

Acquisition and Processing of Passive Thermography Fatigue Test Data

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ABSTRACT

Passive thermography is a large area inspection technique and is commonly used during fatigue loading of composite structures. Passive thermography allows for real time tracking of damage. This provides an accurate assessment of the damage progression as a function of load cycles and determines when the loading is stopped for ultrasonic or X-ray CT evaluations for detail damage assessment through-the-thickness. In addition, if new areas of damage growth are detected, with passive thermography, then those areas are additionally inspected with ultrasound or X-ray CT. A custom developed passive thermography inspection system for fatigue loading is presented. Passive thermography of damage progression is compared to ultrasound inspections as a function of the fatigue cycles. Discussion is made on processing of the thermal data for periodic and non-periodic thermal responses.

Keywords: Thermal nondestructive evaluation, passive thermography, fatigue load damage detection, delamination damage, thermal measurement of damage depth, non-immersion ultrasound

1. INTRODUCTION

Real time nondestructive evaluation (NDE) is necessary for composites load testing to track early onset and growth of damage. The NDE allows for controlling the growth of the damage as a function of the applied load. When damage is detected with the real time NDE, the loading is stopped and another inspection technique such as ultrasound or X-ray computed tomography (CT) is used to provide a detailed assessment of the panel damage as a function of depth. The real time NDE also provides documentation of the structure during failure. Damage onset, growth, and panel failure will provide valuable information for development and validation of progressive damage analysis (PDA) models [1,2]. It has been demonstrated that passive thermography is effective for real time NDE of a structure during load testing [3-5].

Passive thermography is similar to active thermography where both techniques rely on detecting small surface temperature differences due to applied or removed energy. Passive thermography implies no control of the energy such as the sun, hot air, moisture evaporation, and structural loading. The infrared camera passively records the component surface thermal response. The challenge of passive thermography for this application is to detect the small, transient thermal signals generated during quasi-static and fatigue loading [4, 6-7].

In this work, a fatigue load is applied to single-stringer and a four-stringer stiffened composite panels. Passive thermography is used to monitor the structure during load testing. Any small increases in temperature, resulting from delamination damage formation in the panel during the fatigue loading, is monitored in real time while the thermal data was recorded. The temperature rise at the surface is composed of periodic and non-periodic heating. The periodic heating consists mainly of thermoelastic heating that is due to the compression loading. The thermoelastic heating can also be affected by the damage progression since the structure's response to the applied load changes. Damaged areas can also produce periodic heating due to friction heating as a function of the cyclic load. In addition, newly formed rapid growth damage can produce non-periodic heating due to large jumps in the damage progression. This increase in temperature has been detected previously during quasi-static loading [8] and has been observed during cyclic loading. This heating is challenging to detect during cyclic loading because the thermoelastic response is dominant. This paper discusses the data processing technique to detect the periodic and non-periodic damage using passive thermography.

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2. SAMPLE DESCRIPTION AND MEASUREMENT SYSTEMS

2.1 Composite Samples Tested and Measurement Setup

The single-stringer and four-stringer panels have the same stringer profile and thickness. The skin of both the stiffened composite panels are made up of 12 plies with a total thickness of 0.22 cm and the stiffener flange is made up of 12 plies with a total thickness of 0.24 cm. The stiffener hat top is made up of 16 plies with a total thickness of 0.32 cm. The stiffener is a woven composite. The dimensions of the single-stringer panel are width 21.6 cm and length 51.3 cm. The dimensions of the four-stringer panel are width 82.8 cm and length 82.8 cm. Figures 1a, 1b, 1c show the single-stringer composite panel skin side, stringer side, and test setup respectively. Figures 2a, 2b and 2c show the four-stringer composite panel skin side, stringer side and test setup respectively. The panel is painted for digital image correlation measurements to record panel deformation. The load is applied from the bottom while the top is held stationary. This configuration allows for panel deformation that resulted in damage formation between the stiffener flange and skin. The maximum applied cyclic fatigue loads are approximately -25,000 pounds for the single-stringer and approximately -85,000 pounds for the four-stringer panel. The frequency of the fatigue load is 2 Hertz (Hz).

