# An Acoustic Emission Approach to Assess Remaining Useful Life of Aging Structures under Fatigue Loading

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# Acknowledgments

## The Team:

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2. Ms. Christine Sauerbrunn (MS Student, Graduated)
3. Dr. Ali Kahirdeh (Postdoc)
4. Prof. Mohammad Modarres (PI)

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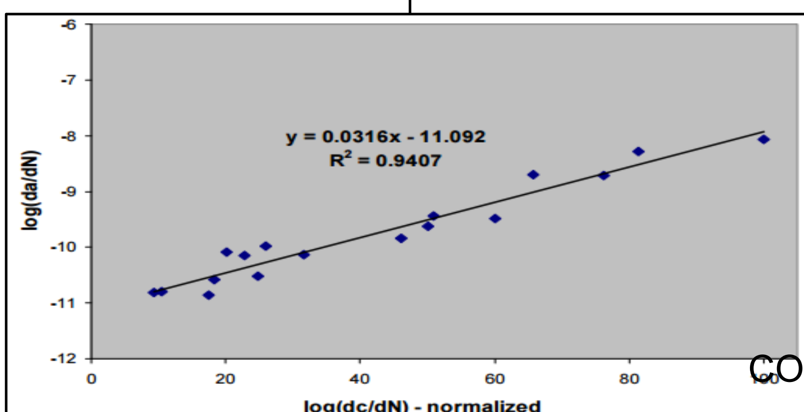
# Outline

- Introduction: Motivation and Objective
- Scope of Research
- Information Entropy (Stage 1)
- Excitation Loading (Stage 2)
- Conclusions

# Introduction

## Motivation

- Full-scale fatigue testing and safe-life methodology is employed to estimate aircraft fatigue life
  - Time demanding, expensive, and often leads to premature aircraft retirement
- Nondestructive evaluation methods are appropriate supplements to service life models
- Previous work has correlated acoustic emission (AE) signals to large crack growth

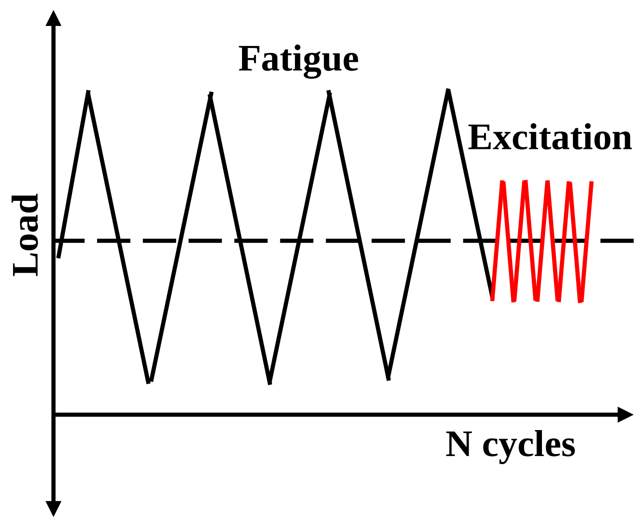


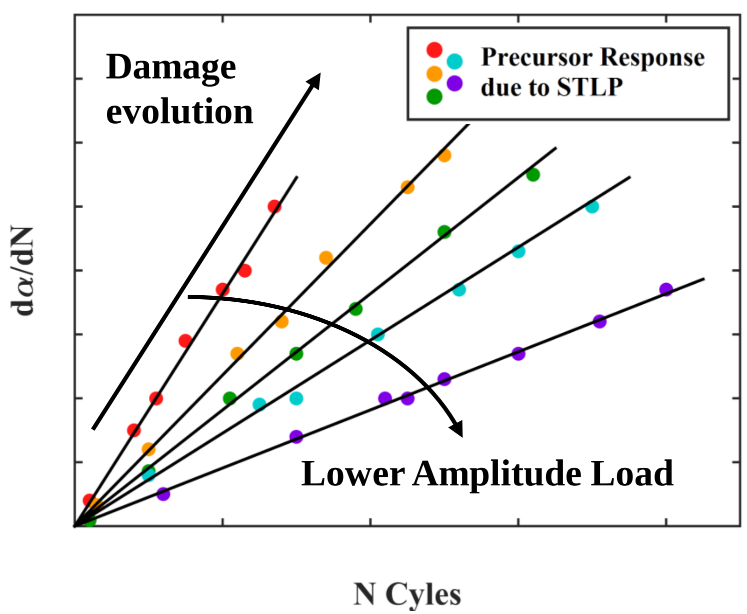

## Objective

- Estimate Remaining Useful Life (RUL) based on behavior of some damage precursors in AE signals
  - Identify potential damage precursors in AE signals and correlate to fatigue damage both prior to and after a visible crack has initiated
  - Observe behaviors of damage precursors during short excitation loading or small vibrations

