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Evaluation of Ultrasonic and Thermal Nondestructive Evaluation for the Characterization of Aging Degradation in Braided Composite Materials

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Abstract

This paper examines the ability of traditional nondestructive evaluation (NDE) techniques to measure the degradation of braided polymer composite materials subjected to thermal-humidity cycling to simulate aging. A series of braided composite coupons were examined using immersion ultrasonic and pulsed thermography techniques in the as received condition. These same specimens were then examined following extended thermal-humidity cycling. Results of this examination did not show a significant change in the resulting (NDE) signals.

Introduction

Polymer composites have seen an increasing role in aerospace structures due to their light weight and high strength properties. Even though these materials have beneficial properties, concerns exist regarding long term performance in hostile environments. In particular, long term exposure to temperature and humidity can lead to material changes such as weight loss, and growth of microcracks and corresponding changes in mechanical properties such as loss in stiffness and strength (Refs. 1 to 4).

Although much work has been done to understand and characterize degradation mechanisms in composite materials, little work has been published regarding methods to nondestructively measure the condition of a material subjected to environmental loadings. Methods employing ultrasound, thermography, eddy currents, and x-rays are regularly employed to locate and measure discrete damage such as cracks and delaminations, but not for the measurement of aging related material degradation. When degradation occurs in a distributed fashion throughout the entire material volume and without any visible changes of physical and geometrical properties or when surface changes do not correspond to the degree of volume degradation, a simple visual inspection of the structure will not reveal any dangerous conditions. Therefore, there is a compelling need for nondestructive techniques to measure the degree of degradation. Limited success in this area has been achieved using methods such as ultrasonic spectroscopy and specialized x-ray techniques for measurement of microcrack growth in composite materials (Refs. 5 and 6). These methods are typically limited to small area inspections, simple composite architectures, or require highly specialized equipment. The purpose of this research is to examine the ability of ultrasonics and thermography to detect and characterize the aging related degradation of a braided carbon/epoxy polymer composite material subjected to thermal-humidity cycling.

Ultrasonics

Ultrasonic techniques are widely used for the inspection of composite materials (Ref. 7). Typically methods employ either a handheld contact method where a part is inspected point by point or more elaborate scanning techniques where ultrasonic probes are coupled to the part through immersion in water or through the use of a squirter or bubbler system. In either case, material discontinuities are identified by examining the amplitude and time response of an ultrasonic pulse after interacting with the material of interest. This is typically accomplished in either a single sided pulse-echo mode or in a through transmission mode where a separate transducer is used to send and receive the ultrasonic signal. In this

study, both pulse-echo and through transmission immersion ultrasonic scanning techniques are used. Measurement of degradation mechanisms is conducted by comparing the amplitude of the received signals in both the baseline and aged condition.

Thermography

One of the more widely used methods for the thermographic inspection of materials and components is pulsed thermography. As the name implies, the technique imparts a pulse of thermal energy, usually provided by a photographic flash lamp, on the surface of a specimen. The thermal energy on the surface will conduct into the cooler interior of the sample. In turn, there is a reduction of the surface temperature over time (Ref. 8). This surface cooling will occur in a uniform manner as long as the material properties are consistent throughout the specimen. Subsurface defects that possess different material properties (thermal conductivity, density, or heat capacity) will affect the flow of heat in that particular region. This resistance in the conductive path causes a different cooling rate at the surface directly above the defect, when compared to the surrounding, defect free, material. This results in a non-uniform surface temperature profile. Unprocessed, as-received data is typically displayed sequentially on a computer monitor and contrast enhanced. Images are then visually inspected for signs of a subsurface defect by locating areas with anomalous surface temperatures. This method depends on the skill of the operator and a material with a relatively uniform surface condition.

Another technique for the processing of the thermal image data has been developed to improve the detection capabilities (Refs. 9 and 10). This method involves the creation of a set of mathematical equations that represent the time response of each pixel in the raw data set. This “reconstruction” process exploits certain general features of the thermal response of materials to pulsed heating, and has been shown to allow significant improvement in detection of subsurface features without the use of a reference (Ref. 11).

