ORNL Crack-Related Development for Structural Assessment of Naval Aircraft

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Structures fail due to a variety of crack-related causes, and the life of an individual structure can only be estimated

- Fatigue
- Stress corrosion
- Corrosion fatigue
- Low temperature creep
- High temperature creep

Methods have been developed to manage fleets subject to crack-related failure, and each has its advantages and disadvantages

- **Safe flight is based on the probability of failure for the individual aircraft based on fleet statistics.**
  - **Characteristic: Aircraft is rated for certain number of flight hours, certain number of takeoffs/landings, etc.**
  - **Advantages: Assures low probability of failure for aircraft, allows assurance of fleet safety within reasonable limits**
  - **Disadvantages: Limits majority of fleet members' lifetimes to that of the "weakest" members of the fleet, assumes certain number of structural failures are inevitable.**

Methods have been developed to manage fleets subject to crack-related failure, and each has its advantages and disadvantages

- Damage Tolerance accepts initial presence of flaws, and determines their growth based on LEFM and projected operational and environmental effects
  - Characteristic: Flaws equal to the minimum detectable size by NDE are postulated, and fracture mechanics is used to predict future growth of these flaws, providing a basis for establishing future inspection intervals
  - Advantages: Based on fundamental physical mechanisms which are deterministic in nature; Obtains maximum useful life of member; Assures flight safety
  - Disadvantages:Requires frequent and expensive NDE of flight safety-related structures for flaws; Uncertainties associated with future operational and environmental conditions; Analytical difficulties with corrosion, WFD.

A new technique for assisting both methods by experimentally detecting the end of crack-related life has been discovered

- Basis in previously patented nonlinear mathematical techniques applied to electroencephalographic data to detect the onset of epileptic seizures in patients
- Similar methods applied to structural crack-related failure
- Datum selected for analyzing was hysteresis strain energy

Using this technique improves the advantages and decreases the disadvantages of both methods

- For structures managed according to safe flight methods, implementation of this new technique will:
  - Avoid the occurrence of probabilistic crack-related structural failures
  - Will utilize each member of an aircraft fleet to its maximum potential life, thereby significantly increasing the fleet average overall life

Using this technique improves the advantages and decreases the disadvantages of both methods

- For structures managed according to damage tolerance methods, implementation of this new technique will:
  - Increase the reliability of flaw growth detection by using more global detection approaches
  - Reduce the cost and frequency of full-scale fleet NDE for flaws

Significant ORNL-funded initial research has been conducted, with promising results

- Repeatable fatigue forewarning established under lab conditions for fiberglass, aluminum, and steel
- Repeatable fatigue forewarning established under lab conditions for simulated Multiple Site Damage (MSD) in 2024-T3 aluminum
- Technique proven to reliably forewarn for pristine and for corroded samples
- Technique shown to forewarn of both fatigue and stress corrosion failure
- Potential for spectrum loading application shown by “stairstep” loading testing
- Basis of technique in fracture mechanics established

A number of questions need to be answered to establish the potential for future field application

- Effect of fatigue frequency and loading spectrum
- Effect of environmental variation
- Effect of interaction of crack-related failure modes (fatigue, stress corrosion, corrosion fatigue, creep)
- Effect of mode of loading (tension, flexure, shear)
- Effect of crack growth mode (Mode I, II, III)

A method for sensing impending failure of fatigued structures has been discovered

- Basis: nonlinear analysis of cycle-to-cycle losses in strain energy
  - Nonlinear analysis previously used successfully to predict onset of brain seizures in epileptics (current ORNL/DOE patent)
- Potential benefit: prevention of crack-dominated failures
- Patent application filed for US Government
- Inventors:
  - Don Welch, Fracture Mechanics
  - Lee Hively, Nonlinear Mathematical Analysis
  - Ray Holdaway, Fiber Optic Strain Measurement

Current methods for assessing fatigue status of structures requires “experts” & judgments

- Current methods rely on locating and measuring cracks, and predicting crack growth, or using statistical lower bounds on residual strength to limit fleet use.
  - Requires frequent non-destructive inspection to locate and measure existing cracks
  - Requires knowledge of future loading to account for variations in extreme loads & complex models
  - Requires knowledge of future environments
- Uncertainty leads to conservatism & redundancy
  - Weight & cost penalty
  - Premature retirement of assets

NCGM is based on established fracture mechanics principles

- NCGM measures consumption of strain energy with each fatigue cycle (hysteresis strain energy).
- Energy consumption is caused by several factors, but changes are eventually dominated by surface energy of newly formed crack surfaces.
- Significant changes in energy loss rate (crack size) represents approach of failure.

