Visitor Research Report

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Area of Research: **Applicability of Scanning Infrared Thermography as a Large Area Inspection Technique for Composite Structures**

Period of Visit: **September 3, 2008 – January 30, 2009**

Goal:

My intended research goals for this sabbatical leave were:

1. Literature review of thermographic applications to microcracking in carbon fiber composites
2. Develop a computational model which varies microcracking density to incoming heat pulses
3. Compare quartz, flash, line-scan, and thermal photocopier systems with the detection of microcracking in carbon fiber composites
4. Compare thermographic findings with published (and experimental if time permits) ultrasonic attenuation measurements on microcracking in carbon fiber composites
5. Begin to use microcrack density measurements as means to determine remaining composite life

Strategy:

While my overall objective was to investigate microcracking in carbon composites, my actual work concentrated on goal #2 – development of a computational model of carbon composites. This change came about for two reasons:

1. It was assumed at the time of my sabbatical proposal that my start date at NASA Langley would coincide with the Aircraft Aging and Durability Program's early study of microcracking in carbon composites. Program delays during the 12 months between my proposal and the start of my research pushed back the microcracking study beyond my leave window.

2. While equations to describe one-dimensional heat conduction in defect-free materials are known, they are difficult to modify to incorporate flaws. Therefore an alternative solution was sought – one that could readily incorporate defects, such as microcracking.

The main focus of my research was with a computational model to describe the heat conduction in carbon composites using Thermal Quadrupoles. This approach used the Laplace Transform method to solve the one-dimensional heat equation for an insulated slab. It is based on 2 x 2 matrices that relate both temperature and flux on one surface to temperature and flux on another surface.

For a defect-free material the Laplace Temperature (θ) with the Laplace Heat Flux (ϕ) on the front (subscript 1) and rear (subscript 2) surfaces are shown in equation 1:

$$\begin{bmatrix}\theta_1\\ \phi_1\end{bmatrix}=\begin{bmatrix}A & B\\ C & D\end{bmatrix}\begin{bmatrix}\theta_2\\ \phi_2\end{bmatrix} \tag{1}$$

The variables in equation 1 are defined as follows:

$$A=D=\cosh(\alpha e)$$

$$B=\frac{\sinh(\alpha e)}{\alpha S\lambda}$$

$$C=\alpha S\lambda\sinh(\alpha e) \tag{2}$$

$$\alpha=\sqrt{\frac{p}{a}}$$

$$p=\frac{\ln(2)}{t}$$

where p is the Laplace parameter, a is the thermal diffusivity, S is the surface area, e is the material thickness, and λ is the thermal conductivity.

Assuming a Dirac heat pulse of total energy density Q on an insulated slab results in equations for the Laplace Temperature for the front surface (equation 3) and rear surface (equation 4)

$$\theta_1=\frac{Q}{\lambda\sqrt{p/a}\tanh(e\sqrt{p/a})} \tag{3}$$

$$\theta_2=\frac{Q}{\lambda\sqrt{p/a}\sinh(e\sqrt{p/a})} \tag{4}$$

MatLab code was written to calculate the Laplace Temperatures at both the front and rear surfaces and converted to them to actual temperatures using the Gaver-Stehfast algorithm. The Gaver-Stehfast method for the Inverse Laplace Transform of was selected for its simple numerical algorithm.

Accomplishments:

Figures 1 – 2 show the theory and experimental temperature-time curves for one of the carbon composites tested. The theoretical curves match nicely with the experimental curves for all of the materials. The only deviation between the two occurs later in time on the rear surface plots. In Figure 1, for example, the experimental curve peaks at approximately 5 seconds and then falls off whereas the theoretical curve peaks at this time and levels off. This is seen in all of the rear surface plots because the Thermal Quadrupole Numerical Model was based on an insulated slab. Once the heat pulse reached the rear surface, it had no place to go. In reality, though, the heat would exit the material into the air. This accounts for the experimental temperature versus time curve to rise, peak, and then decline.

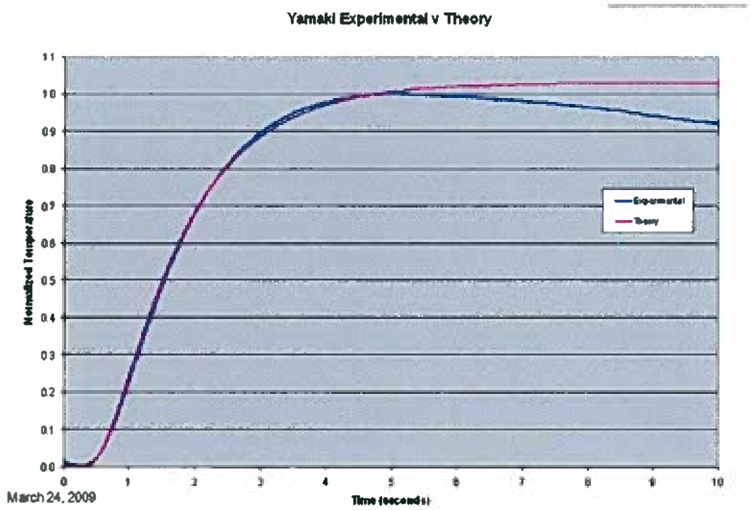

Figure 1. Temperature versus time plot for the rear surface of the Yamaki carbon composite sample. Experimental results are shown in blue and the theory in pink.

