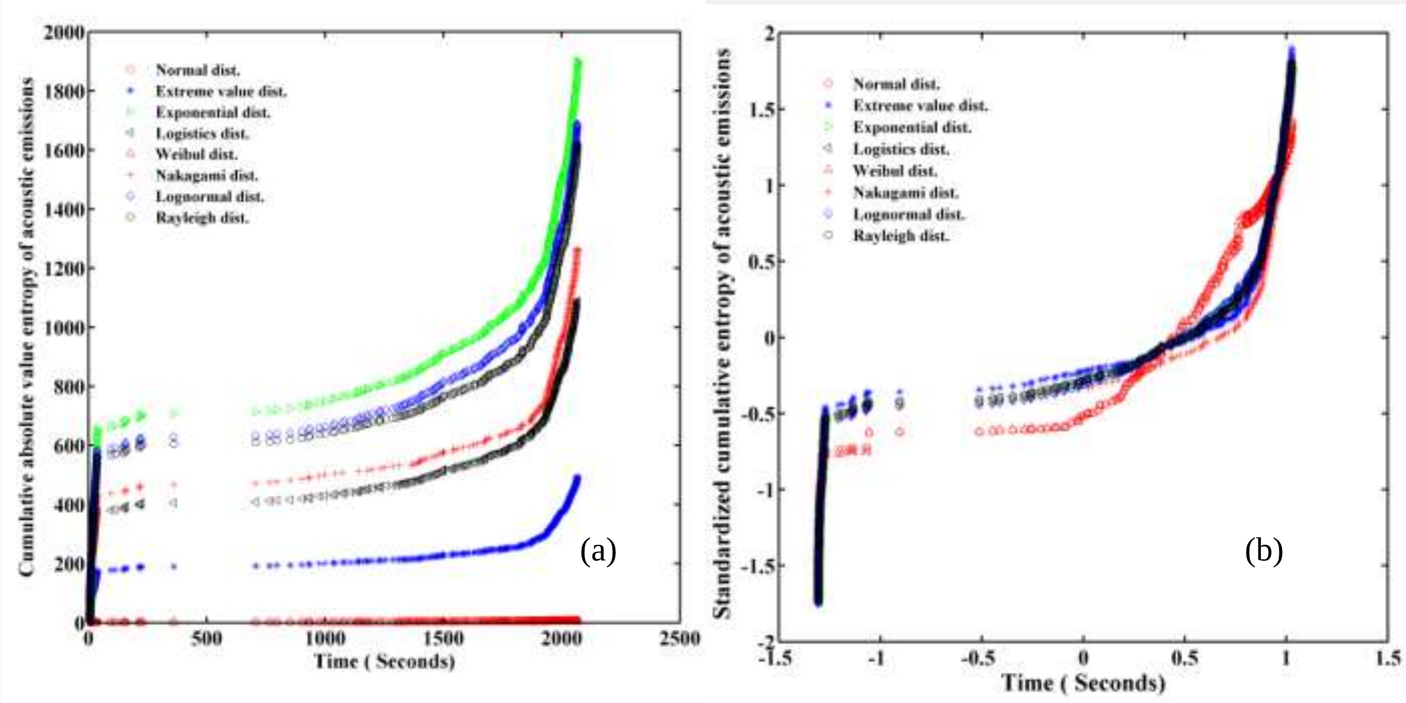
Information Entropy of acoustic signals



Normalized cumulative trend for 3 parameters with respect to measured damage where a one-to-one relationship is desired: (a) Instantaneous entropy; (b) Counts; (c) Energy.

Sauerbrunn, Christine Marie. *Evaluation of Information Entropy from Acoustic Emission Waveforms as a Fatigue Damage Metric for Al7075-T6*. Diss. 2016.

Information Entropy (Shannon Entropy) of acoustic signals

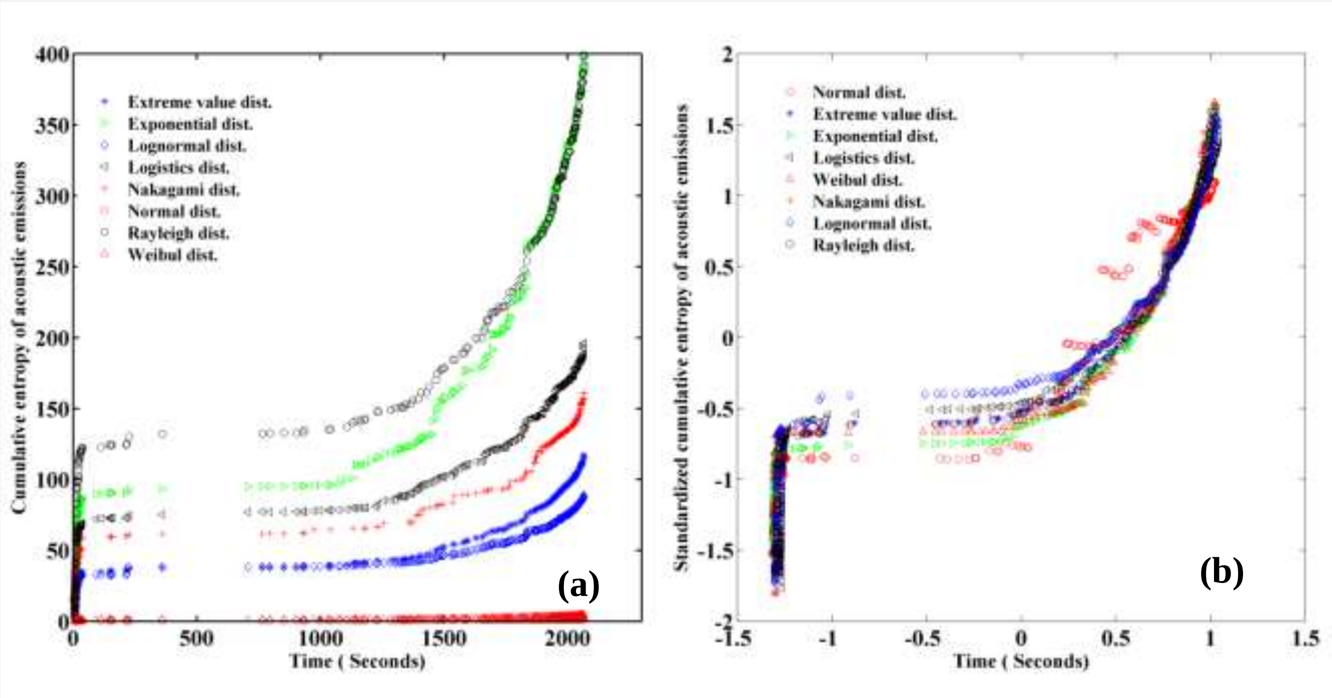


$$I[p(x)] = -k_B \int p(x) \log p(x) \, dx$$

A) The absolute value of the estimated acoustic emission information entropy. B), The standardized cumulative acoustic emission entropy where the eight graphs related to eight trial probability density function are plotted.

A Parametric Approach to Acoustic Entropy Estimation for Assessment of Fatigue Damage,
A. Kahirdeh, C. Sauerbrunn, H. Yun, M. Modarres, International Journal of Fatigue (Submitted, 2017).