NCGM offers a dramatically different approach for assessing fatigue

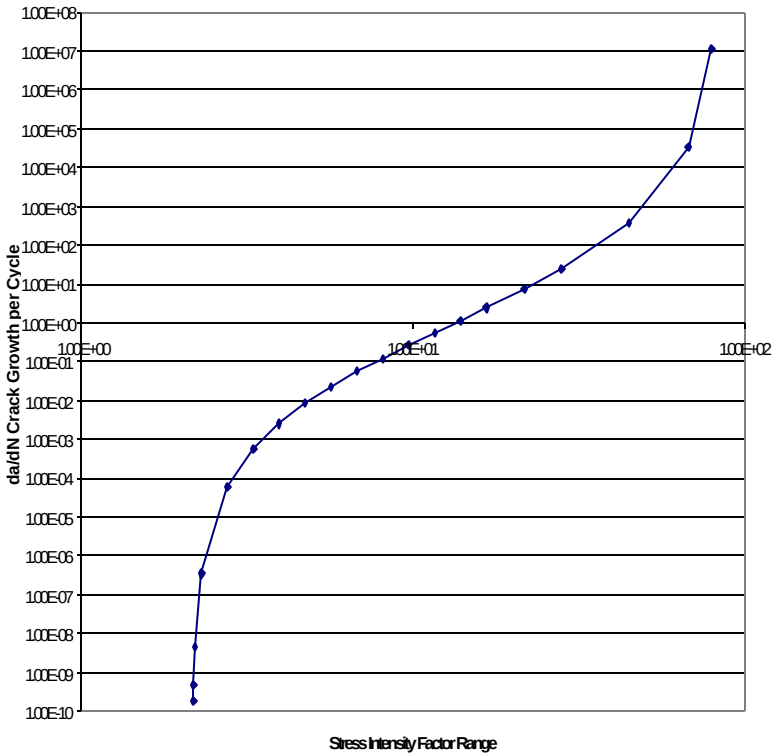
- Works with various materials (composite, aluminum, steel)
- Works equally well with uncorroded or corroded materials
- Works with multiple site damage (MSD) situations
- Works with widespread fatigue damage (WFD), which is difficult to analyze with conventional fracture mechanics
- Works with periodic overloads, which alter fatigue crack growth rate patterns
- Requires no inspections, analysis, or judgments

NCGM is based on fracture mechanics principles

- Crack growth is an energy exchange - strain energy to surface energy
- Griffith Relation $G = \frac{dU}{da} = \frac{K^2}{E}, K = s\sqrt{pa}$
- Fracture occurs when strain energy released by crack extension equals surface energy of newly created crack surfaces (material property G_c)

Fatigue crack growth occurs in 3 stages

- **Fatigue cracks grow in 3 stages, nucleation, steady growth, and tertiary growth**
- **Tertiary stage represents end of life**



The current method for fatigue monitoring is costly, time-consuming, and requires judgments

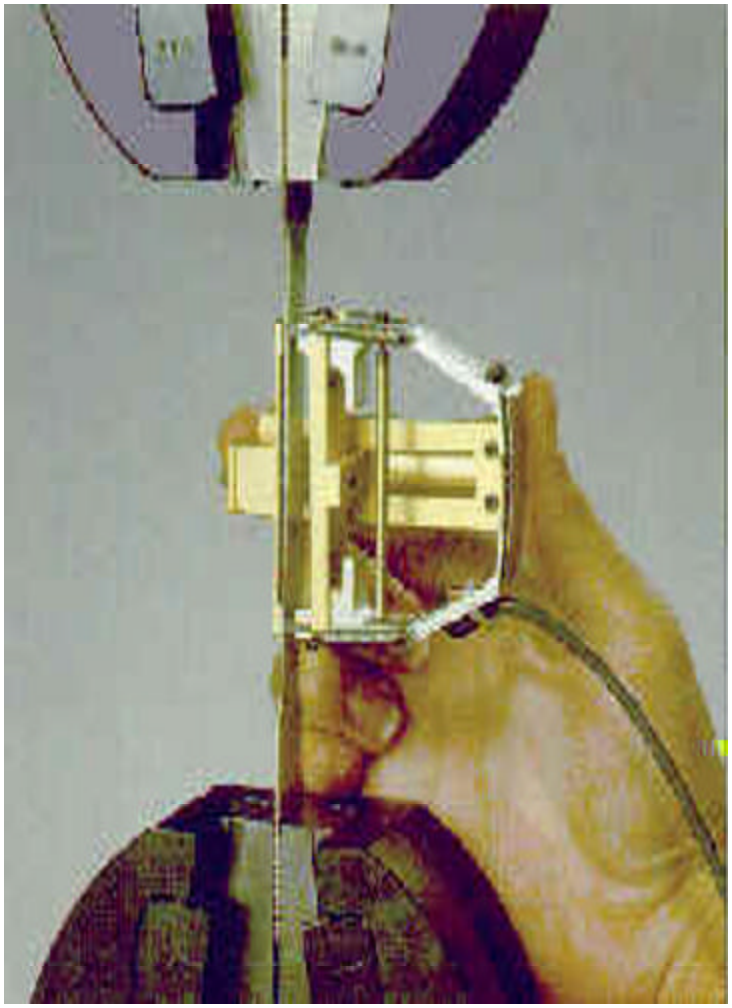
- Inspect structure for nucleated cracks
- Measure crack size and location, and calculate stress intensity factor, and predict time for growth to tertiary stage from fatigue crack growth rate curve
- Schedule new inspection interval at less than half this time
- Predictions of future fatigue crack growth require knowledge of future loadings and of future environmental accelerants