The mathematical expressions used in the thermal image reconstruction process are based on the response of a uniform material subjected to an instantaneous heat pulse. Through the application of these relationships, the time dependent logarithmic behavior of each pixel can be approximated by a polynomial function of order, *n*:

$$ln(T(t)) = a_0 + a_1 ln(t) + a_2 [ln(t)]^2 + ... + a_n [ln(t)]^n \quad (1)$$

Using the coefficients calculated in Equation (1), it is possible to create a reconstruction of the original thermal signal based on the relationship:

$$T(t) = exp\left[a_o + a_1 ln(t) + a_2 [ln(t)]^2 + ... + a_n [ln(t)]^{nj}\right] \quad (2)$$

By applying this approximation to the collected data, the time dependent temperature response of each pixel can be represented by the coefficients of the polynomial, greatly reducing the storage requirements for large data sets. Depending on the order of the polynomial, high frequency noise components of the thermal data can be eliminated, in turn, sharpening the thermal image.

Application of the reconstruction technique has benefits beyond those mentioned above. Since the image data has been reduced to coefficients of a polynomial, instantaneous derivatives of the image sequence can be calculated and displayed in the same manner as the original data set. Through the examination of the rate of change in the thermal data, more defect data can be extracted than is possible with time based images alone.

Experimental Setup

Specimen

The specimens used in this study consisted of a triaxially braided T700S/E862w composite in the form of 23 flat coupons 50.8 mm (2 in.) wide by 305 mm (12 in.) long by 3.2 mm (0.125 in.) thick. Specimens oriented both in the direction of and transverse to the axial tows were cut from larger panels. Eight of the samples were removed following 4 months of aging and the remaining samples removed after 13 months.

Aging

Aging was accomplished by subjecting the material to a cyclic temperature-humidity profile. A single cycle consists of a ramp up to 121 ºC (250 ºF) , hold for 2 hr, ramp down to 29 ºC (85 ºF) and hold for 5 hr at 85 percent humidity and then ramp down to –54º (–65 ºF) and hold for 1hr. The profile is shown graphically in Figure 1. This profile was continuously repeated until specimen removal.

Ultrasonics

Specimens were examined using both through transmission and pulse echo ultrasonic techniques using a commercially available ultrasonic scan system. In the through transmission mode, a 5MHz focused transducer (focal length = 69.9 mm (2.75 in.), and focused on front surface) was used to send the ultrasonic signal which was received by a 5MHz flat focus transducer. Transducer excitation was provided using a UT340 square wave pulser/receiver manufactured by UTEX Scientific. The received signal was digitized and stored for later analysis. Scans were performed over the specimen area with data collected in 0.5 mm (0.020 in.) increments in both scan and step directions. For pulse echo scanning, the same 5MHz focused transducer was used as both the sending and receiving transducer. Scanning was performed using the same increments as the through transmission mode.

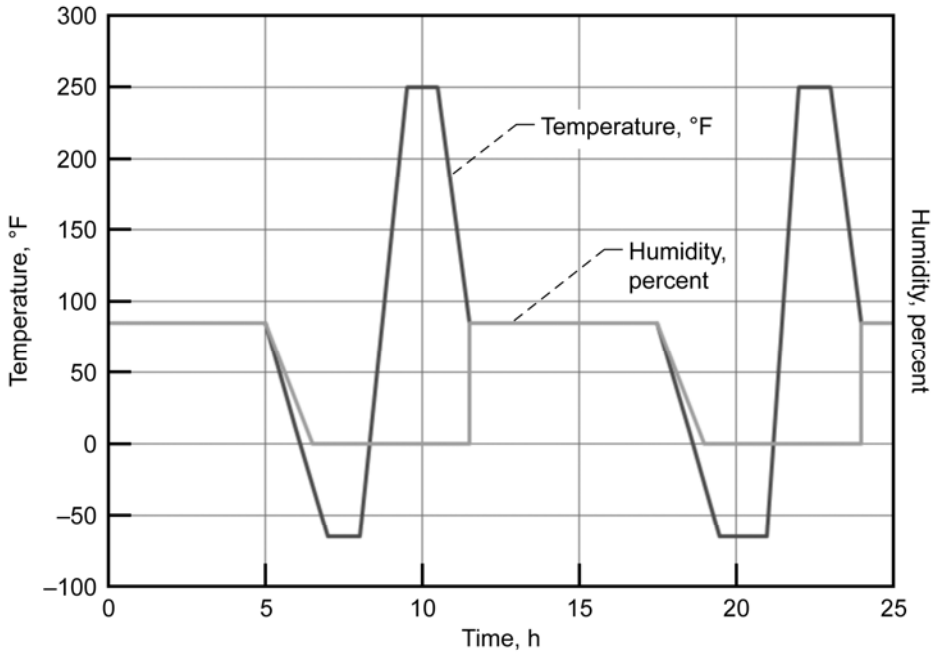

Figure 1.—Temperature-humidity cyclic profile.