# Scope of Research

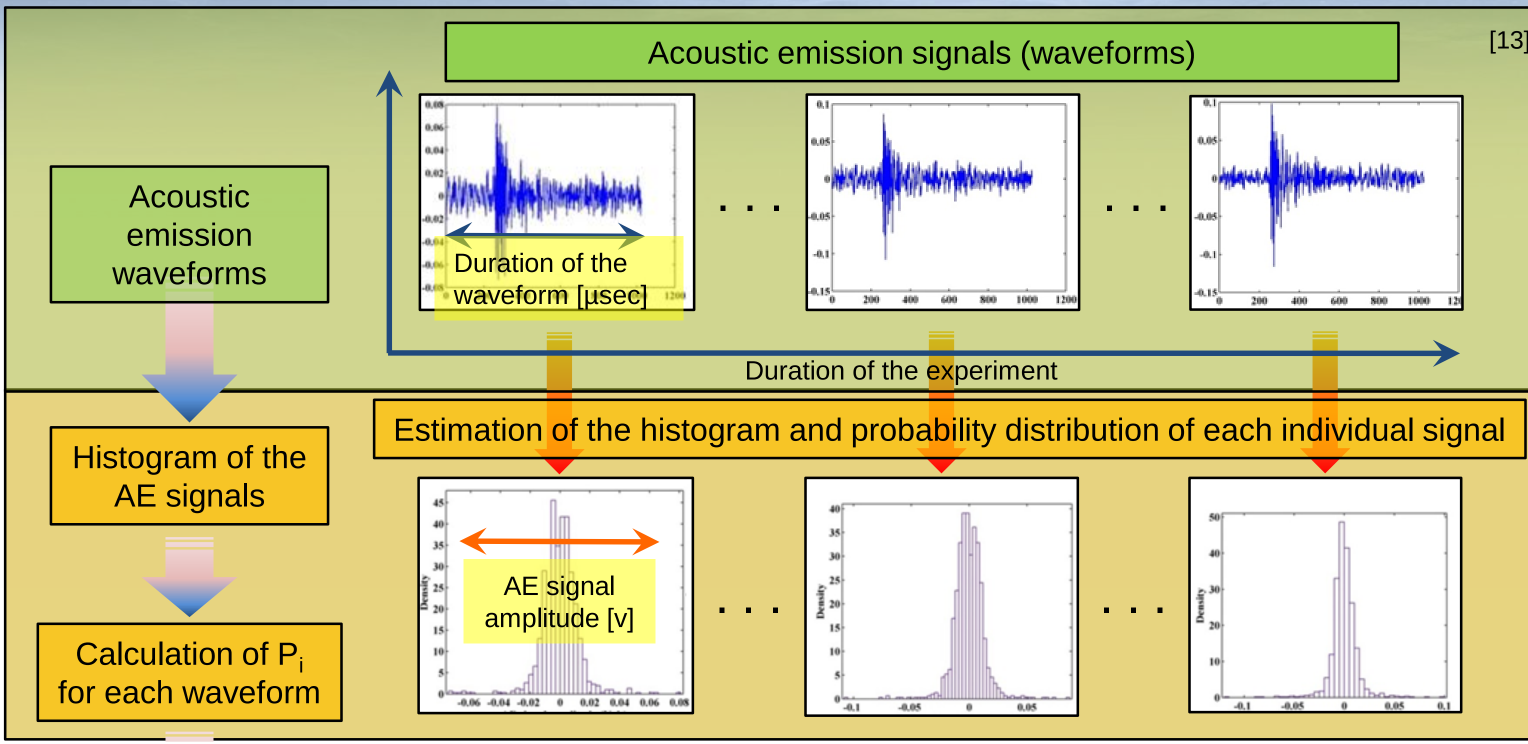
- Stage 1: Identify damage precursors attributed to microcracks prior to visible damage (crack initiation)
- Stage 2: Observe behaviors of damage precursors during short-term, high-frequency, excitation loading




STLP = Short-term loading procedure = excitation loading

# Stage 1: Information Entropy Analysis Procedure




Probability distribution ($P_i$) → Entropy

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

[13] Ali Kahirdeh, Christine Sauerbrunn, Mohammad Modarres, Proceedings of the 35th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering, MaxEnt_2015, Potsdam, NY, 2015

# Approaches to quantify entropy

**Entropy**

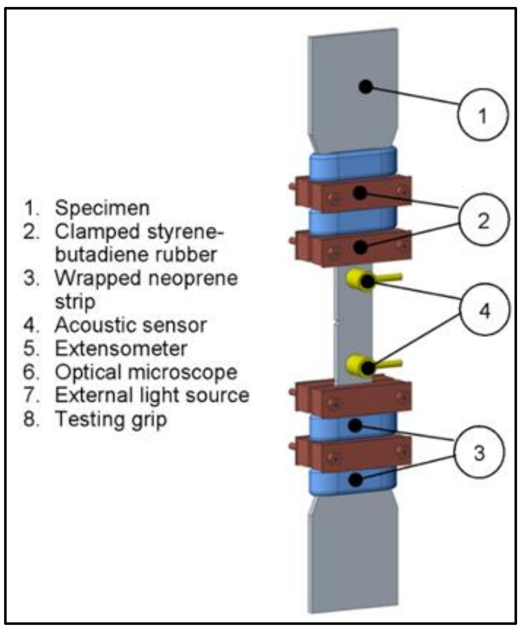
- **Statistical mechanics**
  - $S = K_B \ln W$
  - $\Delta S_i(W) = k_B log \frac{\pi_{F,i}(+W)}{\pi_{R,i}(-W)}$
- **Classical thermodynamics and continuum mechanics**
  - $$\sigma = \frac{1}{T^2}\boldsymbol{J}_q . \nabla T - \Sigma_{k=1}^{n}\boldsymbol{J}_k\left(\nabla \frac{\mu_k}{T}\right) + \frac{1}{T}\boldsymbol{\tau}\colon \dot{\boldsymbol{\epsilon}}_p + \frac{1}{T}\Sigma_{j=1}^{r} v_j\, A_j + \frac{1}{T}\Sigma_{m=1}^{h} c_m \boldsymbol{J}_m(-\nabla\psi)$$
- **Information theory**
  - $S = \sum p_i \log p_i$