The NCGM method measures changes in hysteresis strain energy as an indication of fatigue crack growth rate

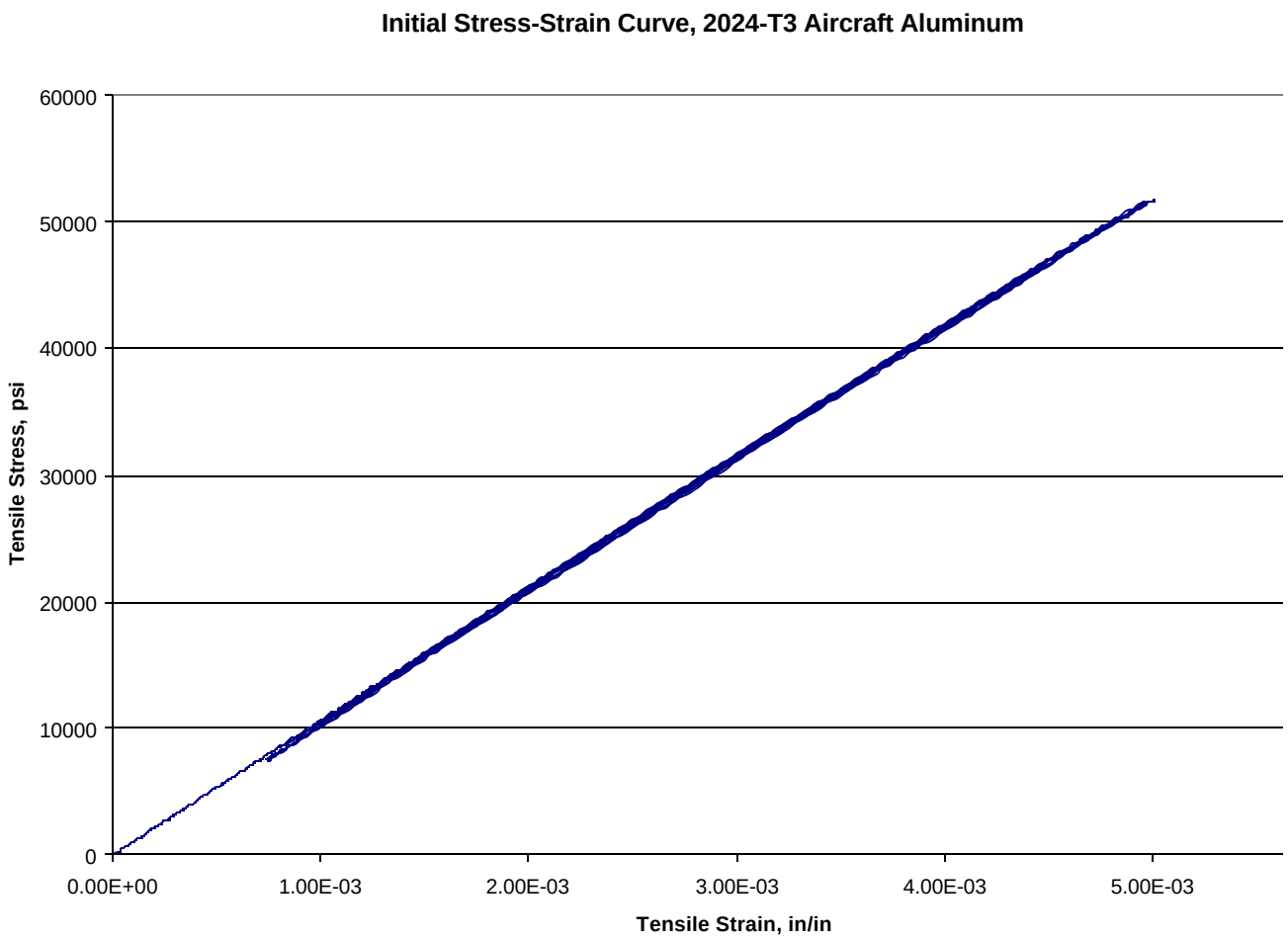
- Measure change in strain energy with each cycle (hysteresis strain energy = dU/dN = dU/da ´ da/dN)
- By measuring dU/dN, can infer da/dN = rate of crack growth
- By monitoring dU/dN, can tell when entering secondary or tertiary crack growth stage

