New Technology for Periodic or Real Time Monitoring of Crack-Related Life of Structures

Applicability to USAF Aging Aircraft Program

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This presentation has two basic objectives

- To provide AFRL personnel with a general background of ORNL development in Aging Aircraft techniques, and to explore USAF applications of this technology
- To provide information to AFRL personnel sufficient to allow them to formulate their recommendations on the joint Tennessee Air National Guard (TN-ANG) /ORNL Aging Aircraft proposal, “Condition Assessment of Aircraft Structures”, by 25 Feb, 2000.

Background to Aging Aircraft Problems

A common element to many structural failures are cracks, 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 cracks, and each has its advantages and disadvantages for cost, safety, and operability

- **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 cracks, and each has its advantages and disadvantages

- **Damage Tolerance accepts initial presence of flaws, and determines their growth based on Linear Elastic Fracture Mechanics (LEFM) and projected operational and environmental effects**
  - **Characteristic: Flaws equal to the minimum detectable size by Nondestructive Inspection (NDI) 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 NDI of flight safety-related structures for flaws; Uncertainties associated with future operational and environmental conditions; Analytical difficulties with corrosion, Multiple Site Damage (MSD), and Widespread Fatigue Damage (WFD).**

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

- Structural application modeled on previously patented nonlinear mathematical techniques applied to electroencephalographic (EEG) data to detect the onset of epileptic seizures in patients
- Similar method applied to structural crack-related failure
- Datum selected for analyzing was hysteresis strain energy
- US patent application filed with US Government rights reserved (patent pending)

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 NDI for flaws**

Significant ORNL-funded initial development 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 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

Technical Basis for ORNL Nonlinear Crack Growth Monitoring Technique (NCGM)

A new 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 unanticipated 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**

Nonlinear Crack Growth Monitoring (NCGM) is based on established fracture mechanics principles

- NCGM measures consumption of hysteresis strain energy with each fatigue cycle (hysteresis strain energy).
- Energy consumption is caused by two primary factors
  - Thermoelastic damping
  - Fatigue crack growth surface energy consumption
- Significant changes in total energy loss rate (crack size) represents approach of failure.
- Since this technique measures changes in HSE, not the value of HSE itself, the technique can be applied at any time in a structure's life.

Current methods for assessing fatigue status of structures requires estimates & 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 offers a dramatically different approach for assessing fatigue

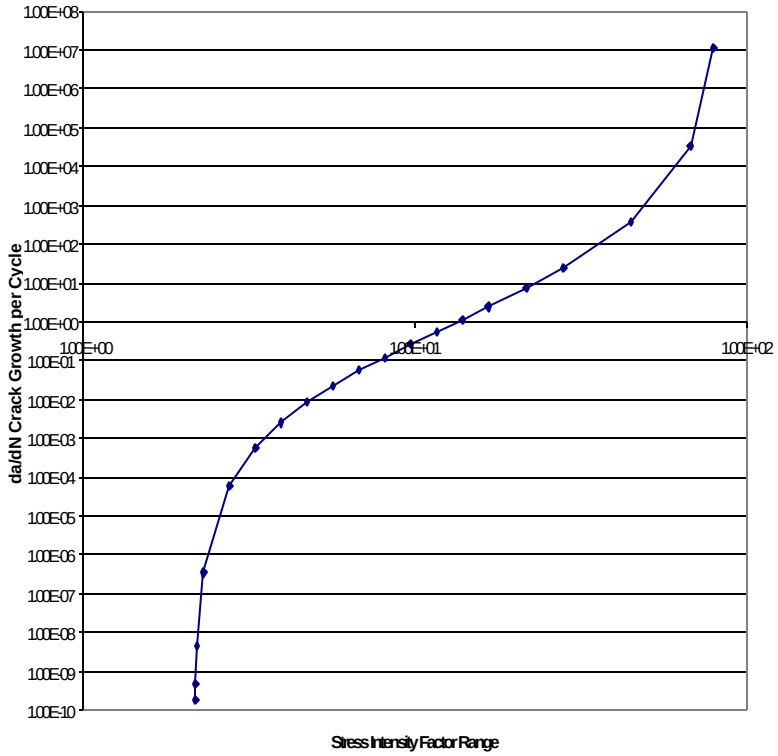
- Works with various materials (composite, aluminum, steel)
- Works equally well with uncorroded or corroded materials
- Works with multiple site damage (MSD) situations
- Works with widespread fatigue damage (WFD), which is difficult to analyze with conventional fracture mechanics
- Works with periodic 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 uncertainty of the crack-related life of an individual structure is due to the wide variation in initial nucleation site sizes

- Given the sigmoidal form for the fatigue crack growth rate relation, the integrated time (cycles) to a critical size is strongly dependent on the starting initial nucleation flaw size
- Individual nucleation flaw sizes in otherwise pristine structures can vary over many orders of magnitude, leading to considerable variation in fatigue life of individual elements of a fleet of structures

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

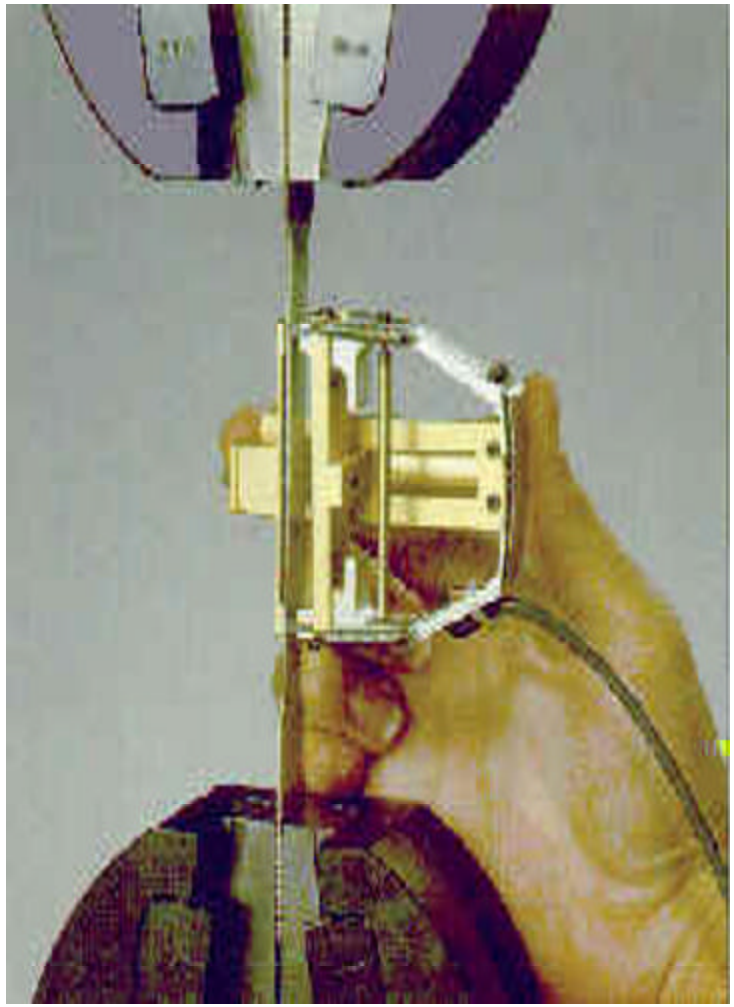
- Measure change in strain energy with each cycle (hysteresis strain energy = dU/dN = dU/da ´ da/dN)
- By measuring dU/dN, can infer da/dN = rate of crack growth
- By monitoring dU/dN, can tell when entering tertiary crack growth stage

