Coating tolerant thermography for the detection of cracks in structures

Jon R. Lesniak[a], Daniel J. Bazile[a], Michael J. Zickel[a]

[a]Stress Photonics Inc., 3002 Progress Rd. Madison, WI 53716

ABSTRACT

A new variation of Forced-Diffusion Thermography, Coating Tolerant Forced Diffusion Thermography, is described. This new thermal method is specifically designed to inspect large steel bridge structures. To increase effectiveness in the field Coating Tolerant Thermography separates the effects of structural defects from variations in emissivity. The technique is a derivative of Forced Diffusion Thermography which uses patterned radiation to force heat flow in-plane to specifically target cracks. This paper presents the fundamentals of Coating Tolerant Forced Diffusion Thermography including the mathematical bases for the separation of thermal gradients and emissivity gradients. Also, presented are case studies including the inspection of a bridge girder samples at FHWA Turner Fairbanks Lab.

Keywords: Thermography, NDE, Crack, Bridge, Coating Tolerant, Forced Diffusion Thermography

1.0 INTRODUCTION

A very sizable investment has been made in steel highway bridges, the integrity of which is often taken for granted. It is vital that the Federal Highway Administration has the tools necessary to assess and monitor the health of key structures quickly and accurately. Thermal methods have been recognized above other NDI methods for rapid inspection of large structures. Thermal methods are safe, convenient and relatively inexpensive tools; however, the techniques' dependence on emissivity makes them sensitive to field conditions such as chipped paint. This paper describes an exciting new crack detection technology: Coating Tolerant Thermography, which is specifically designed to meet the demands of more challenging field conditions. The paper shows that Coating Tolerant Thermography exhibits high probability of detection, low false signals, easy interpretation, speed and portability.

1.1 Technology review

Thermal methods correlate structural integrity with thermal diffusivity . If the molecular structure is altered impairing transfer of forces, the conduction of heat energy is also impeded[1, 2]. Coating Tolerant Thermography projects a pattern of dynamic heat to force flow across cracks (Fig. 1b) thereby, optimizing the measurable thermal gradient[3, 4, 5].
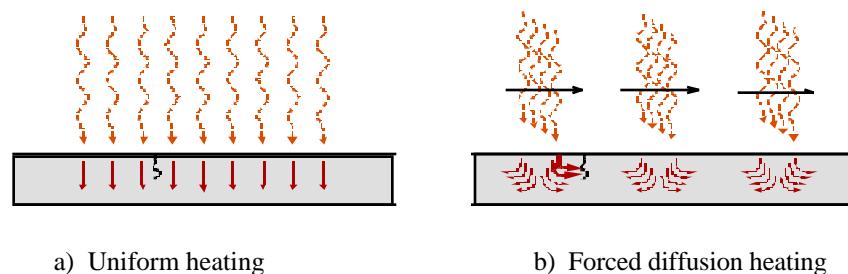