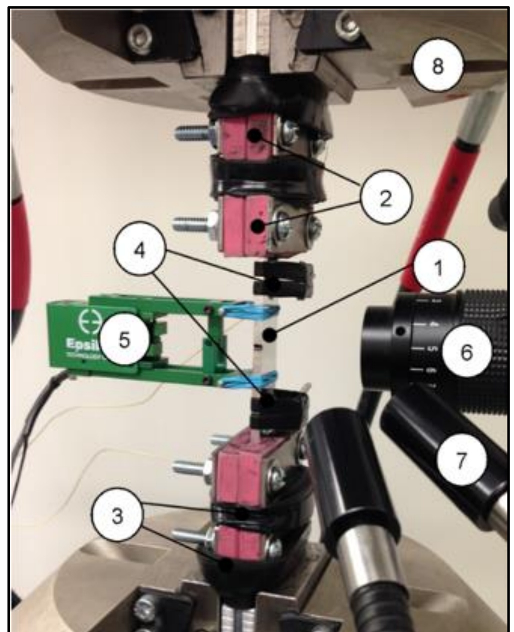
# Stage 1: Information Entropy Material & Test Setup

- Material / Specimen: Al alloy 7075-T6 / Dogbone ASTM E466

| Element | Al | Zn | Mg | Cu | Cr | Fe | Mn | Si | Ti | V | Zr | Others [14] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Composition [wt%] | 89.7 | 5.7 | 2.6 | 1.4 | 0.2 | 0.15 | 0.08 | 0.06 | 0.02 | 0.01 | 0.01 | 0.05 |

| Material Property | Ultimate Strength [MPa] | Yield Strength [MPa] | Elastic Modulus [GPa] |
|---|---|---|---|
| Property Value | 587 | 538 | 67.8 |




- Dogbone specimen with round notch (1 mm)

- $K_t$=2.61

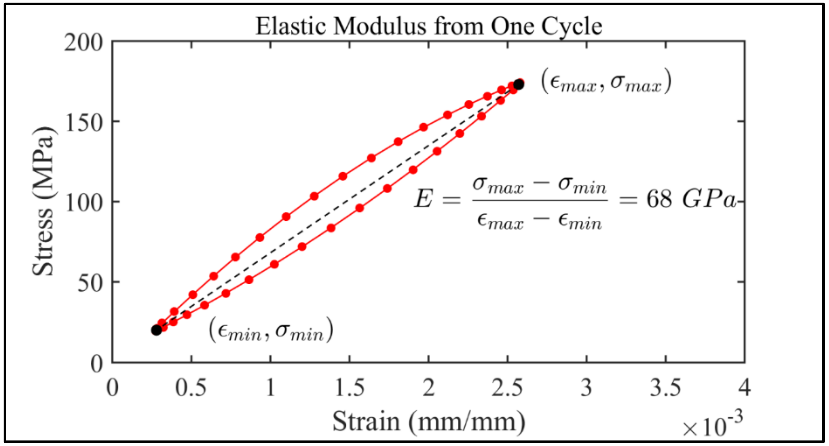
- Eraser and neoprene rubber bands were used for mechanical damper for AE signal noise reduction

[14] Sauerbrunn, Christine M., et al. "Damage Assessment Using Information Entropy of Individual Acoustic Emission Waveforms during Cyclic Fatigue Loading." *Applied Sciences* 7.6 (2017): 562

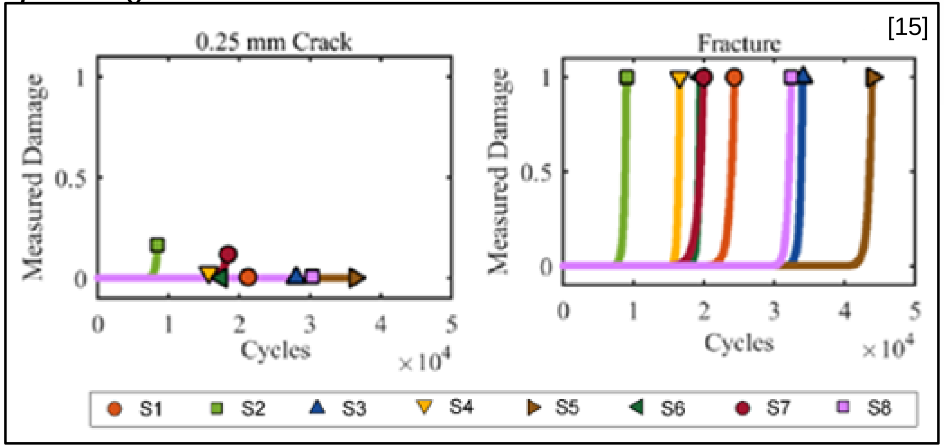
# Stage 1: Information Entropy Measurement of Damage