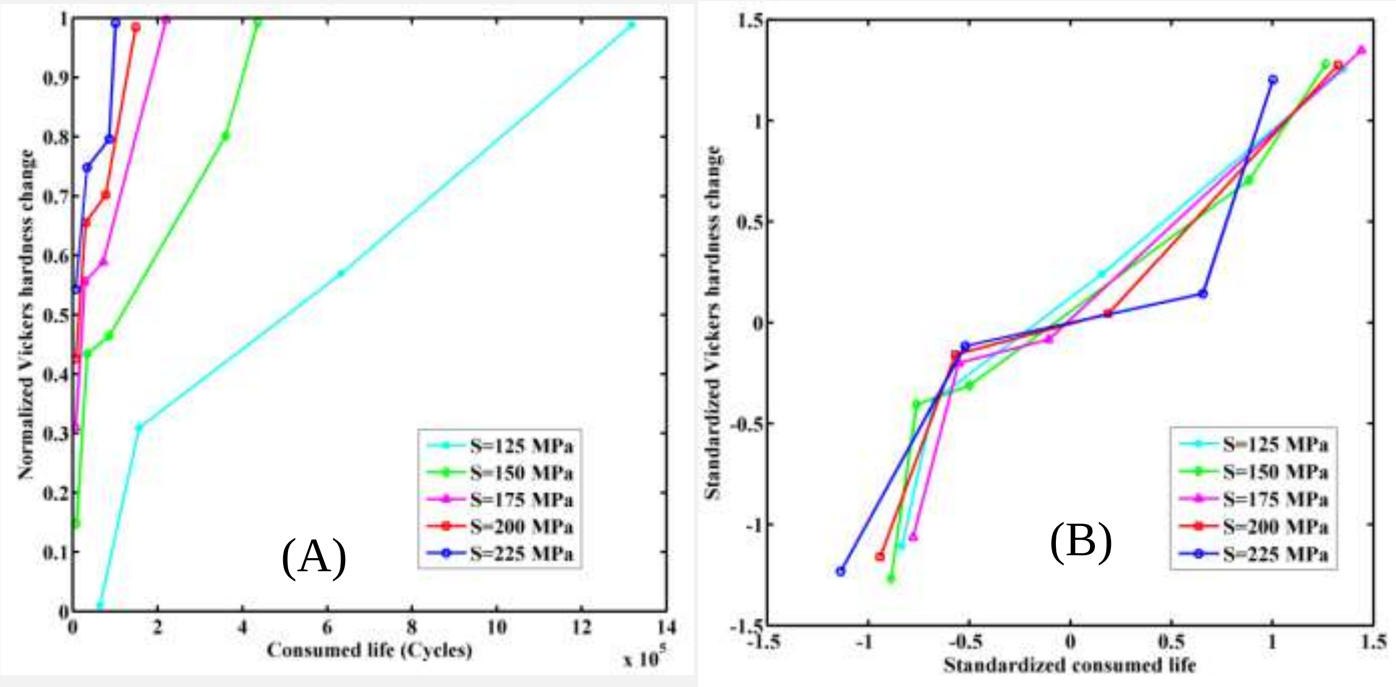
Relative entropy of acoustic signals



$$S(P|Q) = -\int_{-\infty}^{+\infty} p(x) \log\left(\frac{p(x)}{q(x)}\right) dx \quad \Rightarrow \quad S_i(P|Q) = -\int_{-\infty}^{+\infty} p_i(x) \log\left(\frac{p_i(x)}{p_{i-1}(x)}\right) dx$$

A Parametric Approach to Acoustic Entropy Estimation for Assessment of Fatigue Damage, A. Kahirdeh, C. Sauerbrunn, H. Yun, M. Modarres, International Journal of Fatigue (Submitted, 2017).

Hardness change prior to crack initiation



A) Hardness change in Al 2024-T42, B) Standardized hardness change in Al 2024-T42. The data of the hardness change are obtained from the study by Pavlou

D.G. Pavlou, A phenomenological fatigue damage accumulation rule based on hardness increasing, for the 2024-T42 aluminum, Engineering Structures, 24 (2002) 1363-1368.

Statistical Mechanics Entropy

- Theoretical Basis for Acquiring Entropy
  - 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

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

$$\Delta F = \Delta U - T\Delta S$$

$$\Delta F = W + Q - T\Delta S$$

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

$$\frac{\pi_F(+W)}{\pi_R(-W)} = e^{\frac{W-\Delta F}{k_B T}} \quad [3]$$

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

[3] Crooks, Gavin E. "Entropy production fluctuation theorem and the nonequilibrium work relation for free energy differences." *Physical Review E*60.3 (1999): 2721.

Entropy Originated from Statistical Mechanics

- Forward / reverse process representing equations in statistical mechanics

$$\frac{\pi_F\ (+W)}{\pi_R\ (-W)} = exp\left[\frac{W - \Delta F}{k_B T}\right]$$

Crooks' fluctuation theorem

[3]

$$\frac{W_F^{diss}}{k_B T} = \frac{\langle W_F \rangle - \Delta F}{k_B T} = D(\pi_F | \mu_R) = \int \pi_F ln\left(\frac{\pi_F}{\pi_R}\right)$$

Relative entropy

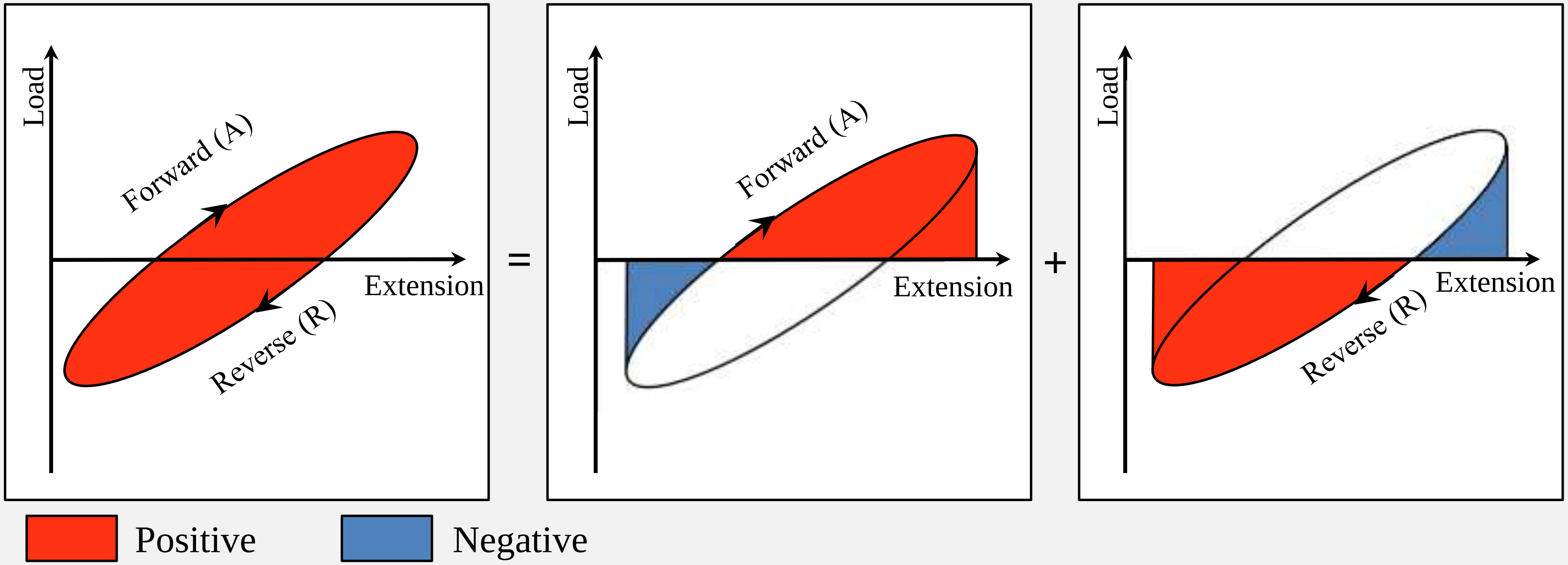
- In order to define forward / reverse distribution,
  - Repeats fatigue test with same (internal & external) condition
  - Collects matching data (e.g. work with same life ratio)

[3] C. Jarzynski, Equalities and Inequalities: Irreversibility and the Second Law of Thermodynamics at the Nanoscale, Annu. Rev. Condens. Matter Phys. 2.1 (2011): 329-351

Test & Data Arrangement

Forward / Reverse Work Computation

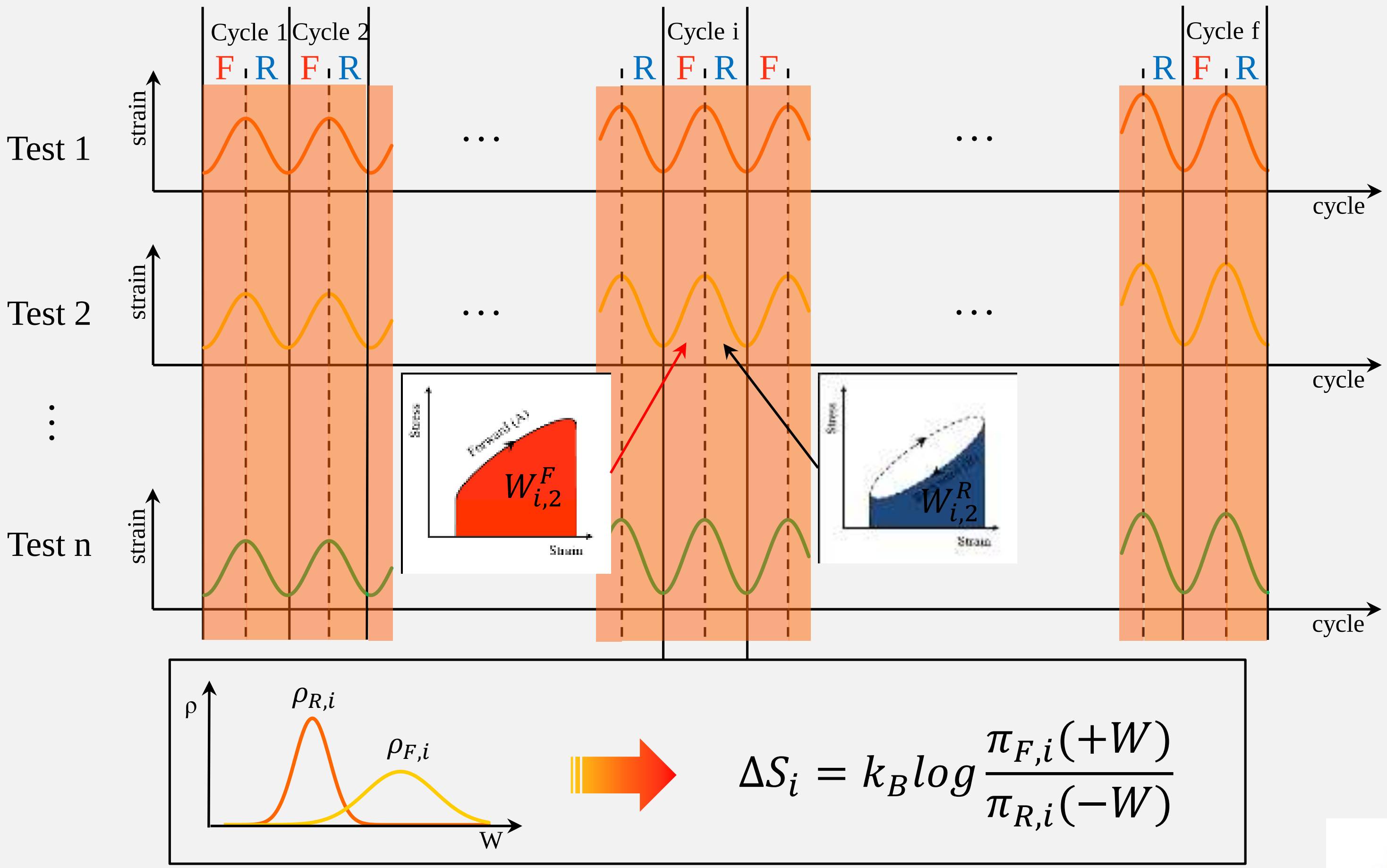
- For the fully-reversed fatigue loading condition