Pulsed Thermography

Pulsed thermography data was collected using a commercial system manufactured by Thermal Wave Imaging Inc. A schematic representation of the setup is shown in Figure 2. The system uses a cooled 640 by 512 InSb focal plane array camera operating in the 3 to 5 μm range for imaging. A series of thermal images were collected at a 30 Hz frequency and for a 30 sec duration. Thermal excitation is provided using 2 linear xenon flash lamps with a pulse duration of approximately 5 ms. Thermal response at the specimen surface is stored for later analysis and processing.

Thermography data was processed within the acquisition software by applying a polynomial fit to the front surface temperature time response following thermal excitation as mentioned previously. Analysis of the image sequence data in the baseline and aged condition as well as analysis of the rate based cooling response were used as measures for identifying distributed damage that may be present due to aging.

Results

Ultrasonics

Figures 3 and 4 show representative ultrasonic C-scans of samples in the baseline and aged condition. Visual inspection of the scan results did not reveal any obvious discrete damage. Further examination was conducted by comparing the attenuation (received peak amplitude response) of the signal in both the baseline and aged conditions over the entire sample. Results indicated a large range of values resulting from the scatter of the ultrasonic signal by the braided architecture of the material. This scatter prevented the measurement of any significant change in the material response.

Pulsed Thermography

Figure 5 shows representative images for a single specimen in the baseline condition and following 13 months of aging. Visual examination of thermography images for all of the specimens did not reveal any obvious discrete damage within the specimens. Further examination of the cooling curves was conducted in order to identify any possible distributed damage within the specimen volume. Figure 6(a) shows a typical log-log display of the temperature-time curve following thermal excitation. The two curves represent a similar point on the same specimen in the baseline and aged condition. The point of interest is identified in Figure 5. Figures 6(b) and (c) show the first and second derivative curves respectively for the same location.

Using the information contained in the derivative images further analysis was conducted in an attempt to quantify any changes in the response of the material. This was achieved by calculating the time at which the second derivative curve reaches a peak value. This point was chosen to provide a consistent measurement location within the time series of data. In addition, this point in time is associated with the thermal front reaching the back wall of the sample, thus allowing interrogation of the entire specimen volume. It is expected that distributed flaws within the material will act as barriers to the flow of heat thus affecting the resulting time to reach a peak value. Second derivative peak times were calculated for a region of interest of each sample in both the baseline condition and following aging and an average was calculated for all samples in the baseline and aged condition. Results of this analysis are shown in Figure 7. Based on these values and the examination of individual samples, no significant trend was identified.

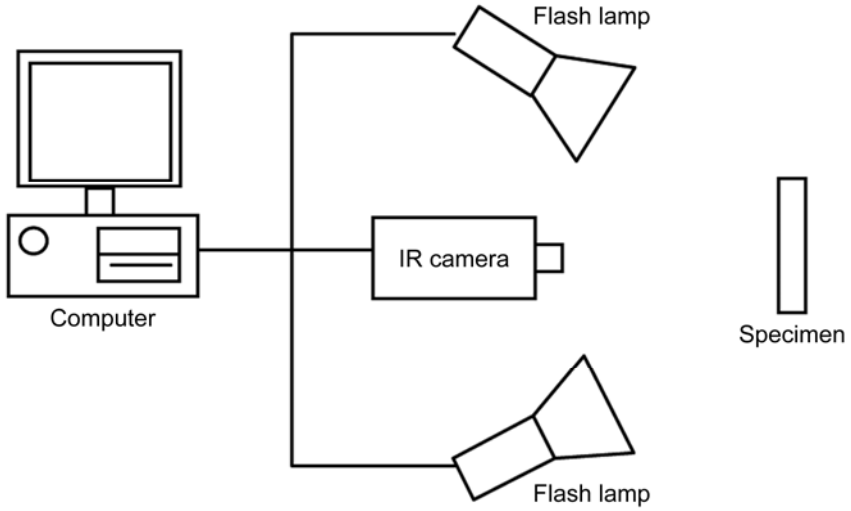

Figure 2.—Pulsed thermography experimental setup.