Nonlinear mathematics are used to help extract impending changes in noisy data

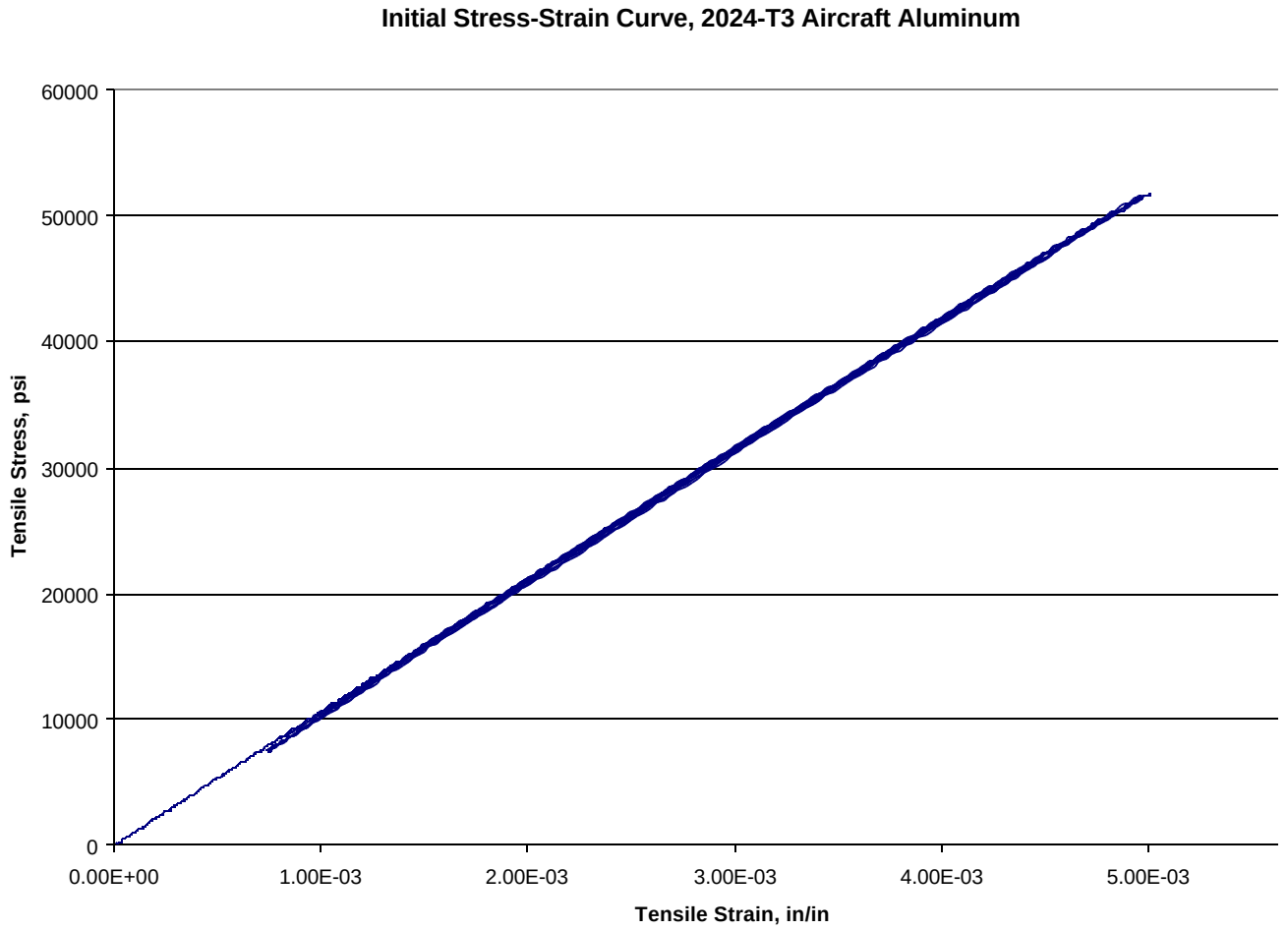
- Increased forewarning can be obtained by considering slope or curvature of underlying hysteresis strain energy (HSE) vs. cycles curve, rather than the HSE vs. cycles curve itself.
- Calculation of derivatives of noisy data is assisted by using ORNL-patented nonlinear mathematical technique to pre-process HSE vs. cycles data to filter out noise and to determine the underlying data trend in the form of a quadratic model, from which successive derivatives of the data can be obtained.

NCGM relies on monitoring load and deflection of sample

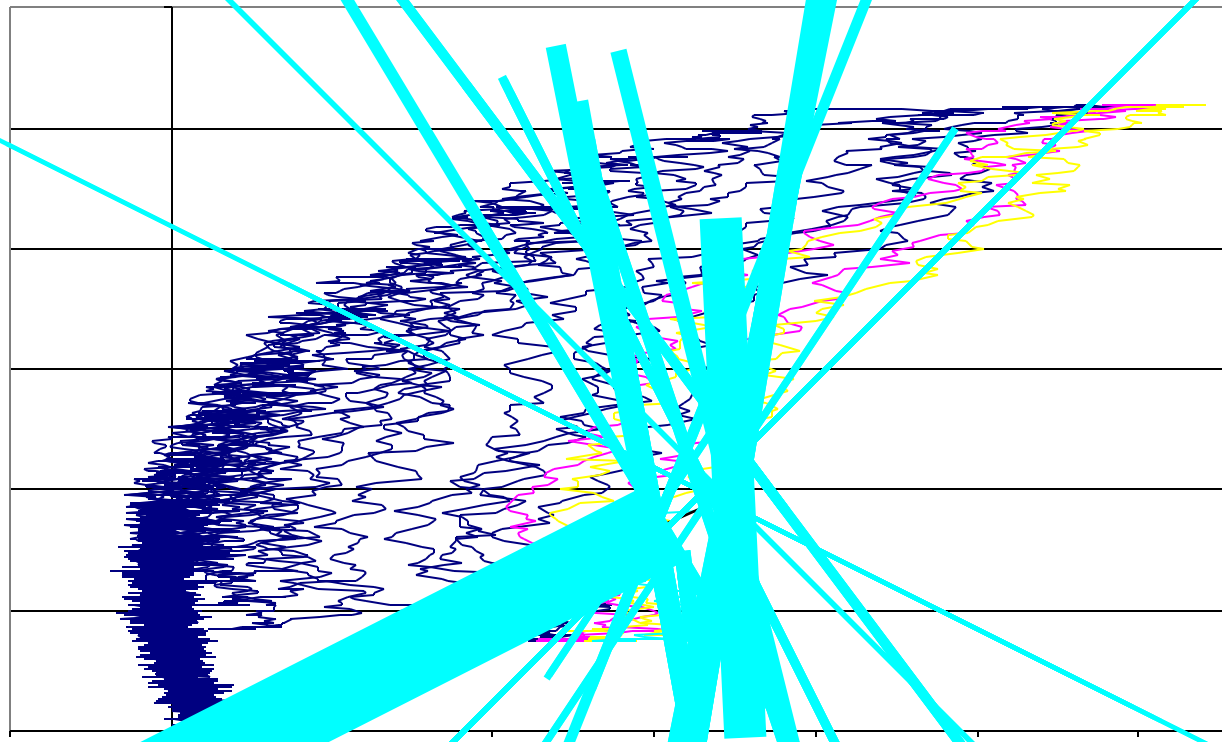
- For energy loss, measure load, P, and deflection, *
- Integrate ŠPd* over a loading cycle
- Integral is energy consumption per cycle, dU/dN
- Failure is indicated by significant change in dU/dN, not by value of dU/dN itself