- Physical damage is assumed and computed by using modulus degradation
  - Assumes that structural degradation is reflected as a decrease in elastic modulus
  - Normalizes modulus to compare trends between tests to yield modulus degradation damage (MDD)

$$MDD = \frac{E_i - E_0}{E_f - E_0}$$



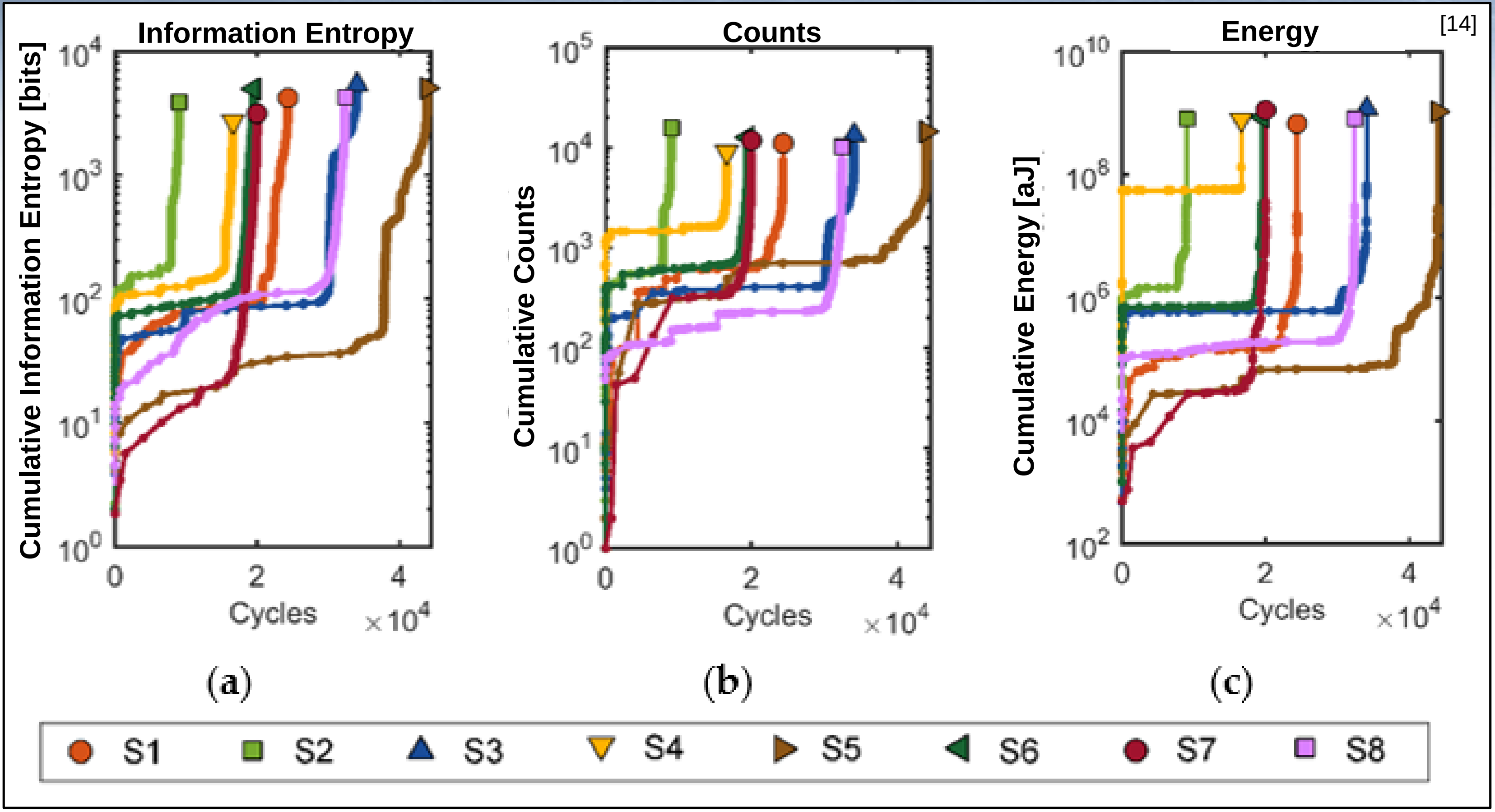

Elastic modulus measurement




MDD trend throughout fatigue life


[15] Christine M. Sauerbrunn, Evaluation of Information Entropy from Acoustic Emission Waveforms as a Fatigue Damage Metric for Al7075-T6, 2016, University of Maryland, Master of Science Thesis

