ON-LINE STRAIN AND DAMAGE ASSESSMENT OF ROTORCRAFT STRUCTURAL COMPONENTS

John Holmes, George Kardomateas, Massimo Ruzzene, Andrew MaKeev
Structural Durability and Fatigue Laboratory
Wave Propagation Laboratory
Georgia Institute of Technology

Rotorcraft HUMS

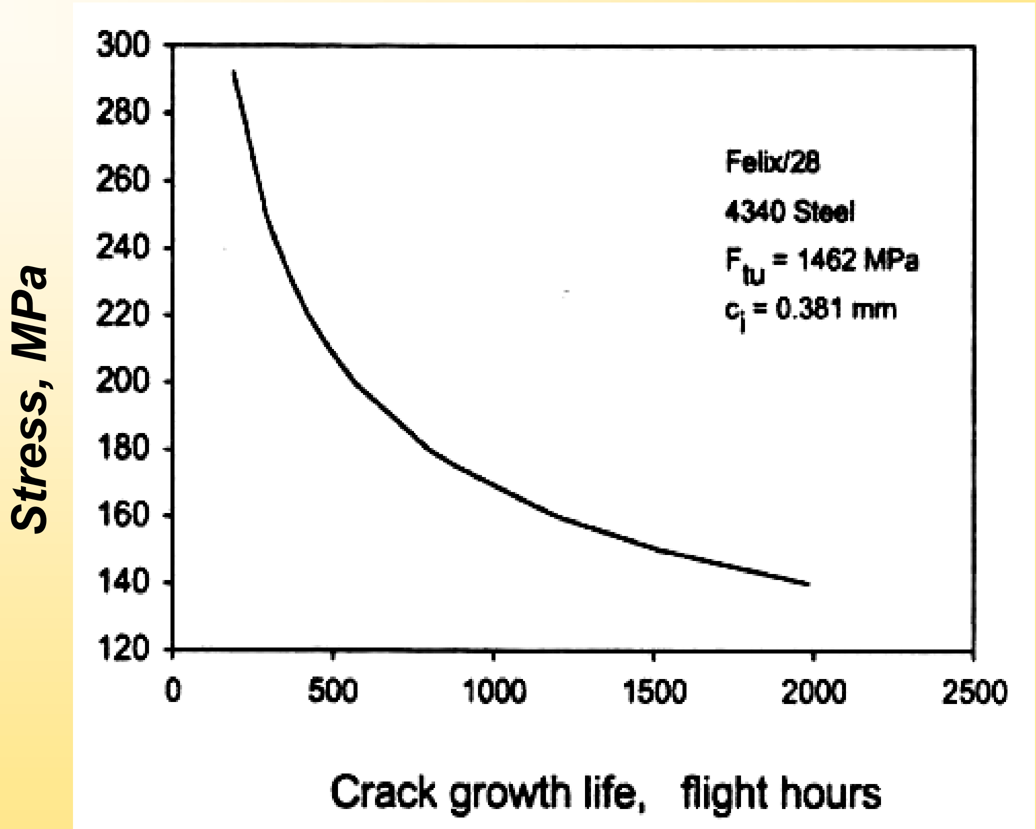
- **One approach would be to use a universal sensor to monitor strain and damage in various materials**

This approach will not work for rotorcraft health monitoring

(Health monitoring of rotorcraft metallic components requires a much higher resolution than that required fixed-wing aircraft)

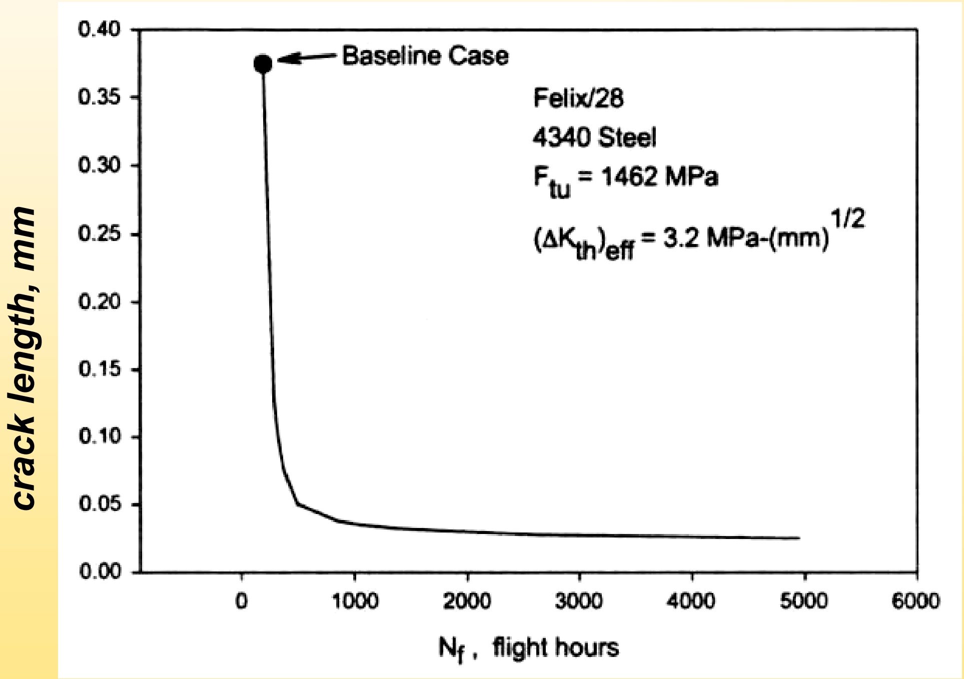
- **Modular approach: select the sensor type based upon the type of material to be monitored and the resolution required**
  - **High resolution, proven ACPD technology will be used for detection and monitoring of strain and crack growth in metallic structures**
  - **Embedded sensor arrays for high frequency vibration monitoring of larger scale, distributed damage in composite structures**
- **Risk assessment (e.g., sensor failure)**

Background

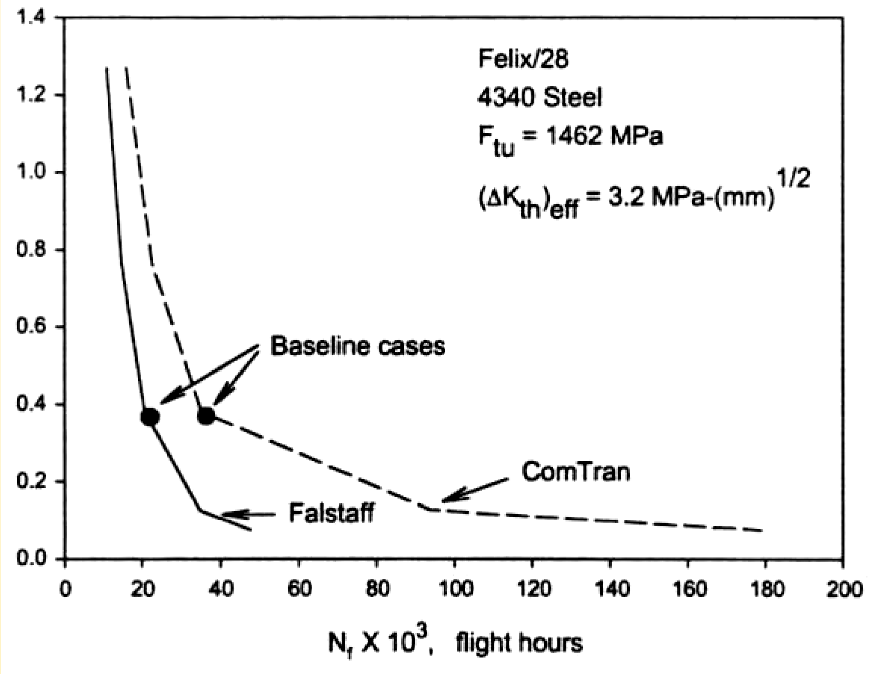


Crack-growth time-to-failure
(data from Everett, 2002)