- Forward and reverse work for each cycle is numerically computed

Statistical Mechanics Entropy

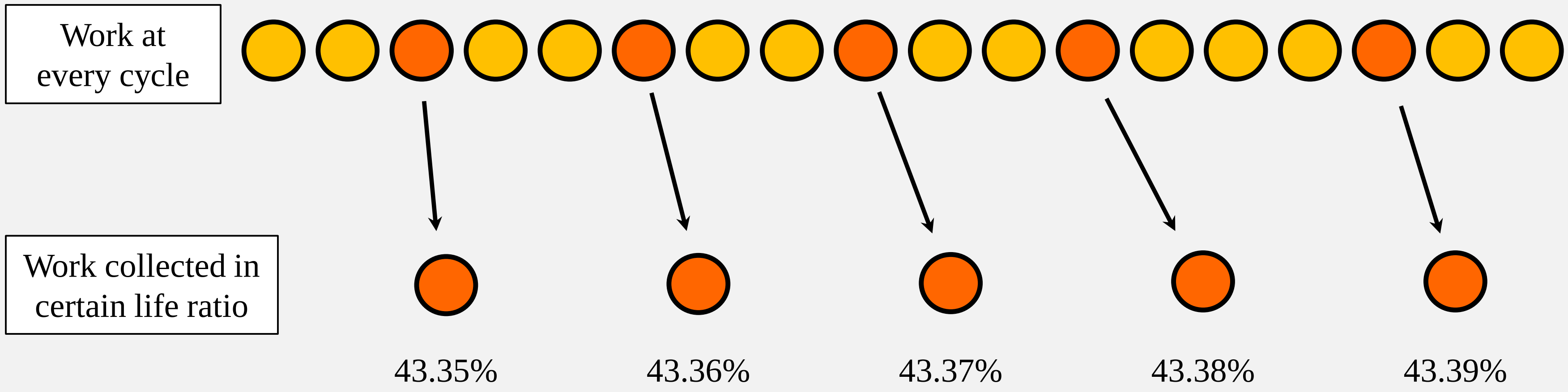
Schematics of Entropy Computation



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

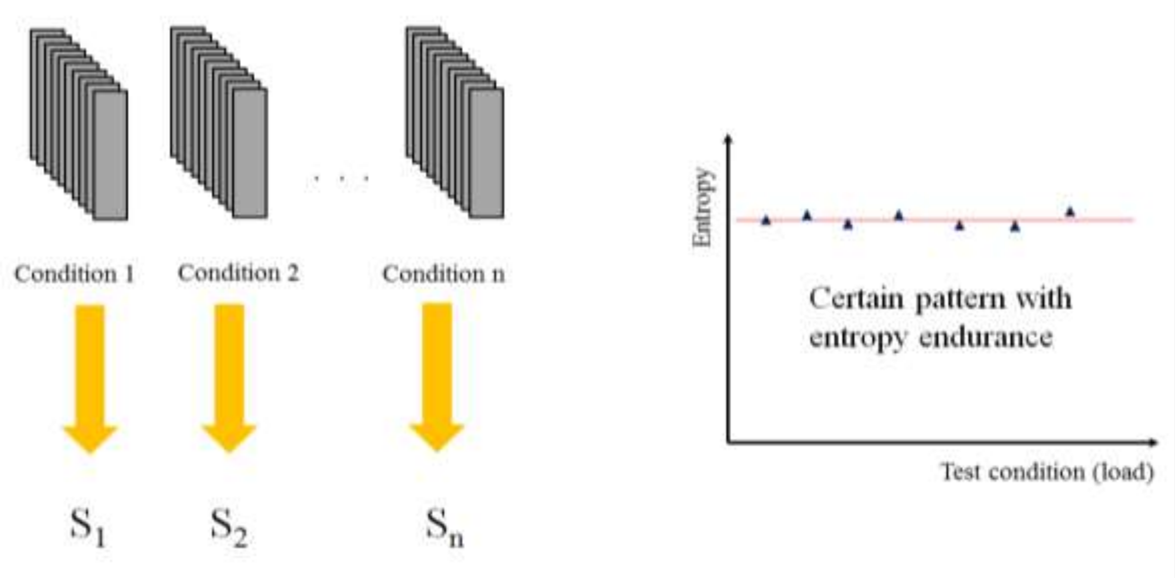
Test & Data Arrangement

- Arranging Work Data by Making up Matching Table
  - Collected forward / reverse work data at the cycle of every 0.01 % increment
  - This process made up 10,000 by 20 tables of forward / reverse work

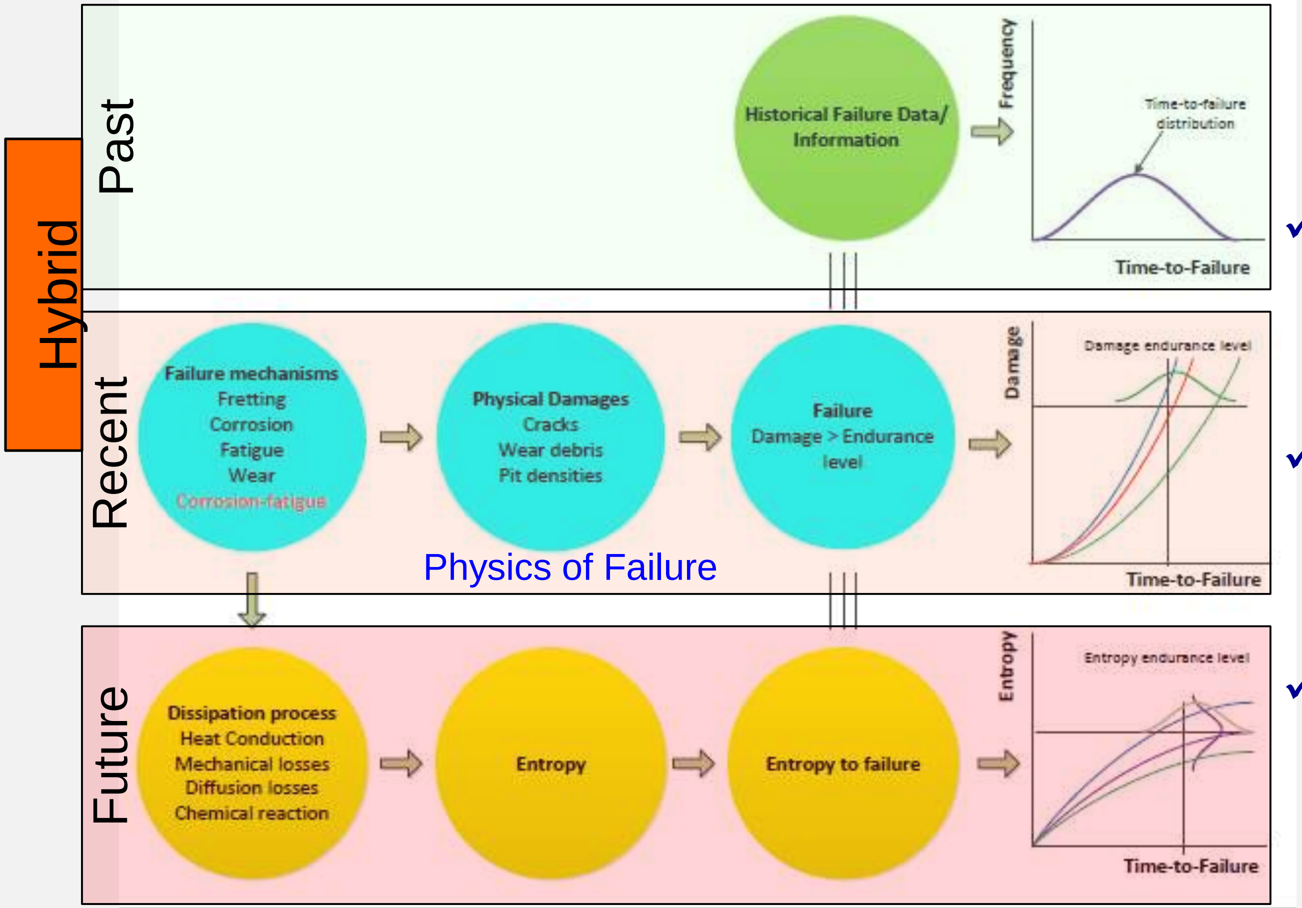


Works to be done

- Crook's fluctuation theorem is developed in microscale. The validity of such theorem needs to be investigated in macroscale where the sources of fluctuations are different from microscale.
- Experiments needs to be performed in different experimental conditions to investigate the existence of the entropic limit.