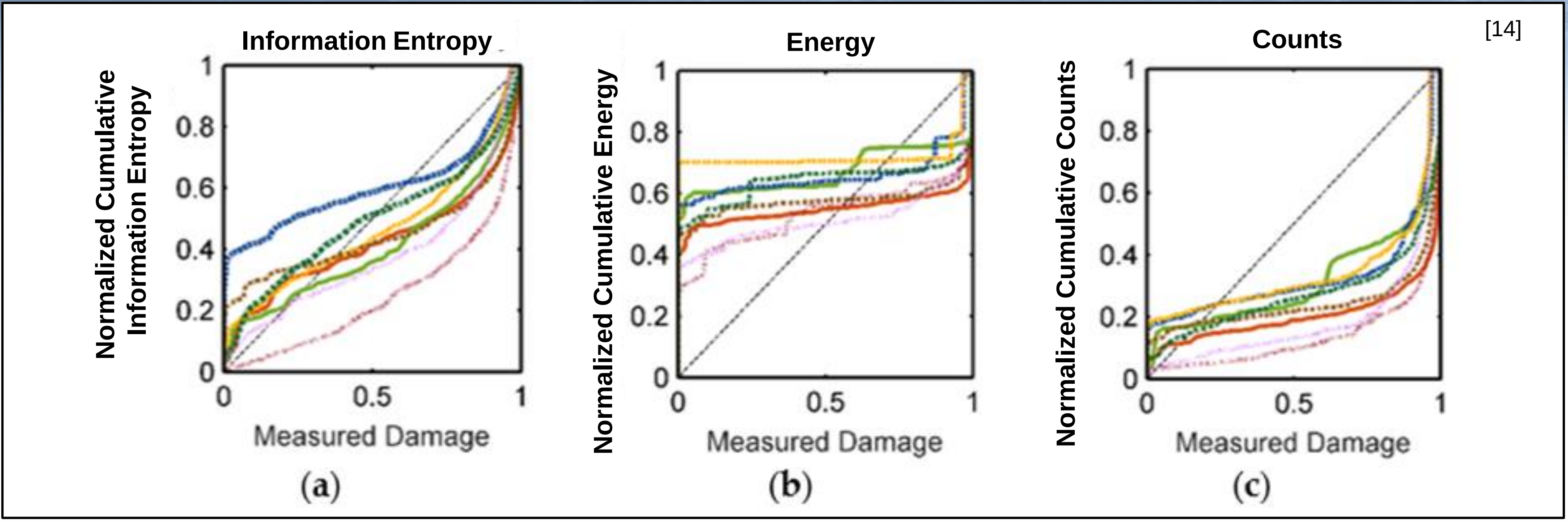
# Stage 1: Information Entropy vs. Cumulative AE Features

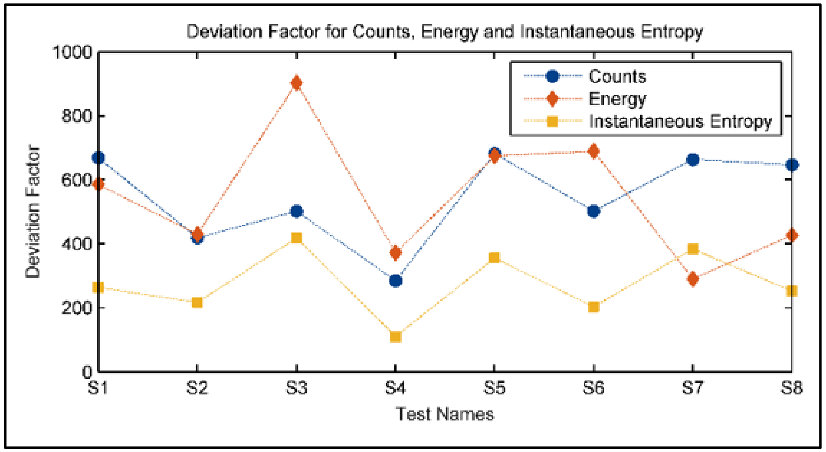



⇨ The cumulative features were normalized for comparing with measured damage


[14] Sauerbrunn, Christine M., et al. "Damage Assessment Using Information Entropy of Individual Acoustic Emission Waveforms during Cyclic Fatigue Loading." *Applied Sciences* 7.6 (2017): 562

# Stage 1: Information Entropy of AE Signal to Crack Initiation



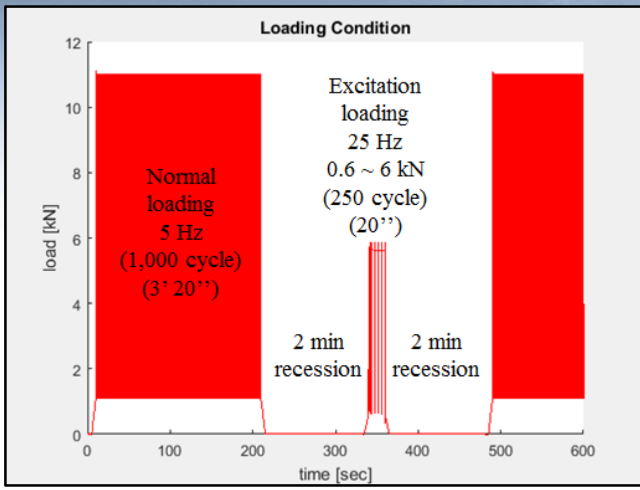




- The correlation results were evaluated with deviation factor

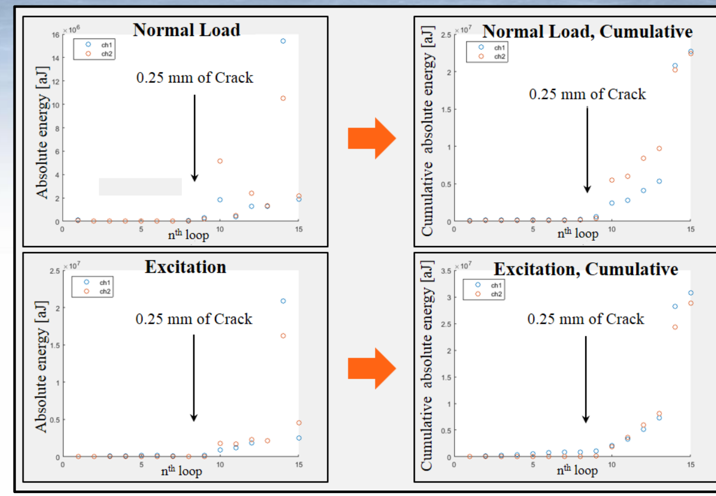
- The information entropy is closer than raw AE features