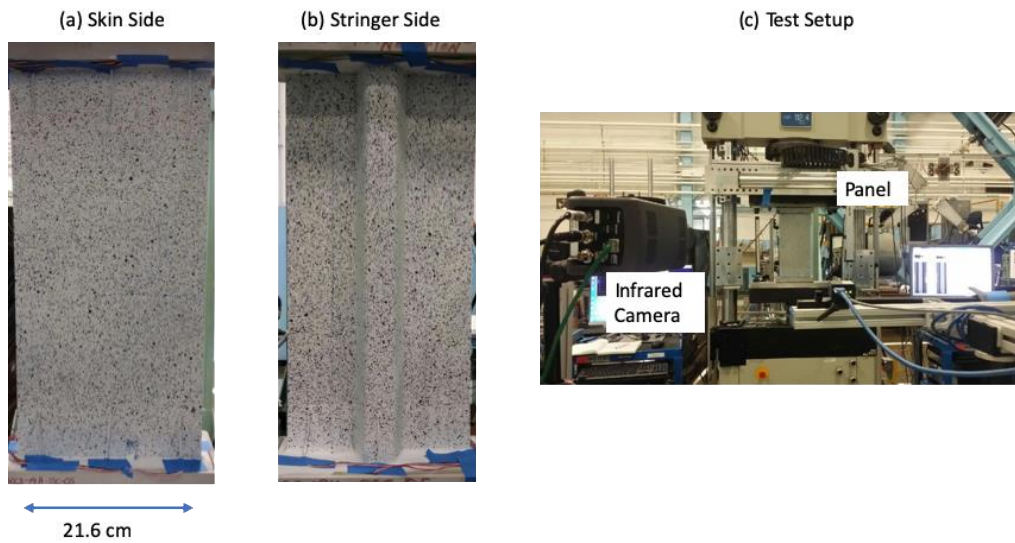


Figure 1: Single-stringer composite panel (a) skin side, (b) stringer side and (c) test setup.

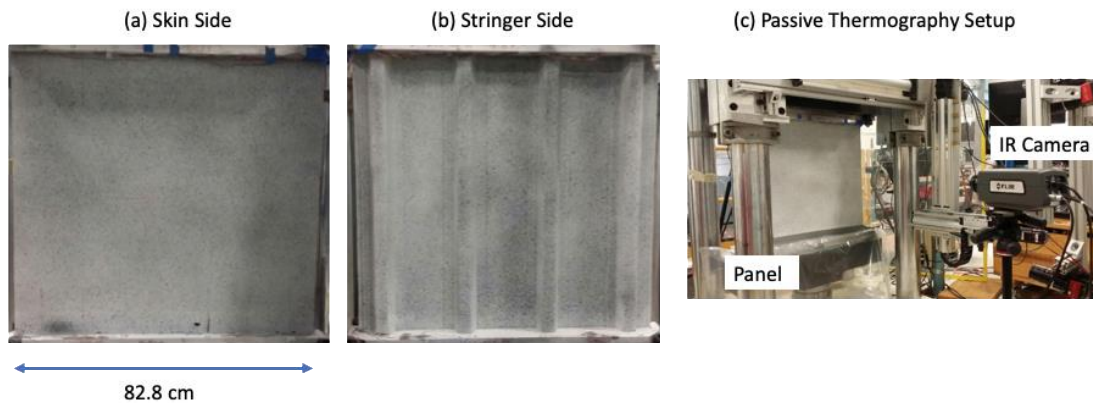


Figure 2: Four-stringer composite panel (a) skin side, (b) stringer side and (c) test setup.

The test setups in Figures 1c and 2c show the infrared camera viewing the skin side. The basic system consists of an IR camera operating in the 3–5 micrometer IR band and an image data acquisition computer. The IR camera is configured with 25 mm germanium optics for the single-stringer panel and 13 mm germanium optics for the four-stringer panel. The focal plane array size of the camera is 640x512. The setup for both panels, require a Plexiglas[®] shield (positioned behind the IR camera and in front of the sample opposite the camera) to filter out spurious IR background sources. The shields are not shown in the setup pictures. The camera frame rate is externally triggered and operated at a frequency of 80 Hz. The load signal is also acquired using a USB based 12-bit data acquisition module. For each infrared camera frame, a load value is acquired. Furthermore, real time averaging, a delayed image subtraction, and real time contrast adjustment are used to enhance detection of the small thermal transient signatures due to the damage. Without this processing, the faint thermal signatures that indicate early damage would be difficult to nearly impossible to detect in real time. The processed imagery is displayed in real time to allow the load frame operator to monitor the damage.

