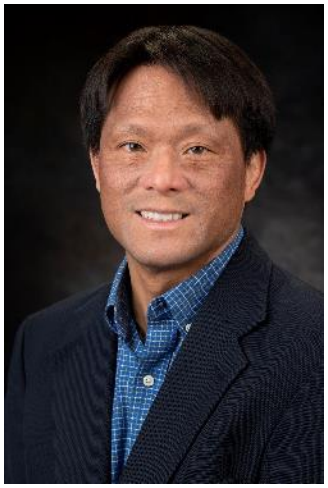
Acquisition and Processing of Passive Thermography Fatigue Test Data



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Outline

- Introduction
- Periodic Response Passive Thermography
  - Single Stringer Panel and System Setup
    - ✓Imaging for Damage Growth with Ultrasonic Comparisons
  - Four Stringer Panel and System Setup
    - ✓Imaging for Damage Growth with Ultrasonic Comparisons
- Non-Periodic Response Reduction of Thermal Data to Damage Depth Imaging for
  - Rapid Growth Damage Depth Image
- Conclusions

Introduction

Objectives

• Real time inspection for early detection of onset damage and controlled growth of damage up to failure.

• In-situ wide area real time inspections on composite structures during load testing using passive thermography.

• Implementation of a detailed inspection (ultrasonics or X-ray CT) for through thickness detail.

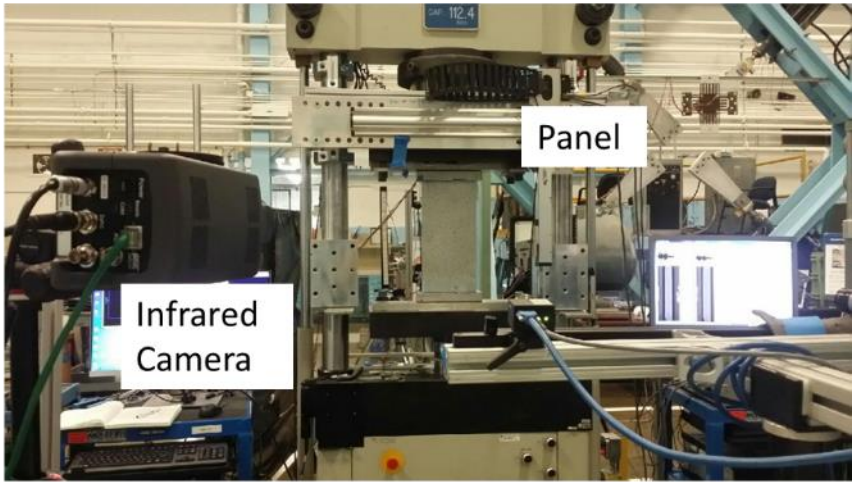
Payoffs

• Early detection and quantitative measurement of damage onset and growth validates test articles and feeds damage prediction models which decreases certification times.

Single Stringer Panel with Test Setup







21.6 cm

• Skin is 12 plies (0.22 cm thick), stiffener flange is woven composite 12 plies (0.24 cm thick), frequency of loading = 2 Hz, and maximum compressive load is -25,000 pounds, camera is synchronized to loading, 640 x 512 cooled InSb sensor, 25 mm Ge optics, and load is acquired for each frame.

Periodic Thermal Response Data Processing

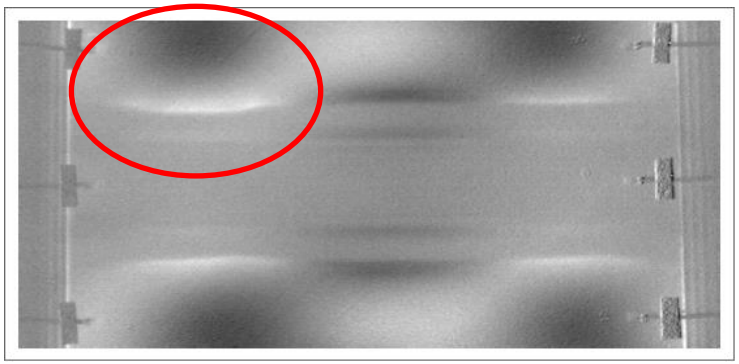
$$processed\ image[i] = y[k - delay] - y[k]\ \ for\ \ y[k] = \frac{1}{N} \sum_{j=(k-1)*(N-1)}^{k*N} x[k + j]$$

- Frequency of loading = 2 Hz. *Y[k]* is the averaged thermal image, x[k + j] is the raw acquired thermal image (rate = 80 Hz), *j* is the acquired image number, *k* is the averaged image number, *i* is the processed image number, *N = 10* is the number of boxcar averages, *j* is the acquired image number, *delay = 2* is the offset subtracted averaged image.

- Processed image is average 4 times so the image displayed real time is updated every 2 seconds.

