

THERMOGRAPHIC DETECTION OF
DELAMINATIONS IN LAMINATED STRUCTURES

William P. Winfree, Christopher S. Welch[†]
P. H. James* and Elliott Cramer**
MS 231
NASA Langley Research Center
Hampton, VA 23665

INTRODUCTION

The detection of disbonds in a laminated structure is the focus of many nondestructive techniques. One of the promising techniques is thermography, where heat is applied to a structure, and the subsequent temperature profiles are detected with an infrared (IR) imager. If there is an even application of heat, an elevated temperature profile will appear, as a result of the reduction in heat flow from the surface layer to subsurface layers. Two advantages of the thermographic technique over more conventional ultrasonic techniques are that it can be easily made noncontacting and that large areas can be inspected in a short period of time.

A problem of thermographic inspection for disbonds is that it is often difficult to apply heat evenly to a large area. The result often is a temperature profile dominated by the initial heating profile rather than the presence of disbonds. A second problem occurs when the surface layer has a thermal conductivity significantly higher than that of the next layer in the structure. For this case the width of the thermal contrast profile resulting from the disbond is much larger than the width of the disbond, and so the image of the disbond does not clearly delineate the region of the disbond.

This paper presents a technique for enhancing the contrast due to a delamination, as well as more clearly delineating the region of the delamination. The technique also reduces the effects of uneven heating. The technique uses a two-dimensional filter convolved with the thermal image. The filter is designed to approximate operating on the temperature images with a Laplacian operator. For prescribed conditions, this operation approximately gives the image of heat flux from the top layer to the subsequent layer. The filtering results in an image which clearly delineates the disbond. Measurements were performed on samples with fabricated defects, and a comparison is presented between the resulting temperature images and the filtered images.

[†]College of William and Mary

*Analytical Services and Materials, Inc.

**Indiana University of Pa

EXPERIMENTAL TECHNIQUE

To investigate the technique samples were fabricated with known defects. The samples consisted of a sheet of steel .16 cm thick, backed by a rubber layer .63 cm thick, backed by an aluminum layer 2.5 cm thick, all 15.0 cm square. The layers were bonded together with a slow curing two-part epoxy system. To produce a disbond a portion of the rubber was removed to form a hole before assembly.

Measurements were made by heating the steel surface of the samples for approximately 15 seconds with a hot air gun which produces temperatures greater than 200 C. The subsequent temperature images were detected with an IR imager which outputs standard video frames. The imager uses a scanned HgCdTe detector cooled by liquid nitrogen. The video images were input into an image processor, which was capable of digitizing and averaging 30 frames a second. The image processor averaged 256 frames and then transferred the averaged signal to a minicomputer for analysis and archival. Averaged temperature profiles were recorded every 15 seconds after heating, for a period for 240 seconds.

THEORY AND ANALYSIS

A thin plate bonded to a backing material with heat flow is described by the equation

$$\nabla^2 T(x, y, t) - \frac{F(x, y, t)}{wK} = \frac{1}{\kappa} \frac{\partial T(x, y, t)}{\partial t} \quad (1),$$

where $F(x, y, t)$ is the flux into the second material, κ is the thermal diffusivity of the plate, w is the thickness of the plate and K is the thermal conductivity of the plate. If the diffusivity of the backing material is significantly lower than that of the plate, the flux quickly becomes nearly constant in time, and equation (1) reduces to

$$\nabla^2 T(x, y, t) - \frac{F(x, y)}{wK} = \frac{1}{\kappa} \frac{\partial T(x, y, t)}{\partial t} \quad (2).$$

The solution to equation 2 can be divided into two parts, a dynamic part $T_d(x, y, t)$ and a static solution $T_s(x, y)$, such that

$$\nabla^2 T_d(x, y, t) = \frac{1}{\kappa} \frac{\partial T_d(x, y, t)}{\partial t} \quad (4)$$

and

$$\nabla^2 T_s(x, y) = \frac{F(x, y)}{wK} \quad (5).$$

For $T_d(x, y, t)$, it can be shown with Fourier analysis that temperature fluctuations with a characteristic length of L will decay over a time on the order of $L^2/(4\kappa\pi^2)$, leaving a temperature profile dominated by the static contribution to the solution at that characteristic size. Thus, for a delamination of size L , if one waits for a time greater than $L^2/(4\kappa\pi^2)$, the local temperature distribution then is dominated by the flux variations caused by the delamination, and the Laplacian of the local temperature distribution (Eq. 5) gives an image of the flux variation out of the plate. If the delamination region is clearly delineated by the flux pattern, then it is clearly delineated in the Laplacian of the temperature profile.

