Improved Sizing of Impact Damage in Composites Based on Thermographic Response

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ABSTRACT

Impact damage in thin carbon fiber reinforced polymer composites often results in a relatively small region of damage at the front surface, with increasing damage near the back surface. Conventional methods for reducing the pulsed thermographic responses of the composite tend to underestimate the size of the back surface damage, since the smaller near surface damage gives the largest thermographic indication. A method is presented for reducing the thermographic data to produce an estimated size for the impact damage that is much closer to the size of the damage estimated from other NDE techniques such as microfocus x-ray computed tomography and pulse echo ultrasonics. Examples of the application of the technique to experimental data acquired on specimens with impact damage are presented. The method is also applied to the results of thermographic simulations to investigate the limitations of the technique.

Keywords: Thermography, NDE

1. INTRODUCTION

Methods for rapid large area inspections of both commercial and military aircraft are increasingly important for ensuring aircraft safety and reliability. This is particularly important as carbon fiber reinforced polymer (CFRP) composite materials are increasingly used as primary structure due to their high stiffness and strength to weight ratio. Of particular interest is the detection of the delaminations resulting from impacts that can appreciably reduce the compressive strength of a composite.

One technique capable of rapid inspections of materials and structures is thermography. Thermography has been shown to have great potential for detection of the delaminations resulting from impacts in CFRP composites[1-2]. Efforts have included a variety of heating and data reduction techniques to improve the detectability and assessment of the size and depth of delaminations. Typically the quantification of the characteristics of the delamination is calibrated by performing measurements on composites specimens with machined flat-bottom holes. This assumes that delaminations totally block the heat flow from the region above a delamination to the region below the delamination.

Impact damage in composites results in multiple delaminations that are air gaps between two layers in the composite. It is well known that for long times, the response of the temperature over the delamination is not characteristic of a single layer response. This effect is in part a result of lateral heat flow around the delamination as the heat diffuses to the region on the opposite side of the delamination. The diffusion of heat around the delamination reduces the spatial size of the temperature increase resulting from the delamination. If deeper delaminations are large enough, they are detectable in the presence of a smaller delamination close to the surface.

A method for determining the depth and size of delaminations based on a one dimensional solution is presented in section 3. Three dimensional simulations of the thermal response of flash heating of a multilayer composite are presented in section 4. The reduction of these simulations to size and depths of delaminations enable an assessment of how much a deep delamination must extend beyond a near surface delamination to be detectable. The reduction of an experimentally measured thermal response of a composite with impact like damage to the size and depth of delaminations is presented in section 5. These measurements are compared to a measurement of the size and depth of delaminations based on ultrasonic time of flight measurements.

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2. THERMAL INSPECTION SYSTEM

Data was acquired with a commercially available single-sided configuration that features an infrared (IR) imager with a 640 x 512 sensor array of indium-antimonide elements and two 4800-Joule xenon photographic flash tubes mounted in a hood to contain and focus the flash. The camera’s noise equivalent temperature difference (NEΔT), cited by the manufacturer, is 0.02°C operating the detector in the 3 to 5 micrometer wavelength range. External optics, consisting of a 25mm lens using germanium optical elements was used for all datasets. The hood has dimensions of 36.8 cm wide by 26.7 cm deep by 40.6 cm tall and is configured such that the IR camera views the inspection surface directly. The flash produces a flash energy density of 7.15 joules per square centimeter at the mouth of the hood. The inspection hood is connected to a computer base station that also houses power sources for various components. Data was acquired at 60 Hz for approximately 6 seconds.