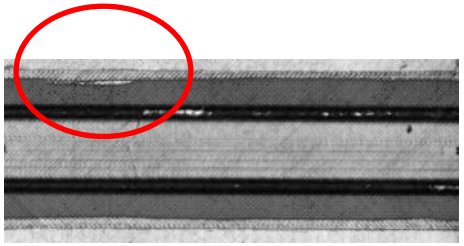
Single Stringer Damage Formation

Passive Thermal Image @101K Cycles

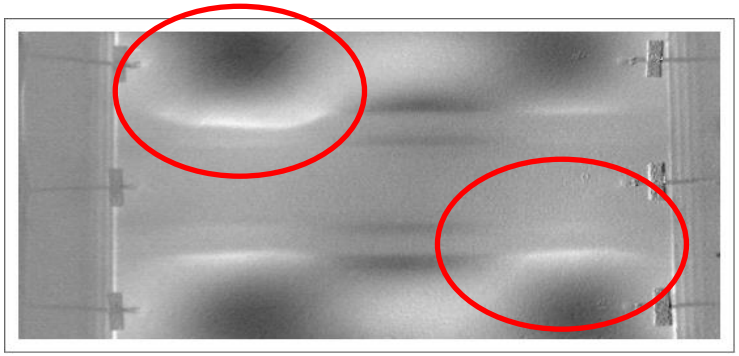


21.6 cm

Ultrasonic Inspection Image @100K Cycles

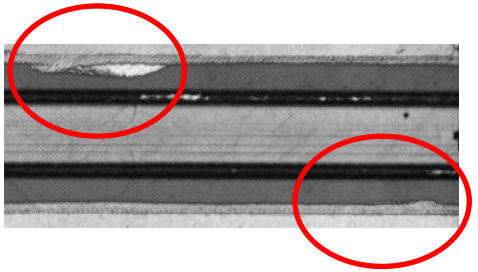


Passive Thermal Image @450K Cycles



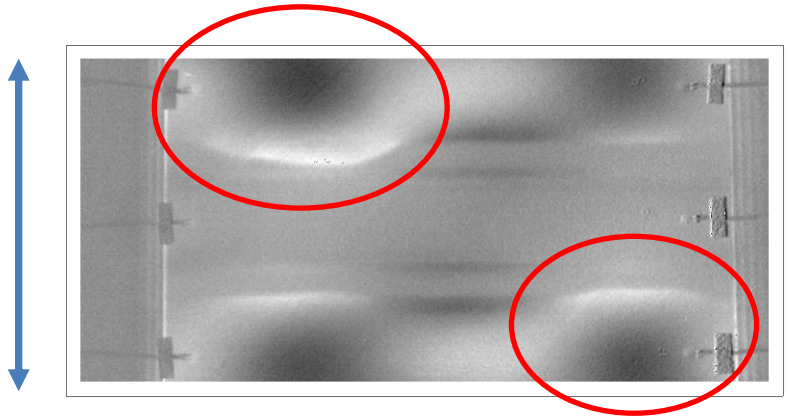
21.6 cm

Ultrasonic Inspection Image @450K Cycles



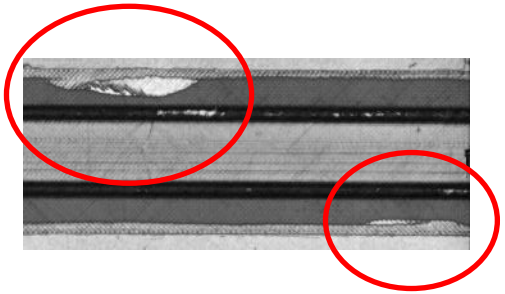
Single Stringer Damage Formation

Passive Thermal Image @660K Cycles

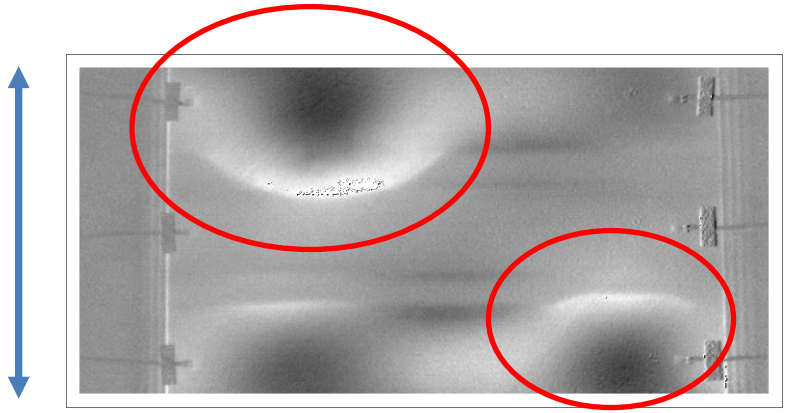


21.6 cm

Ultrasonic Inspection Image @650K Cycles

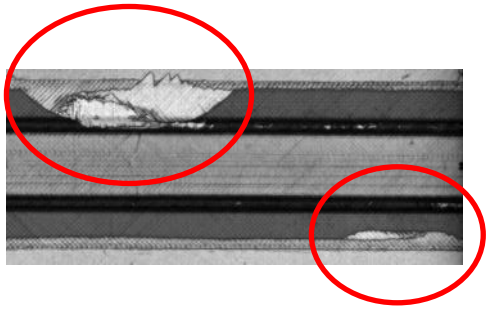