NCGM relies on monitoring load and deflection of sample

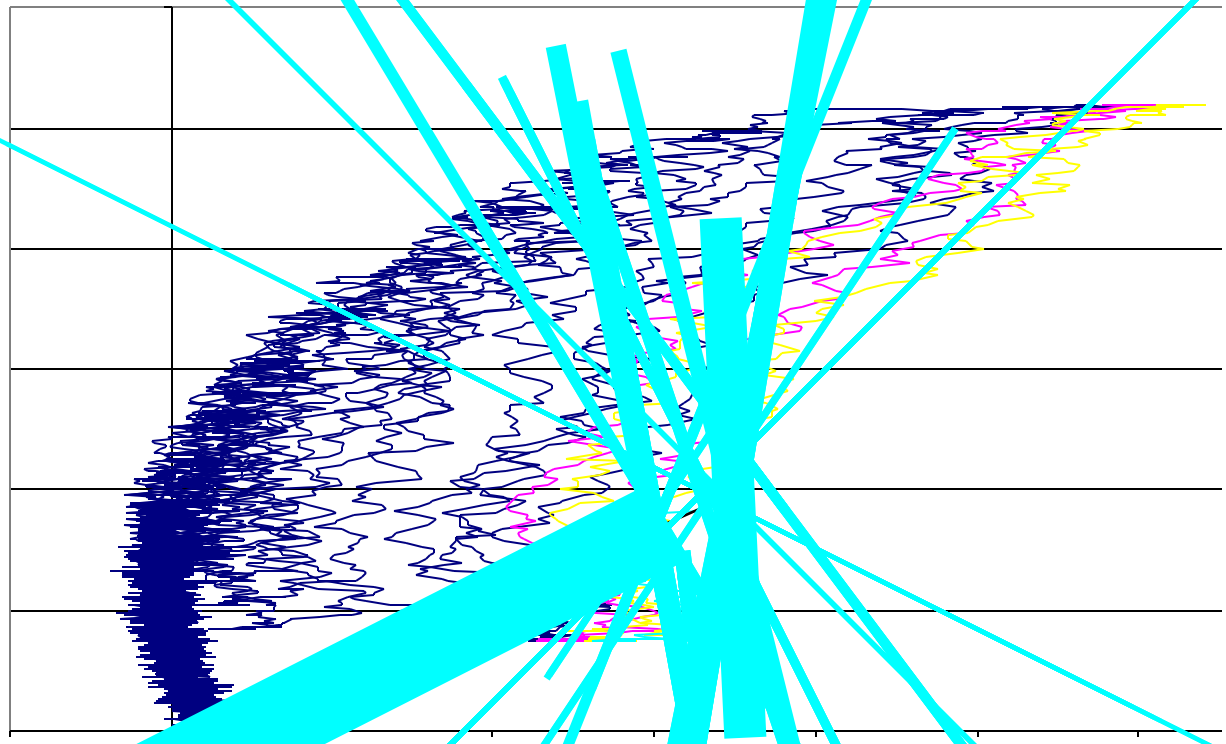
- For energy loss, measure load, P, and deflection, *
- Integrate ŠPd* over a loading cycle
- Integral is energy consumption per cycle, dU/dN
- Failure is indicated by significant <u>change</u> in dU/dN, not by value of dU/dN itself