Background



Crack length vs. flight hours (rotorcraft) Everett, 2002



Crack length vs. flight hours (fixed-wing) Everett, 2002

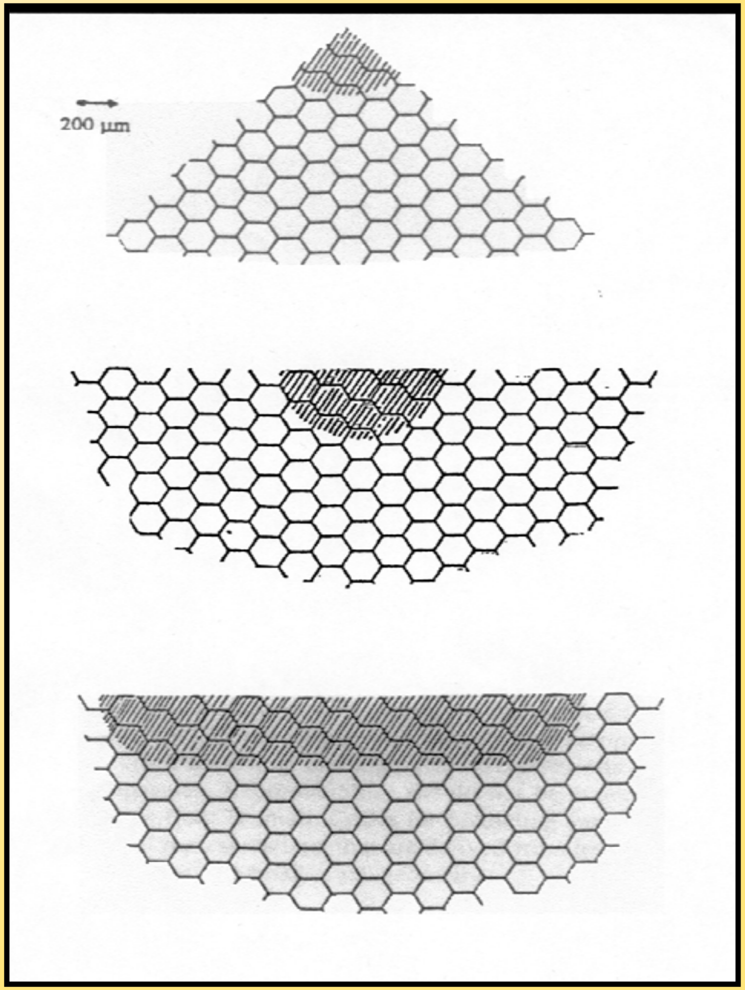
Background

	Material		
Load Spectra	4340 Steel	7075-T6 Aluminum	Ti-6Al-4V Titanium
Felix/28	189 hrs.	146 hrs.	357 hrs.
Falstaff	20,670 hrs.	18,523 hrs.	55,705 hrs.
Comtran	35,214 hrs.	28,453 hrs.	121,811 hrs.
Full Felix	25 hrs.		

- **If a total life approach is used (with initial flaw size of 30 μm), the life estimate (Flelix/28) for 4340 steel increases to 1183 h (versus 189 h if an initial defect size of 0.38 mm is assumed)**
  - **The total life approach requires very accurate monitoring of small cracks at critical locations**
  - **This type of resolution is only attainable using ACPD techniques**

Small Crack Problem (Fatigue Life Prediction)

- *1 to 10 grains*
- *Growth at <u>smaller S.I.F.'s</u> and at <u>faster rates</u> than equivalent long cracks*
- *<u>Scatter</u> significantly greater than that for long cracks*
- *<u>Growth-arrest</u>*
- *<u>Coalescence</u> of micro-cracks*



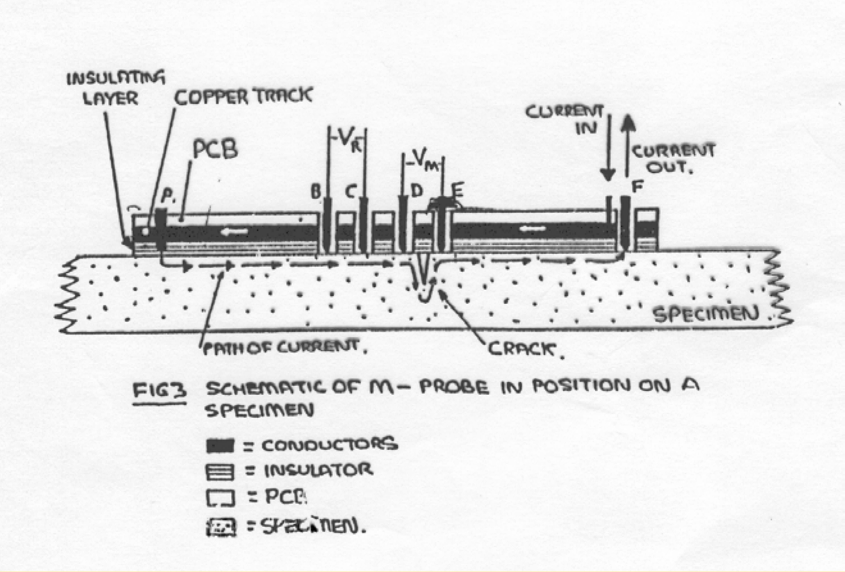
AC Potential Drop

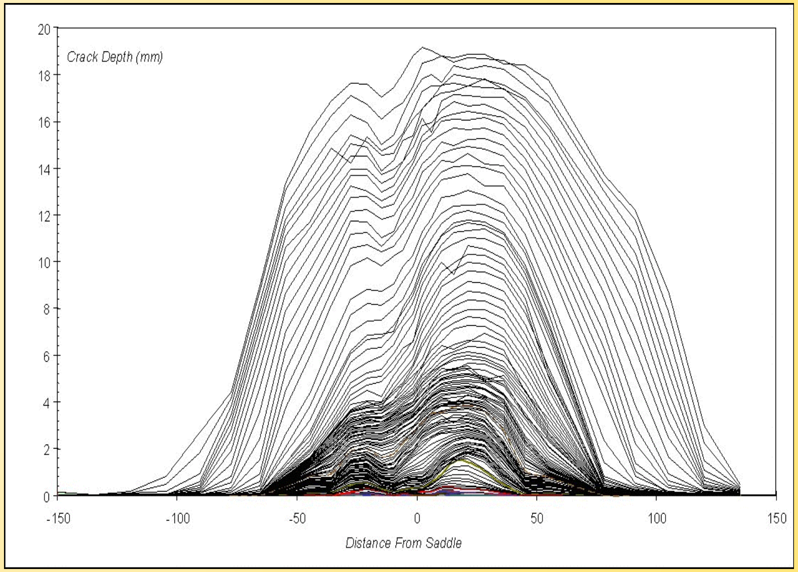
- Both ACPD and Eddy Current (EC) methods are electromagnetic based
  - Measure disturbances to the passage of current in a solid
    - Strain changes the resistivity
    - Flaws/cracks modify the path of the current flow
  - Eddy current techniques rely upon currents induced by a magnetic field
    - induced current depends upon properties of the solid, coil geometry, distance between coil and surface
    - for paramagnetic alloys (e.g., Al, Ti), induced current densities are very small
    - volume into which the current is being induced is often unknown
    - if a corner or change in geometry is present e.g., bolt hole or curvature), current density becomes highly disturbed (edge effect)
    - changes in geometry can cause lift-off effect (distance between coil and surface changes)

AC Potential Drop

- **ACPD directly injects current into a material**
  - **allows much higher current densities and increased resolution**
    - ***for a given frequency* current densities in Al & Ti are approx. 10^3 higher than with eddy current approaches**
    - **even small disturbances can be detected**
    - **surface finish is not an issue – as with eddy current techniques**
  - **Amplitude of injected current density in part is known and is independent of properties of the part**
  - **With current focusing, the current distribution can be further confined which allows highly precise monitoring of bolt holes, notches, bends, etc. in a structure). No edge-effect of lift-off.**

AC Potential Drop





- *An alternating current is injected into a metal surface and flows across defects. A contacting voltage probe is deployed on the surface. Voltage readings are used to calculate crack depth*