Passive Thermal Image @905K Cycles



21.6 cm

Ultrasonic Inspection Image @900K Cycles



Four Stringer Panel with Test Setup

Skin Side

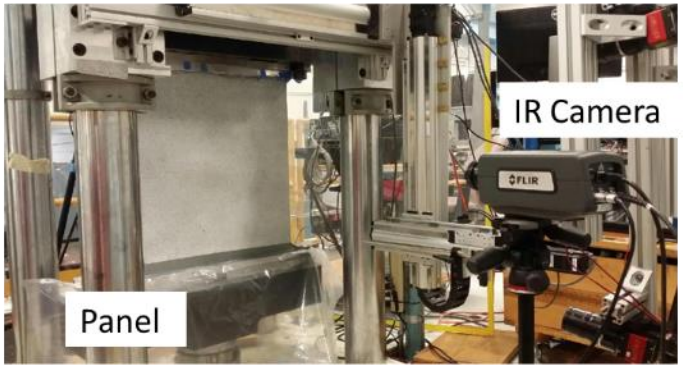


82.8 cm

Stringer Side



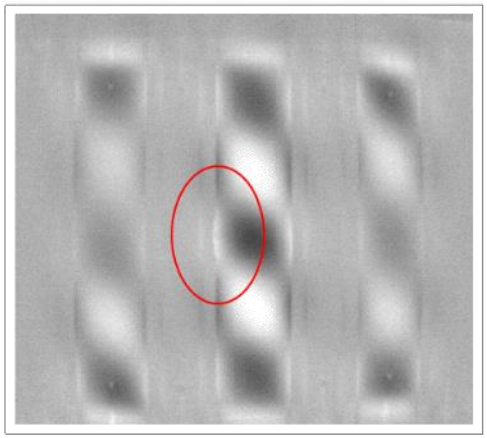
Passive Thermography Setup



• Same geometry and thickness as single stringer panels, skin is 12 plies (0.22 cm thick), stiffener flange is woven composite 12 plies (0.24 cm thick), frequency of loading = 2 Hz, and maximum compressive load is -85,000 pounds, camera is synchronized to loading, 640 x 512 cooled InSb sensor, 13 mm Ge optics, and load is acquired for each frame.