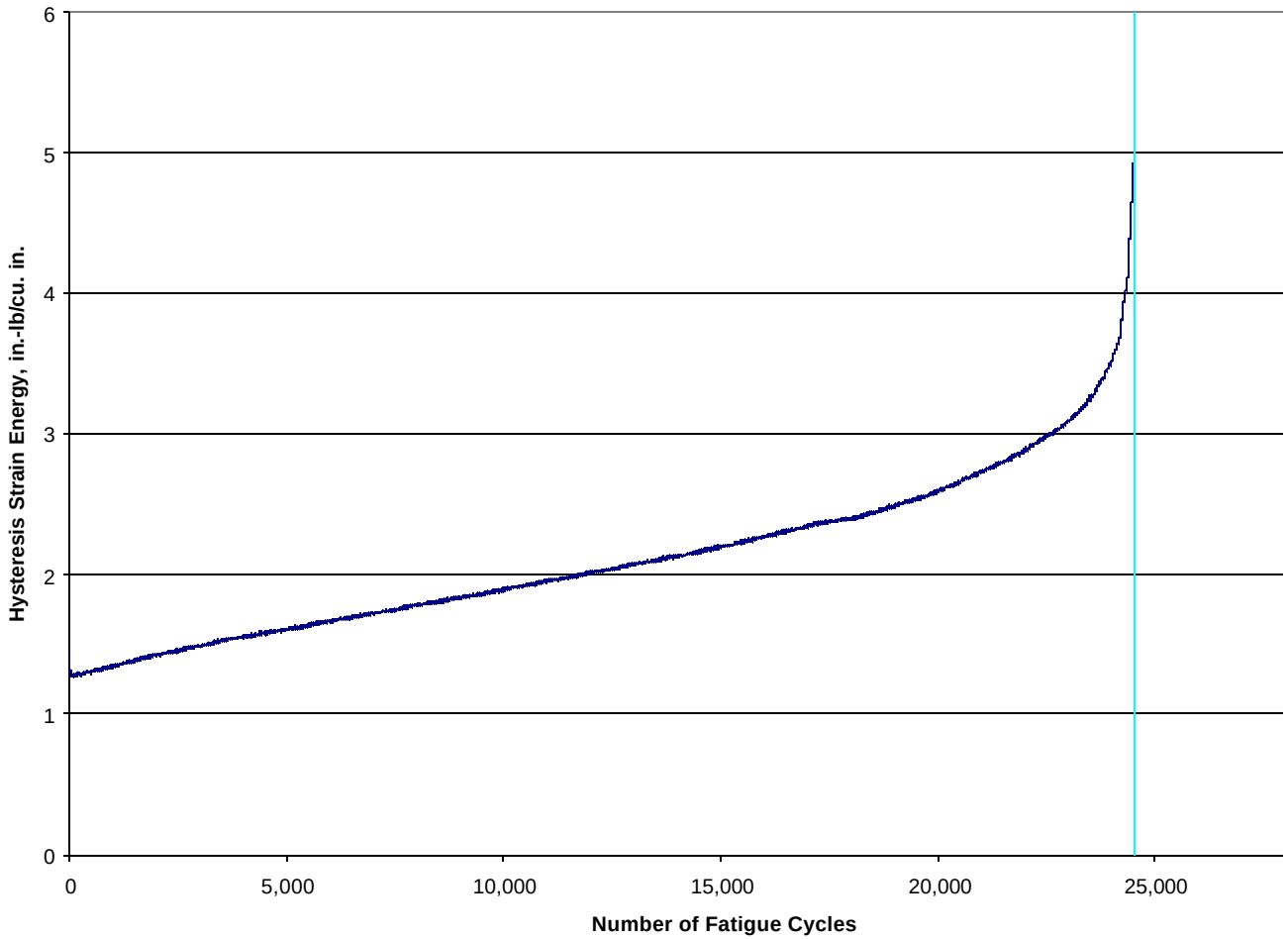
Initial Stress-Strain Curve



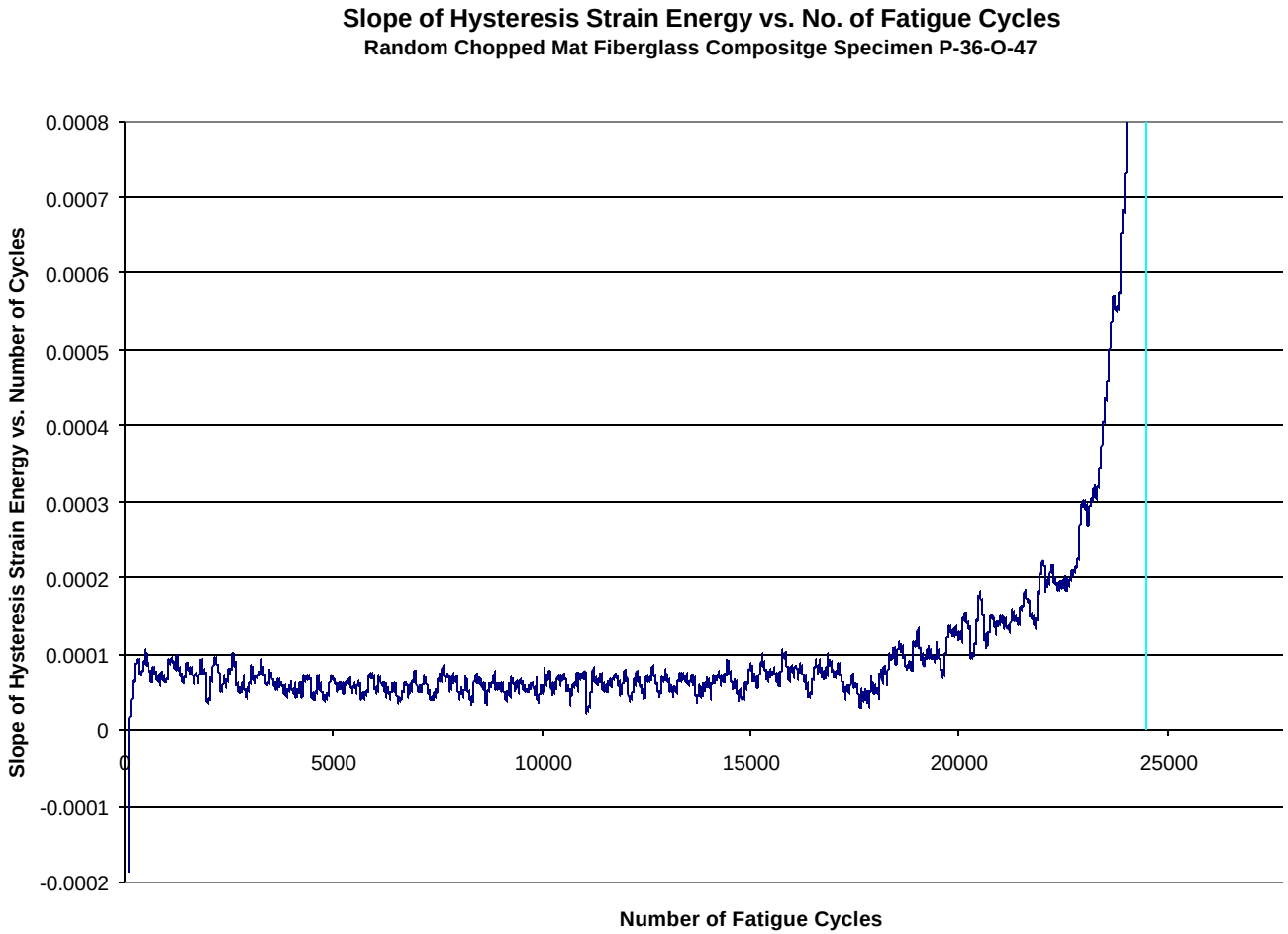
Hysteresis Energy in Stress-Strain