To approximate the Laplacian of the thermal image, a 7 by 7 array of temperature data centered on a point of interest was fit to the expression

$$T(x, y) = A_1 + A_2x + A_3x^2 + A_4y + A_5y^2 + A_6xy \quad (6),$$

Table 1. Elements of 2 Dimensional filter convolved with thermal image to approximately calculate its Laplacian. Each element has been multiplied by 294.

10	5	2	1	2	5	10
5	0	-3	-4	-3	0	5
2	-3	-6	-7	-6	-3	2
1	-4	-7	-8	-7	-4	1
2	-3	-6	-7	-6	-3	2
5	0	-3	-4	-3	0	5
10	5	2	1	2	5	10

by a linear least squares fitting routine. This fit was performed at each point in the image to build up images of the A's. A sum the A_3 and A_5 images times two is approximately equal to the Laplacian.

To reduce the processing time, a 7 by 7 square filter was designed which was equivalent to this process. The coefficients of the filter are given in table 1. The filter was then convolved with the thermal image to give its Laplacian.

RESULTS

A typical thermal image for a sample with a 1.2 cm diameter circular disbond in the center 75 seconds after application of heat is shown in figure 1. From the image it is possible to see first that the heat was not applied evenly. There is a large variation in the temperature from corner to corner, greater than the small variation in temperature at the center of the image, attributed to a disbond. The Laplacian of this temperature image is shown in figure 2. In the image of the Laplacian the presence of the disbond is clearly seen and is the largest contrast in the image. Profiles of the image through the delamination are shown in figure 3. The second derivative profile delineates the region of the disbond much more clearly than the temperature profile. As can be seen

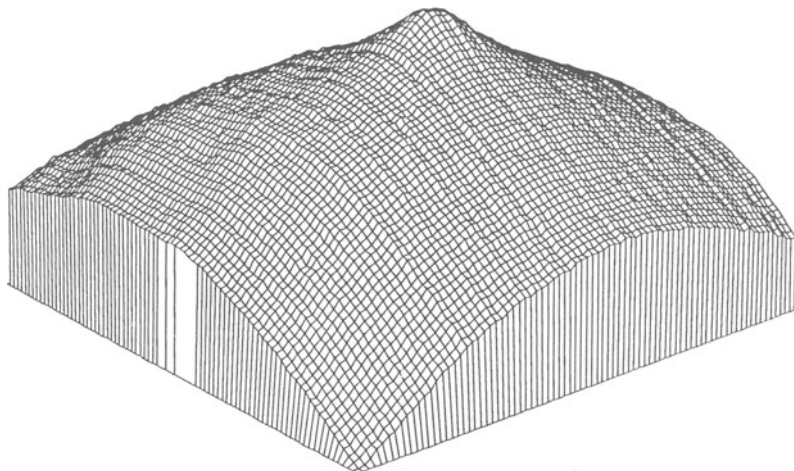


Figure 1. Typical thermal image for first sample described in the text 75 seconds after application of heat