Thermodynamics as the Science of Reliability



Why Entropy?

- ✓ Entropy is independent of the path to failure ending at similar total entropy at failure
- ✓ Entropy accounts for complex synergistic effects of interacting failure mechanisms
- ✓ Entropy is scale independent

An Entropic Theory of Damage

Degradation mechanisms → Damage → Dissipation energies → Entropy generation

Damage ≡ Entropy

An entropic theory follows[1]:

Failure 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

- In this context we define Damage as: $D = \frac{\gamma_d - \gamma_{d_0}}{\gamma_{d_E} - \gamma_{d_0}}$

Entropy generation, γ_d, monotonically increases starting at time zero from a theoretical value of zero or practically some initial entropy, γ_0, to an entropic-endurance value, γ_d

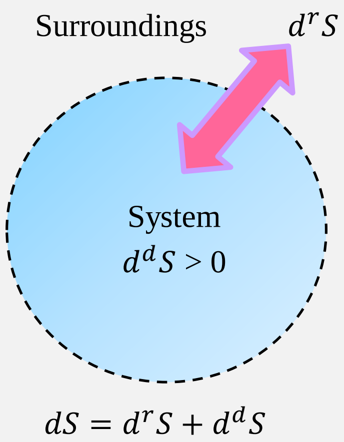
[1] Anahita Imanian and Mohammad Modarres, A Thermodynamic Entropy Approach to Reliability Assessment with Application to Corrosion Fatigue, Entropy 17.10 (2015): 6995-7020

Total Entropy

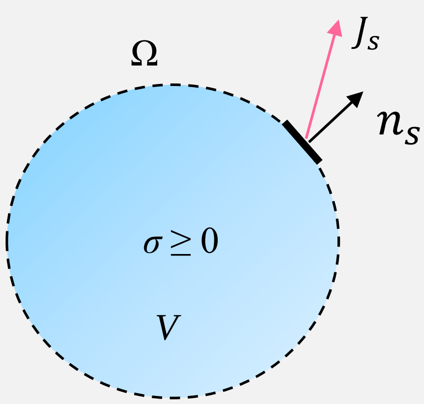
- The variation of *total entropy*, dS, is in the form of: $dS = d^r S + d^d S$.

  $d^r S$ = exchange part of the entropy supplied to the system by its surroundings through transfer of matters and heat: $\frac{d^r S}{dt} = -\int^{\Omega} \boldsymbol{J}_s . \boldsymbol{n}_s dA$

  $d^d S$ = irreversible part of the entropy produced inside of the system: $\frac{d^d S}{dt} = \int^{V} \sigma dV$.



- Divergence theorem leads to: $\frac{ds}{dt} + \nabla . \boldsymbol{J}_s = \sigma$, where, s is the specific entropy per unit mass.
- Damage, D, according to our theory is expressed by the entropy generated: $D|t \sim \int_0^t [\sigma | X_i(u), \boldsymbol{J}_i(u)] du$



J=entropy flux; σ=entropy generation/unit volume/unit time

* Imanian, A. and Modarres, M., *A Thermodynamic Entropy Based Approach to Prognosis and Health Management*, The Annual Conference of the PHM Society, 2014.

Total Entropy Generated

- Entropy generation σ involves a thermodynamic force, X_i, and an entropy flux, J_i as:

$$\sigma = \Sigma_{i,j} X_i J_i(X_j)\ ; \quad (i, j=1,\ldots, n)$$

For near equilibrium condition interactions between multiple dissipation processes is captured by the Onsagar reciprocal relations define forces and fluxes. $J_i = \sum_j L_{ij} X_j$ *For example for Fatigue (f) and Corrosion (c)*

$$J_c = L_{cc}X_c + L_{fc}X_f \text{ and } J_f = L_{cf}X_c + L_{ff}X_f$$

$[L_{ij}]$= Onsager matrix of phenomenological coefficients

- Entropy generation of important dissipation phenomena leading to damage:

Thermal energy | Diffusion energy | Plastic deformation energy

$$\sigma = \frac{1}{T^2}\boldsymbol{J}_q . \nabla T + \Sigma_{k=1}^{n} \boldsymbol{J}_k \left(\nabla \frac{\mu_k}{T}\right) + \frac{1}{T}\boldsymbol{\tau} : \dot{\boldsymbol{\epsilon}}_p + \frac{1}{T}\Sigma_{j=1}^{r} v_j\ A_j + \frac{1}{T}\Sigma_{m=1}^{h} c_m \boldsymbol{J}_m(-\nabla\psi)$$

Chemical reaction energy | External fields energy

$\boldsymbol{J}_n\ (n = q, k, and\ m)$ = 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, $\dot{\boldsymbol{\epsilon}}_p$ =the plastic strain rate, A_j =the chemical affinity or chemical reaction potential difference, ψ =potential of the external field, and c_m =coupling constant *, **

* D. Kondepudi and I. Prigogine, *"Modern Thermodynamics: From Heat Engines to Dissipative Structures,"* Wiley, England, 1998.
** J. Lemaitre and J. L. Chaboche, "*Mechanics of Solid Materials,*" 3rd edition; Cambridge University Press: Cambridge, UK, 2000.

Examples of Force and Flux of Dissipative Processes

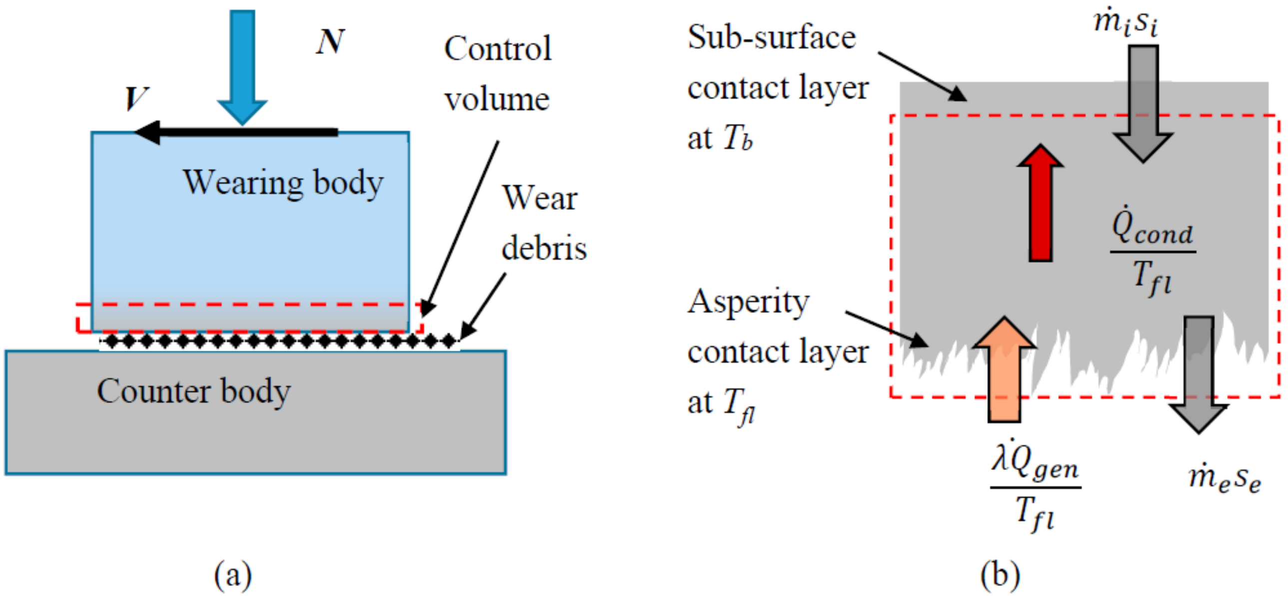
$$\sigma = \Sigma_{i,j} X_i J_i(X_j)\ ; \quad (i, j=1,\ldots, n)$$

Primary mechanism	Thermodynamic force, X	Thermodynamic flow, J	Examples of materials damage process
Heat conduction	Temperature gradient, $\nabla(1/T)$	Heat flux, $\boldsymbol{q}$	Fatigue, creep, wear
Plastic deformation of solids	Stress, $\boldsymbol{\sigma}/T$	Plastic strain, $\dot{\boldsymbol{\varepsilon}}_p$	Fatigue, creep, wear
Chemical reaction	Reaction affinity, A_k/T	Reaction rate, v_k	Corrosion, wear
Mass diffusion	Chemical potential, $-\nabla(\mu_k/T)$	Diffusion flux, $\boldsymbol{J}_k$	Wear, creep
Electrochemical reaction	Electrochemical potential, $\tilde{A}/T$	Current density, i_{corr}/z	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 $(\tilde{\boldsymbol{\sigma}} - \omega \boldsymbol{I})/T$	Creep deformation rate, $\boldsymbol{R}$	Creep

Table From: Amiri, M. and Modarres, M., *An Entropy-Based Damage Characterization*, Entropy, 16, 2014.