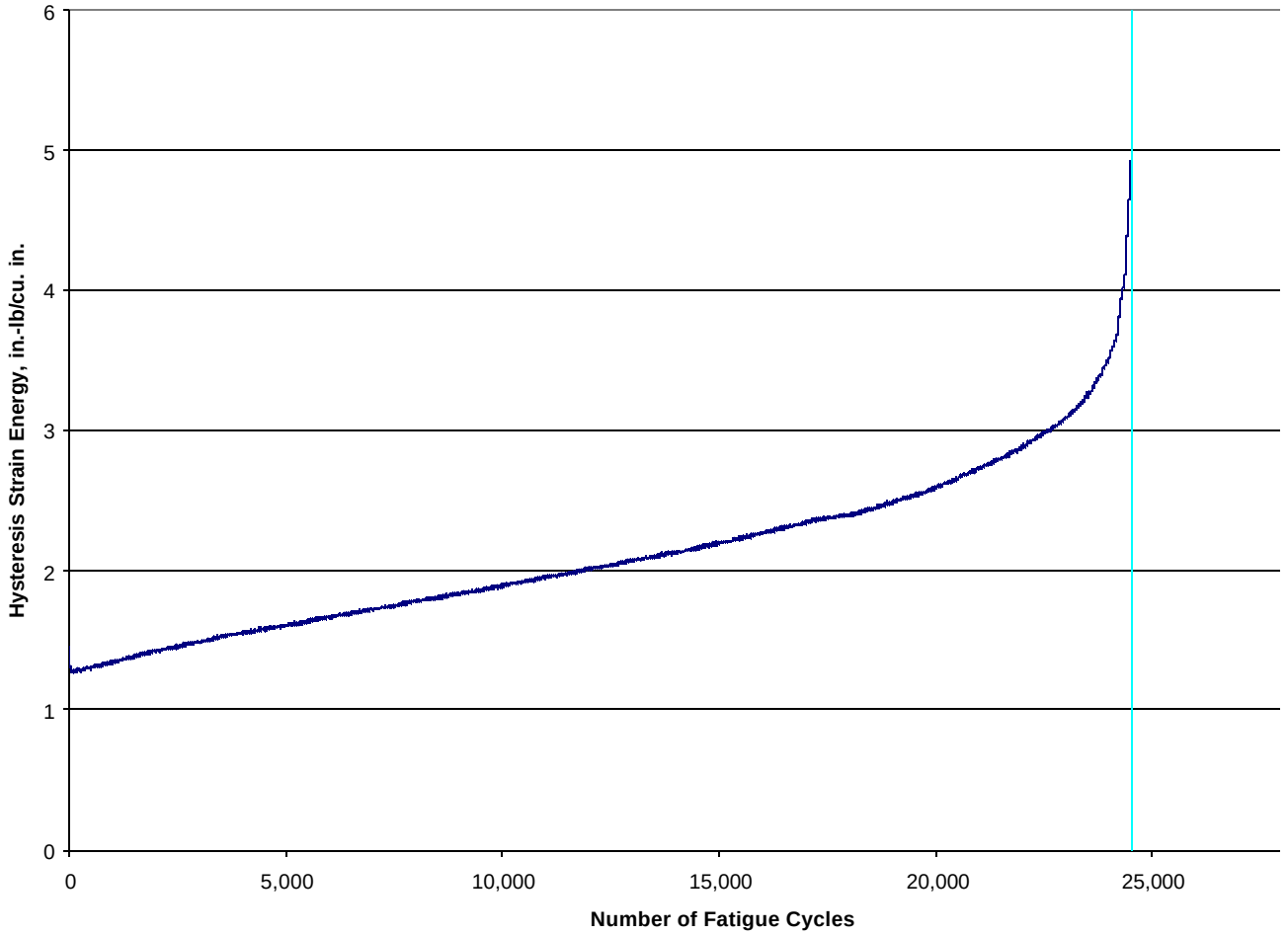
Initial Stress-Strain Curve



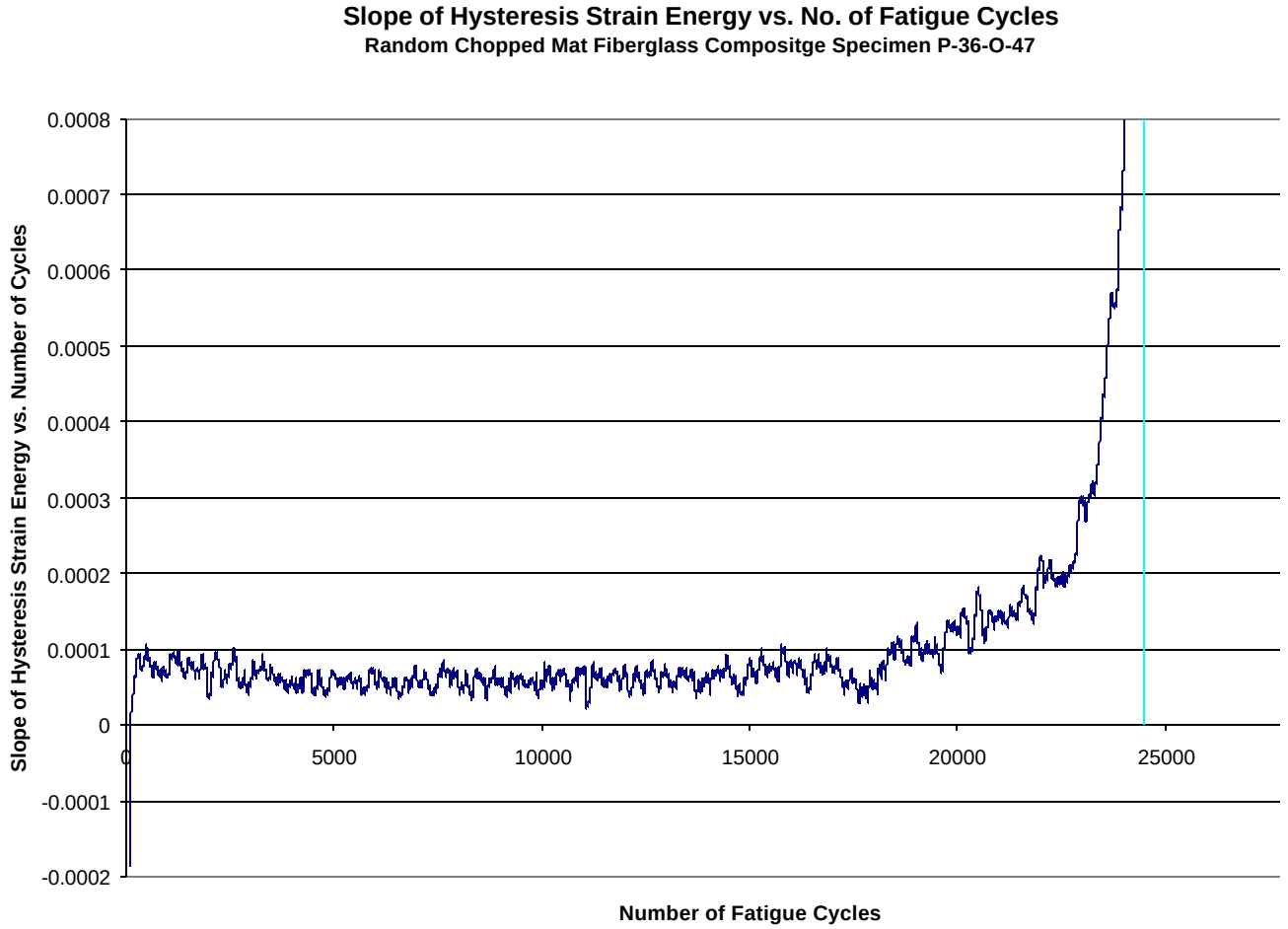
Hysteresis Energy in Stress-Strain



Initial Experiments with Random Chopped Mat Fiberglass Composites

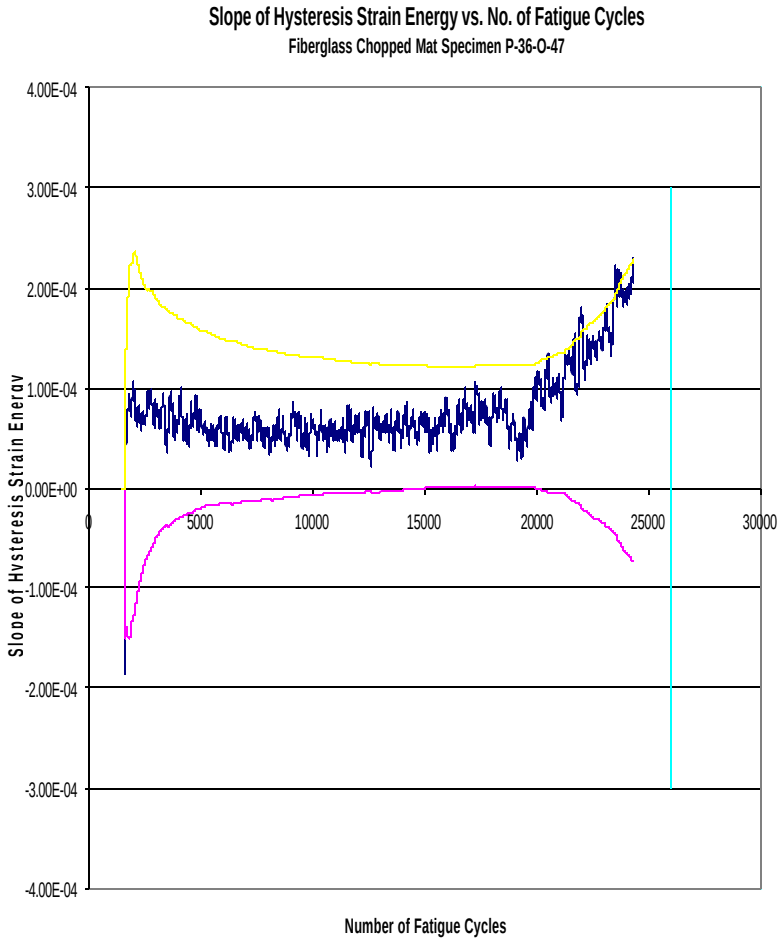


Sudden Increase in Slope of Hysteresis Strain Energy Reveals Imminent Fatigue Failure



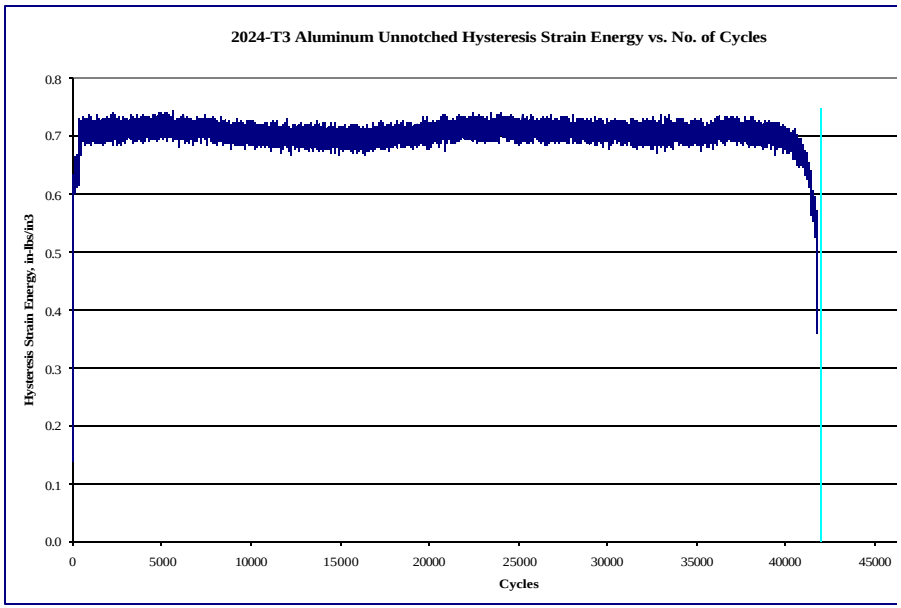