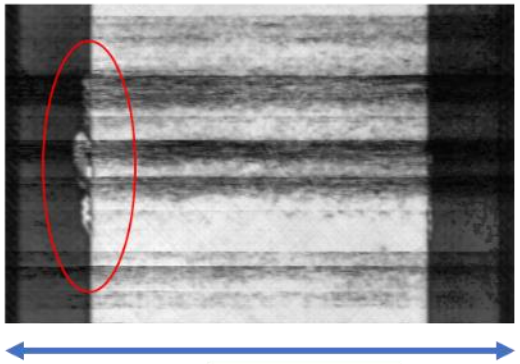
Four Stringer Damage Formation

Passive Thermal Image @95K Cycles



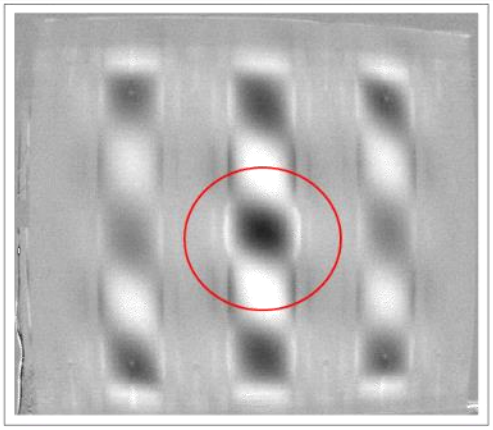
82.8 cm

Ultrasonic Inspection Image @95K Cycles



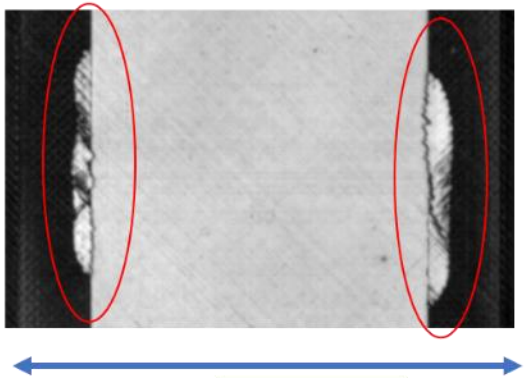
10.8 cm

Passive Thermal Image @345K Cycles



82.8 cm

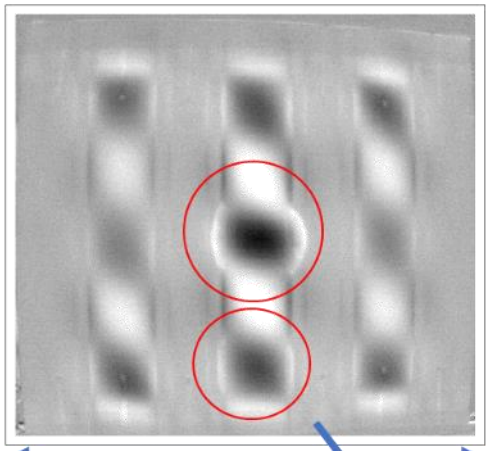
Ultrasonic Inspection Image @345K Cycles



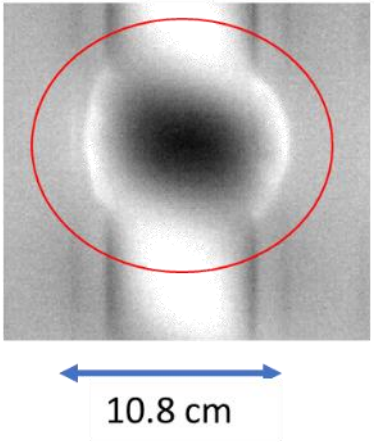
10.8 cm

Four Stringer Damage Formation

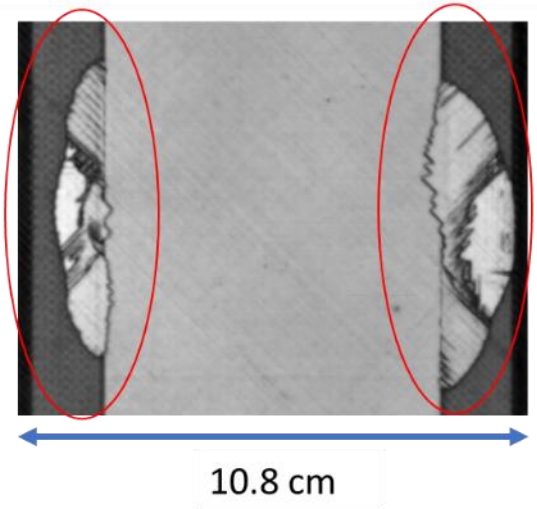
Passive Thermal Image @675K Cycles



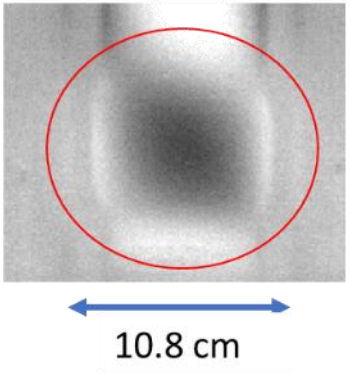
Passive Thermal Closeup
Center Middle Bay



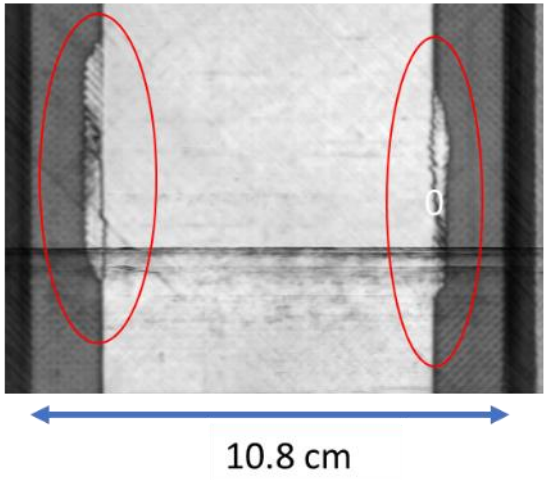
Ultrasonic Inspection Image @675K Cycles