[14] Sauerbrunn, Christine M., et al. "Damage Assessment Using Information Entropy of Individual Acoustic Emission Waveforms during Cyclic Fatigue Loading." *Applied Sciences* 7.6 (2017): 562

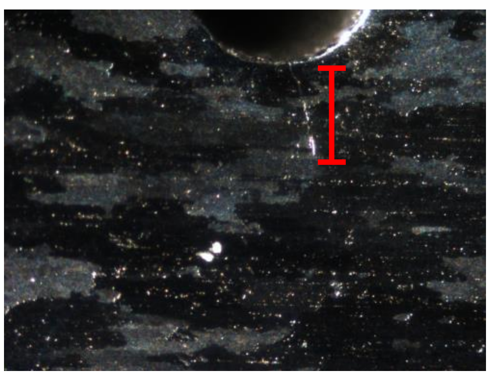
# Stage 2: Excitation Loading Analysis Procedure



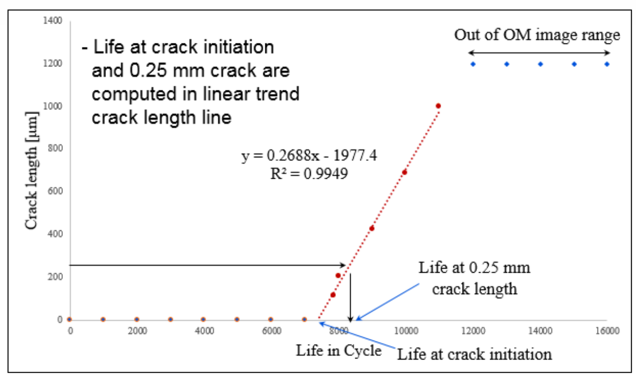

Fatigue testing combined with excitation