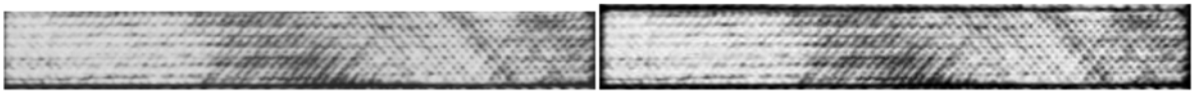

Figure 3.—Pulse-echo C-scan results. Baseline condition left and 13 month aged right.

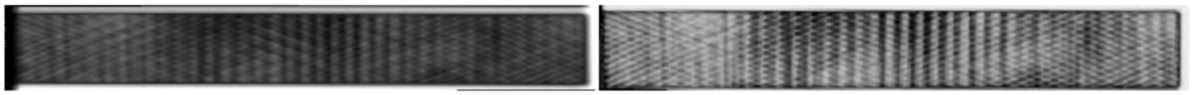

Figure 4.—Through transmission C-scan results. Baseline condition left and 13 month aged right.

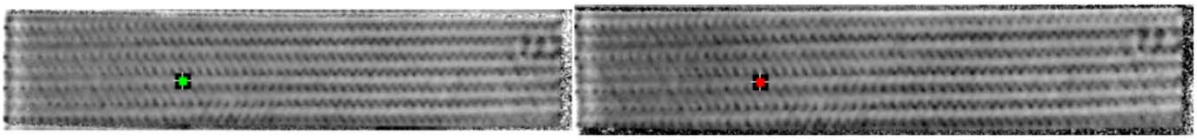

Figure 5.—Braided composite 1st derivative image 4.9 sec after flash. The image on the left is the unaged sample while the one on the right represents the material following 13 months of aging.