3. MEASUREMENT RESULTS

3.1 Single-stringer Periodic Thermal Response

Real time passive thermography is used for the single-stringer composites testing. These processed passive thermal images are shown in Figures 3 and 4 and shows the periodic heating pattern due to the applied load. The periodic heating is composed of the thermoelastic heating, the change in the panel's thermoelastic heating pattern due to the damage growing, and friction heating from the damage areas. An image averaging/difference processing technique is used to produce a processed image for real time display. The fatigue load frequency is 2 Hz and the image acquisition rate is 80 frames per second. The acquisition is synchronized to the cyclic loading where 40 frames per cycle are acquired. To improve signal to noise, the frames are averaged (10 frames) to give 4 averaged images per cycle. The 2nd averaged frame, representing the temperature at maximum compression load is subtracted from the 4th averaged frame representing the temperature at the lowest applied load within a load cycle. This is given in equation (1).

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

For equation (1), i is the processed image number, k is the averaged image number, N is the number of boxcar averages, j

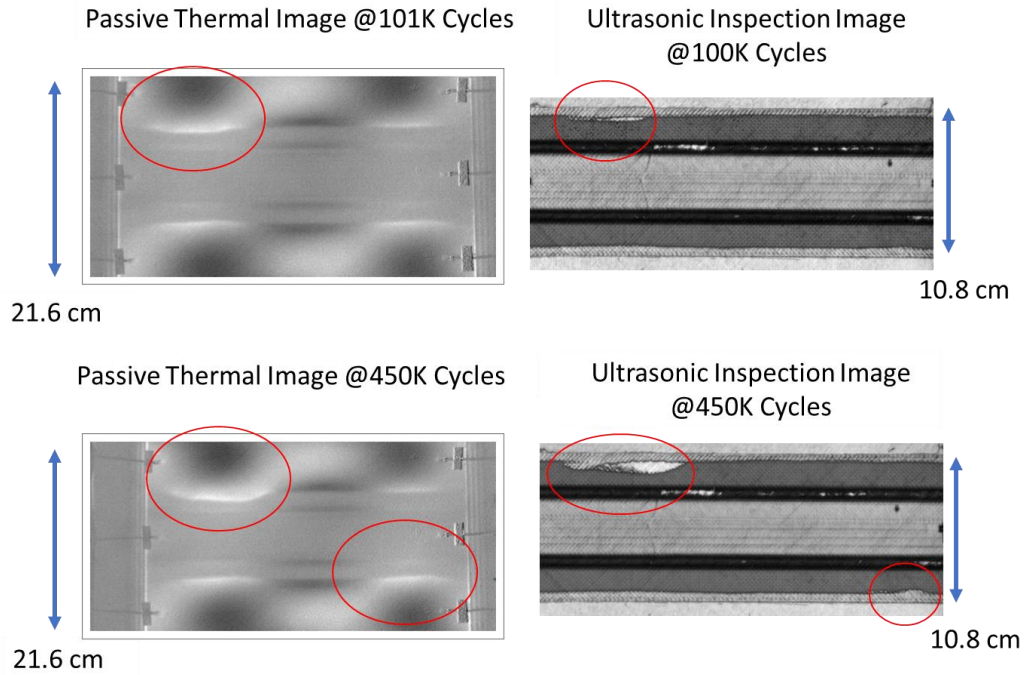


Figure 3: Single-stringer composite panel testing results with ultrasonic inspection image comparison at cycle counts of approximately 100k and 450k.