a) Uniform heating   b) Forced diffusion heating

Fig. 1 Thermal methods

Heat travels from "hot" stripe to "cool" stripe as the stripes slowly comb the structure for cracks. The in-plane heat flow is impeded by a structural flaw, such as a crack, creating a gradient in the thermal image (Fig. 2a), which clearly defines the crack (Fig. 2b). The direction of the heat flow (from the left or from the right) defines the sign of the gradient (negative or positive). In Fig. 2c the heat flows from the right causing the sign of the gradient to be negative.
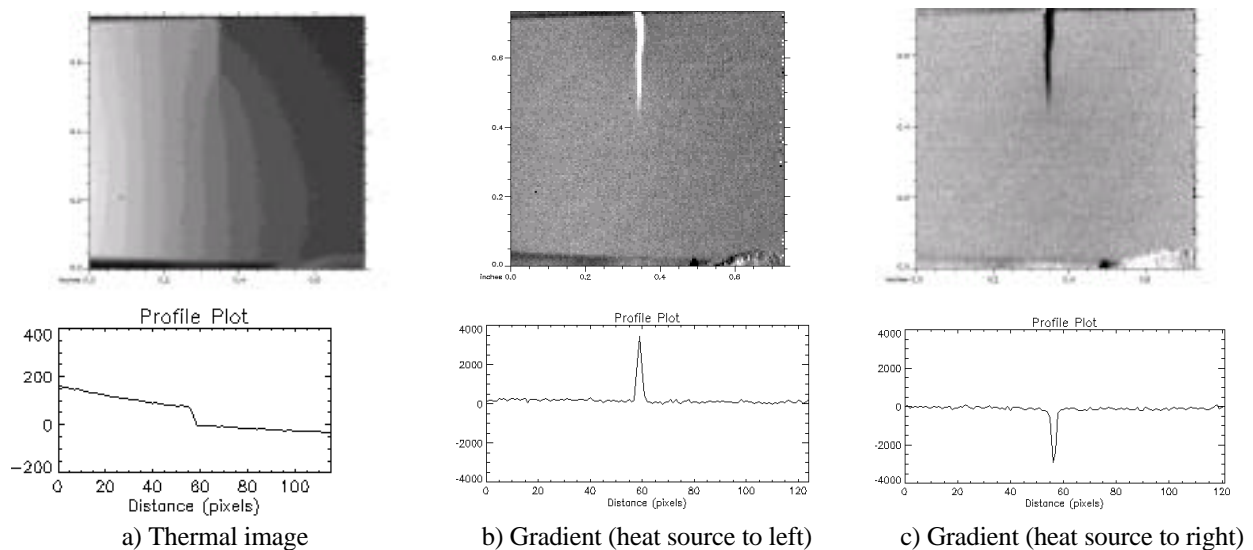
Fig. 2 Thermal gradient across crack

2.0 SEPARATION OF FLAWS AND EMISSIVITY EFFECTS

2.1 Reflections

Reflections from ambient sources are reasonably constant over short periods of time and can be eliminated.   A thermal image is collected before the incremental heating of the specimen and subtracted after heating. A reflection and initial condition reduced image I(x,y) is in the form

$$I(x,y) = \quad (x,y) \quad (x,y) \tag{1}$$

where   (x,y) is the photon flux resulting from the added heat or heat lost since the capture of the initial image and   (x,y) is the emissivity map. This reduction of reflections allows work on even high-gloss paint.

2.2 Emissivity effects

If all structures had perfectly uniform coatings, the simple unidirectional gradient method depicted in Fig. 2 would be sufficient to locate cracks. However, gradients caused by emissivity variances can often be misconstrued as cracks. The total gradient in the x-direction $I_x(x,y)$ of the corrected images I(x,y) is by the product rule

$$I_x(x,y) = \quad (x,y) \quad _x(x,y) + \quad _x(x,y) \quad (x,y) \tag{2}$$

At this point in the development of the technique an emissivity gradient has the same effect as a structural defect. The fundamental principle behind Coating Tolerant Thermography is that only the thermal spatial derivative of a true structural anomaly will change sign with opposing heat flow (Fig. 2b and 2c). When the heat is flowing from the left, the gradient is positive (as defined) because the heat builds up behind the crack on the left. When heat is flowing from the right, the gradient changes sign becoming negative because now heat builds up behind the crack on the right side. Only a true structural flaw has this characteristic.

Gradients caused by paint chips or other emissivity changes on the surface of the structure are not conduction direction sensitive. In other words, the sign of the differential is independent of the direction of heat flow. As a material (e.g. steel) is heated from the left (Fig. 3), the region under the paint edge is uniformly heated because there is no flaw in the steel substrate. On the left edge of the paint chip (Fig. 3a), the differential is apparently hot on the left and apparently cold on the right. Similarly, if the heat conducts from the right (Fig. 3b), the area under the left edge is heated uniformly and the left side

of the edge remains apparently hot and the right side stays apparently cold. Therefore, the gradient is independent of the direction of the heat flow. This is the cornerstone of Coating Tolerant Thermography.