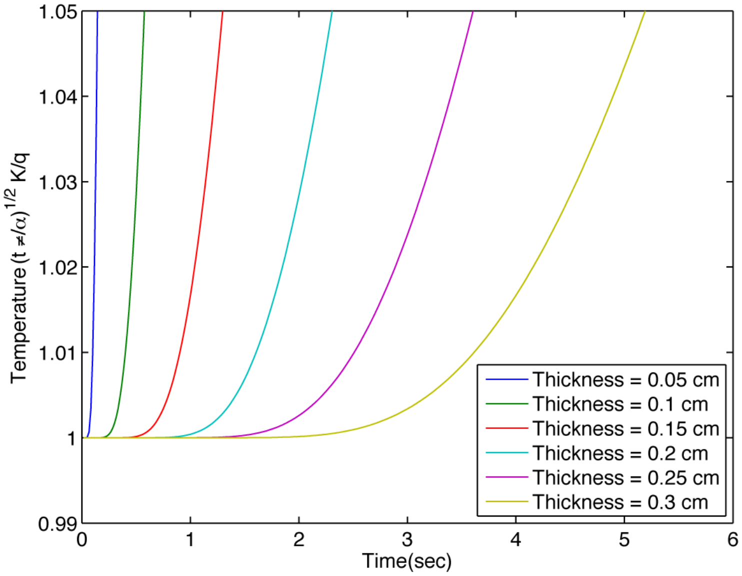

Figure 1. Normalized temperature, *p(t)*, as a function of time for different thickness of a layer assuming a thermal diffusivity of 0.0047 cm^2/sec.

3. SINGLE LAYER THERMAL RESPONSE

The front surface thermal response of a single layer material for impulse heating is given by

$$T_f(t) = \frac{f\sqrt{\alpha}}{K\sqrt{\pi t}}\left(1 + 2\sum_{n=1}^{\infty} e^{-(nl)^2/\alpha t}\right) \qquad (1),$$

where f is the energy in the heating impulse per area, , l is the thickness of the layer, K and α are the thermal conductivity and diffusivity of the material. If $\alpha t/l^2 \ll 1$, then a good approximation for Eq. 1 is

$$T_f(t) = \frac{f\sqrt{\alpha}}{K\sqrt{\pi t}}\left(1 + 2e^{-l^2/\alpha t}\right) \qquad (2),$$

Which can be also be expressed as

$$p(t) = T_f(t)\sqrt{\frac{\pi t}{\alpha}}\frac{K}{f} = 1 + 2e^{-l^2/\alpha t} \qquad (3).$$

In the subsequent sections, $p(t)$ will be referred to as the normalized temperature. The time dependence of this normalized temperature for different thicknesses of a layer with a diffusivity of 0.0047 cm^2/sec is shown in figure 1. From this equation it is clear that by multiplying the temperature by the square root of time, the early time response is equal to $f/(\alpha/\pi)^{1/2}/K$. By dividing the temperature by $f/(\alpha t/\pi)^{1/2}/K$, it is possible to find the thickness of the layer, for a small threshold value (v), from the time that $p(t)$ crosses that threshold is cross (t_v), the thickness can be calculated from

$$l = \sqrt{-\alpha t_v \log((v-1)/2)} \qquad (4),$$

if the diffusivity of the material is known.

For a delaminated multilayer material, the thickness would be approximately equal to the depth of the delamination. Setting a threshold that is significantly larger than the noise in the thermal response, if $p(t)$ becomes greater the threshold at a time less than that for the material in general, it indicates the presence of a delamination at that depth. Therefore, calculating t_v can be used both to determine if a delamination exist and its approximate depth.

4. FINITE ELEMENT SIMULATION OF THERMAL RESPONSE OF DELAMINATED COMPOSITE

Finite element simulations of a composite were performed to investigate the spreading of the effect of a near front surface delamination on the thermal response of a composite, and to what degree it masks the thermal response of deeper delaminations. The three dimensional representation of the composite simulation is shown in figure 2. The thermal properties and density used in the simulation are from literature values and shown in table 1[4]. The diffusivity perpendicular to the fiber direction was experimentally found to be 0.0047 cm^2/sec. This value is in reasonable agreement with 0.0042 cm^2/sec, the value calculated from the thermal conductivity, specific heat and density in table 1. The ply layup and thickness are the same as an existing composite specimen with impact-like damage. The simulation assumes a short heat flux pulse lasting 0.01 seconds is applied to the front surface of the composite.