Statistical Methods Determine Fatigue Failure Point

- 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



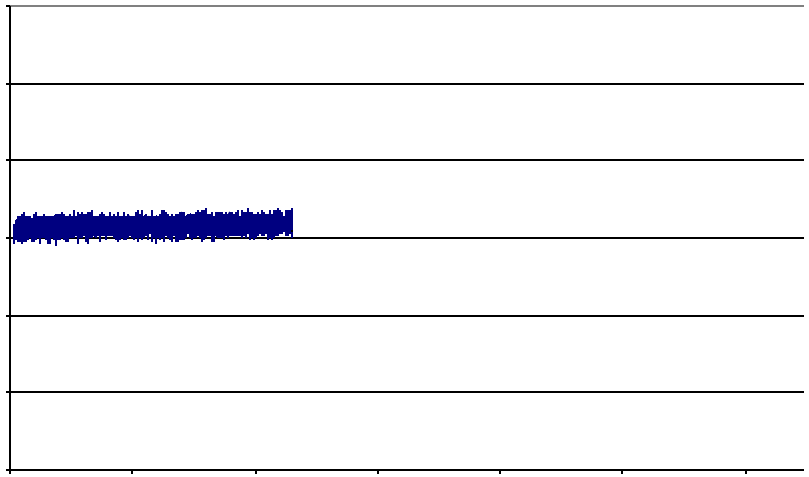
Additional experiments have verified the NCGM technique with aircraft aluminum

- 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)



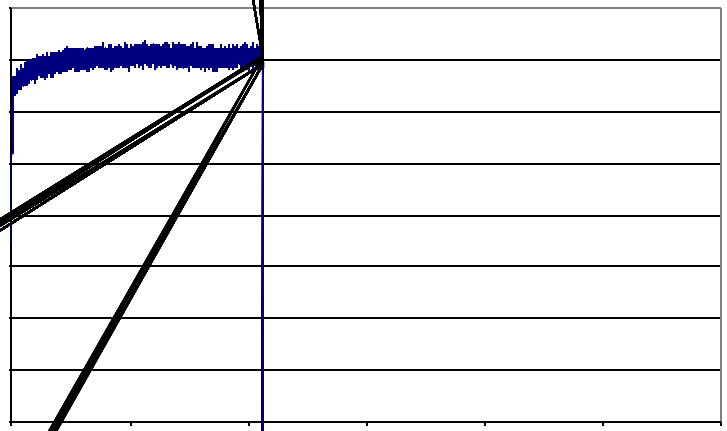
Simulated Multiple Site Damage specimens were also successfully tested