AC Potential Drop

- *Only method proven capable of detecting small cracks (10 to 50 μm) and monitoring* ***both*** *small and large crack growth in metals. Provides real-time strain monitoring for overload warning.*

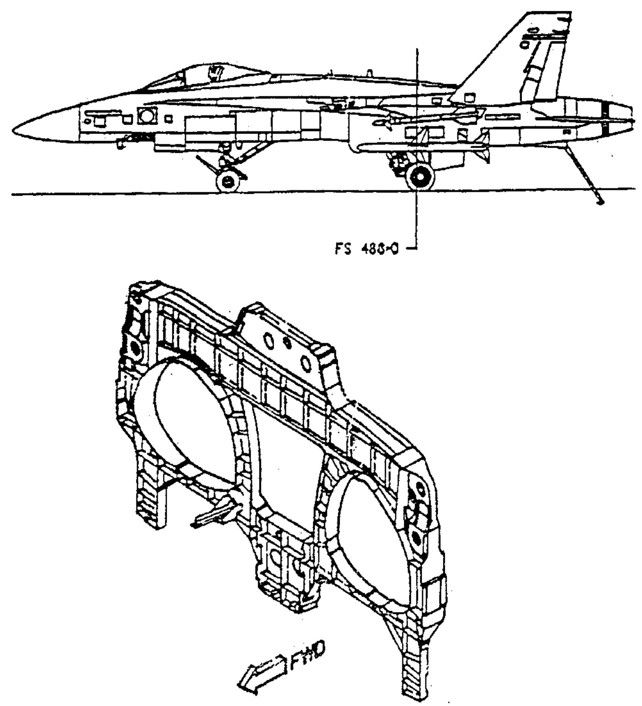


Figure 4.1 Schematic showing the bulkhead 488 and the location of bulkhead 488 in a CF- 18 aircraft.

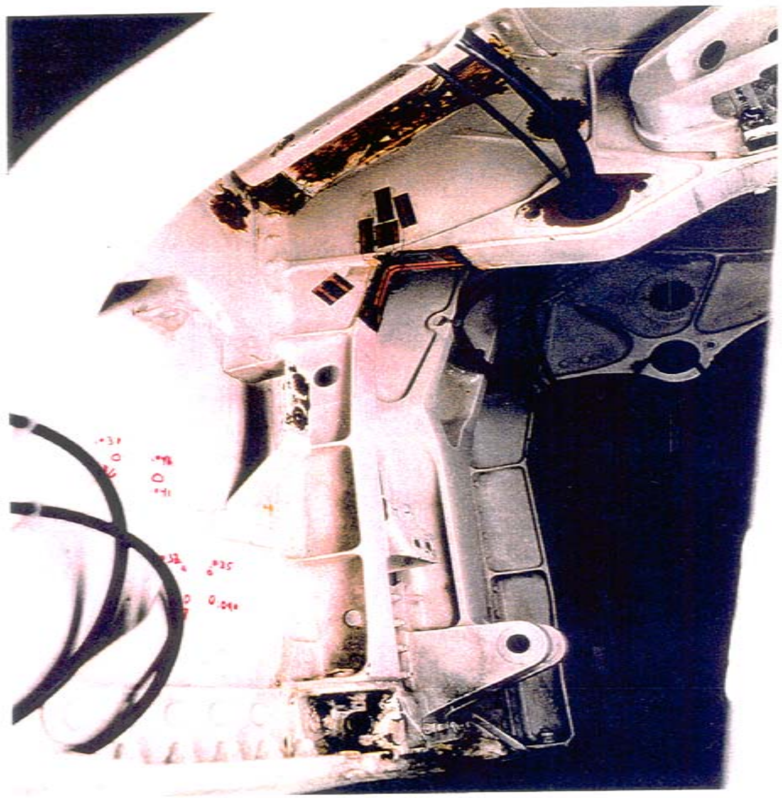


Figure 4.7a Photograph showing the location of the former segment flange radius on bulkhead 497 (L.H.S) and the ACPD probes installed on the location.

AC Potential Drop

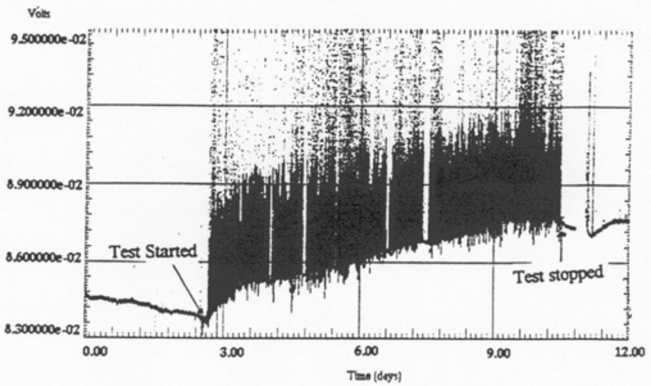


Figure 4.12a Zoom of figure 4.11b.

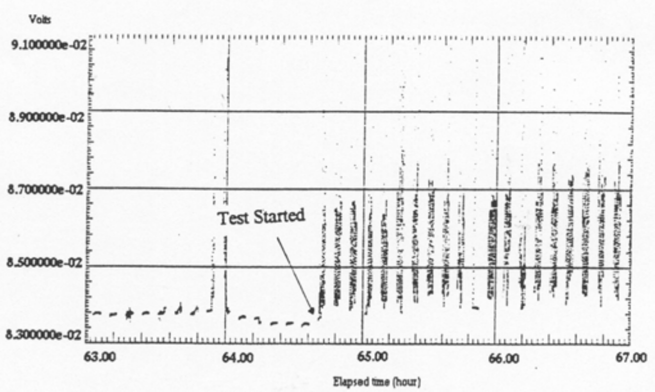


Figure 4.12b Further zoom (63-67 hours) of fig. 4.12a showing the start of block 11.

<u>Instrumentation of F18 bulkheads</u>

- **centerline**
- **hydraulic hole**
- **flange radius**

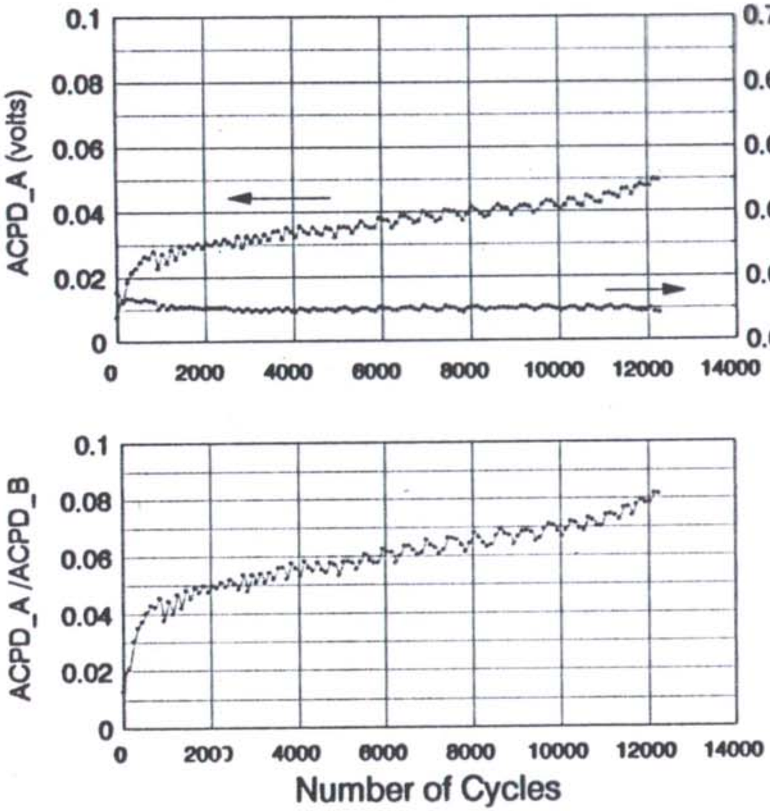
Monitor strain and damage during flight spectrum loading