Multiple simulations were preformed assuming circular delaminations of different sizes ranging from 0.2 to 8 cm diameter between plies in the composite. All delaminations were 30 μm gaps with the thermal properties of air. A gap with the thermal properties of air results in a contact resistance across the delamination which is a more realistic representation of the delamination than a void that blocks heat transfer across the interface.

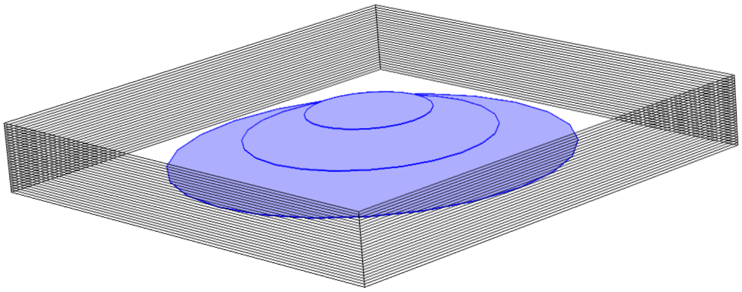

Figure 2. Typical geometry for finite element simulations of the composite with different size delaminations at different depths.

Table 1. Composite properties used in simulation of thermal response to flash heating of front surface of composite.

Property	**Value**
Composite thermal conductivity perpendicular to fibers	0.8 Watt/meter/^{o}Kelvin
Composite thermal conductivity parallel to fibers	7 Watt/meter/^{o}Kelvin
Composite specific heat	1200 Joule/kilogram/ ^{o}Kelvin
Density	1600 kilogram/meter^3
Ply layup	$[(0/+45/-45/90)_3\ 0]_s$
Ply thickness	0.123 mm

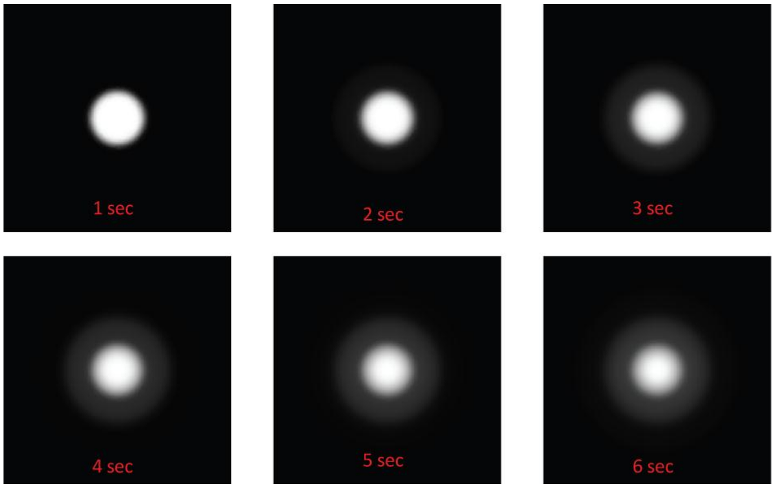

Figure 3. Typical simulation results for flash heating of a composite with size 2.5 cm diameter delamination 2 plies down from front surface, 5 cm diameter delamination 12 plies down from the front surface and 8 cm diameter delamination 24 plies down from the front surface. The total number of plies in the sample was 26 with a total thickness of 3.2 mm

Gray scale images of the calculated front surface temperatures are shown in figure 3. The simulation results are linearly scaled from 0 to 255, with the smallest value in the data being set to zero and the largest value 255. This shows the contrast in the results at a particular time and is not indicative of the change in the average temperature as a function of time. As expected the smallest delamination close to the surface is clearly visible in at the earliest times. The delamination at approximately the center of the composite is has a much lower intensity and visible after 3 seconds. The largest delamination, 4 plies from the back surface is not apparent in any of the images.