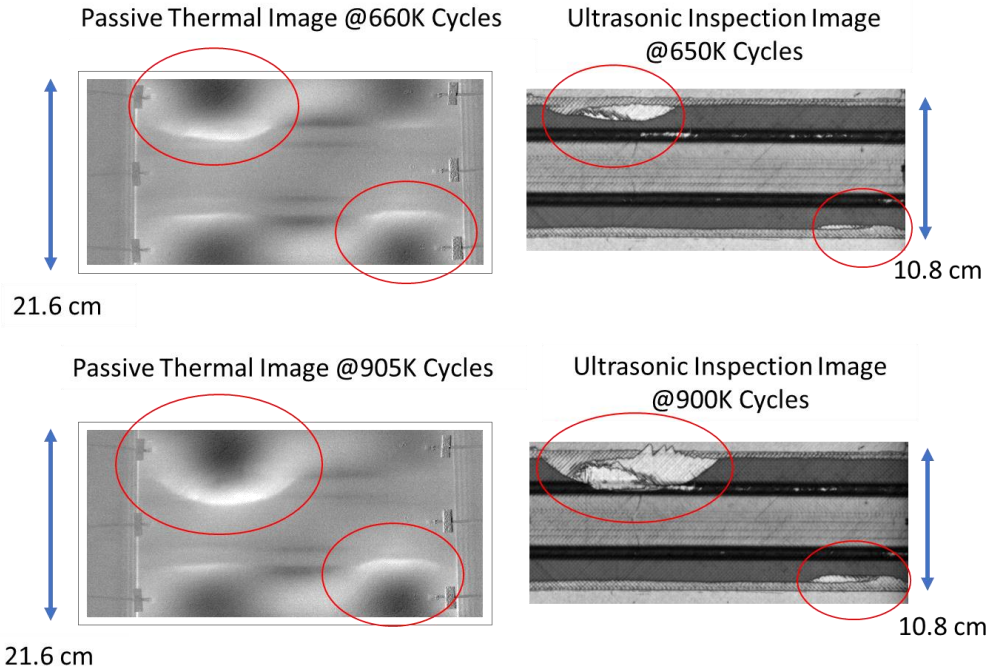


Figure 4: Single-stringer composite panel testing results with ultrasonic inspection image comparison at cycle counts of approximately 650k and 900k.

is the acquired image number, and *delay* determines the subtracted image offset (*delay* = 2) which is used to compute the difference images. These difference images are then averaged over four cycles to produce the final inspection image and therefore the processed image is updated every 2 seconds. The damage growth can be detected by the change in the heating pattern where areas of increased heating (circled in red) indicate damage. The thermally detected damage is confirmed by non-immersion ultrasonic inspections [9] with good qualitative agreement even for the smallest detected damage. As the number of cycles increased over time, new damage growth is found diagonal to the original damage area as shown in Figure 3 starting at 450K cycles and growing toward the stiffener hat as shown for 900k cycles.

3.2 Four-Stringer Periodic Thermal Response

Real time passive thermography is used for the composites testing. The same single-stringer processing technique and parameters are used to calculate the periodic thermal image for real time display. The fatigue load frequency is 2 Hz. The acquisition was synchronized to the cyclic loading. To improve signal to noise, the frames were averaged (10 frames) to give 4 averaged images per cycle. The averaged images are stored in an array. The 2nd averaged frame, representing the temperature at maximum load is subtracted from the 4th averaged frame representing the temperature at the lowest applied load. These difference images are then averaged over four cycles to produce the final inspection image and therefore the processed images are updated every 2 seconds. These processed images are shown in Figures 5, 6 and 7 and reveal the periodic heating pattern due to the applied load. The periodic heating is composed of the thermoelastic heating, the change in the panel's thermoelastic heating pattern due to the damage growing, and friction heating from the damage areas. The damage growth areas are circled in red. For the four-stringer panel, the damage growth is symmetrical, growing on the opposite stringer flanges. The thermally detected damage is confirmed by the non-immersion ultrasonic inspections [9]. The thermal imagery can locate new areas of damage growth that could significantly affect how the structure responds to the applied load. This is shown in Figure 6 where new areas of damage growth are detected in the lower center bay area with passive thermography. Additional ultrasonic scans are then performed in that area as the damage is tracked, however, compared to the center middle bay area the damage did not grow significantly as the cycle count increased. This is shown in the left passive thermography images of Figure 7 (circled in red lower center bay). The damage growth is similar to the growth at 675K cycles shown in Figure 6, and therefore additional ultrasonic scans in that area were not required thus saving testing time.