Passive Thermal Closeup
Lower Center Bay

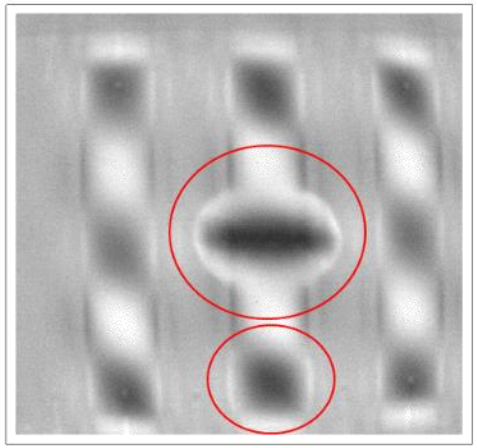


Ultrasonic Inspection Image Lower Center Bay

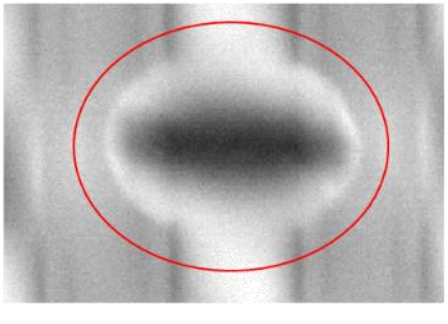


Four Stringer Damage Formation

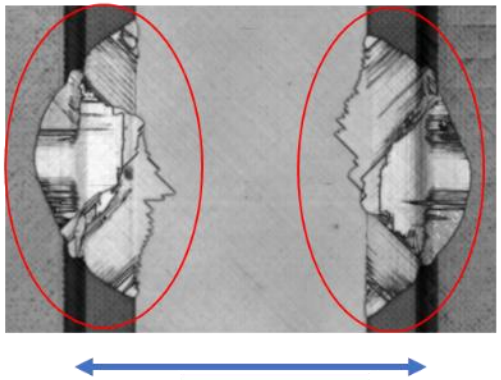
Passive Thermal Image @800K Cycles



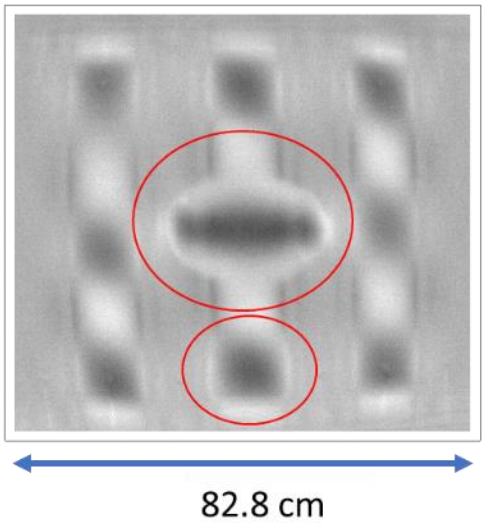
Passive Thermal Closeup



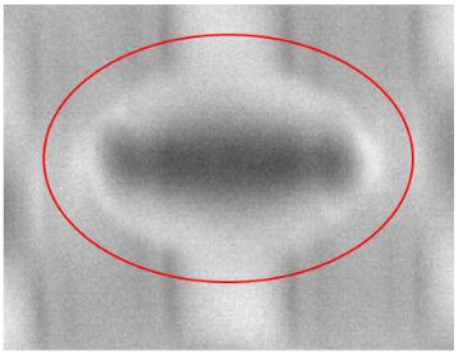
Ultrasonic Inspection Image @800K Cycles



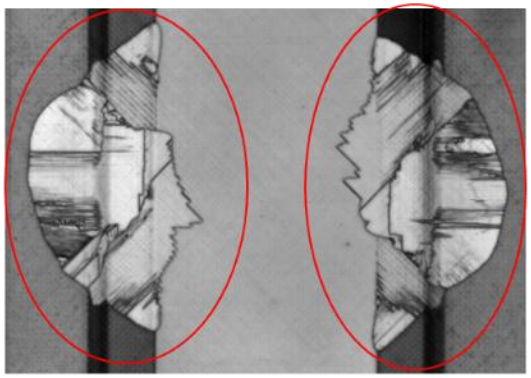
Passive Thermal Image @1,210K Cycles



Passive Thermal Closeup



Ultrasonic Inspection Image @1,210K Cycles



Data Processing for Non-Periodic or Rapid Growth Response (Single Stringer)

$$processed\ image[i] = y[k - delay] - y[k]\ \ for\ \ y[k] = \frac{1}{N} \sum_{j=(k-1)*(N-1)}^{k*N} x[k + j]$$

- Frequency of loading = 2 Hz. *Y[k]* is the averaged thermal image, x[k + j] is the raw acquired thermal images (80 Hz), *j* is the acquired image number, *k* is the averaged image number, *i* is the processed image number, *N = 40* is the number of boxcar averages, *j* is the acquired image number, *delay = 25* is the offset subtracted averaged image.

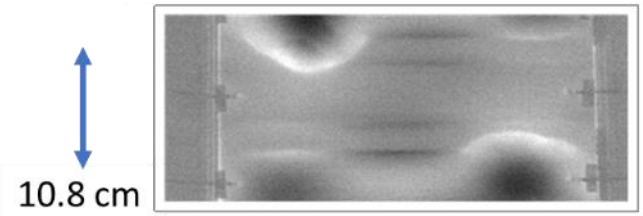
- Parameter for processing behaves as a simple notch filter.

- Delay is sufficient to capture transient thermal response 12.5 seconds or less.