The temperature profile across the center of the delaminations is shown in figure 4. Simulations with the deepest delamination removed and the deepest two delaminations removed are also shown in the same figure. If one uses the full width at half maximum for calculating size of the delamination, a reasonable approximation of the size of the delamination closest to the front surface is achieved; however, the size of the delaminations deeper in the composite are not reflected estimated size of the delaminations.

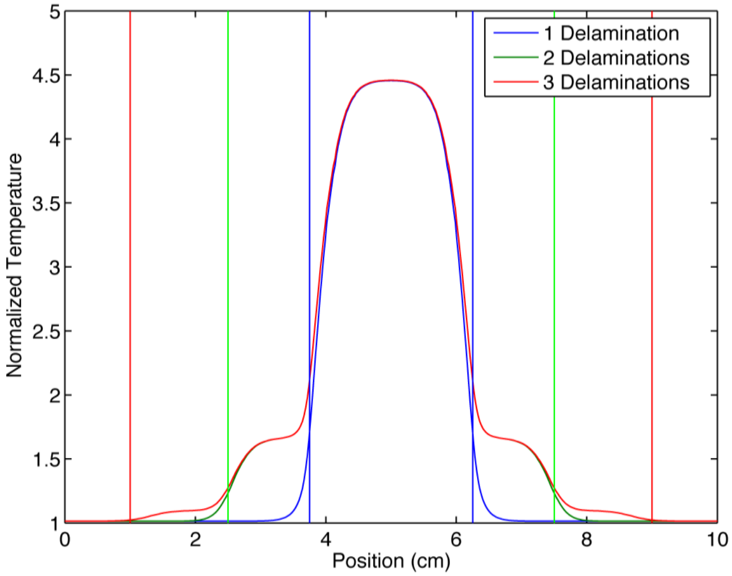

Figure 4. Temperature profiles at 4.5 seconds across center of simulation results for flash heating of a composite with size 2.5 cm diameter delamination 4 plies down from front surface, 5 cm diameter delamination 12 plies down from the front surface and 8 cm diameter delamination 20 plies down from the front surface. For comparison, results are also shown with the deepest delamination removed and the two deepest delaminations removed. Vertical lines indicate the edge of the delamination.

It is possible to use equation (3) to determine the size of delaminations in the simulated data, by setting a threshold then determining the size of the delamination by the number of pixels exceeding that threshold as a function of time. The depth of the delamination is determined from the time at which the threshold is exceeded. The data acquired for the earliest times before any of the delaminations affects the front surface response are used to calculate a value of $K/(f\alpha^{1/2})$. The threshold chosen is 1.03, which is a threshold significantly larger than the noise floor for the experimental data.

Figure 5 uses the threshold technique and shows that can be seen from the figure, it is possible to accurately estimate the depths of all of the delaminations, when the deeper delamination extends far enough beyond the edge of a delamination closer to the front surface. To simplify interpretation of the figure, the depth is given in number of plies. The second delamination must extend about 2.5 mm beyond the delamination 4 plies down before the second deepest delamination is detectable. In the region without a delamination, the thickness is the thickness of the composite.

Another way of viewing the diffusion of the effect from the delaminations is shown in figures 6 and 7. From the simulation it is possible to calculate the area in the normalized thermal response that is greater than 1.03. Figure 6, shows the radius calculated from the difference between the area above the threshold and the known radius. Initially this difference is negative, since at early times, the delamination has not significantly affected the thermal response. When the time is equal to $-l^2/(\alpha\ (\log(0.03/2)))$, (ie, v = 1.03), where l is the depth of the delamination, the area starts significantly growing and the estimated radius quickly becomes greater than the radius. This is a result of when the time is equal to $-l_c^2/(\alpha\ (\log(0.03/2)))$, where l_c is the thickness of the composite, the estimated radius becomes the square root of the area of the simulation divided by pi, which in this case occurs at approximately 5 seconds. For small delaminations at longer times, the heat diffuses from the region over the delamination to the region below the delamination and the estimated radius starts to decrease. This is apparent for the 0.1 and 0.3 cm radiuses and reflects what is expected, that the effect from smaller voids and delaminations disappears for long times. For the larger delaminations, the heat diffuses to increase the size of the affected area by approximately the same linear distance, independent of the size of the delamination. This is reasonable since as the region becomes large, the diffusion approximates a one dimensional heat flow, in the direction normal to isotherms.