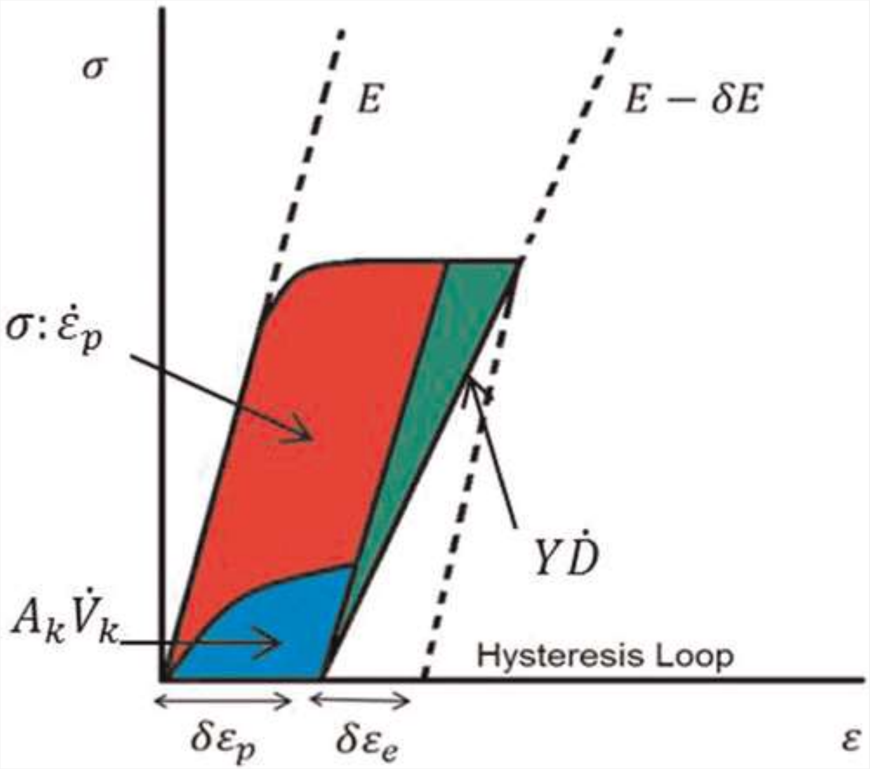
Entropic approach to wear damage

Schematic of a tribosystem (**a**) including wearing body and counter body, (**b**) control volume enclosing interface of dissipative processes, thermodynamic model.



Amiri, Mehdi, and Mohammad Modarres. "An entropy-based damage characterization." *Entropy* 16.12 (2014): 6434-6463.

Entropic approach to Low cycle fatigue of metals

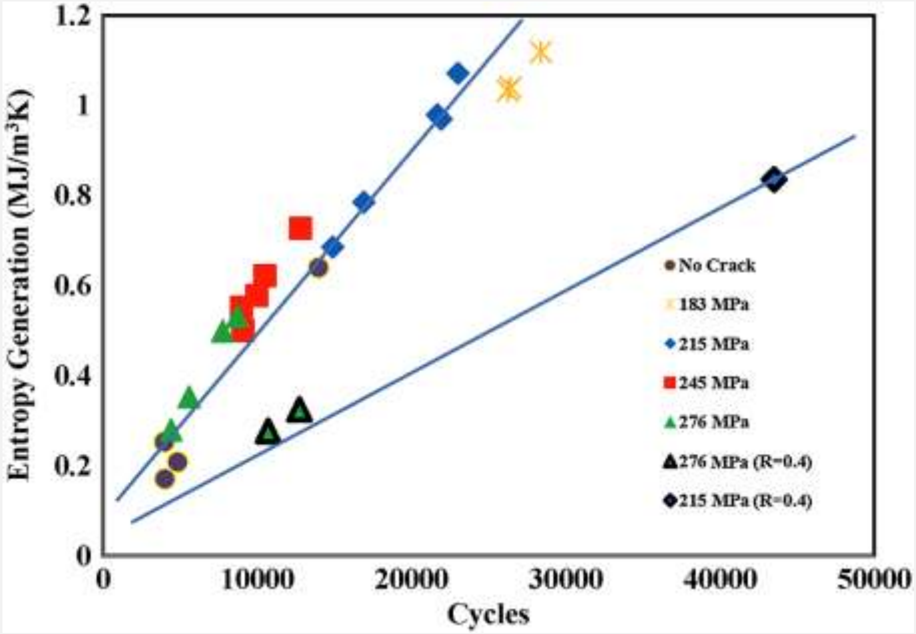


Hysteresis energy

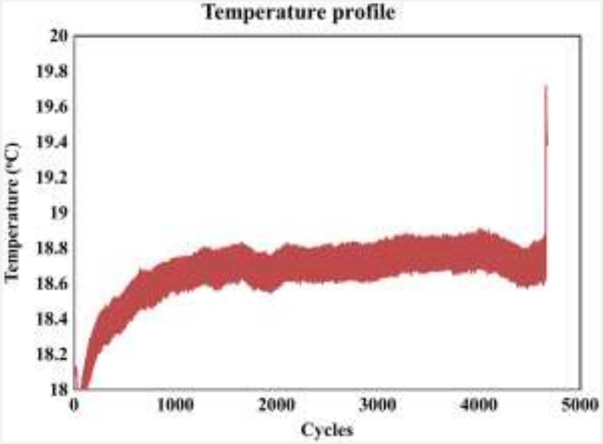
Ontiveros, V. L., Modarres, M., & Amiri, M. (2015). Estimation of reliability of structures subject to fatigue loading using plastic strain energy and thermodynamic entropy generation. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 229(3), 220-236.

Entropic approach to low cycle fatigue of metals

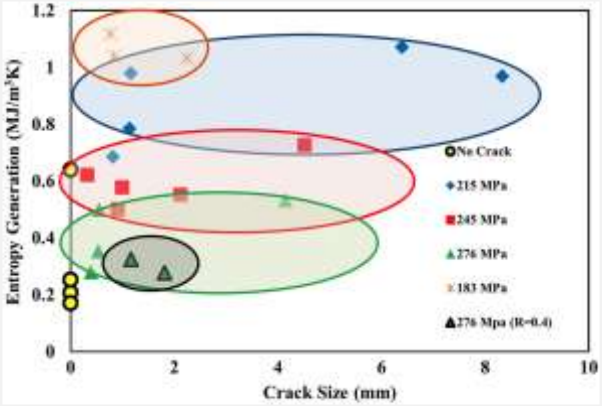
$$\sigma = \frac{1}{T}\boldsymbol{\tau} : \dot{\boldsymbol{\epsilon}}_p$$ Plastic deformation entropy



Entropy generation at crack initiation.



Example of a specimen temperature evolution.



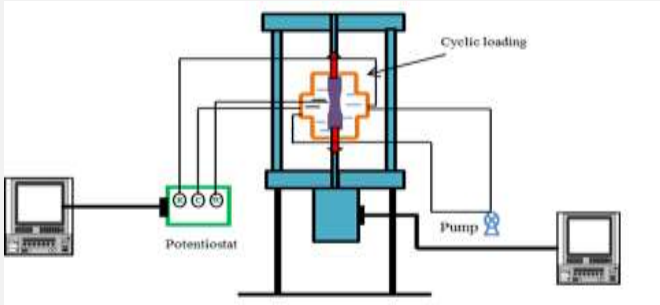
Entropy generation for various crack sizes.

Ontiveros, V., Amiri, M., Kahirdeh, A., & Modarres, M. (2016). Thermodynamic entropy generation in the course of the fatigue crack initiation. Fatigue & Fracture of Engineering Materials & Structures.