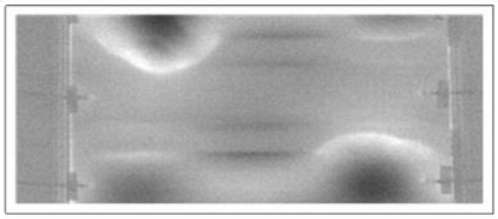
Comparison of Periodic to Rapid Growth Thermal Responses

Periodic Response

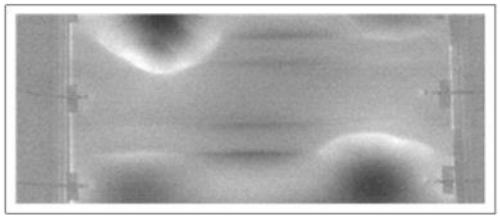
Thermal Image @422.0 Seconds



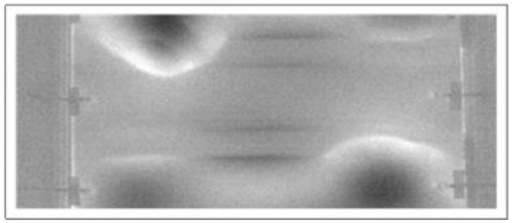
Thermal Image @422.5 Seconds



Thermal Image @425.0 Seconds

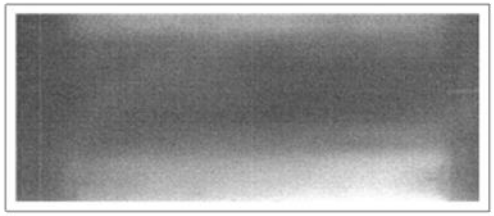


Thermal Image @432.5 Seconds

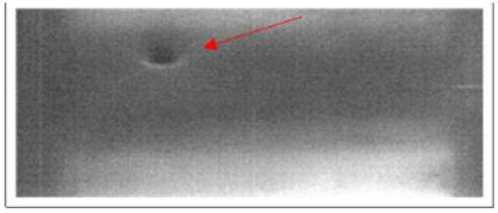


Non-periodic Response

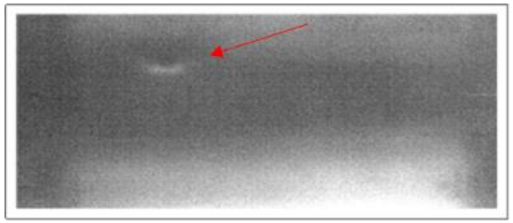
Filtered Image @422.0 Seconds



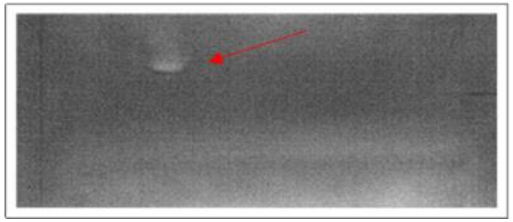
Filtered Image @422.5 Seconds



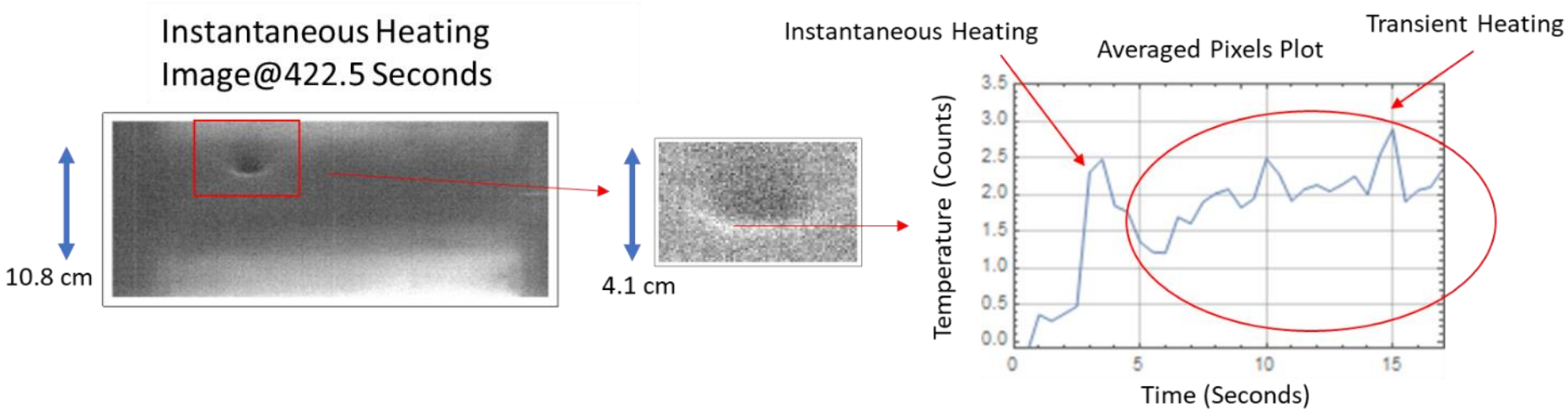
Filtered Image @425.0 Seconds



Filtered Image @432.5 Seconds

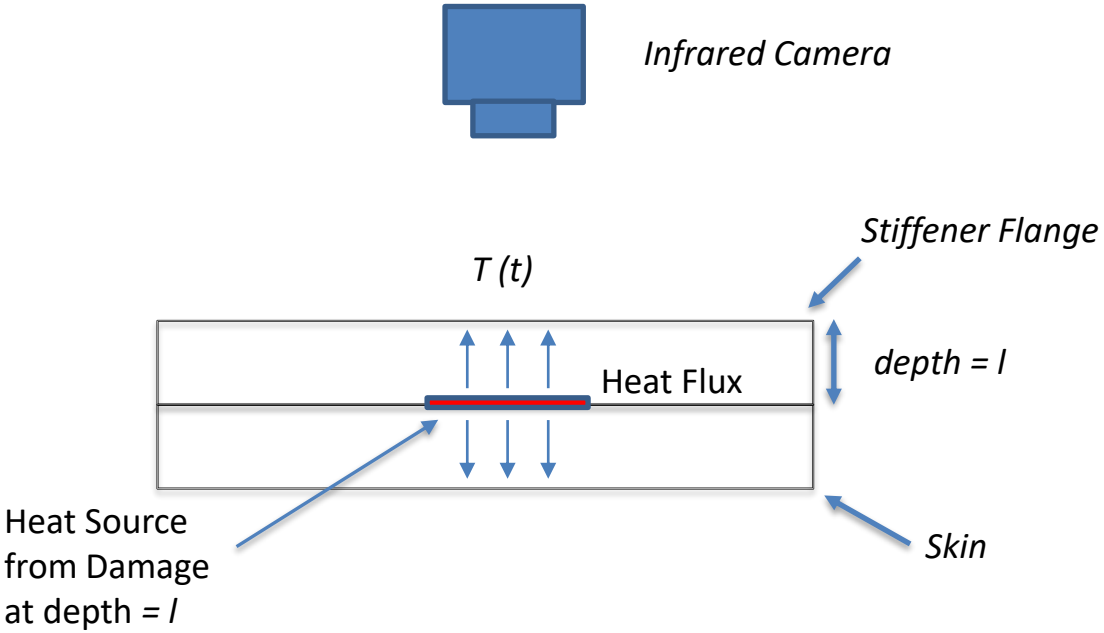