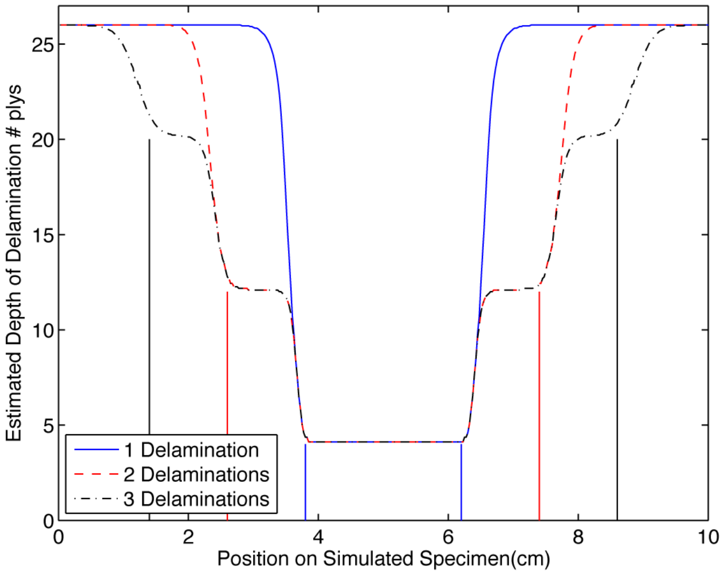

Figure 5. Estimated depth of the delamination for a line across center of a composite with size 2.5 cm diameter delamination 4 plies down from front surface, 5 cm diameter delamination 12 plies down from the front surface and 8 cm diameter delamination 20 plies down from the front surface. For comparison, results are also shown with the largest delamination removed and the two largest delaminations removed. Vertical lines indicate the edge of the delamination.

Figure 6, shows the difference between the radius of the area above the threshold and the known radius for delaminations at different depths from the front surface as a function of the time of the image used to calculate the size of the delamination. For comparison, the growth of the response from a 2 cm diameter flat bottom hole from the back side of the composite to within 2 plies below the surface and results from a composite with no delamination, but an initial condition with a 2 cm diameter raised cylinder with an increase initial temperature relative to the rest of the composite are also shown in the figure. The flat bottom hole is a typical standard used for assessing the viability of a NDE technique for delamination detection. It should be noted that the size of the thermal response and rate at which it diffuses into the surrounding area are greater than for the delamination. The size of the response is slightly larger as a result of the delamination acting as contact resistance between the region above the delamination and below the delamination. The rate of movement of an isotherm away from the hole is greater, since the material for the heat to diffuse into behind the delamination does not exist for the flat bottom hole.

For the simulation of a composite with a cylinder of increased initial temperature and the rest of the composite set to zero, the area is calculated for the region with a temperature greater than 0.03 the size of the initial temperature of the region. The response starts at zero at a time equal to zero (no time is required for the heat to diffuse to a subsurface feature) and increases rapidly at first, then at approximately a constant rate for the duration of the simulation. The rapid increase that occurs for other simulations at approximately 4.5 seconds, does not occur for this case, since the main diffusion is not from the front surface to the back surface, rather in the plane of the composite. This curve would represent an upper limit on the size of the region affected by the delamination.

The deeper delaminations appear at later times as is expected. The distance the lower delamination must extend beyond the upper delamination is easily determined from the figure. For example a delamination 13 plies down needs to extend 2.5 mm beyond the edge of the delamination 2 plies down.