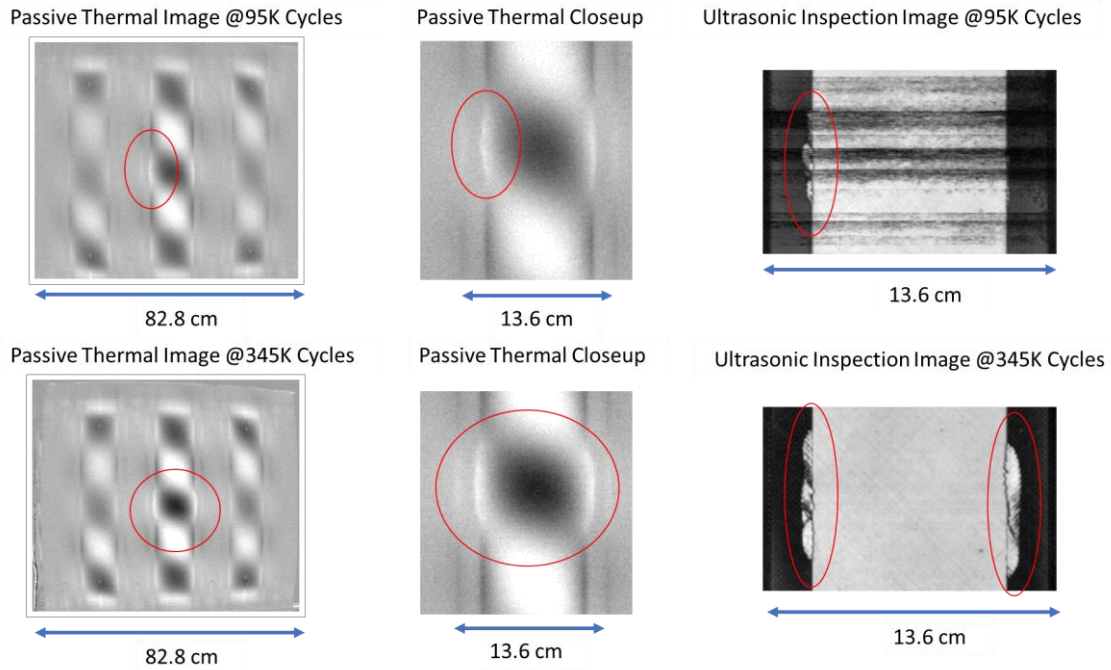


Figure 5: Four-stringer composite panel testing results with ultrasonic inspection image comparison at cycle counts of approximately 95k and 345k.

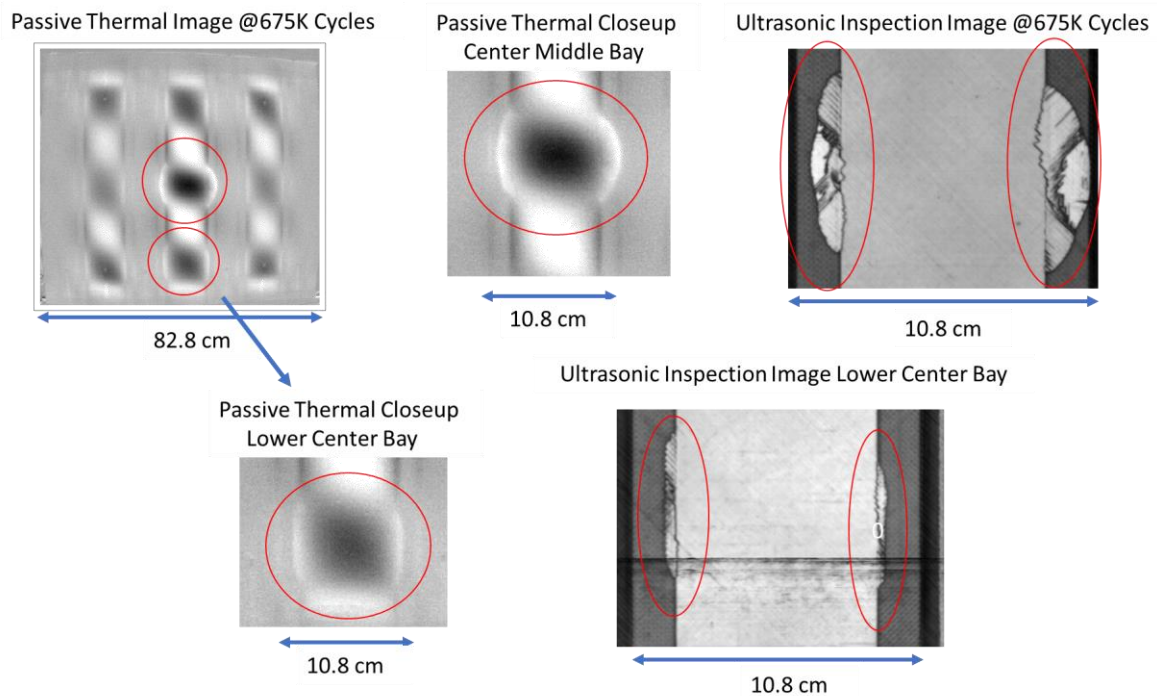
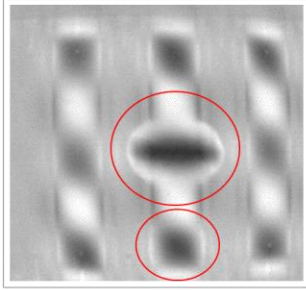


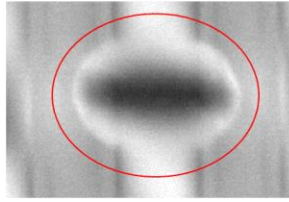
Figure 6: Four-stringer composite panel testing results with ultrasonic inspection image comparison at cycle count of approximately 675k.