Initial Experiments with Random Chopped Mat Fiberglass Composites

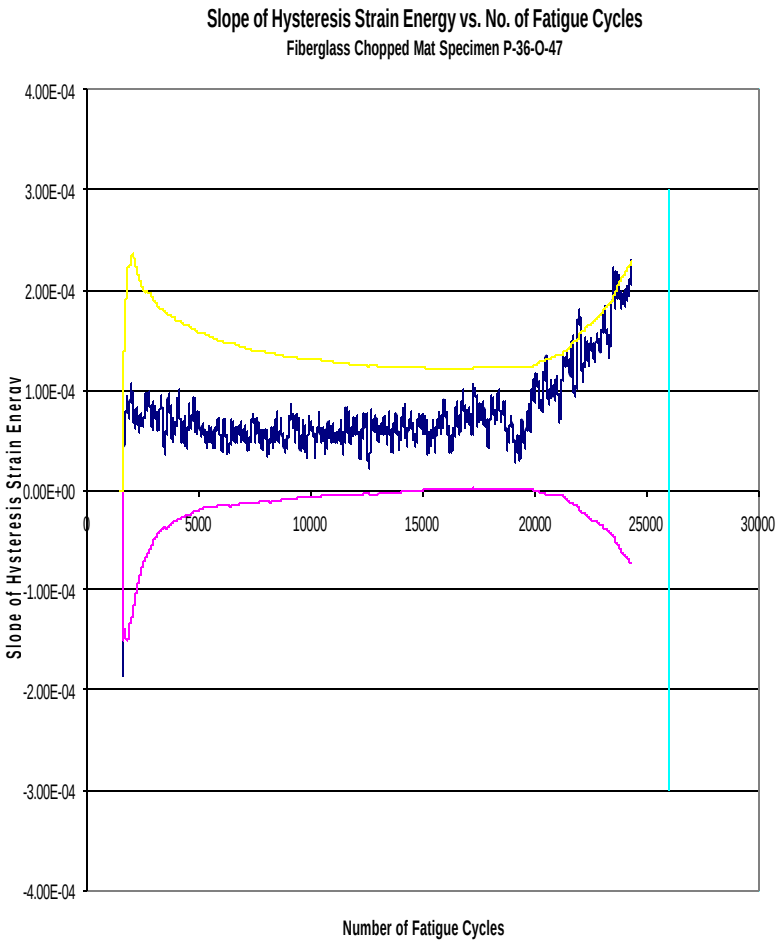


Sudden Increase in Slope of Hysteresis Strain Energy Reveals Imminent Fatigue Failure