- 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

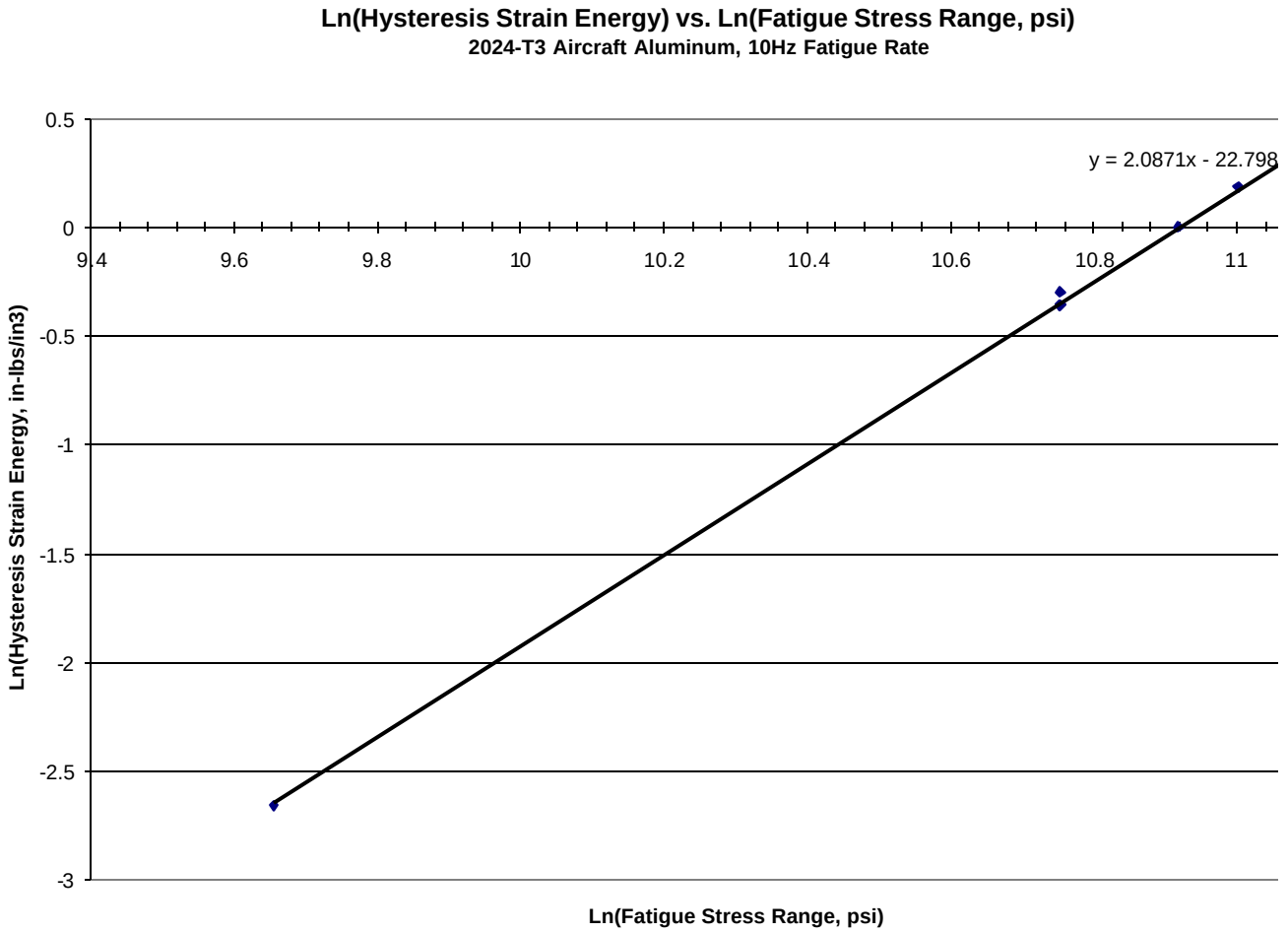


Simulated Salt Water Corroded specimens were also successfully tested

- 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)

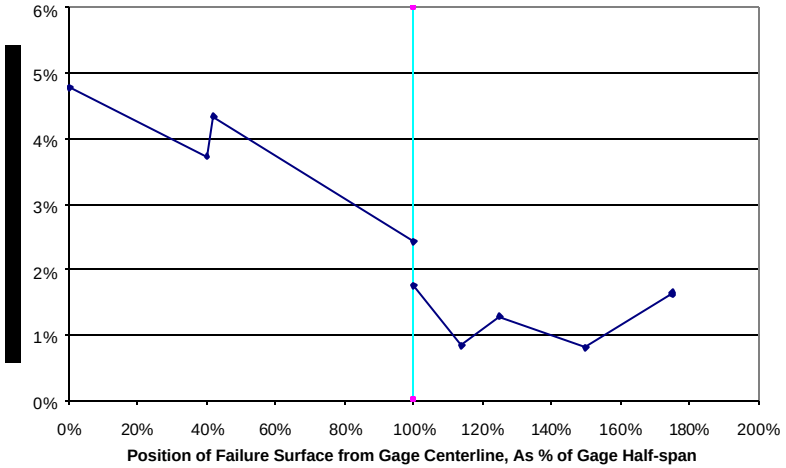


Residual HSE Level depends on fatigue stress level squared



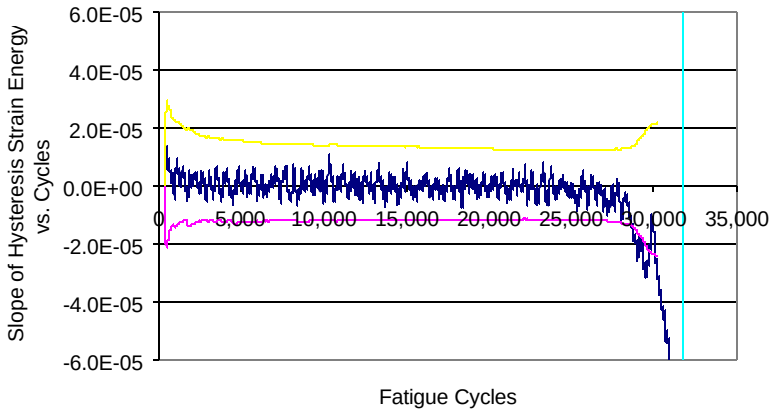
How close must deflection sensor be to critical defect?

- Deflection/strain sensor must be located closely enough to critical defect so that the increase in total energy consumption due to tertiary crack growth is not “swamped” by measuring a large amount of unrelated damping energy nearby
- Exact answer depends on application

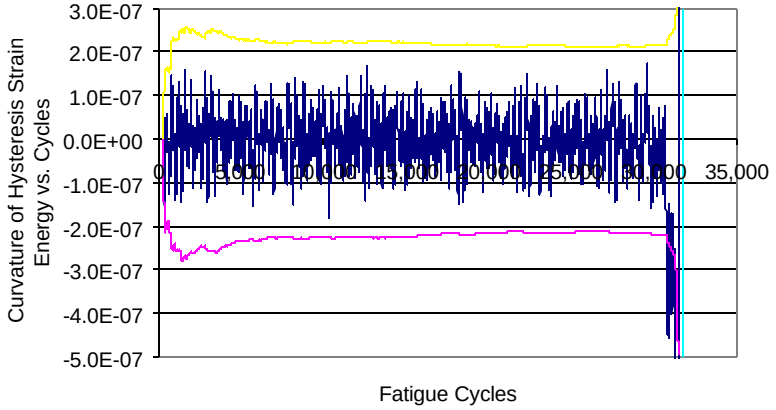


NCGM shows statistical exceedance for monitoring beginning at any point during fatigue life - Monitoring begins at 0% of fatigue life