Entropic-Based Damage from Corrosion-Fatigue (CF)

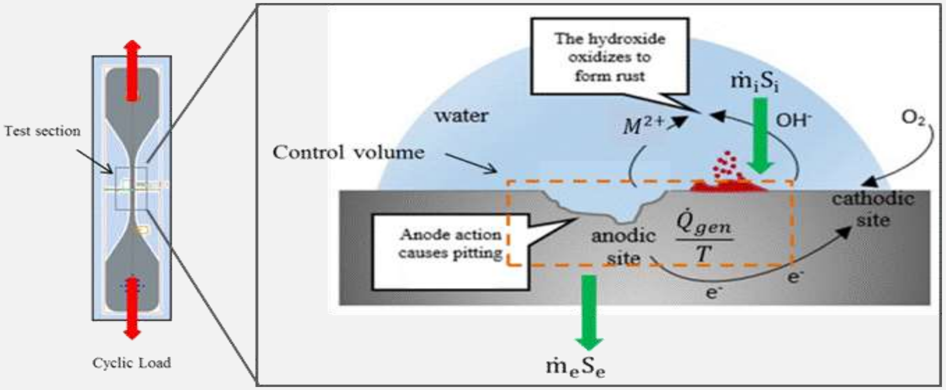
- Oxidation and reduction reactions of metallic electrode, M, under CF:

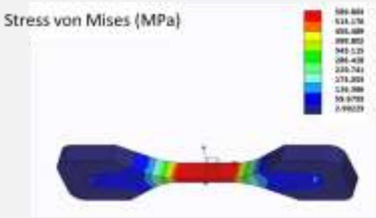
$$M \leftrightarrow M^{z_M^+} + z_M e^-$$
$$O + z_O e^- \leftrightarrow R$$



O = Certain oxidant in solution resulting in formation of the reduction product R.

- The entropy generation results from:
  - Entropy flow to the surrounding
  - Entropy generation from:
    - Corrosion reaction processes
    - Electrochemical processes
    - Mechanical losses
    - Diffusion losses
    - Hydrogen embrittlement losses





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 [1]:

Electrochemical dissipations

$$\sigma = \frac{1}{T}\left(\boldsymbol{J}_{M,a} z_M F E_{M_{act,a}} + \boldsymbol{J}_{M,c} z_M F E_{M_{act,c}} + \boldsymbol{J}_{O,a} z_O F E_{O_{act,a}} + \boldsymbol{J}_{O,c} z_O F E_{O_{act,c}}\right)$$

$$+ \frac{1}{T}\left(\boldsymbol{J}_{M,c} z_M F E_{M_{conc,c}} + z_O F \boldsymbol{J}_{O,c} E_{O_{conc,c}}\right)$$

Diffusion dissipations

$$+ \frac{1}{T}\left(\boldsymbol{J}_{M,a}\alpha_M A_M + J_{M,c}(1-\alpha_M)A_M + \boldsymbol{J}_{O,a}\alpha_O A_O + \boldsymbol{J}_{M,a}(1-\alpha_O)A_O\right)$$

Chemical reaction dissipations

Mechanical dissipations

$$+ \frac{1}{T}\dot{\boldsymbol{\epsilon}}_p : \boldsymbol{\tau} + \frac{1}{T} Y \dot{\boldsymbol{D}}$$

$$+\sigma_H$$

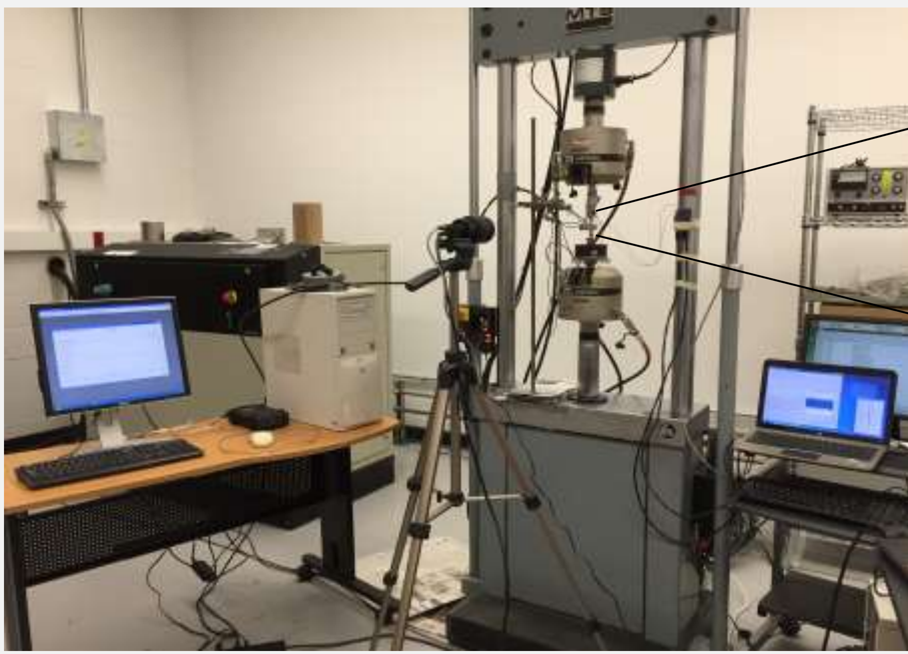
Hydrogen embrittlement dissipation

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.

Corrosion Fatigue (CF) Experimental Set up

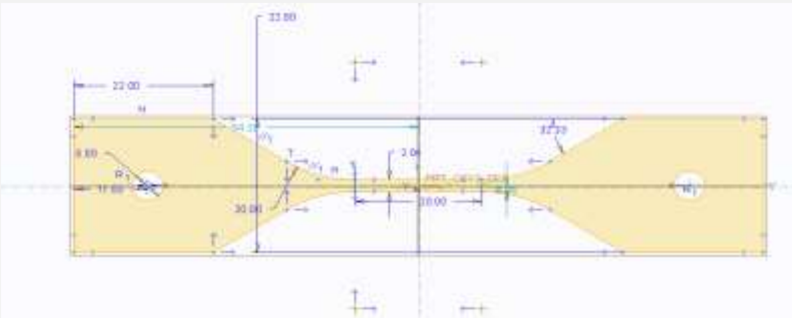
- Fatigue tests of Al 7075-T651 in 3.5% wt. NaCl aqueous solution acidified with a 1 molar solution of HCl, with the pH of about 3.5, under axial load controlled and free corrosion potential
- Specimen electrochemically monitored via a Gamry potentiostat using Ag/AgCl reference electrode maintained at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

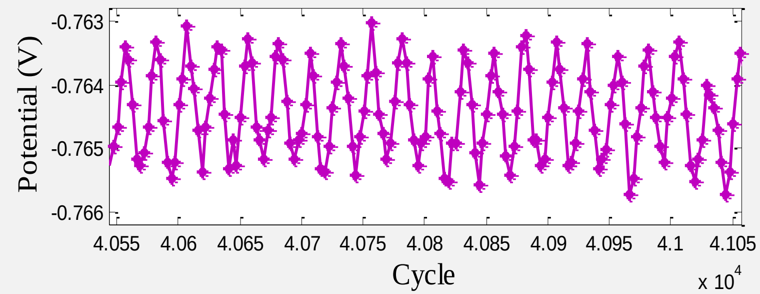
CF tests done while measuring the open circuit potential (OCP) vs. reference electrode during load-unload



Electrochemical corrosion cell made of plexiglass

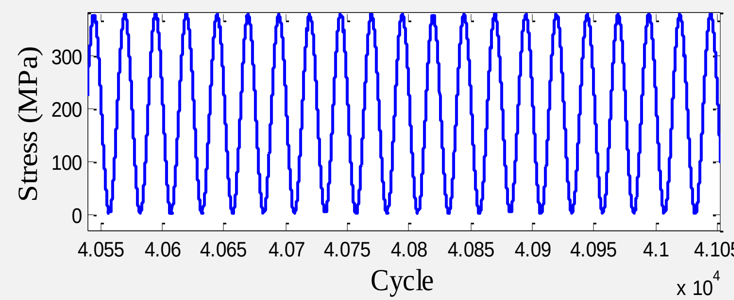
CF Test Procedures





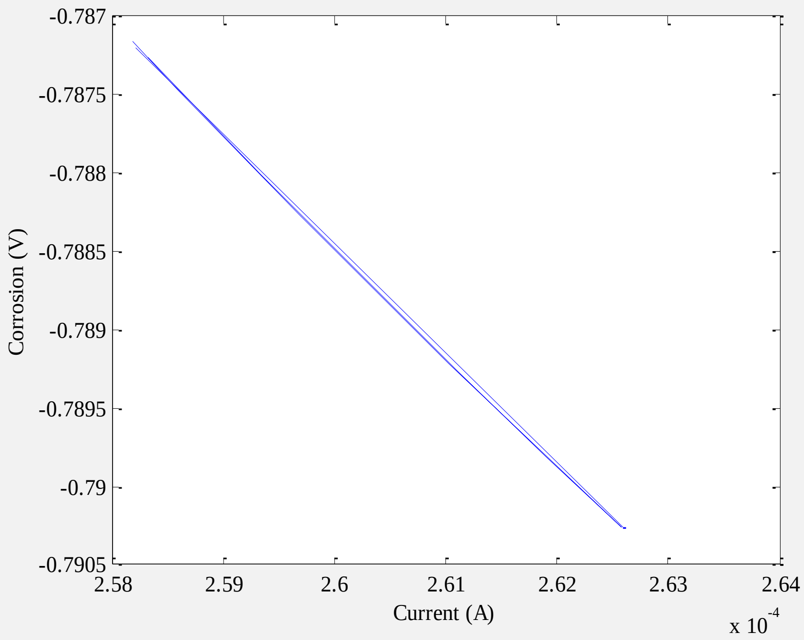
Forces and fluxes were measured under CF