Rapid Growth Thermal Response Temporal Plot



- The instantaneous and transient heating was observed for quasi-static load testing: Zalameda, J.N., Jackson, W.C., and Rose, C.A., Estimation of Delamination Crack Depth using Passive Thermography. Proc. SPIE 2019, 11004, doi:10.1117/12.2520390.

1-Dimensional Two-Sided Thermal Model

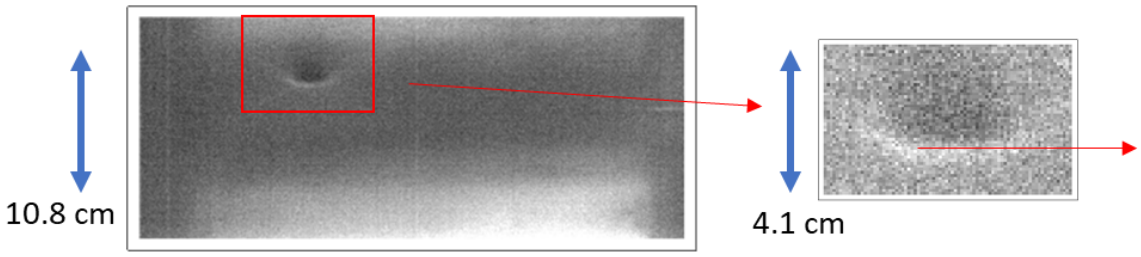


$$T(t) = 2\,T_f \sqrt{\frac{l^2}{\alpha\,\pi\,t}} \left(\exp \frac{-l^2}{4\,\alpha\,t} + \exp \frac{-9\,l^2}{4\,\alpha\,t} \right) for\ t < 0.4\,\frac{l^2}{\alpha} \text{ and}$$

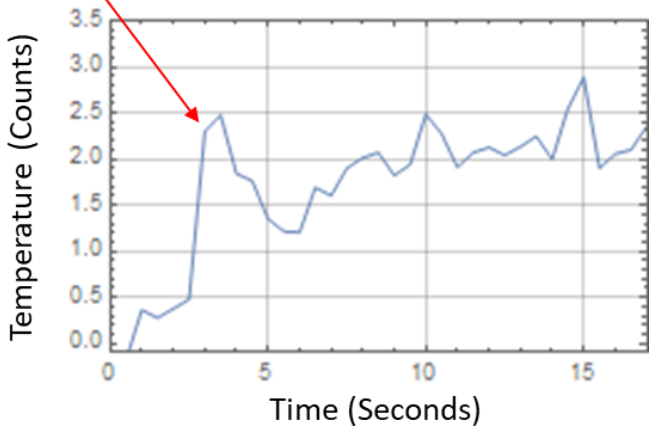
$$T(t) = T_f \left(1 - 2 \exp \frac{-\alpha\,\pi^2\,t}{l^2}\right) for\ t \geq 0.4\,\frac{l^2}{\alpha}$$