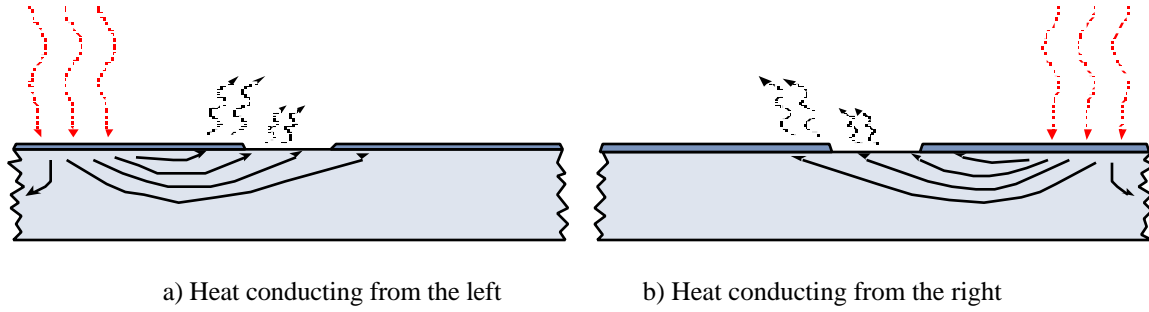a) Heat conducting from the left   b) Heat conducting from the right

Fig. 3 Paint chips

Mathematically this can be thought of as separating the thermal distribution from the emissivity variables. If we normalize the gradient image $I_x(x,y)$ of Eq. 2 by the reflection corrected image $I(x,y)$ of Eq. 1

$$\frac{I_x(x,y)}{I(x,y)} = \frac{_x(x,y)}{(x,y)} + \frac{_x(x,y)}{(x,y)} \tag{3}$$

we separate the influences of thermal distributions and emissivity gradients into two terms.   If two sets of images are collected, one corresponding to heat from the left and the other corresponding to heat from the right, and processed in this manner

$$\frac{I_x^1(x,y)}{I^1(x,y)} = \frac{_x^1(x,y)}{^1(x,y)} + \frac{_x(x,y)}{(x,y)} \tag{4a}$$

$$\frac{I_x^2(x,y)}{I^2(x,y)} = \frac{_x^2(x,y)}{^2(x,y)} + \frac{_x(x,y)}{(x,y)} \tag{4b}$$

the difference of these images Q(x,y) eliminates emissivity as a variable.

$$Q(x,y) = \frac{_x^1(x,y)}{^1(x,y)} - \frac{_x^2(x,y)}{^2(x,y)} \tag{5}$$

If the gradient is flowing from opposite directions then the second term will augment the first. In order to ensure this augmentation and hence detection of the flaw, the denominator must not be allowed to switch sign.

A 12"x 2"x 1/4" steel specimen coated with a rather reflective white paint was prepared with a rusted paint chip near a fatigue crack. The thermal images (Fig. 4) show the emissivity gradient caused by the rust chip. The line plot across the paint chip could be mistaken for a structural flaw in a thermal image. Figure 5 demonstrates the ability of the normalized subtraction process to accentuate cracks and minimize false readings at anomalies like paint chips.
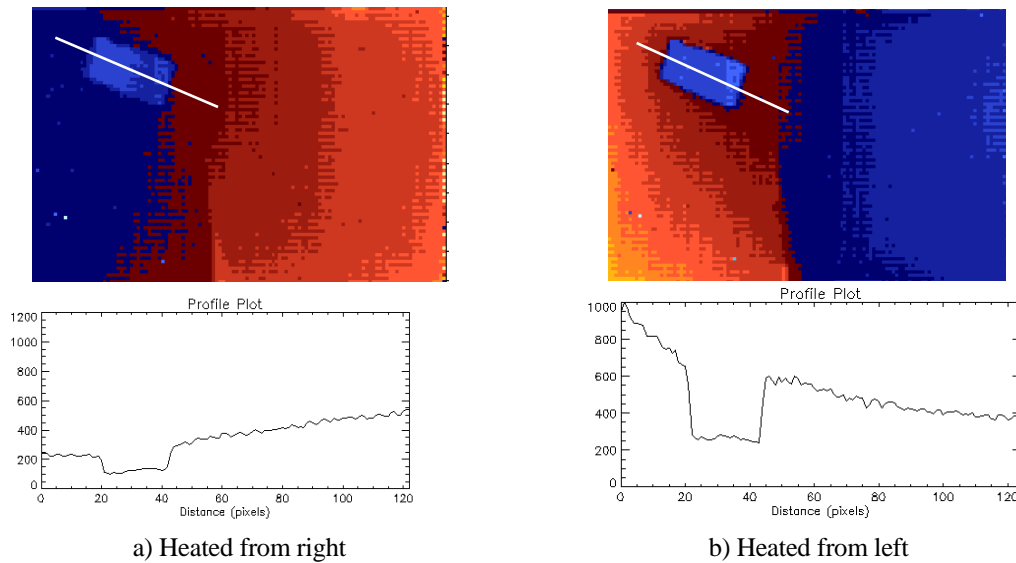
a) Heated from right