AE features analysis



Crack length monitoring

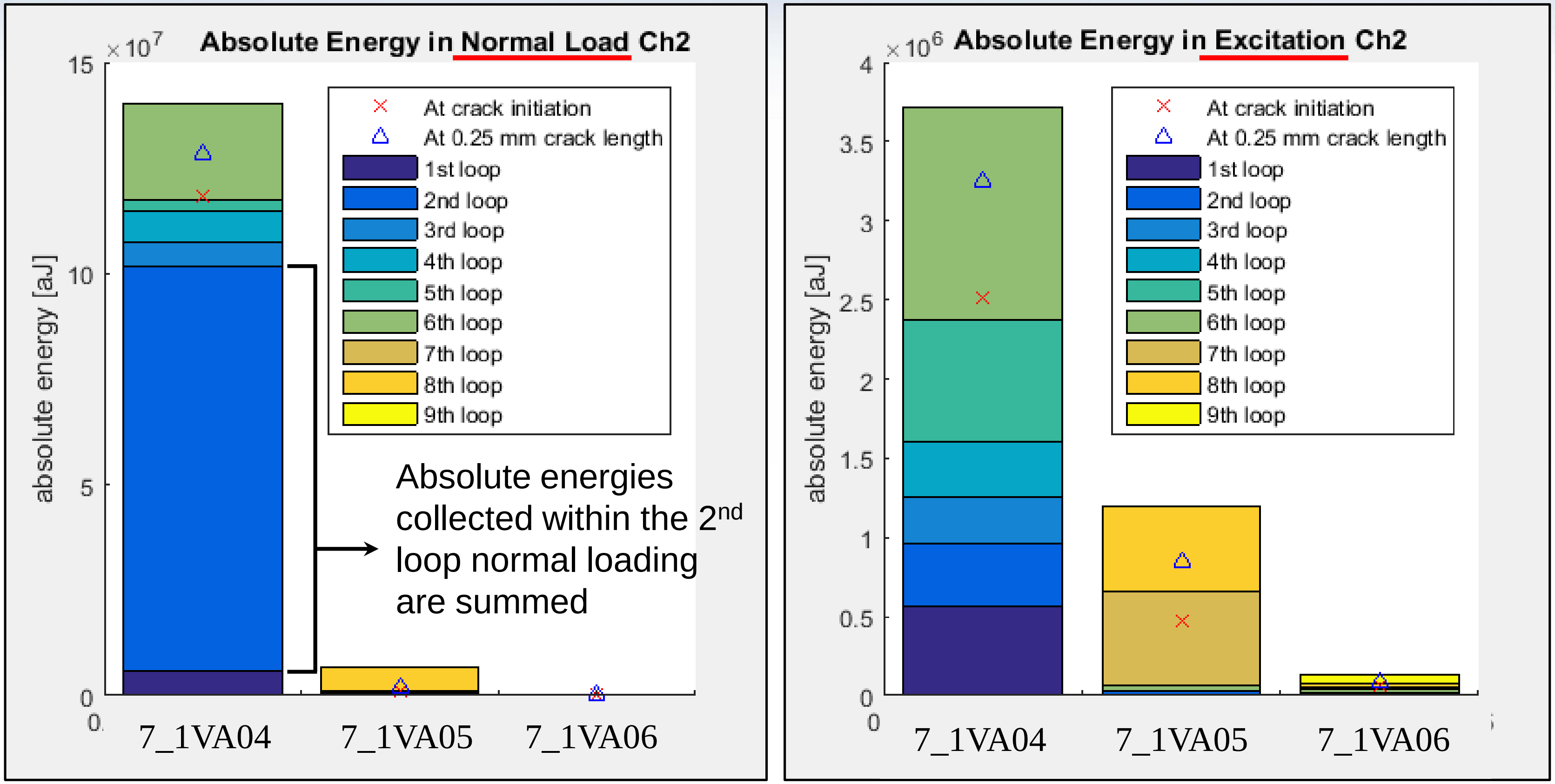



Fatigue life Analysis

Determine Fatigue life endurance

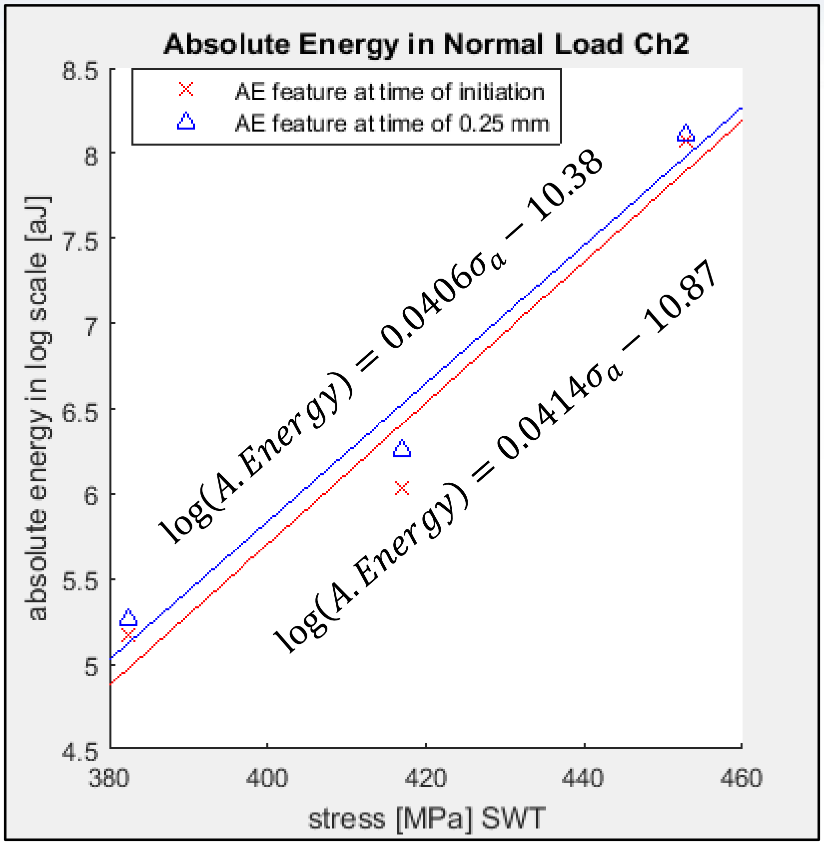
# Stage 2: Excitation Loading Fatigue Failure Endurance

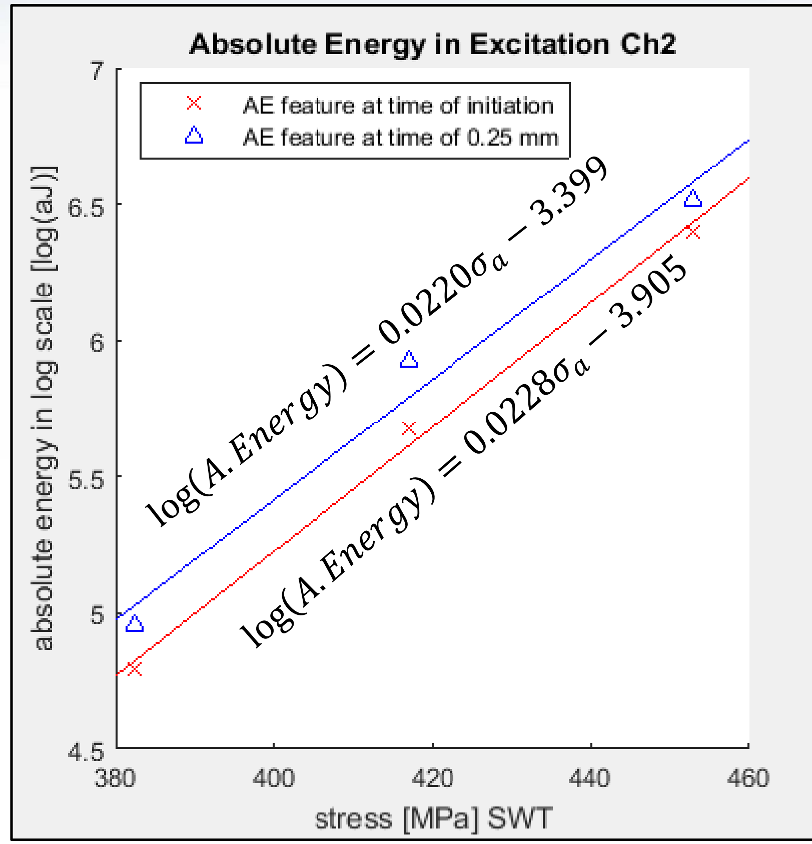
- AE features summed up to the point of determined fatigue life