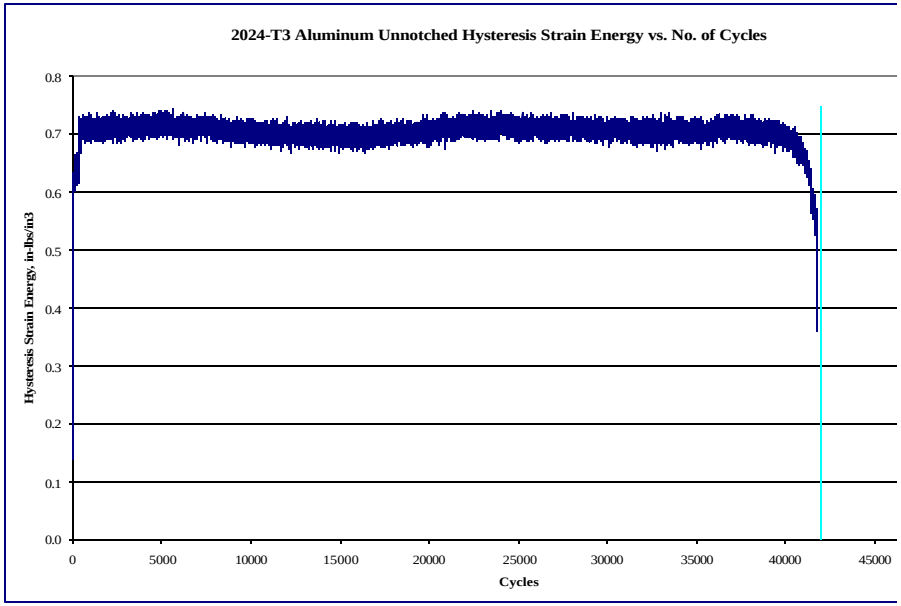
Statistical Methods Determine Fatigue Failure Point

- Glass fiber/polymer matrix composite
- Measure dU/dN=dU/da*da/dN
- $=G_c$*da/dN
- Slope of dU/dN vs.. No. of cycles ± 4F bounds detects change in crack growth rate
- Forewarning with 22% life remaining