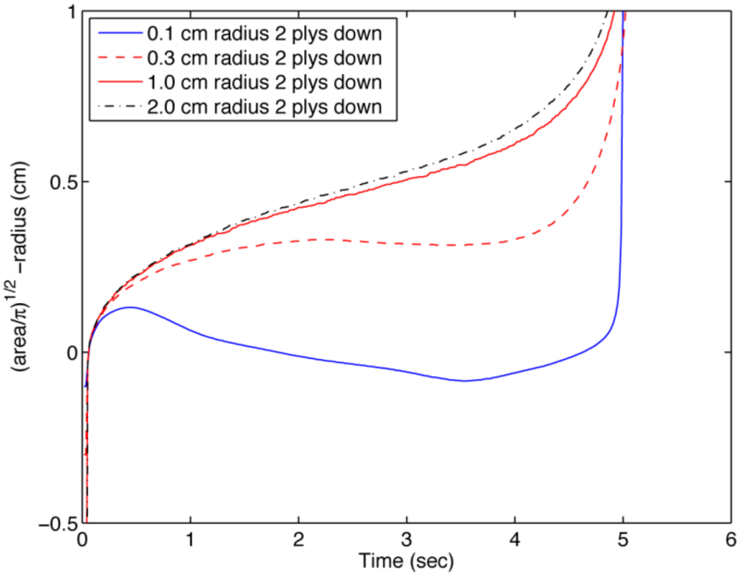

Figure 6. Difference between the estimated radius of the delamination and known radius for delaminations2 plies down from front surface having radiuses of 0.1, 0.3, 1.0 and 2.0 cm.

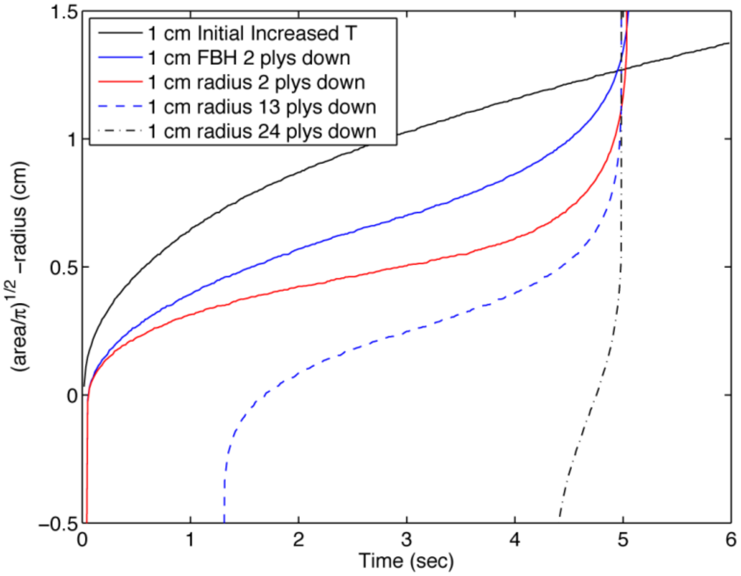

Figure 7. Difference between the estimated radius of the delamination and known radius for 2 cm diameter circular delaminations 2, 13 and 24 plies down from front surface. For comparison, the growth of the response from a 2 cm in diameter flat bottom hole from the back side of the composite to within 24 plies below the surface and results from a composite with no delamination, but an initial condition with a 2 cm diameter cylinder with an increase initial temperature relative to the rest of the composite.

5. ULTRASONIC AND THERMOGRAPHIC MEASUREMENTS ON COMPOSITE WITH MULTILPLE DELAMINATIONS AT DIFFERENT DEPTHS

The experimental sample is a 3.2 mm thick, 26-ply carbon fiber reinforced polymer(CFRP) laminate plate with layup [(0/+45/-45/90)3 0]$_s$. Delaminations were created utilizing a quasi-static indentation technique and were grown by a repeated indentation. This technique is commonly used to grow impact- like delaminations in composite materials in a controlled manner[5]. Figure 8 shows immersion time of flight C-scans of the damage in the initial and grown states obtained with a 20 MHz, 2-inch focal length focused transducer. The grown damage was approximately 50 mm in diameter. Many delaminations are present at various ply interfaces as indicated by the different colors in the image and the three dimensional representation of the data. Also shown are the thermographic images acquired several different times following the flash heating. The thermographic response from the delaminations significantly increases in size as time progresses.