Passive Thermal Image @800K Cycles



82.8 cm

Passive Thermal Closeup



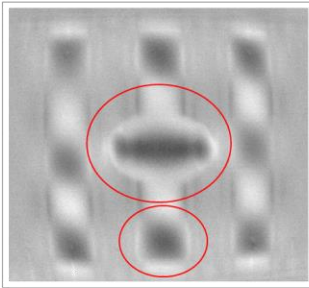
10.8 cm

Ultrasonic Inspection Image @800K Cycles



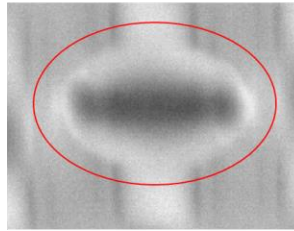
10.8 cm

Passive Thermal Image @1,210K Cycles



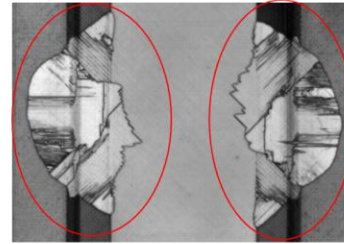
82.8 cm

Passive Thermal Closeup



10.8 cm

Ultrasonic Inspection Image @1,210K Cycles



10.8 cm

Figure 7: Four-stringer composite panel testing results with ultrasonic inspection image comparison at cycle counts of approximately 800k and 1,210K.

4. PROCESSING FOR NON-PERIODIC HEATING RESPONSES

4.1 Single-stringer Rapid Growth Heating

As discussed in Section 3 the periodic thermal response is dominated by thermoelastic heating in addition to heating from the damaged area. One area of interest is to capture the rapid growth heating that results from jumps in damage. This can be masked by the dominant periodic heating response due to the cyclic loading. A technique investigated here is to adjust the number of averages to $N = 40$ (image acquisition rate was 80 Hz) to remove the periodic response. This can be viewed as a notch filter to remove the thermal response at 2 Hz in addition to the harmonic responses. This technique is well suited for thermal data since the rapid growth thermal response is typically fracture damage at a given depth which requires the heat to diffuse to the surface and will be typically much longer than the loading cycle time of 0.5 seconds. Using equation (1), the number of averaged images is set to $N = 40$ and the *delay* = 25 averaged frames. The delay subtraction is sufficient to capture thermal transients that last 12.5 seconds or less while still removing any background heating. The notch filtered images are shown in the right images of Figure 8. The Figure 8 left images show the periodic heating revealing the damage areas. Using the simple notch filter for the same data temporal span, the periodic response at 2 Hz is removed thus revealing heating from sudden damage growth (indicated by the red arrows) not detectable in the periodic response images for similar timeframes as shown in Figure 8. This sudden damage growth has been studied previously and was composed of two heat generation mechanisms: an irreversible thermoelastic release of energy and a release of heat flux at the buried interface of failure thus producing a transient response detected at the surface [5, 8]. The irreversible thermoelastic release of energy is used to determine the start time for the transient response. This can be seen in Figure 9 where a temporal plot over the damage growth area (4x8 pixels average) reveals both the instantaneous and transient heating. Using a thermal model, the depth of the damage can then be determined and is discussed in the next section.