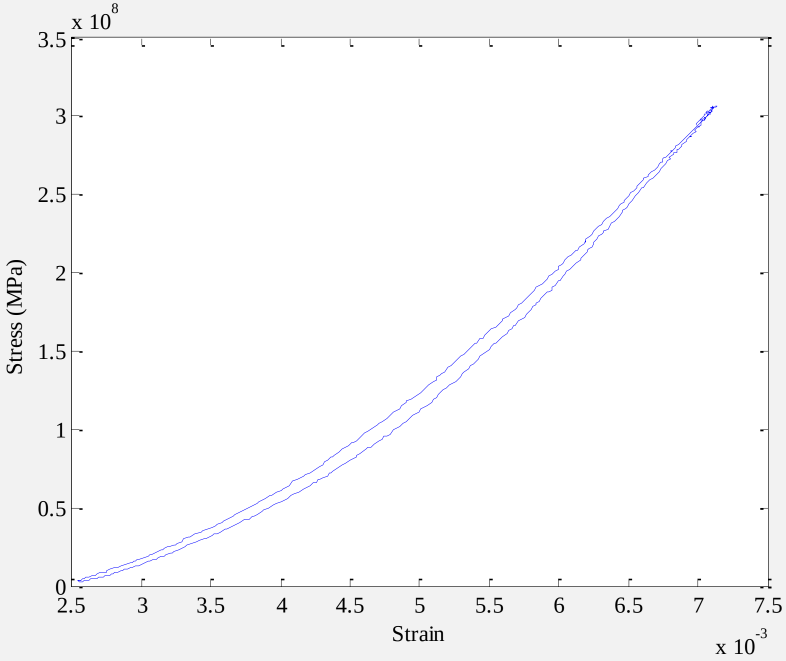
- Performed CF tests for 16 samples at 87%, 80%, 70% and 57% of yield stress (460 MPa), load ratio = 0.01, loading frequency=0.04Hz
- Tests stopped after failure of specimens



Entropy Generation in CF

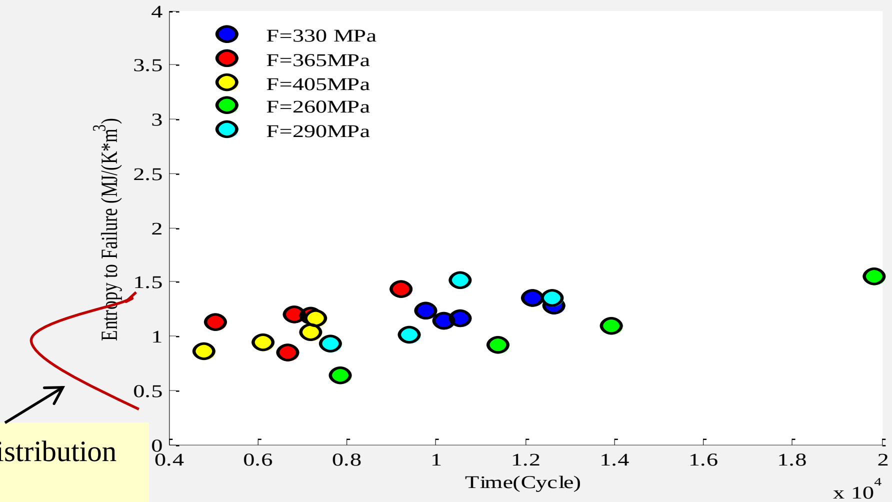
- Total entropy is measured from the hysteresis loops resulted from fatigue (stress-strain) and corrosion (potential-electrical) in each loading cycle



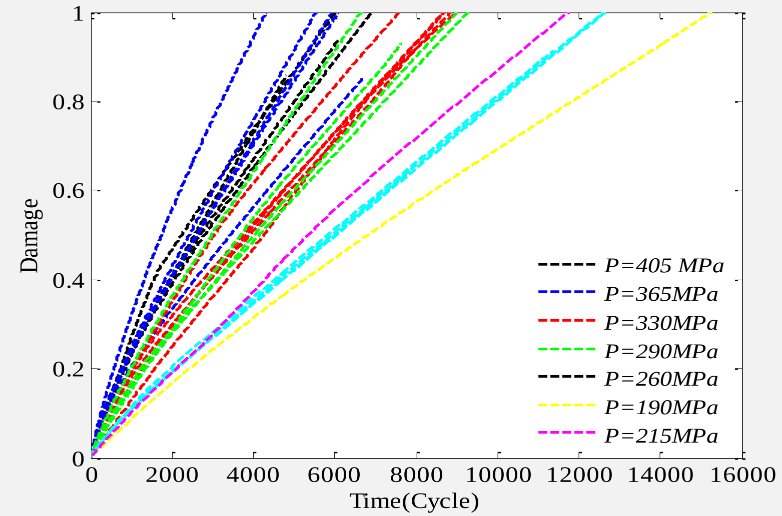


Entropic Endurance and Entropy-to-Failure

- Similarity of the total entropy-to-failure for all tests supports the entropic theory of damage offered proposed
- More tests needed to reduce the epistemic uncertainties and further confirm the theory

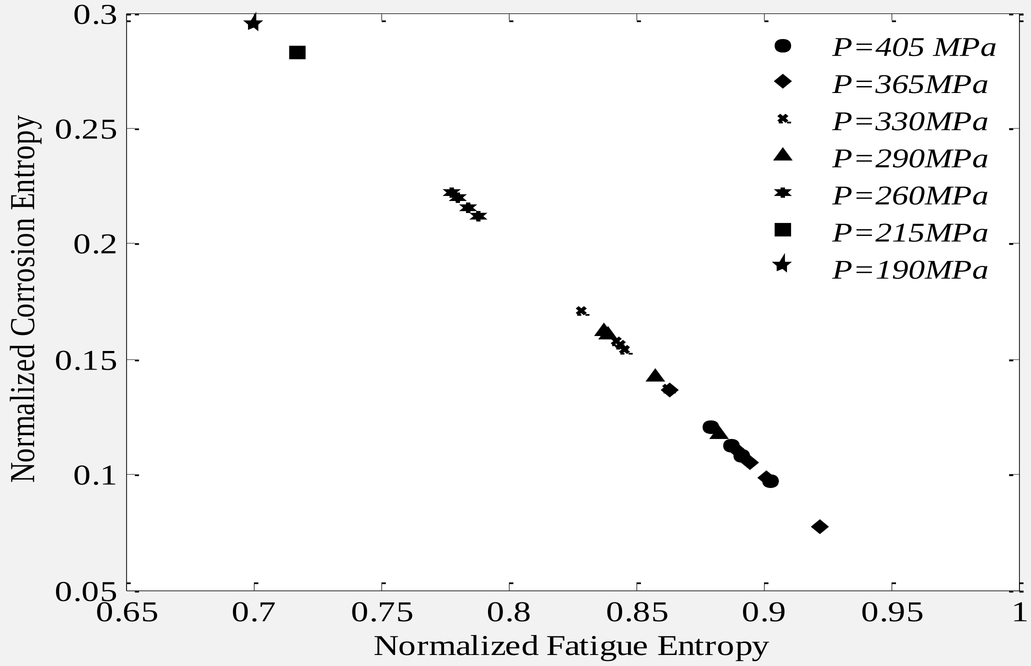


Distribution of entropic-endurance



Ratio of Corrosion and Fatigue Entropies to the Total Entropy

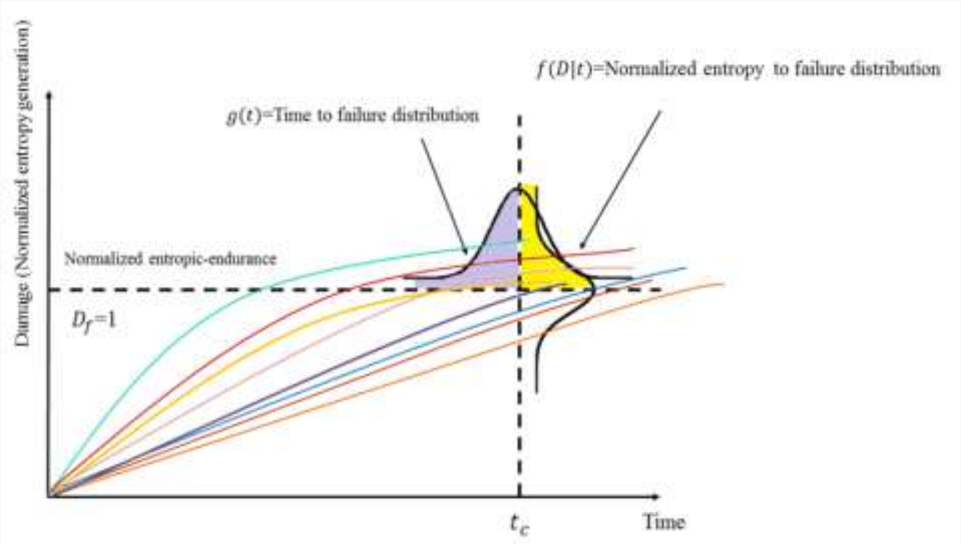
- Reducing fatigue stress allows more time for corrosion