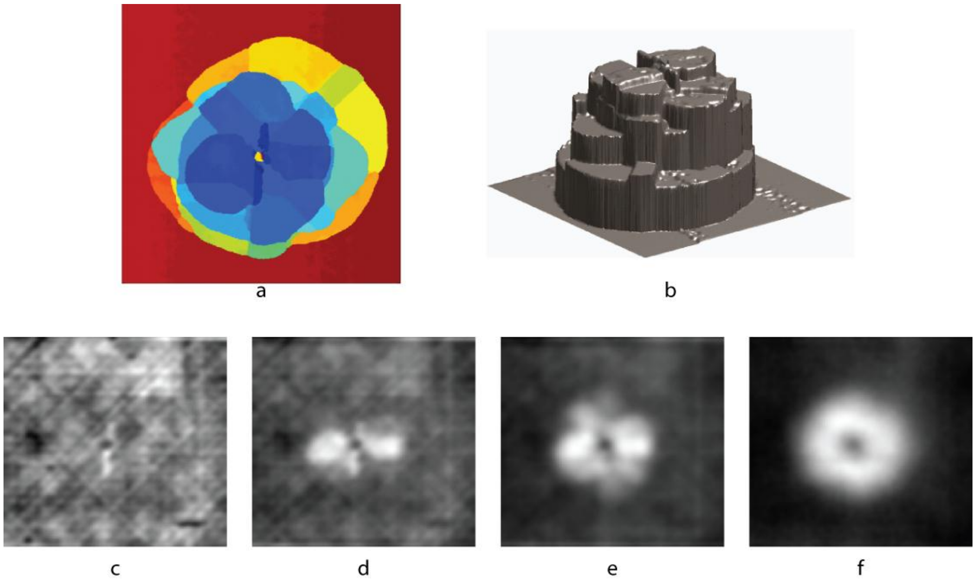

Figure 8. Ultrasonic time of flight data and thermographic response data for composite specimen with impact like damage. (a) Image of ultrasonic time of flight with different colors indicating different depths. (b) Three dimensional representation of the same time of flight data. (c-f) The thermographic images acquired at 0.167, 0.333, 0.833 and 3.33 seconds after flash heating. Region of ultrasonic scan and thermographic images are 6 cm by 6 cm.

6. DEPTH AND SIZE MEASUREMENTS FROM THERMOGRAPHIC DATA

The acquired data was normalized using the same technique described in section 4. The time at which the normalized thermographic response becomes greater than 1.03 can be used to estimate the depth of the delamination. Figure 9 shows the estimation of the depth of the delaminations from both the thermographic data and the ultrasonic data. The diffusivity of the composite used was 0.0047 cm^2/sec, a value obtained from a two sided measurement on the same specimen. The two estimates are in good agreement for the near surface delaminations and full thickness measurement. For delaminations at the center of the composite, the thermographic estimate of depth does not agree with the ultrasonic time of flight measurement. This may be in part a result of the alignment not being accurate. The thermographic technique also yields images with rounded edges as can be seen from figure 5. For this alignment, the thermographic estimation of the depth of the delamination results in depths which are within 10% of the ultrasonic measurements, for approximately 60% of the area of the delamination.