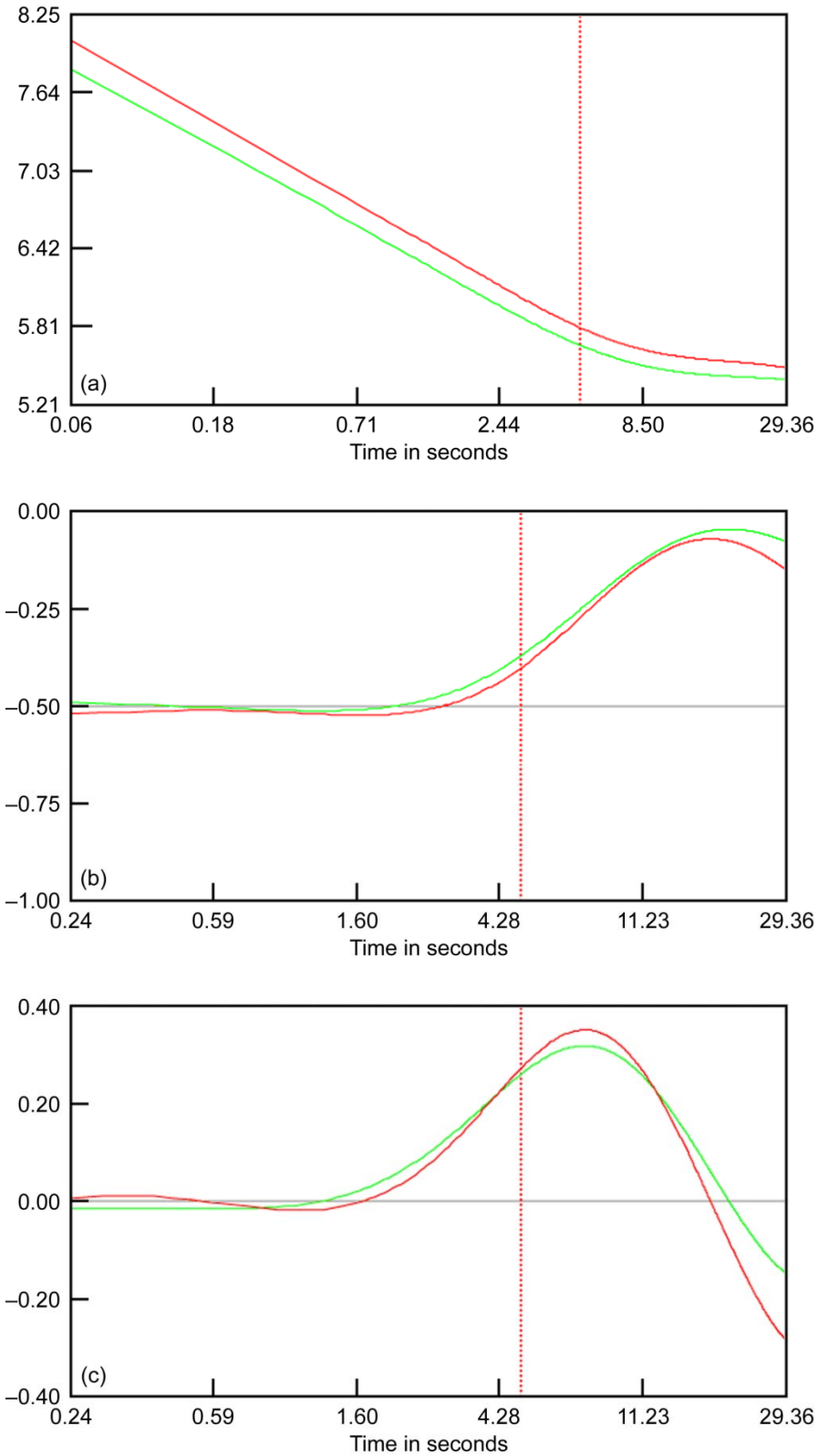

Figure 6.—Typical cooling curves resulting from pulsed thermography examination. (a) Raw data. (b) First derivative. (c) Second derivative.

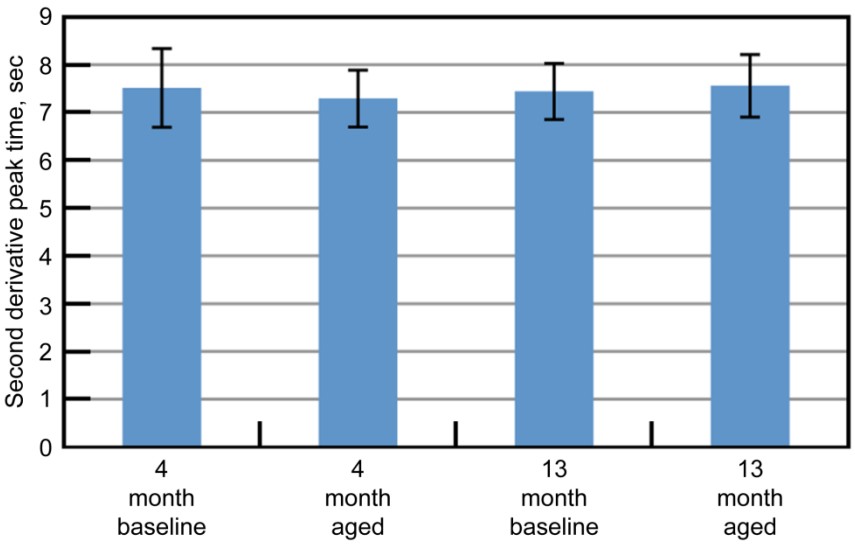

Figure 7.—Average second derivative peak time results.

Summary

A series of braided composite samples were nondestructively investigated to determine quantitative and qualitative measurements of degradation due to thermal-humidity cycling. Results from examination using pulsed thermography and ultrasonics did not reveal a measureable change following aging and showed a consistent visual appearance following aging. There are several possible reasons for this result. In the case of ultrasonic measurements, the size of the expected damage is most likely hidden by the complex composite architecture. This complexity limits the frequency that can be used for inspection and thus limits the sensitivity of the technique. The large amount of scatter in the measured attenuation values within the specimens highlights this masking effect. In the case of thermography, the situation may be similar in the sense that the overall scatter in the data due to composite architecture may overwhelm the sensitivity of the technique.

Further research in this area may yield methods for assessing aging related degradation. For a technique to be successful, there must be a clear separation of the environmental degradation effects from the composite architecture response or by utilizing techniques that measure indirect effects such as strength or stiffness changes. Further data regarding the effect of aging on mechanical properties and microstructure will be examined and correlated with NDE data as it becomes available.

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14. ABSTRACT
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