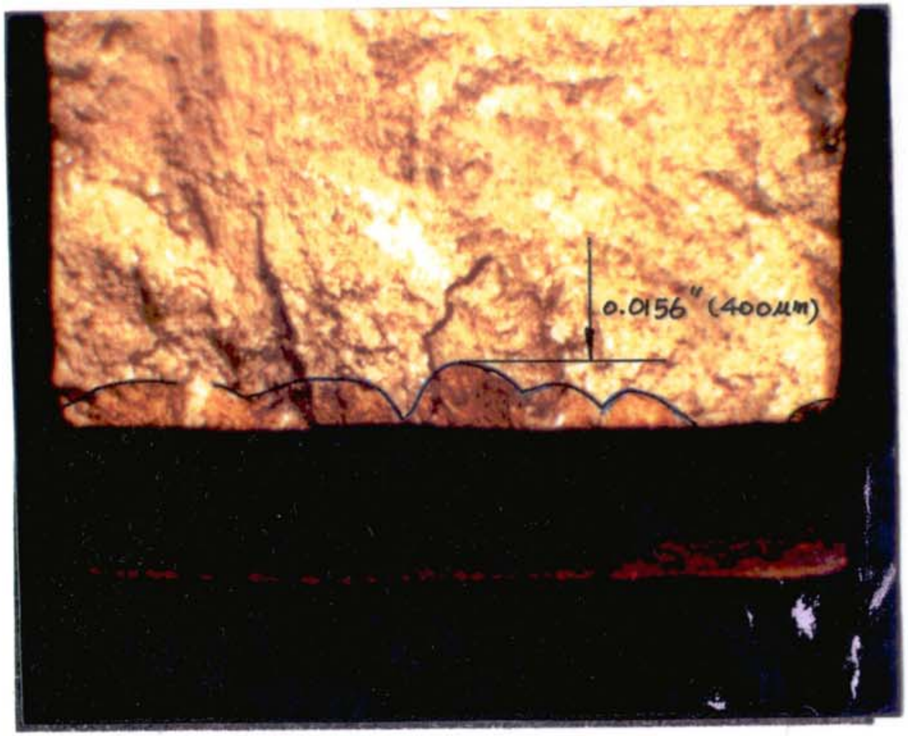
Determine damage during critical maneuvers

F18 Results

- Crack first detected 2500 SFH prior to other techniques.
- The crack grew about 415 μm during loading block 11 and 12 (3250-3900 SFH)
- At 5900 SFH and after 8 complete NDI runs (eddy-current, liquid penetration and ultrasonic) cracks were found in the area indicated much earlier by the ACPD sensors
  - By 5900 SFH the crack had a surface length of approx. 6 mm with and a depth of approx. 750 μm

Additional Applications



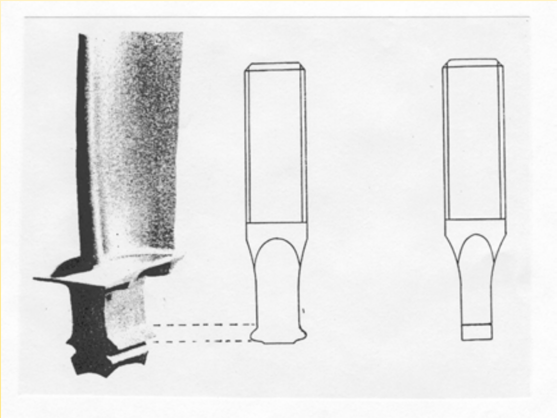


ACPD_A --- working probes
ACPD_B --- reference probes

Figure 5. A typical results of ACPD response to multiple fatigue crack initiations at the root of the notch. (Ti64, RT)

Additional Applications

- *Residual stresses in metals*
- *Cracks in blades, gears and threaded components*



AC Potential Drop

- ***Advantages***
  - proven technology - robust and inexpensive sensors
  - durable sensor design (bonded strips and probes)
  - provides details of crack shape
  - very sensitive – can resolve growth increments of 0.010 mm
  - provides real time monitoring of damage state and strain history
    - ideal technology to warn of strain overloads
  - allows detection of *both* crack initiation and growth in any conductive material at any temperature

- ***Disadvantage***
  - can not be used for composite structures

Embedded Ultrasonics

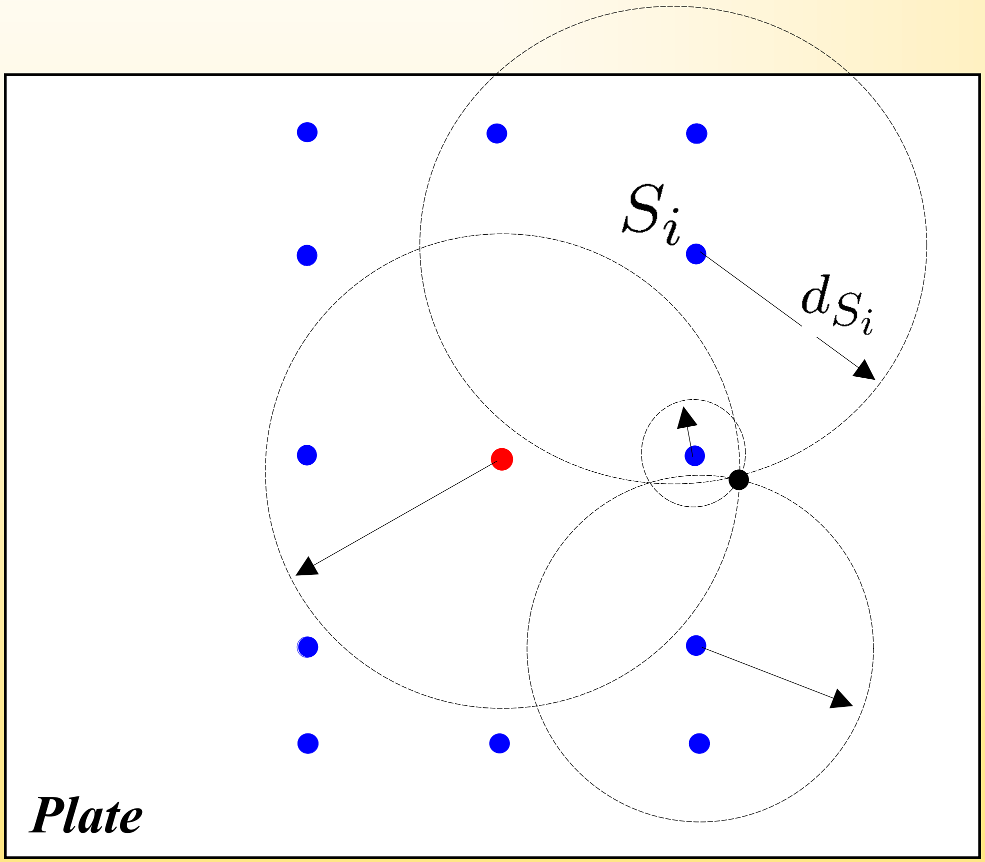
- ***very effective for composites***
- ***Previous shortcomings include:***
  - Local sensitivity to defects (need for scanning devices)
  - Limited information regarding precise damage location
  - High sensitivity to noise and vibrations

⇒ ***difficult to apply in a Usage Monitoring Framework***

- ***GTech is developing LOCALIZATION and SCANNING strategies – e.g., distributed sensor arrays for in-situ monitoring or scanning laser vibrometer***
- ***Studies are supported by simulation tools and state-of-the-art experimental equipment***