It is possible to estimate the damaged area of the composite from the thermographic data. The first estimate is based on the method described in the literature of characterizing the size of the contrast in an image above half the difference between the maximum value and the “sound” material response[2]. Since it is clear that the earliest thermal responses only detect the delaminations very close to the surface, the image acquired at 0.833 seconds after the flash was used to estimate the area of the damage. The estimated size of the delamination based on this technique is shown in red in the figure. The area of damage for this case is only 27% of the area found by the ultrasonic technique. Approximately the same area of damage is found in the first 6 plies below the surface. By comparison, the area based on thresholding the normalized response is approximately 60% of the area found by the ultrasonic technique, or approximately the size of the damage in the top half of the composite. If the damage is considered to approximate a circle, then the change in radius would be 1.2 cm between the two estimates, which in much larger than the simulations predict from diffusion of the heat over the near surface delaminations. For regions where the reduction of the thermal response indicates a delamination, the depths determined from the technique are within 10% of the depths determined from ultrasonic time of flight measurements.

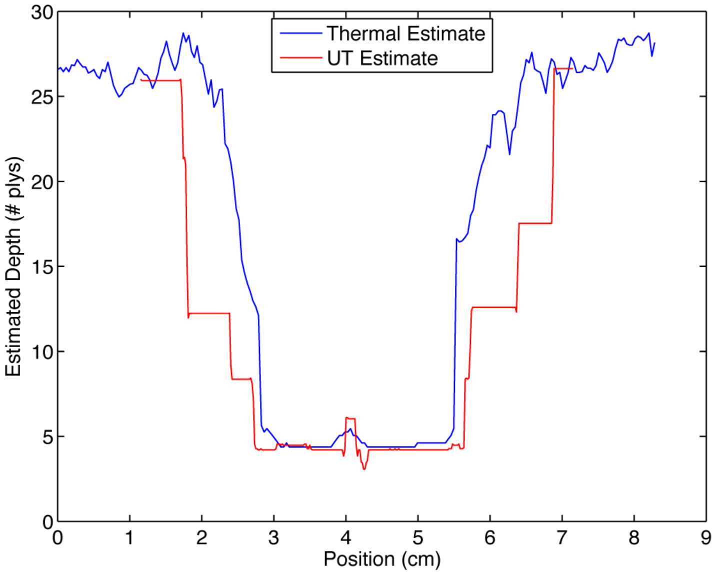

Figure 9. Estimates of the depth of delaminations from ultrasonic time of flight data and thermographic response data for composite specimen with impact like damage. Depth is given in number of plies from front surface.

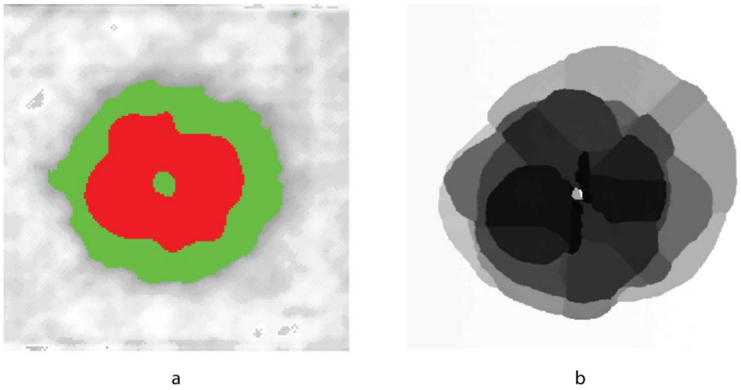

Figure 10.(a) Thermographic estimate of size of delamination based on conventional methods in red and threshold of normalized response in green. (b) Ultrasonic time of flight data acquire for same specimen.

7. SUMMARY

A method for determining the depth and size of delaminations based on a one dimensional solution has been developed then applied to both data obtained from finite element simulations and measurements on a composite coupon with impact like damage. The simulations indicate the effect of near surface delaminations is not as pronounced as a flat bottom hole measurement would indicate. The reduction of an experimentally measured thermal response with impact like damage is compared to a measurement of the size and depth of delaminations based on ultrasonic time of flight measurements. This method for reduction of the thermal response captures approximately 60% of the area of the damage as compared 27% of the area when using conventional methods.

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