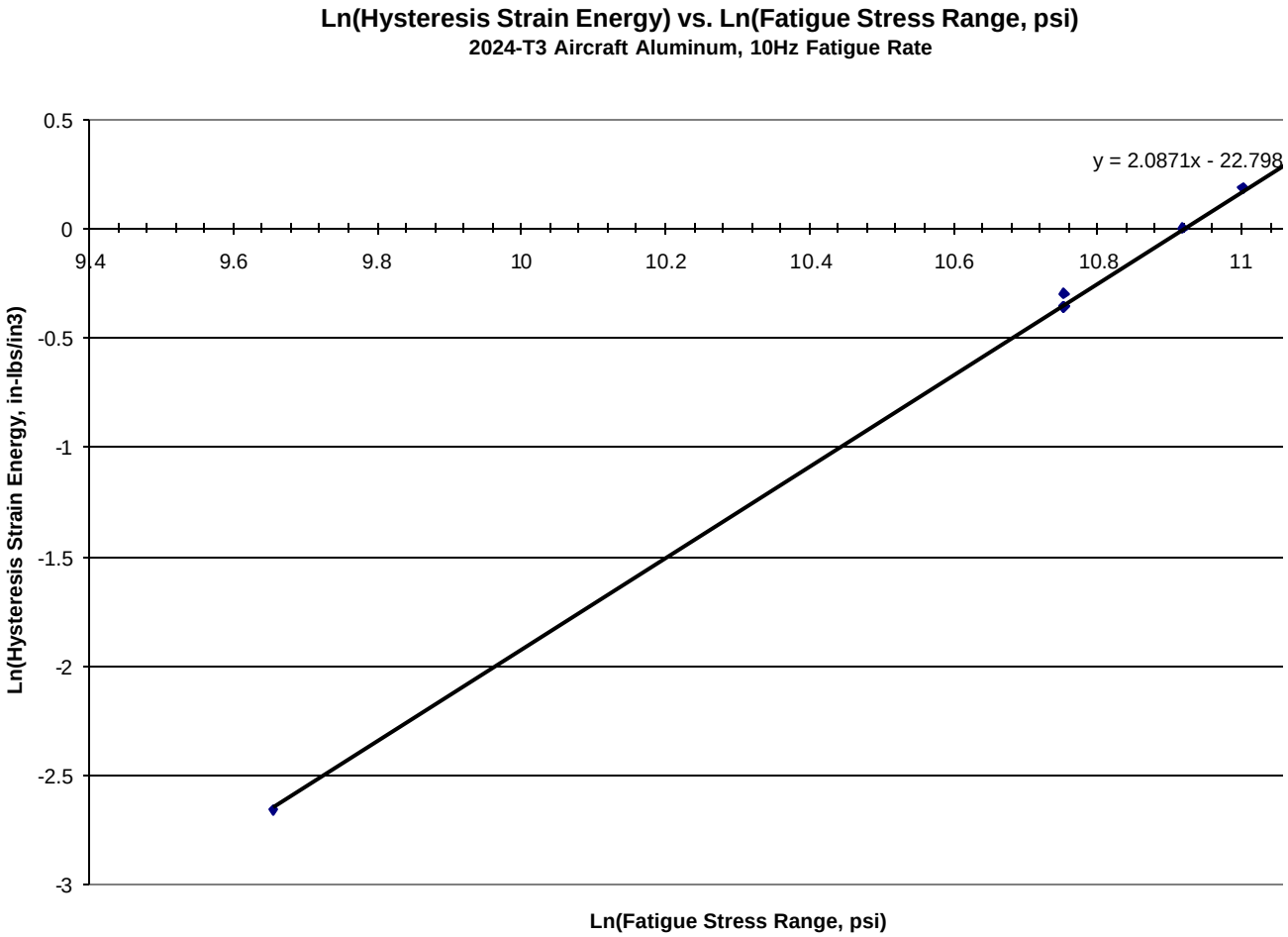


Additional experiments have verified the NCGM technique with aircraft aluminum

- Tensile fatigue tests with 2024-T3 Al coupons, 0.090” thk., L-T orient., (K/C-135 fuselage skin matl.)
- Similar result to composite, HSE decrease at failure, lower residual HSE, less forewarning (1-5% of fatigue life, for no stress concentrator)

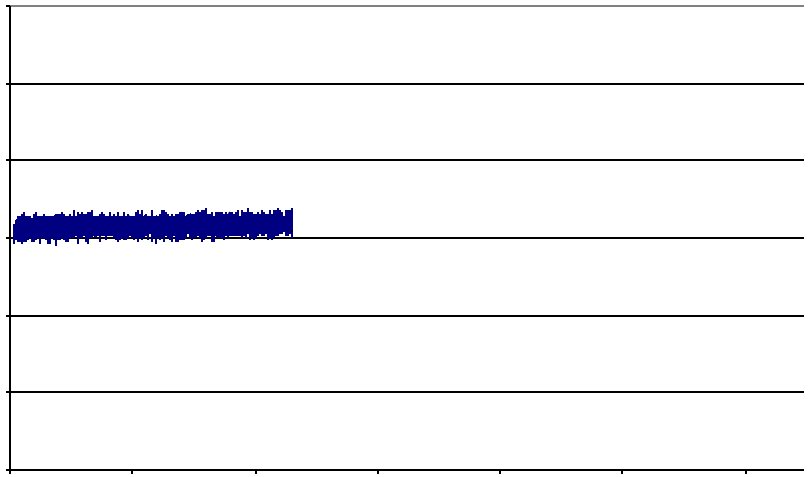


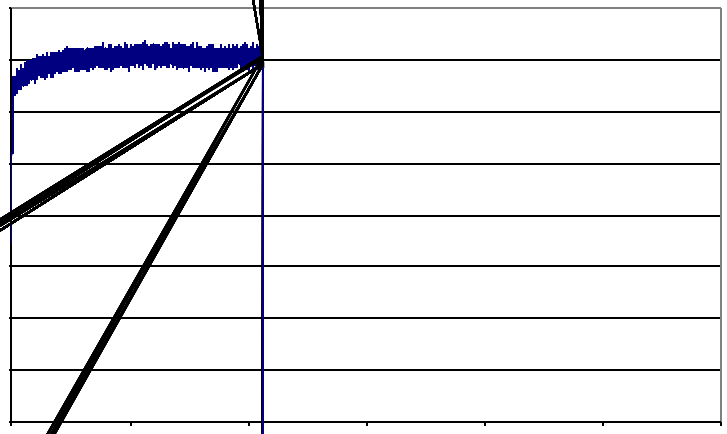
Residual HSE Level depends on fatigue stress level squared



Simulated Multiple Site Damage specimens were also successfully tested

- Similar aluminum coupons were tested with central holes:
- d/w=0.1,d/t=0.6
- Results are similar to pristine unnotched AL
  - Lower residual HSE
  - Earlier forewarning (typically 8-14%of life)
  - Forewarning related to stress level



Simulated Salt Water Corroded specimens were also successfully tested

- Similar unnotched corroded aluminum coupons were tested with thick. reduction of 10%
- Results are similar to pristine unnotched AL
  - Similar residual HSE
  - Similar forewarning (typically 1-5%of life)