Ultrasonic studies

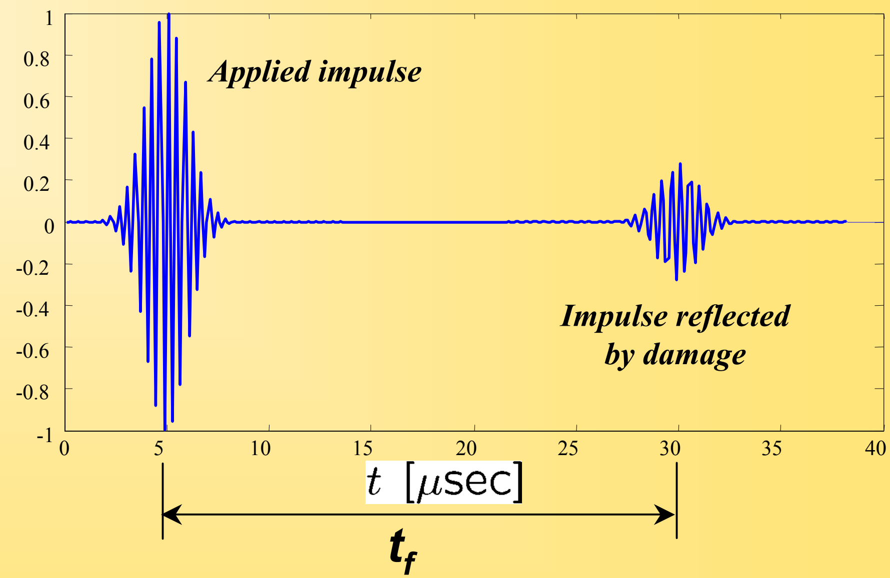
Design of array of sensors for damage localization



● Sensors ● Sensor/actuator

● Damage location

Estimation of "Time of Flight" t_f

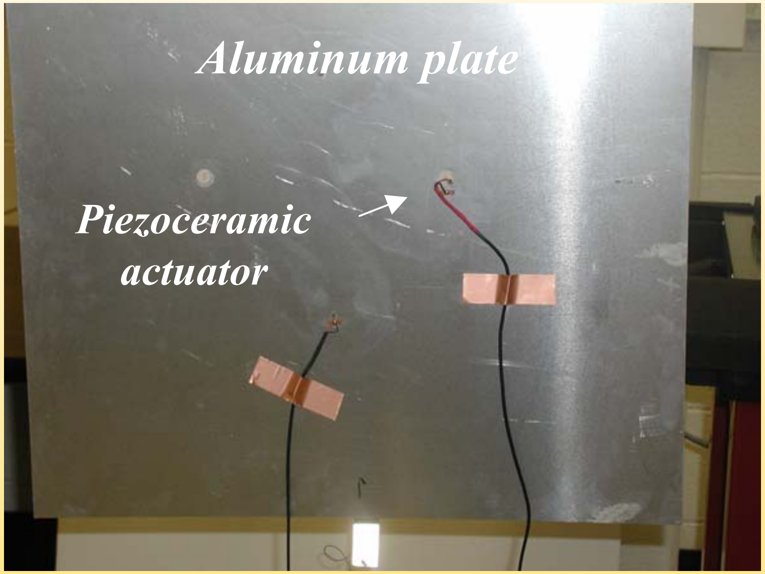


$$d_{S_i} = \frac{c_g}{t_{f_{S_i}}}$$

Ultrasonic waveform detection

- Scanning Laser Vibrometer is used to detect and visualize waveforms at low ultrasonic frequencies (25-200 kHz)
- Technique combines ultrasonics sensitivity with scanning laser technology to achieve multi-point detection capabilities
- Distributed (multi-point) measurements directly provide location information for damage
- Technique can be used for:
  - Differential measurements (variation of waveform pattern with damage progression with respect to baseline configuration)
  - CONFIRMATION purposes on grounded rotorcraft
  - Optimization of sensor location and/or
  - Damage analysis and identification in single point ultrasonic measurements

CASE 1: Aluminum plate (thickness=0.0016')



- Aluminum plate excited by a piezo crystal, sinusoidal bursts triggered by vibrometer
- Response at each scanning point is recorded together with required phase information
- Transient response from scanning points is processed to obtain wave propagation information and visualize waveform
- Waveform in a homogeneous plate is first recorded
- Comparison is made with waveform in a plate with discontinuity added (small mass glued to the back of the plate)

Ultrasonic waveform detection

Visualization of detected waveforms

Uniform plate

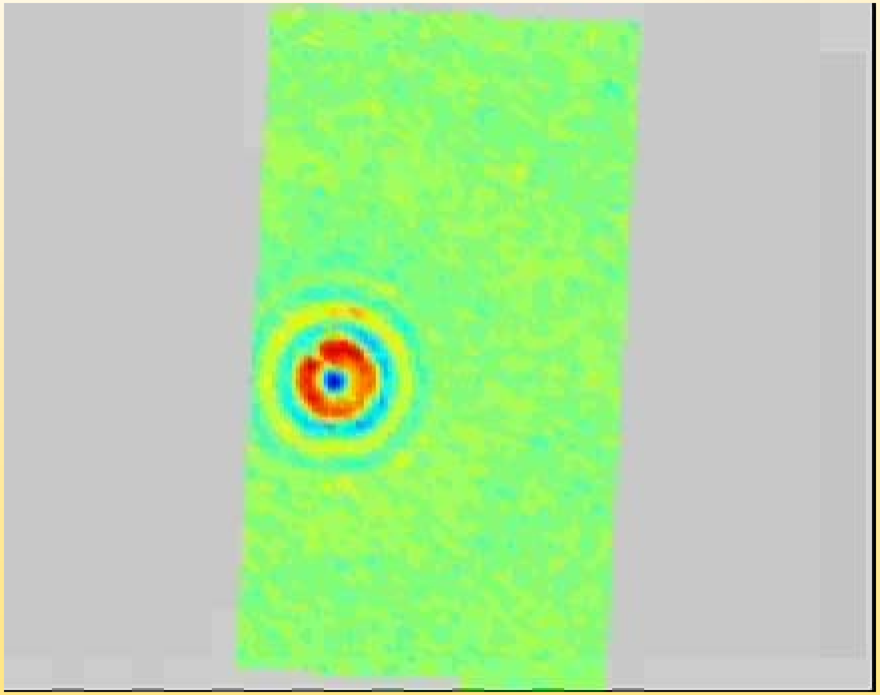
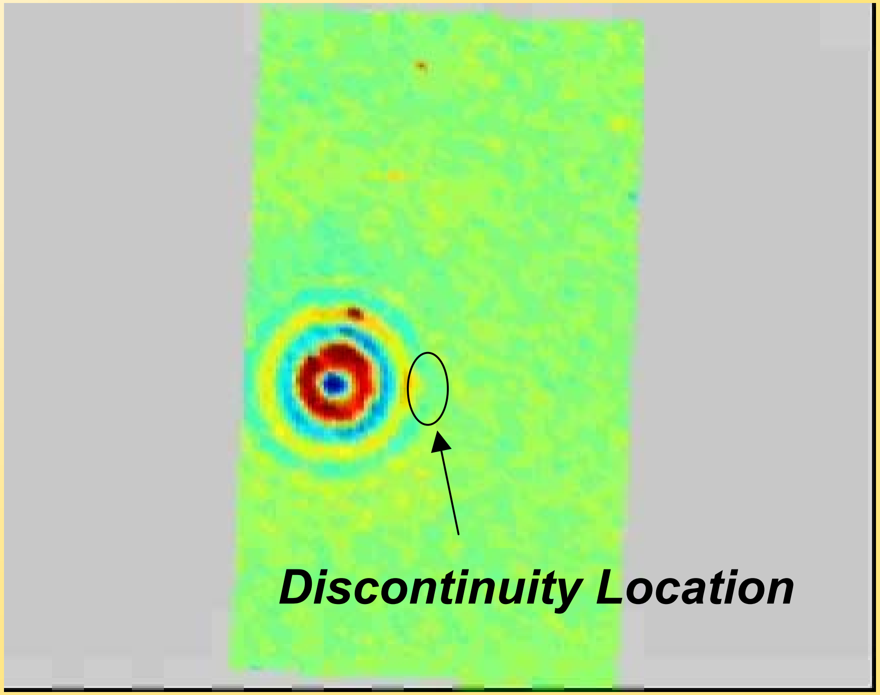