Thermodynamics of Damage: A Reliability Perspective

- Materials, environmental, operational and other types of variabilities in degradation forces impose uncertainties on the total entropic damage

- Assuming a constant *entropic-endurance*, D_f



- The reliability function can be expressed as [1]

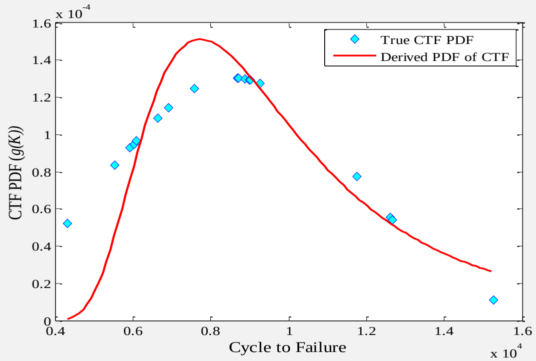
$$P_r(T \leq t_c) = \int_0^{t_c} g(t)dt = 1 - \int_0^{D_f=1} f(D)dD$$

$$R(t_c) = 1 - P_r(T \leq t_c) = \int_0^{D_f=1} f(D)dD$$

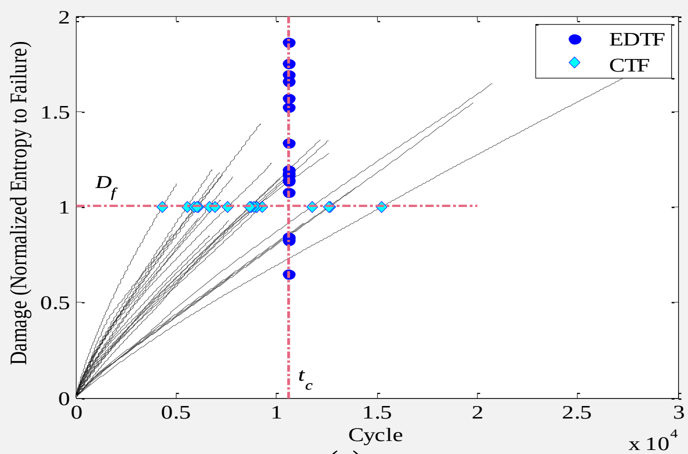
T_c=*Current operating time;* $g(t)$=*distribution of time-to-failure,* $f(D|t)$= *distribution of damage at t*

[1] Thermodynamics as a Fundamental Science of Reliability, A. Imanian, M. Modarres, Int. J. of Risk and Reliability, Vol.230(6), pp.598-608. DOI: 10.1177/1748006X16679578.(2016).

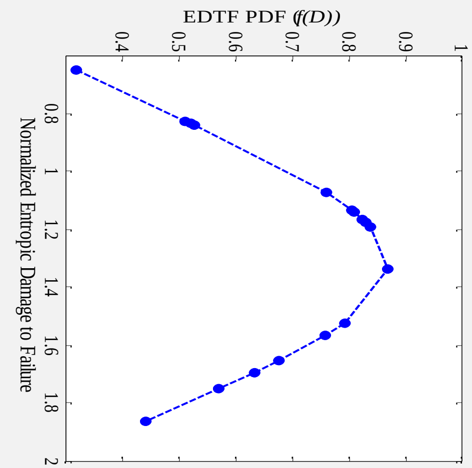
Entropic-Based CF Reliability



(c)



(a)



(b)

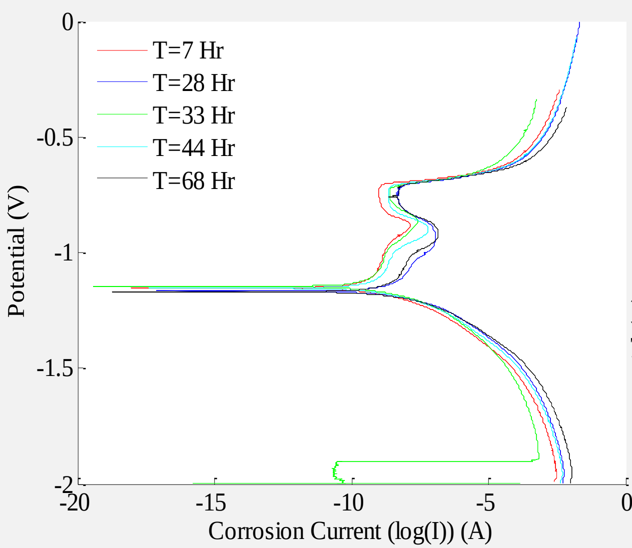
Conclusions

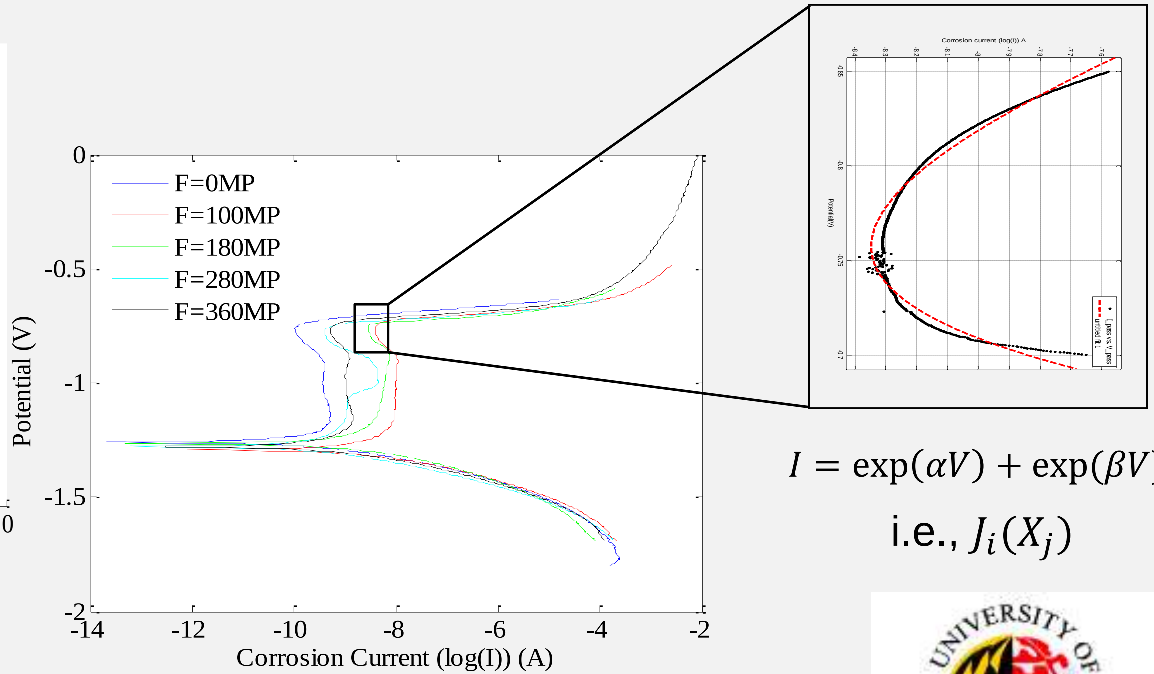
- A thermodynamic theory of damage proposed and tested
- An entropy-based damage model derived from the second law of thermodynamics and used it to develop models for reliability analysis
- The proposed theory offered a more fundamental model of damage and allowed for incorporation of all interacting dissipative processes
- Entropy generation function derived for corrosion-fatigue mechanism in terms of leading dissipative processes
- A simplified version of entropic corrosion-fatigue damage model experimentally studied which supported the proposed theory and the thermodynamic-based interpretation of reliability

Thank you

Corrosion Current vs. Potential: Effect of Time and Stress

- To obtain the correlation between *corrosion current and potential*, polarization curves were developed at different stress and immersion values
- Stress and immersion time variations showed stochastic effect on polarization curve
- The sum of the exponential terms showed a good fit to the part of polarization which involved the open circuit potential (OCP)





$$I = \exp(\alpha V) + \exp(\beta V)$$

i.e., $J_i(X_j)$