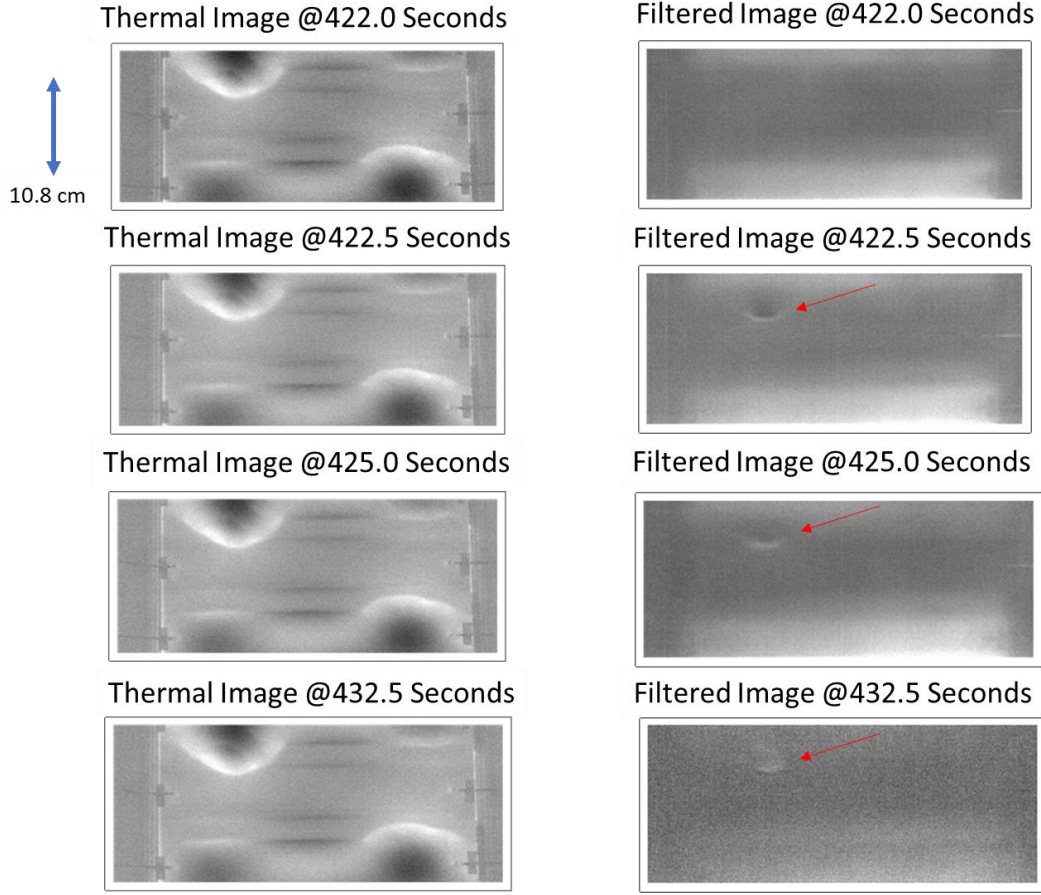


Figure 8: Single-stringer composite panel analysis results using notch filtering for rapid growth heating detection as shown with the arrow on the right images.

4.2 Thermal Measurement of Damage Depth

The heat flux, originating at the interface of failure, is created due to the mechanical failure when the two surfaces separate. The separation is instantaneous and is modeled as an impulse heat flux that creates heating within the separated inner layers. Since the two layers are not in contact after failure, a simple two sided or through-transmission heat flow model is used. The depth of the damage is determined by the heat transfer from the inside to the outer surface. This temperature response will be a function of the damage depth and thermal diffusivity. A simple one-dimensional two-sided thermal measurement model can be used to estimate the damage depth if the thermal diffusivity is known. The analytic solution derived by Winfree [10] is shown in equation (2). This equation is commonly used for a two-sided thermal measurement and is computationally efficient as compared to an infinite series solution.

$$T(t) = 2 T_f \sqrt{\frac{l^2}{\alpha \pi t}} \left(\exp \frac{-l^2}{4 \alpha t} + \exp \frac{-9 l^2}{4 \alpha t} \right) \text{ for } t < 0.4 \frac{l^2}{\alpha} \text{ and } T(t) = T_f \left(1 - 2 \exp \frac{-\alpha \pi^2 t}{l^2} \right) \text{ for } t \geq 0.4 \frac{l^2}{\alpha} \quad (2)$$

$T(t)$ is the surface temperature response, T_f is the final temperature, α is the thermal diffusivity, l is the layer thickness, and t is time. The temperature response equation assumes no convection losses and the heat flux generated is considered instantaneous for the samples inspected. The equation also does not take into account the instantaneous heating response; however, the start time is determined from the instantaneous response. For a known thermal diffusivity, equation (2) is used to determine the damage depth, pixel by pixel, by minimizing the squared difference between the model and measured

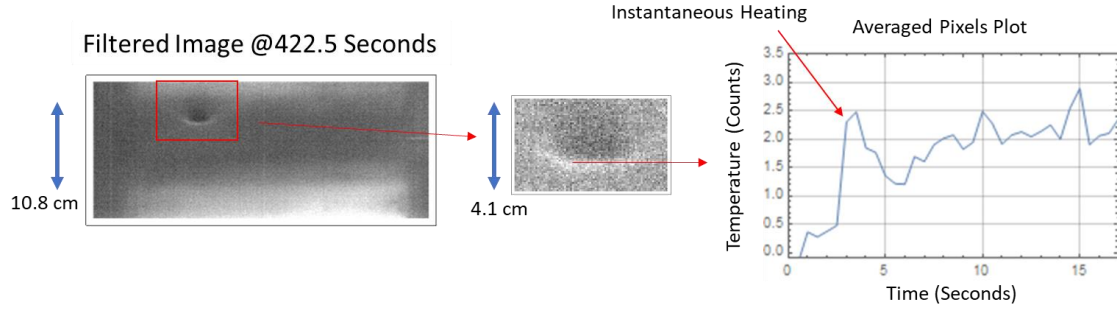


Figure 9: Single-stringer composite panel nonperiodic rapid growth heating detection showing instantaneous and transient heating.