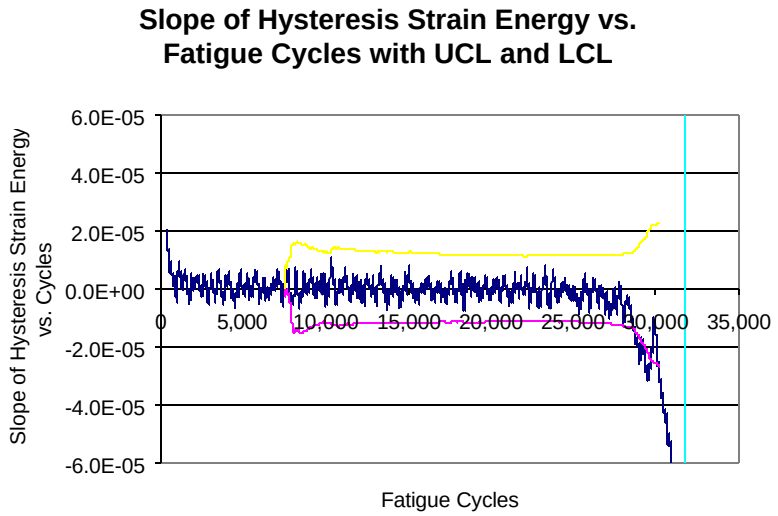
Slope of Hysteresis Strain Energy vs. Fatigue Cycles with UCL and LCL

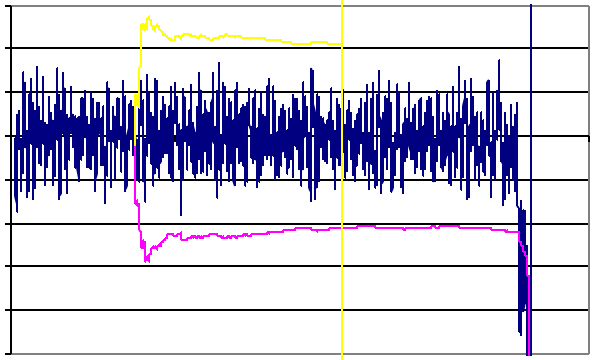


Curvature of Hysteresis Strain Energy vs. Fatigue Cycles with UCL and LCL

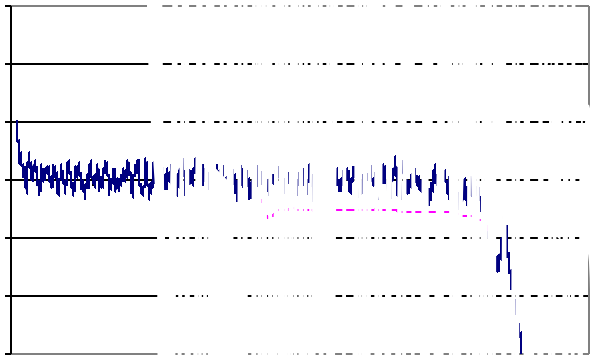


NCGM shows statistical exceedance for monitoring beginning at any point during fatigue life - Monitoring begins at 25% of fatigue life



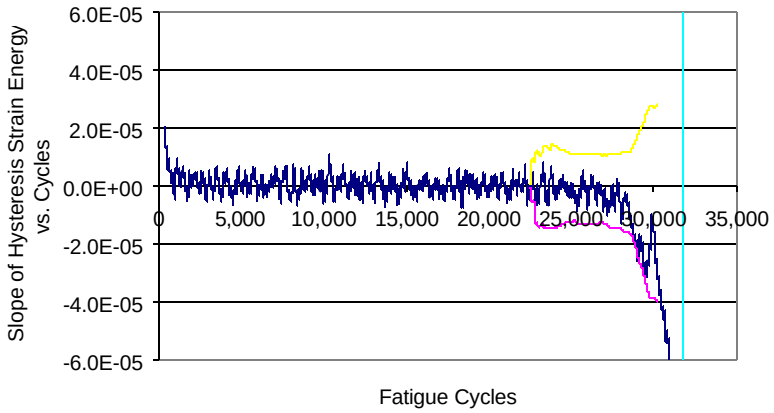


NCGM shows statistical exceedance for monitoring beginning at any point during fatigue life - Monitoring begins at 50% of fatigue life

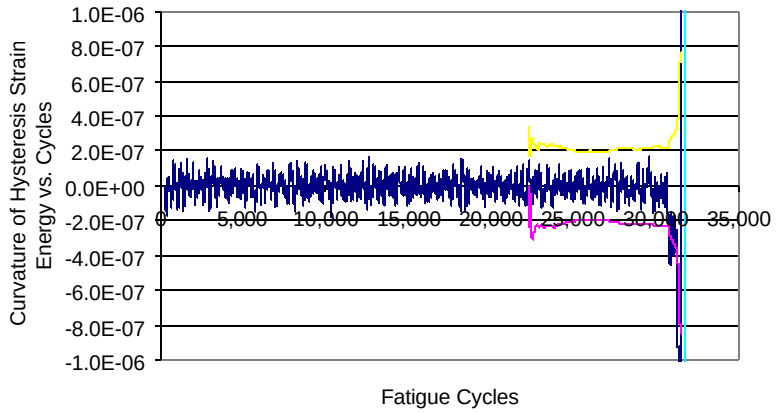


NCGM shows statistical exceedance for monitoring beginning at any point during fatigue life - Monitoring begins at 75% of fatigue life

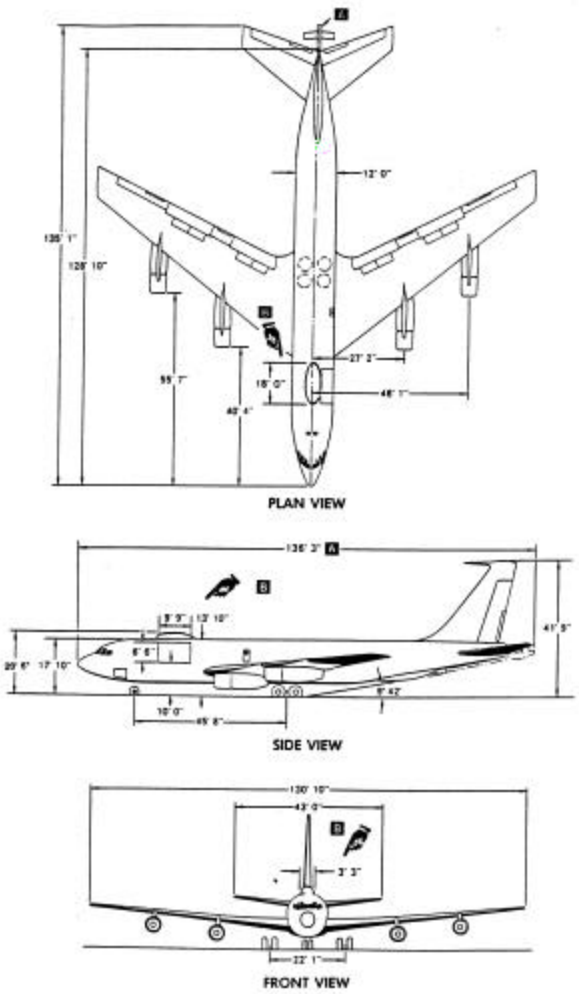
Slope of Hysteresis Strain Energy vs. Fatigue Cycles with UCL and LCL



Curvature of Hysteresis Strain Energy vs. Fatigue Cycles with UCL and LCL



There is a potential for immediate application to the KC-135 stringer tie fatigue crack problem