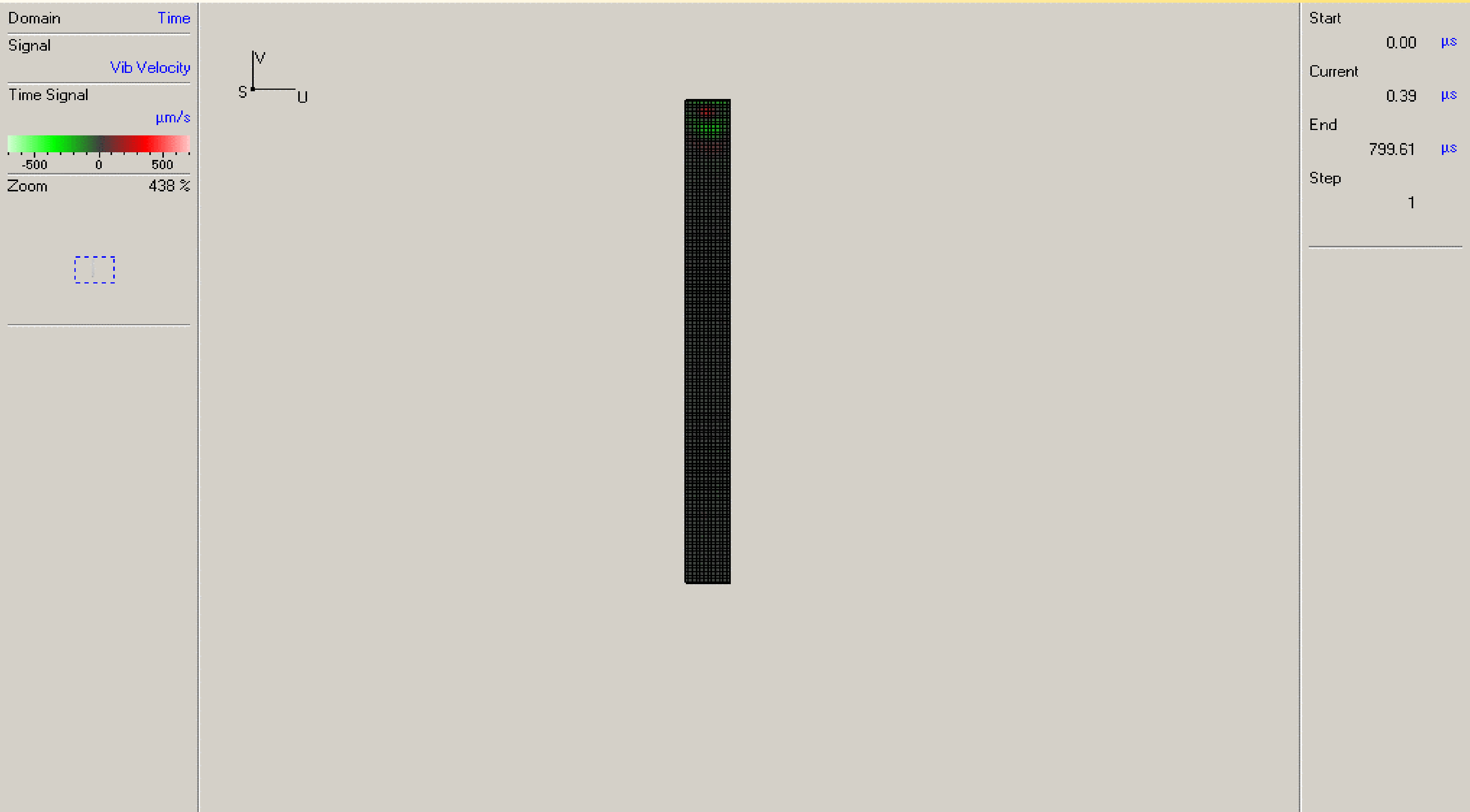
Plate with discontinuity



Excitation: 5-cycle sinusoidal burst at 50kHz

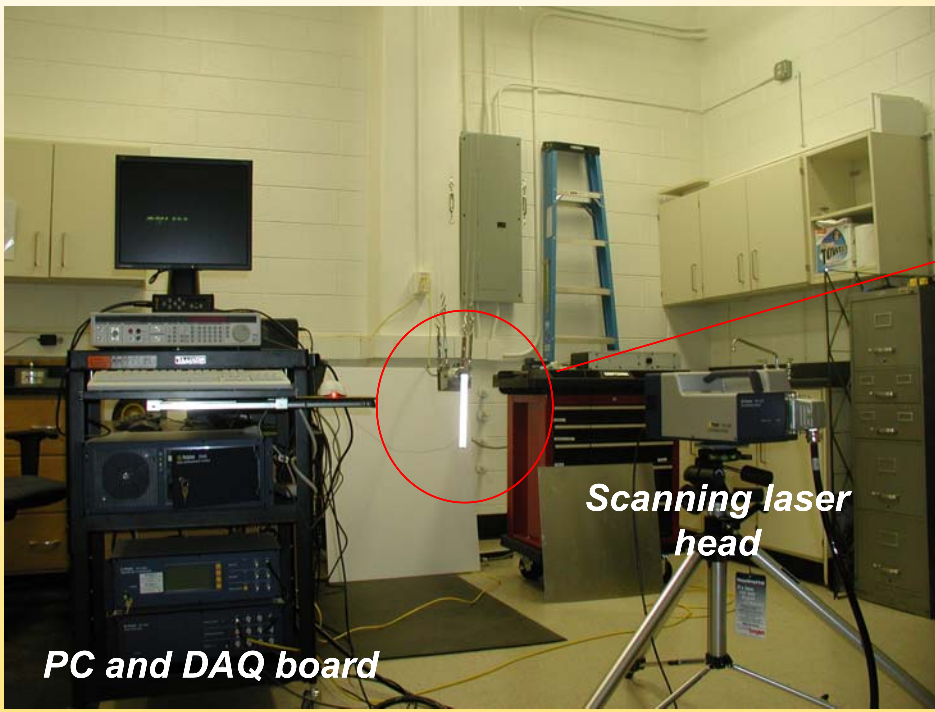
Ultrasonic waveform detection

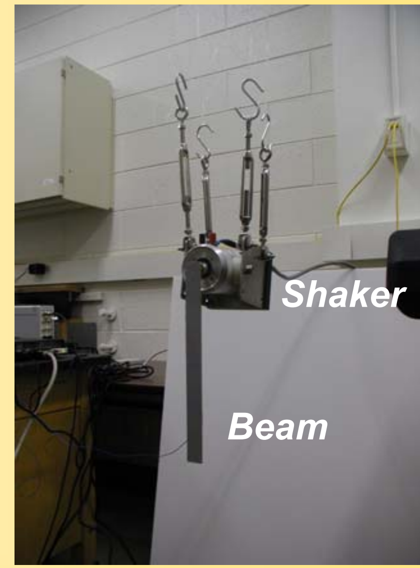
CASE 2: Composite beam with lap joint *(0º lay-up, IM7G fiber, 8551-7 Matrix)*



HF Vibration Analysis

Composite beam: experimental setup





Specimen: 12-ply woven glass and epoxy matrix beam
Damage: Saw cut ~20% of the thickness

Georgia Tech

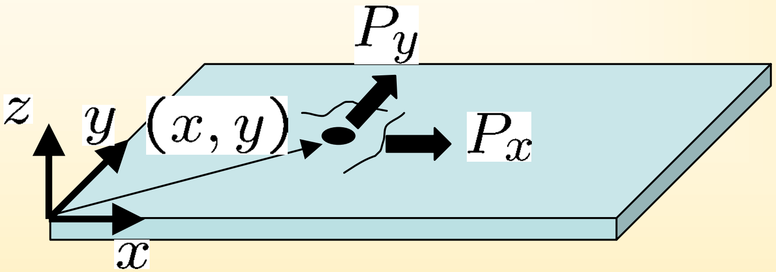
HF Vibration Analysis

- ***Vibrations are "global" damage indicators;***
- ***In service vibrations can be continuously monitored;***
- ***Previous studies:***
  - Detection of changes in modal parameters (natural frequencies and mode shapes);
  - General low sensitivity, but investigations are limited at low frequencies
  - (100 Hz, GTech looking at up to 10 kHz)
- ***Sensitivity can be improved if high frequency (HF) modes are considered;***
- ***<u>Energy flow</u> is highly affected by local discontinuities (damage, localized plasticity);***