thermal response. A two-parameter fit of the final temperature T_F and thickness l (damage depth) is implemented using the Levenberg-Marquardt curve fitting algorithm [11]. For a known thermal diffusivity, equation (2) is used to reduce the thermal data into a thickness image by fitting the thermal data pixel by pixel. The thermal diffusivity of the woven composite flange is measured previously using a two-sided thermal flash technique [9]. The thermal diffusivity value measured is $0.0042 \text{ cm}^2/\text{sec}$. Shown in Figure 10 is an example model fit to the thermal data for an area of 4×8 pixel points (located by the arrow in Figure 9) over the small delamination. The data used for the model fit is truncated to remove the early times which is dominated by the instantaneous heating response. For the small delamination, the fitting times are from approximately 3.5 to 14.5 seconds. The thickness value, l , obtained from the model fit is 0.30 cm . By fitting the thermal model to the data, pixel by pixel, the thermal data can be reduced to a thickness image revealing the damage depth. This is shown in Figure 11. The depth image is blurry due to the early times omitted from the fitting. The damage depth image reveals damage at different depths from 0.20 to 0.40 cm . This indicates that the damage detected is at multiple ply levels. Since this data is analyzed post testing, X-ray CT data was not taken to validate the crack depth, however the results presented here are in excellent agreement to previous measurements that were validated with X-ray CT for similar geometry/material panels [8]. The thermally measured thickness values away from the damage gives erroneous values due to the lack of a thermal response (outside pixels 20 and 50).

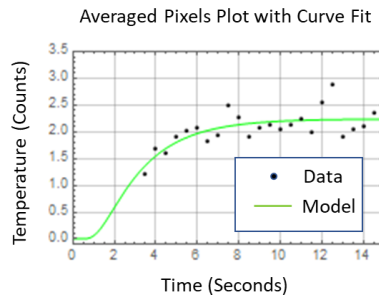


Figure 10: Single-stringer composite panel model fit to the transient heating response for damage depth.

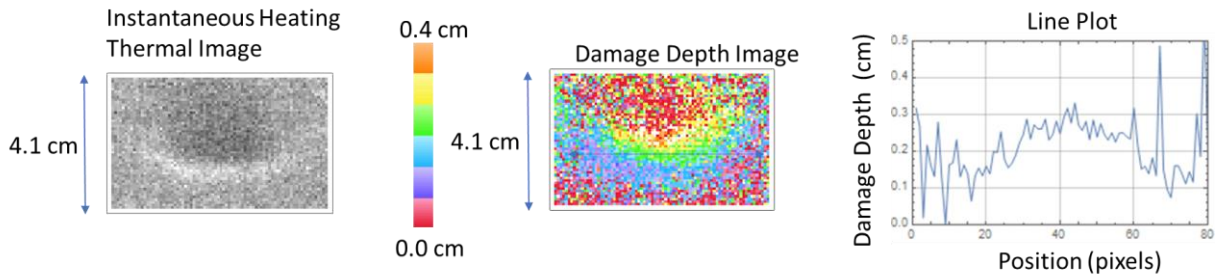


Figure 11: Single-stringer composite panel nonperiodic rapid growth damage depth image with horizontal line plot.

5. CONCLUSIONS

Passive thermography has been shown to be an effective real time NDE inspection technique to track damage onset and growth in composite single and four-stringer panels during fatigue loading. The thermal data is processed for both periodic and non-periodic thermal imagery to inspect for damage. The periodic thermal inspection images, due to the applied cyclic load, reveal the thermoelastic response of the panel, changes in the thermoelastic response due to damage growth, and friction heating at the damage areas. The simple notch filter detects the rapid growth or non-periodic heating. This heating is used to estimate the damage depth. Using both the periodic processing and the rapid growth processing simultaneously will allow for structural engineers to track slow damage growth as well as rapid damage growth in real time. Lastly, for the four-stringer panels if damaged areas did not show significant growth, as in the lower center bay regions shown in Figure 7, then ultrasonic scans are not performed in those areas thus saving testing time.

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