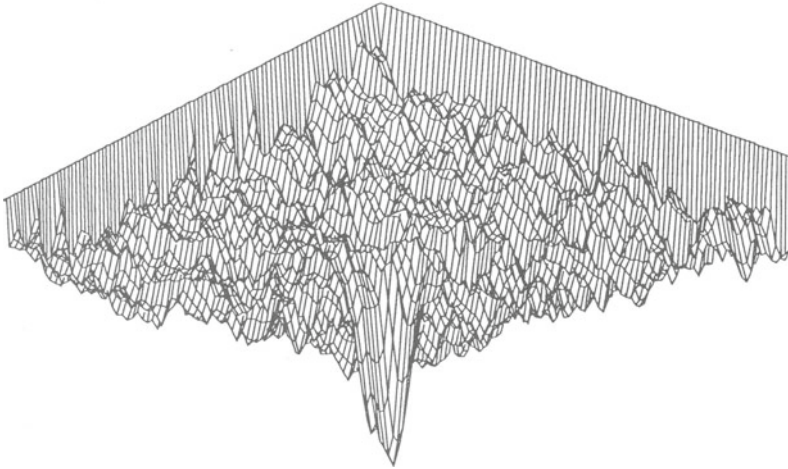


Figure 2. Laplacian of thermal image in figure 1 for sample with single circular delamination in the center.

from figure 3, the width at half maximum of the second derivative profile is approximately equal to the diameter of the disbond.

The thermal image taken 75 seconds after heating of a second sample with two disbands formed by two 1.2 cm wide by 2.5 cm long slots in the rubber separated by 1.6 cm is shown in figure 4. Once again the Laplacian of the temperature, shown in figure 5, clearly delineates the regions of disbond and fully resolves the two disbands. Profiles of the temperature and its Laplacian are shown in figure 6. The width at half maximum of the Laplacian profiles are again approximately the width of the defect.

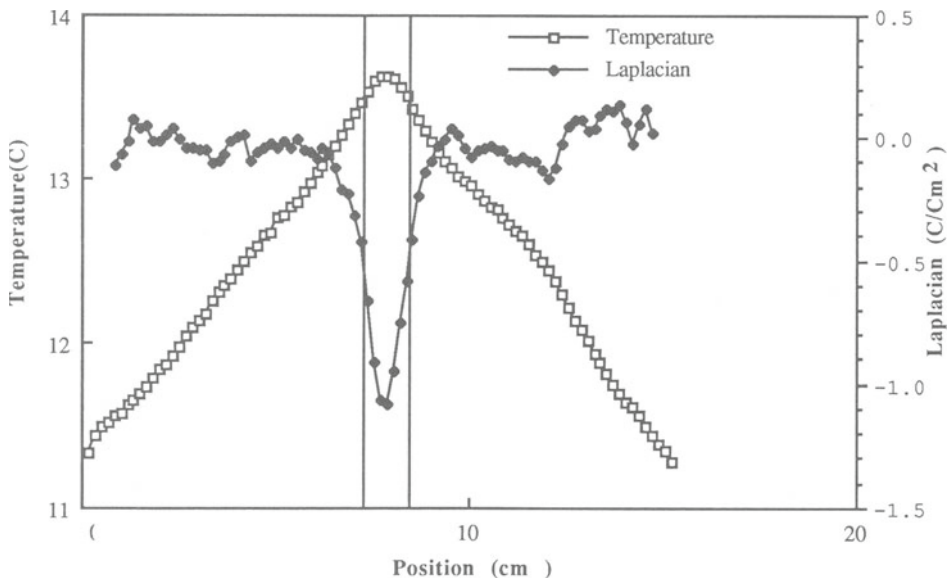


Figure 3. Profiles of temperature and its Laplacian across the center of the delamination with lines drawn to show edges of delamination.

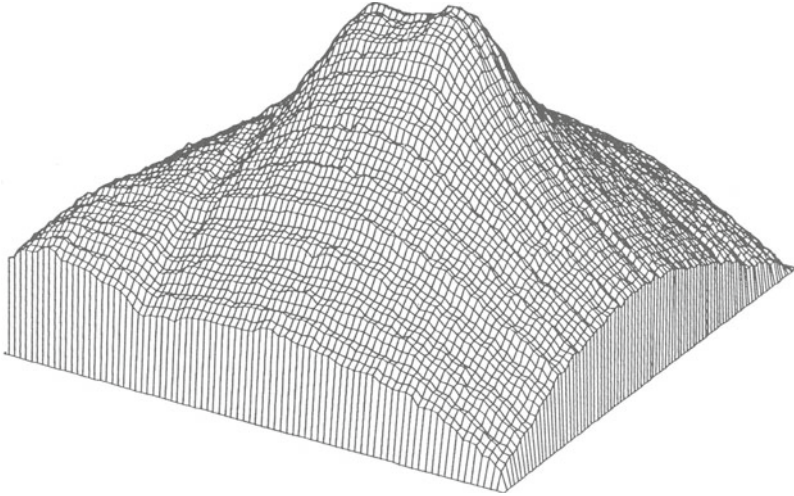


Figure 4. Typical thermal image for second sample described in the text
75 seconds after application of heat