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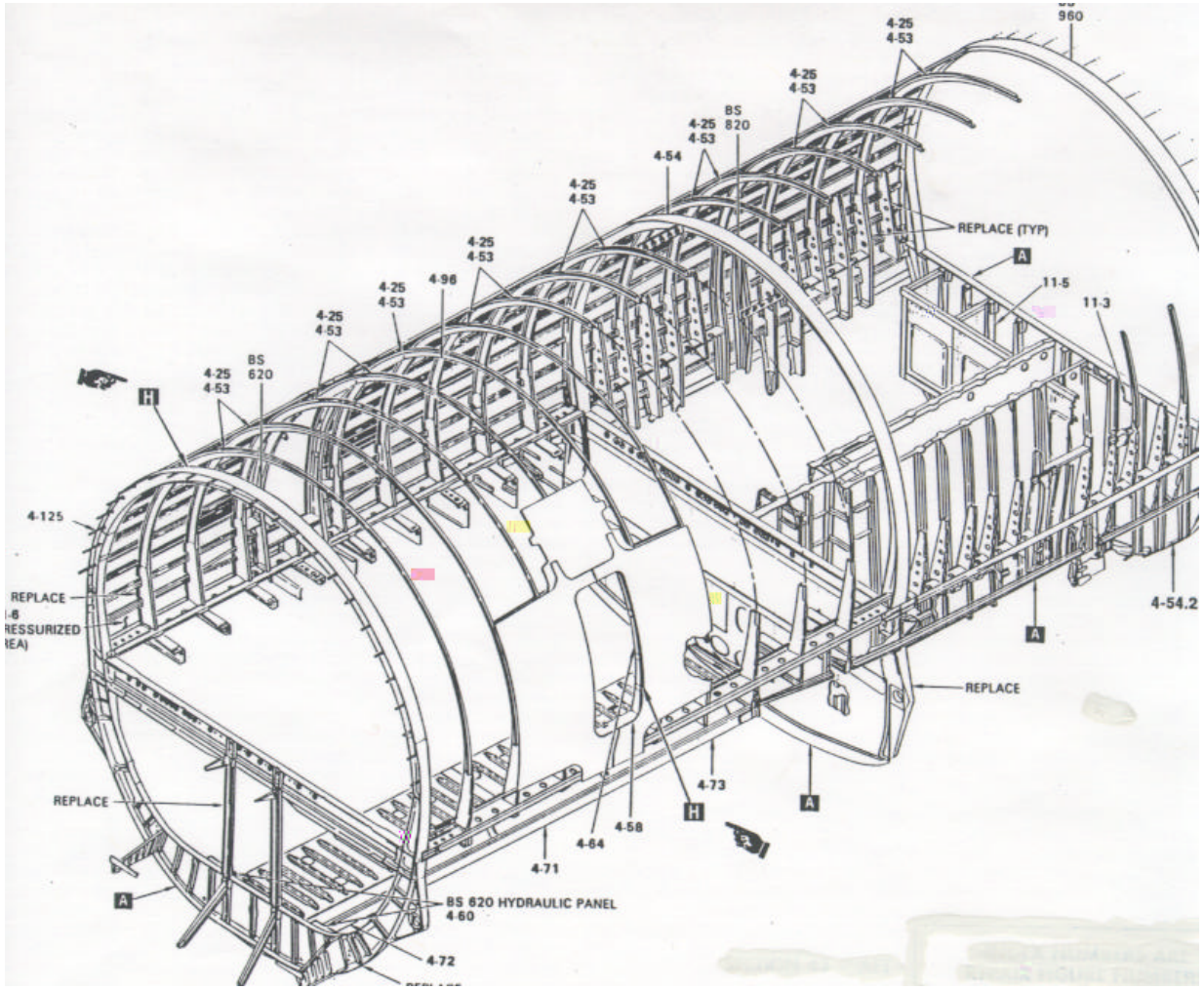

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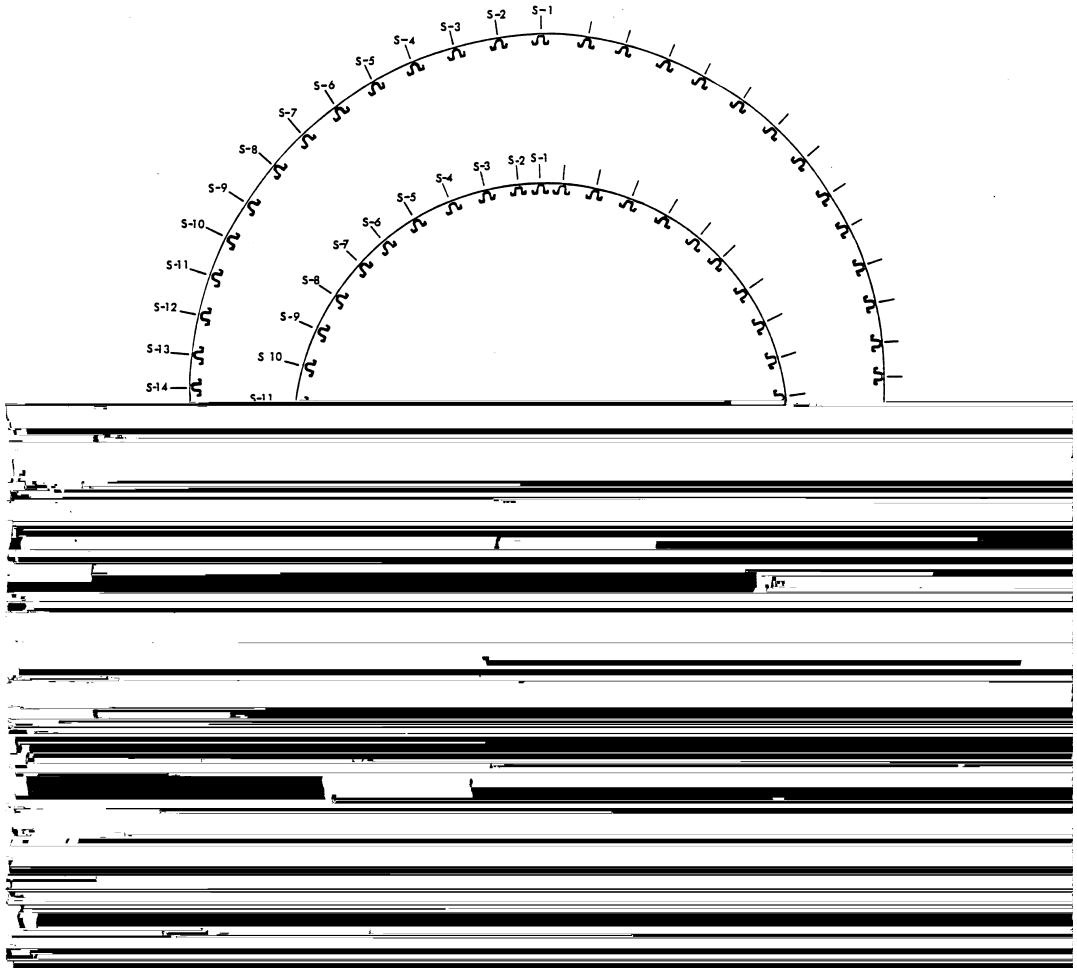