# Stage 2: Excitation Loading Endurance vs. Stress

- The cumulative features at failure versus stress are correlated



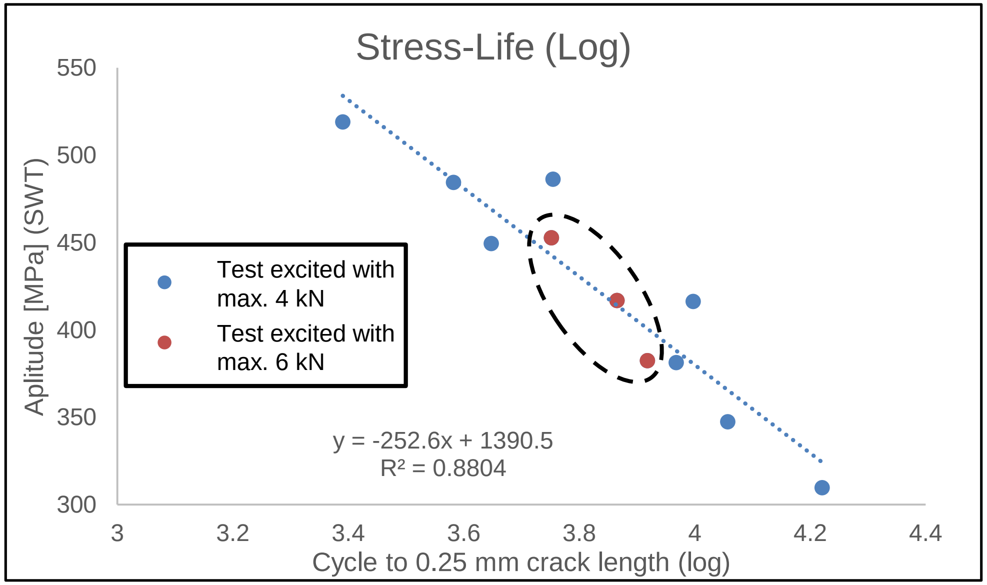



# Stage 2: Excitation Loading Proving Tests

- Additional tests with more spanning stress condition
  - Tested with lower excitation loading condition (max.: 4 kN) to mitigate possible damage from excitation
  - Less consistency seen at low loading excitation conditions

## Stress-life curve: damage in excitation

- No difference in test groups with two excitation condition
- Excitation loading has insignificant contribution to damage
- Additional tests near 6 kN underway



# Conclusions

- AE Features are good NDT surrogates for fatigue damage
- Two methods for AE signal analyses were investigated:
  - Information Entropy

    - AE waveform collected from a series of fatigue test were computed in information entropy

    - Information entropy and raw AE features uniquely correlate with normalized fatigue damage (MDD)
  - Excitation with AE Features

    - AE features collected from excitation has similar pattern to those of actual fatigue loading

    - Endurance to fatigue failure is determined with log-linear AE absolute energy

    - Excitation loading requires proper amplitude to reflect damage level

# Publications

- Journal Papers
  - Kahirdeh A, Sauerbrunn C, Yun H, Modarres M, A Parametric Approach to Estimation of the Acoustic Entropy during the Fatigue, International Journal of Fatigue, Vol. 100, Part 1, July 2017, p. 229-237
  - Christine M. Sauerbrunn, Ali Kahirdeh, Huisung Yun, Mohammad Modarres, Damage Assessment Using Information Entropy of Individual Acoustic Emission Waveforms during Cyclic Fatigue Loading, *Applied Sciences* 7.6, 2017

- Thesis
  - Sauerbrunn C, Evaluating information entropy from acoustic emission waveforms as a fatigue damage metric for Al7075-T6. M.S. thesis, 2016, Department of Mechanical Engineering, University of Maryland, College Park, MD

# Publications, Cont.

- CONFERENCE PAPERS

- Kahirdeh A, Sauerbrunn C, Modarres M (2015) Acoustic emission entropy as a measure of damage in materials. 35th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering, Potsdam, NY

- Sauerbrunn C, Modarres M (2015) Effects of material variation on acoustic emissions-based, large-crack growth model. 5th American Society for Nondestructive Testing Spring Research Symposium, New Orleans, LA

- Sauerbrunn C, Modarres M (2016) Estimating fatigue damage with acoustic emission entropy prior to a visible crack. Nondestructive Evaluation of Aerospace Materials and Structure, St. Louis, MO

- Kahirdeh A, Sauerbrunn C, Yun H, Modarres M (2016) Can energy dissipation and entropy production characterize damage evolution in loaded solid materials? 36th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering, Ghent, Belgium

# Publications

- - A. Kahirdeh, H. Yun, C. Sauerbrunn, M. Amiri, M. Modarres, Feature Extraction of the Acoustic Signals for Monitoring the Fatigue Damage of the Materials, International Conference on Fatigue Damage of Structural Material XI, Sep. 18-23, 2016, MA, USA

  - H. Yun, C. Sauerbrunn, A. Kahirdeh, M. Modarres, Damage Precursors from Acoustic Emission Parameters from Fatigue Loading, 14th International Conference on Fracture (ICF 14), June 18-23, 2017, Rhodes, Greece

  - Huisung Yun, Ali Kahirdeh, Christine M. Sauerbrunn, Mohammad Modarres, Entropic Approaches to Measuring Damage with Applications to Fatigue Failure and Structural Reliability, RAMS2018, Jan. 22-25, 2018, Nevada, USA (under review)