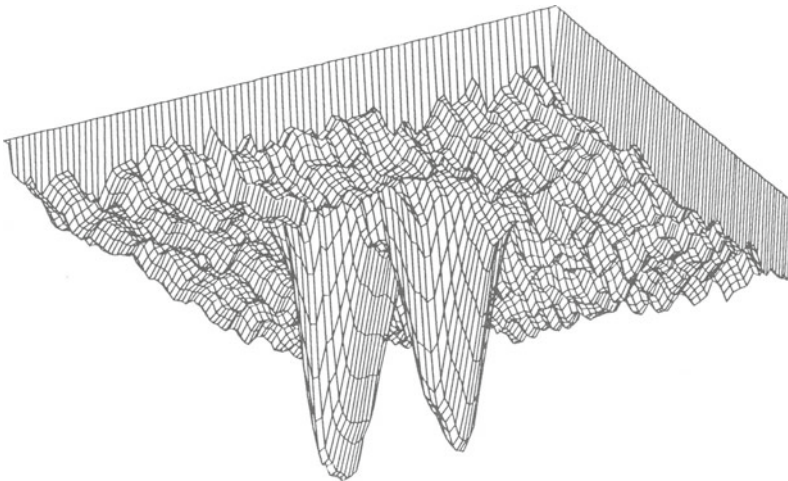


Figure 5. Laplacian of thermal image in figure 4 for sample with two
rectangular delaminations in the center.

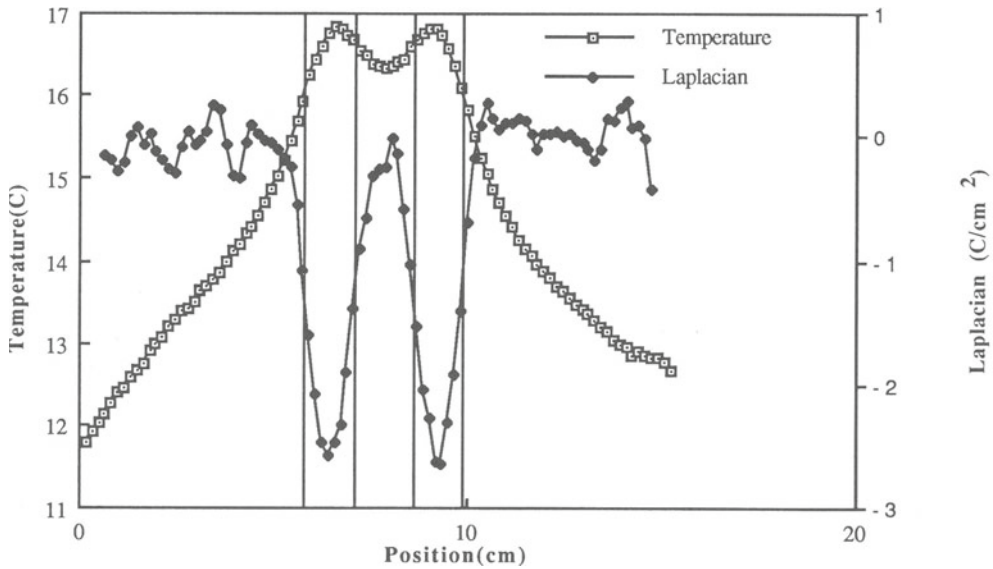


Figure 6. Profiles of temperature and its Laplacian across the center of the delaminations with lines drawn to show edges of delaminations.

SUMMARY

A technique has been presented for processing thermal images which clearly delineates regions of sub-surface disbonds. The processing is approximately equivalent to taking a Laplacian of the temperature image. The technique is shown to discriminate against thermal contrast due to uneven application of heat. For a conductive layer backed by an insulating layer, when a quasi-static condition for flow is met, the technique gives the heat flux through the back surface of the conductor.