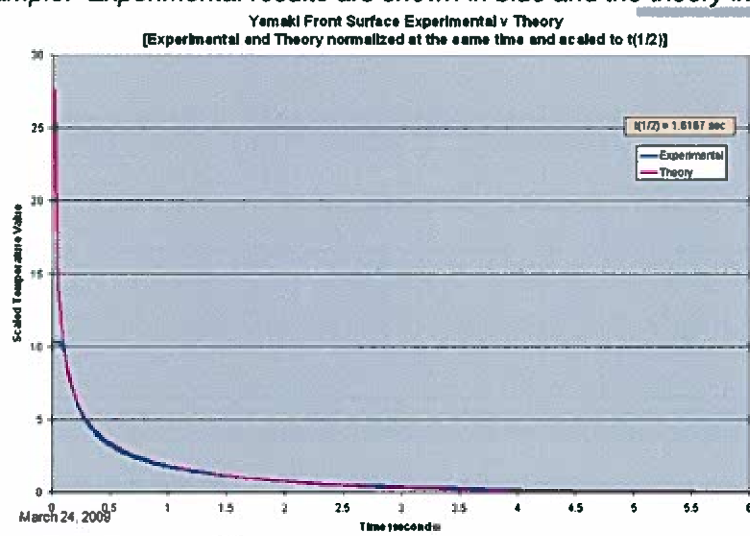

Figure 2. Temperature versus time plot for the front surface of the Yamaki carbon composite sample. Experimental results are shown in blue and the theory in pink.

An interesting correlation was discovered while analyzing the data. The quantity $t_{1/2}$, the characteristic time for the front surface to reach half maximum temperature, was directly related the amount of time necessary for the rear surface to reach peak temperature. Specifically, it took 2 $t_{1/2}$ seconds for the rear surface to reach 90% of its maximum temperature. This relationship held for all samples.

A LN-LN plot of the temperature-time theoretical data for the front surface of the Yamaki sample was constructed. The second derivative of this curve plotted against LN(time), see Figure 3, reviled a peak in the data set. The location of the peak and LN(2 $t_{1/2}$) was consistent for all of the samples used in this study – the ratio between the two times was 1.14.

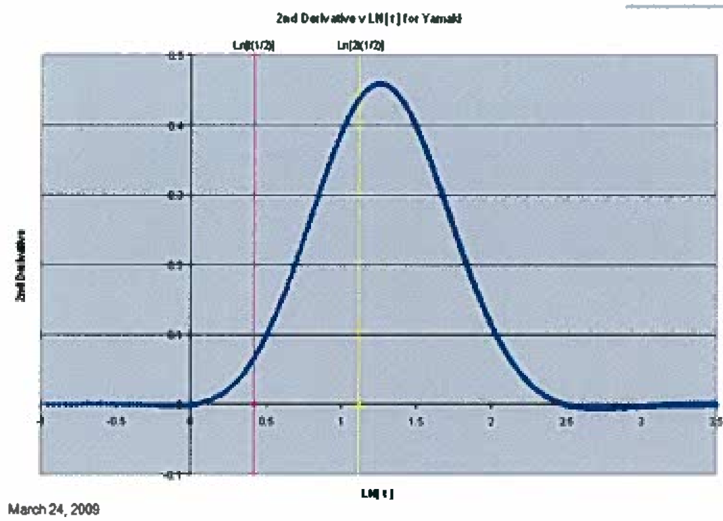

Figure 3 Second Derivative of the LN(Temperature) versus LN(time) plot for the front surface of the Yamaki sample.

A literature search for related work on this topic was conducted and revealed a 2007 paper in which the author made the following conclusions:

- The shape and amplitude of the 2nd Derivative Curve is invariant with respect to material composition
- The width of the 2nd Derivative Curve is constant
- The 2nd Derivative Curve has a maximum amplitude of 0.47 for the case when no heat is transferred from the back wall of the sample to the surroundings
- Peak time of 2nd Derivative Curve will vary and be related to material thickness and thermal diffusivity
- The Peak of the 2nd Derivative Curve occurs when the back wall reaches 91% of its maximum temperature

My model yielded findings consistent with the 2007 paper.

Future Work:

Results from the Thermal Quadrupole Numerical Model are promising. However, further modifications are need. I would like to incorporate

- Heat losses at the rear and front surfaces
- Defects
- Multilayer materials
- Internal heat sources

into the current Thermal Quadrupole Model and compare the results to experimental data. Additionally, I would like to generate the experimental 2nd Derivative Curves for the front surface of the carbon composite materials and compare their peak times to my theoretical results. I would also like to explore why my characteristic time, $2t_{1/2}$, occurs prior to the peak of the 2nd Derivative plot.

Pending Publications:

None at this time

Seminar Presented:

Invited Colloquium Speaker at Roanoke College, Salem, VA on March 24, 2009.

Title, "Thermographic Inspection of Carbon Composites Used in Aerospace Vehicles"