⇨ ***Evaluation of high frequency energy flows in composite structures***

HF Vibration Analysis

Energy flow at location *x,y*:



$$P_x(x,y) = < F_x(x,y,t) * \dot{v}(x,y,t) >$$

$$P_y(x,y) = < F_y(x,y,t) * \dot{v}(x,y,t) >$$

Generalized force — Generalized velocity

- ***Energy flow can be measured through:***
  - ***Scanning laser vibrometer (Lab setting);***
  - ***Embedded distributed sensors (piezoceramics, same as ultrasonics).***

- ***Initial studies have been performed on:***
  - ***Composite plates***
  - ***Cracked composite beams***

HF Vibration Analysis

Plate results: Amplitude of out-of-plane displacement

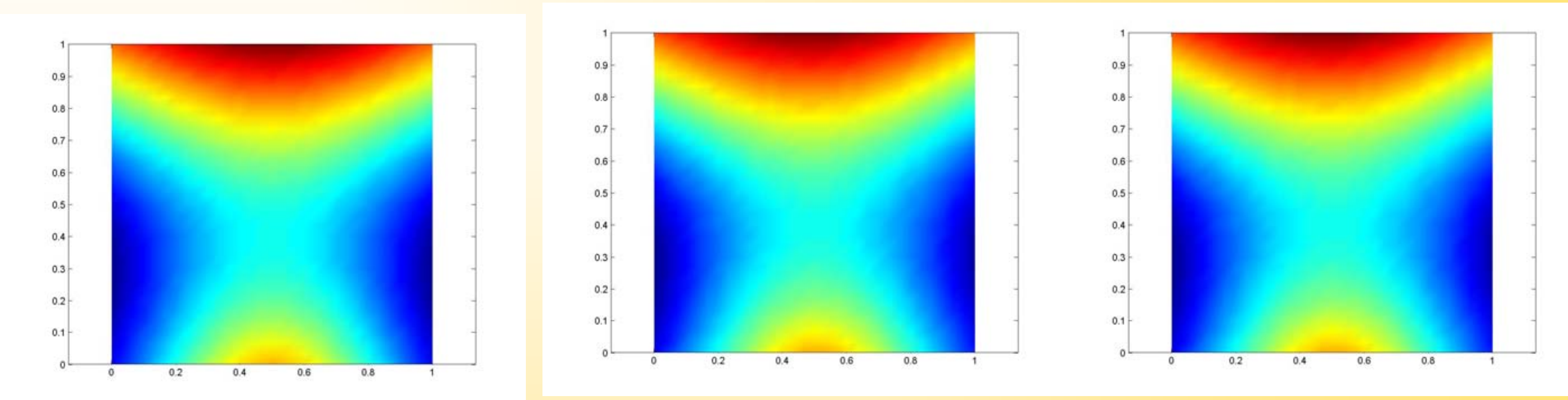
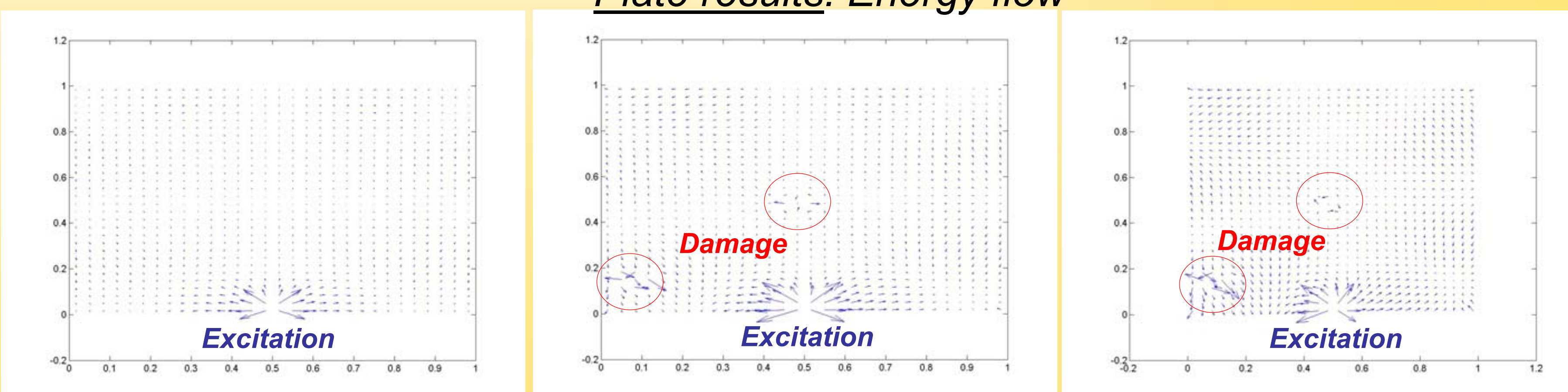