Rapid Growth Thermal Response Temporal Plot with Curve Fit

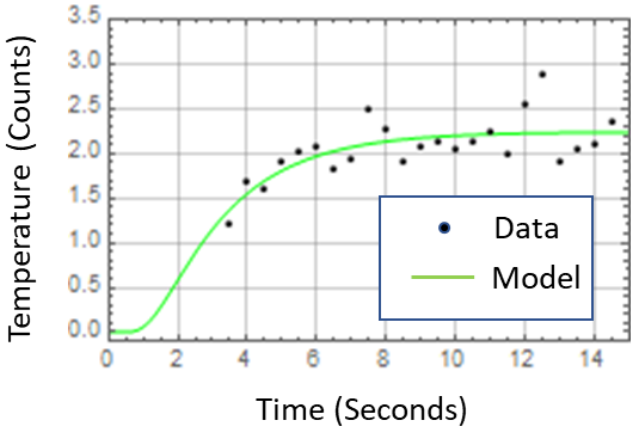
Instantaneous Heating
Image@422.5 Seconds



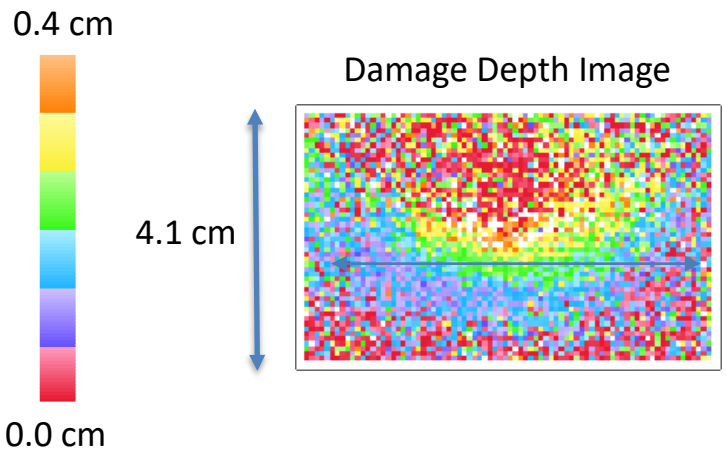
Instantaneous Heating
Averaged Pixels Plot

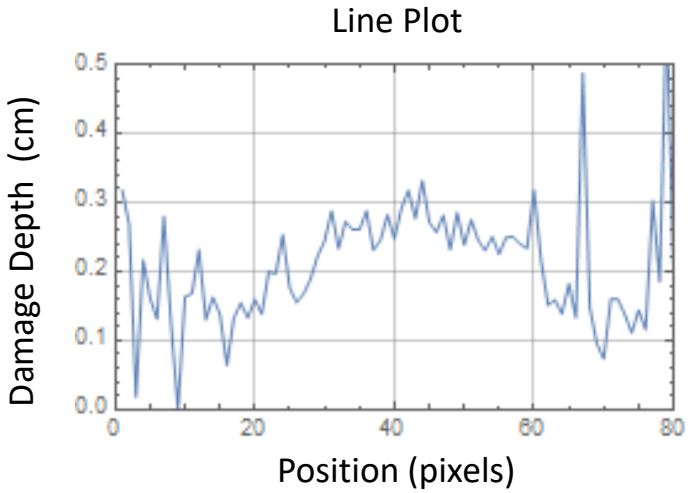


Averaged Pixels Plot with Curve Fit



Conversion of Thermal Data to Damage Depth Image





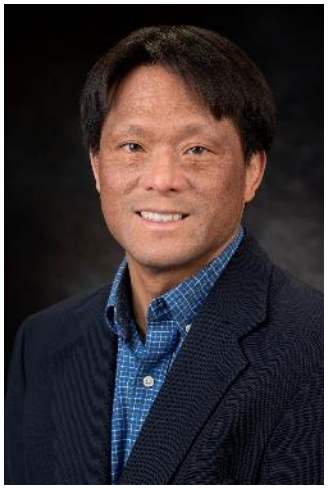
Conclusions

- Passive thermography has been shown to be an effective real time NDE technique for single and four stringer composite panels during fatigue loading. Results agreed well with the ultrasonic imaging results for both size and shape of defect.

- Using notch filtering, the periodic response was removed and the non-periodic (rapid growth) thermal response was captured.

- Rapid growth data: using the transient response we reduced the thermal data to a defect depth image.

- Passive thermography was used to detect new damage or reveal damaged areas not growing. Therefore ultrasonic inspections were not performed thus saving testing time.



Thanks for your attention.

Questions?