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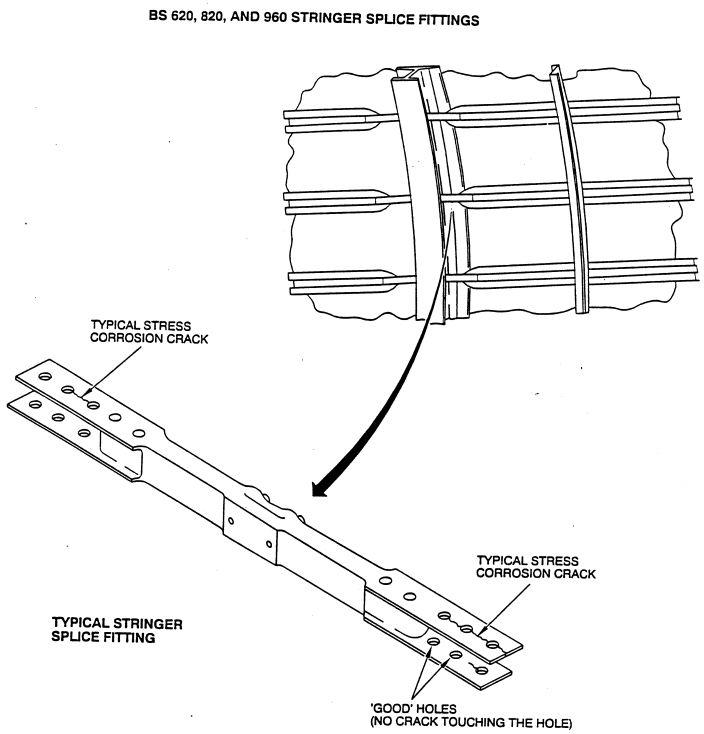

There is a potential for immediate application to the KC-135 stringer tie fatigue cracking problem

- **KC-135 fuselage longeron stringer tie**
  - **transmits axial pressure load between longerons along length of fuselage, in parallel with aircraft skin**
  - **6 critical bulkheads, 58 stringer ties per bulkhead, 12 rivet holes per stringer tie (4,176 rivet holes)**
  - **Loading is slow ramp tension-tension axial fatigue load due to fuselage pressurization in C/KC-135 (negligible G-loading in transport aircraft)**
  - **Failure mode is Mode I fatigue cracking between rivet holes due to tension created by bearing stress; Material is 7075-T6 (subject to stress corrosion)**
  - **Replacement of all stringer ties with new material is safe flight approach (replace all to avoid failure)**

The current management method for this failure mechanism is damage tolerance.

- **The TN-ANG performs field level NDI (visual or eddy current) on only a portion (~75) of these stringer ties when DPM extension is required (every 5 years).**
- **When rivet hole cracks are detected by NDI, stringer ties are replaced by drilling out existing stringer tie, then field drilling holes in new stringer tie to match existing holes in longerons, and installing with bolts.**
- **The potential for misalignment and resulting load distribution problems is great, leading to more frequent reoccurrence of the fatigue problem.**

A solution is the installation of thin fiber optic strain sensors for measuring local critical displacements on stringer ties

- Requires measuring the average strain over the stringer tie end joint with a Fabry-Pèrot fiber optic strain sensor bonded to an attached aluminum cover plate to obtain average strain over joint.
- One sensor for each stringer tie end, with each requiring a 0.6mm fiber optic cable run along fuselage and affixed inside or under longerons
- Sensors cables brought out to a convenient measurement location (such as in tail section) to a cable connector.

There are several potential methods for implementing the NCGM system to assure structural safety of stringer ties

- **Depot mode**
  - **Sensors are applied to each aircraft. When rotated for DPM every 5 years, maintenance brings data reduction instrumentation on board and performs check flight.**
  - **Hysteresis strain energy for each instrumented joint is calculated, then HSE for each joint for that flight is retained and trended over each depot cycle, while in-flight data is discarded**
  - **Upon HSE indication, NDI confirmation and repairs are made as needed**

There are several potential methods for implementing the NCGM system to assure structural safety of stringer ties

- **Field mode**
  - **Fiber optic sensors are applied to selected stringer ties in each aircraft. Field maintenance personnel bring data reduction instrumentation on board and perform check flight of each aircraft on a periodic basis.**
  - **Hysteresis strain energy (HSE) for each stringer tie is calculated and trended over each measurement cycle, while in-flight data is discarded**
  - **Upon HSE indication, NDI confirmation and repairs are made as needed**

There are several potential methods for implementing the NCGM system to assure structural safety of stringer ties

- **Continuous In-flight mode**
  - **Sensors are applied to some, most, or all of the stringer ties on each aircraft. A single channel sensor amplifier system, an optical switching system, and an on-board data acquisition and digital signal processor are installed in each aircraft.**
  - **Hysteresis strain energy for each measured joint is calculated and trended in real time during each flight, while flight cycle data are discarded with each takeoff/landing.**
  - **Structural warnings are issued to pilot as they are indicated.**

The proposed solution would have several advantages to cost, safety, and operability

- **NCGM Solution Advantages**
  - **Upon exceeding the HSE statistical limit, those stringer ties could be scheduled for convenient replacement (fix on approaching fail)**
  - **The nearness to failure of each critical longeron stringer tie in the fuselage would be absolutely established on a periodic or continuous basis.**
  - **The information gained would allow better operational management of the aircraft, potentially deferring non-critical approaching failures to preserve operability**

Fielding this solution will require a phased approach

- **The ground test phase will focus on confirmation testing of the sensor selection/location, and verification/confirmation of actual flight stringer tie hardware fatigue test life results with periodic NDE results.**
- **The prototype flight test phase will utilize the TN-ANG/ORNL partnership to instrument the stringer ties in their fleet of eleven KC-135E tankers, and apply field demonstration.**
- **The fleet implementation phase will involve ORNL working with the KC-135 SPD to implement the technique for the C/KC-135 fleet as a whole (576 C/KC-135 aircraft active)**

The advantages of this solution outweigh the disadvantages

- **NCGM Solution Benefits**
  - **Will utilize each member of the C/KC-135 fleet to its maximum potential life, thereby increasing the fleet average overall life to its maximum potential value**
  - **Avoids the occurrence of unanticipated crack-related structural failures, thus minimizing maintenance effort and cost**
  - **Increases the reliability of flaw growth detection by using more global detection approaches**

The advantages of this solution outweigh the disadvantages

- **Reduce the cost and frequency of full-scale fleet NDI for flaws**
  - **Assume NDI takes 30 minutes per stringer tie joint end (0.50 hr/end x $50/hr x 2 Inspections/yr) = $50/year/stringer tie end**
  - **Proposed solution cost = $100/sensor**
  - **Payback time is 2 years**
  - **Resulting lifetime fleet cost savings of up to $380M over 40 yr life for full inspection of all 348 critical stringer ties on 576 operational aircraft in US fleet.**

Application of technique to more complicated loading situations will require a number of additional questions to be answered

- Effect of fatigue frequency
- Effect of fatigue stress amplitude 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)

Significant opportunities exist to verify the technique using ongoing USAF fatigue tests with little additional cost

- There is a potential for a demonstration of this technique by the addition of minor sensor and data acquisition additions to currently planned USAF T-38 full-scale fatigue tests.
  - Would require global load (strain gage) and local critical deflection/strain sensor installation at expected points of failure
  - Would require data acquisition and processing system to acquire signals from these sensors for subsequent analysis and processing
- There is also a potential for a “simpler” demonstration of the technique in future planned pressure bulkhead tests in the DC-9.

Conclusions

- A new method for sensing impending failure of cracked structures has been discovered
- Using this technique, an engineering solution to the problem of unanticipated KC-135 stringer tie fatigue cracking has been developed.
  - Payback period of 2 years: Potential lifetime savings of $380M over 40 year fleet life
  - Improvement in individual aircraft safety assurance
  - Increase in C/KC-135 operability, due to ability to manage maintenance
- This solution is fieldable in stages with little risk to the Air Force, and potentially great benefits.
- Requires AFRL recommendation to Aging Aircraft Office by Feb. 25th