Plate results: Energy flow



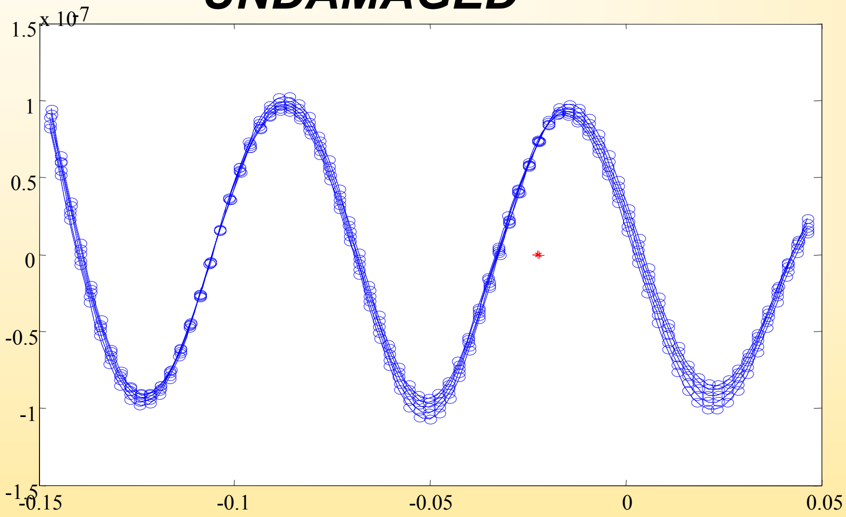
Undamaged | 10% damaged | 20% damaged

DAMAGE

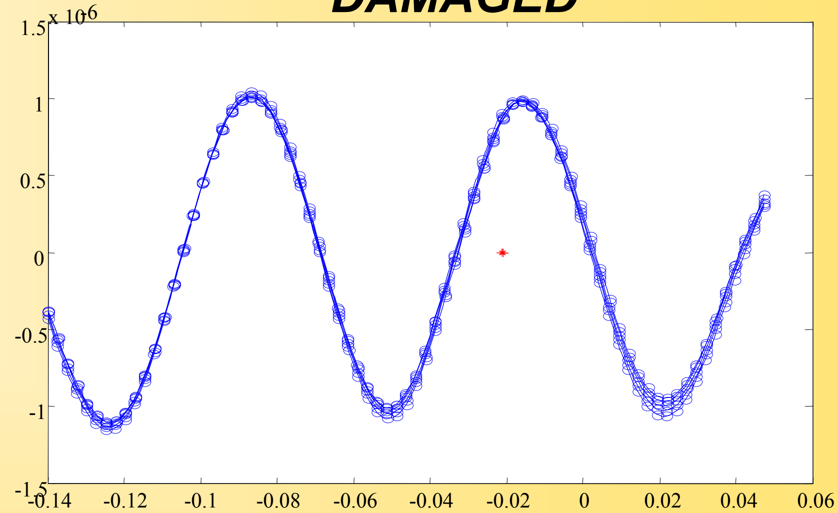
HF Vibration Analysis

Displacement amplitude @ 1200 Hz

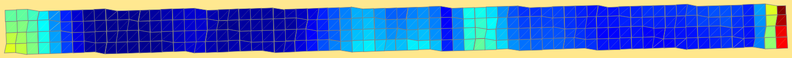
UNDAMAGED



DAMAGED



Energy flow amplitude @ 1200 Hz

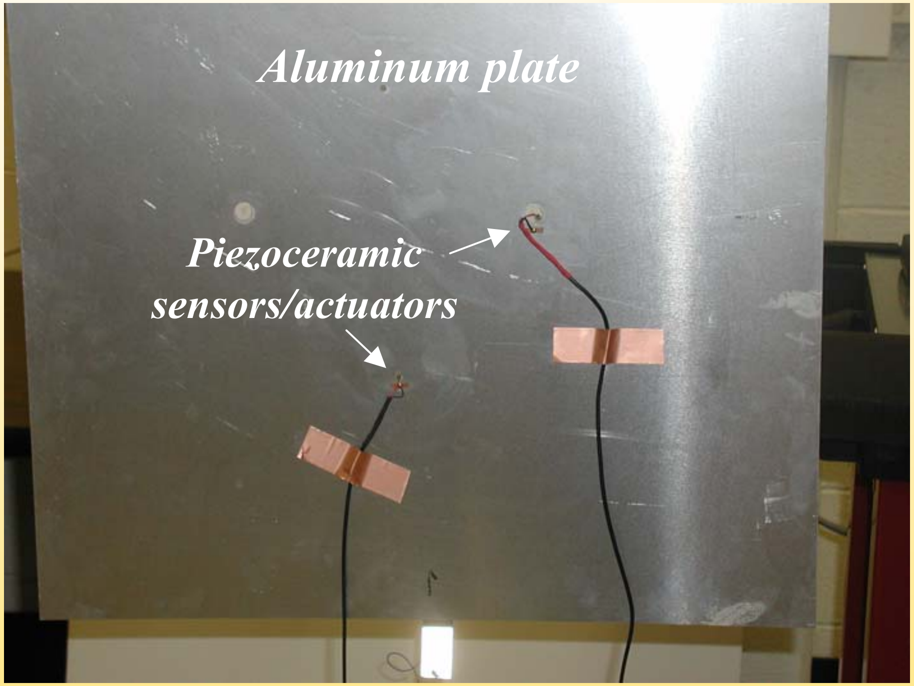


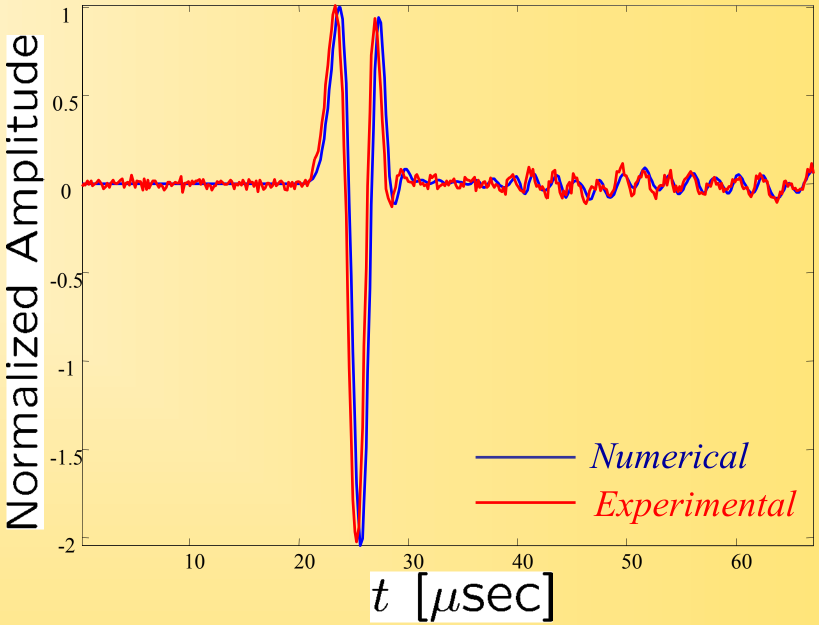
Summary

- Modular approach to health monitoring
  - ACPD sensor design for metallic components
  - Vibration/ultrasonic sensors for composite structures
  - Sensor durability and location
  - Risk assessment (sensor location and failure)
  - Software integration for life prediction
  - Validation
  - Team with industry

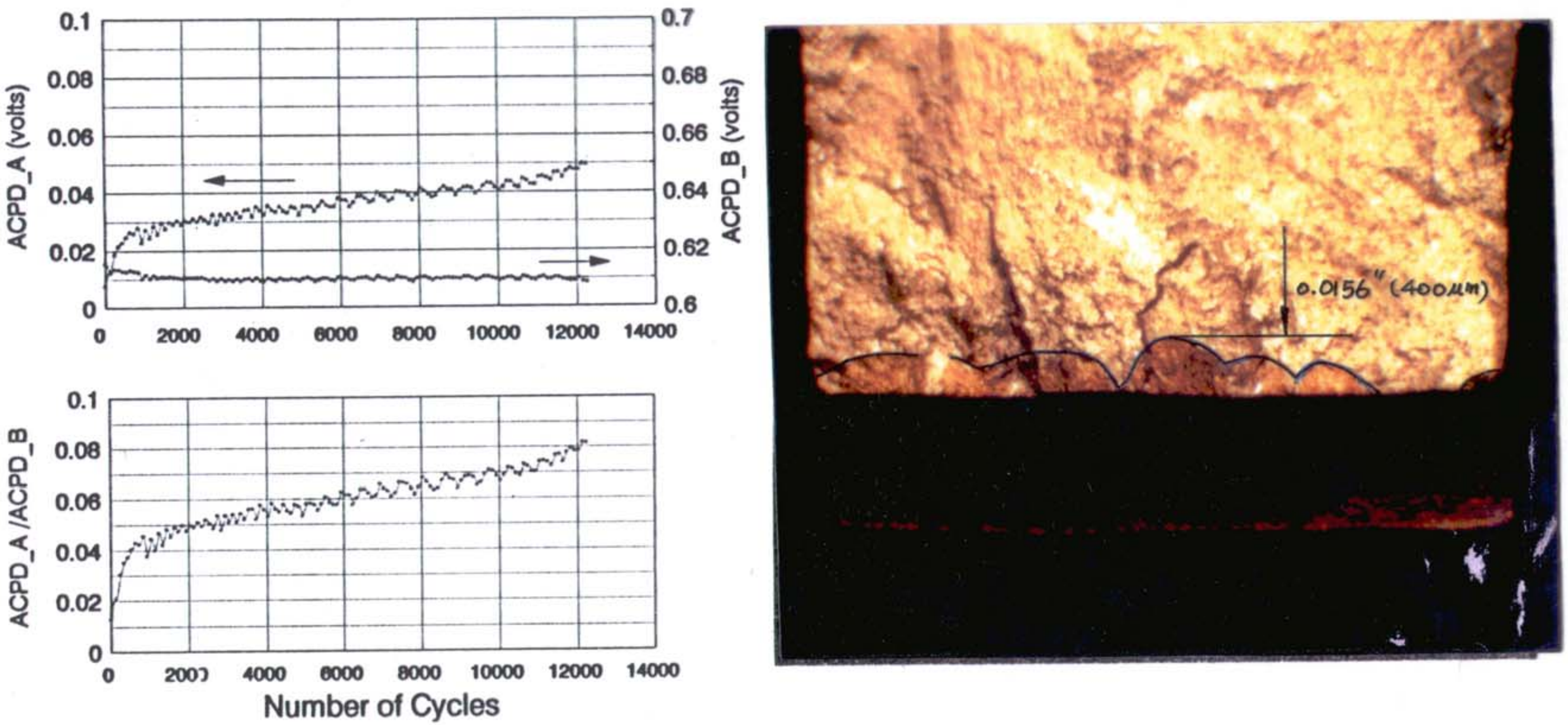
Ultrasonic studies

Experimental Validation





AC Potential Drop



ACPD_A --- working probes
ACPD_B --- reference probes

Figure 5. A typical results of ACPD response to multiple fatigue crack initiations at the root of the notch. (Ti64, RT)