b) Heated from left

Fig. 4 Effects of paint anomalies on thermal images

a) Heated from left

b) Heated from right
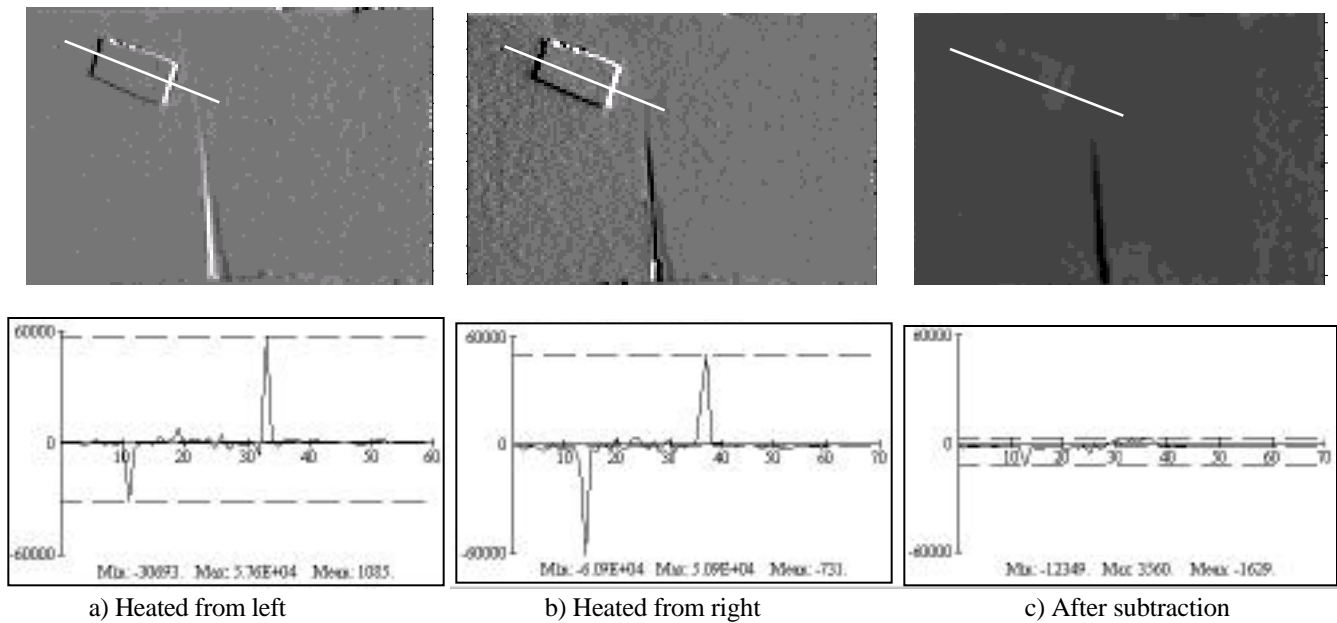
c) After subtraction

Fig. 5 Effects of paint anomalies minimized using the normalized subtraction process

Notice the difference in the maximum values between the first two line plots (Fig. 5a and Fig. 5b) and the third line plot (Fig. 5c). The emissivity gradient caused by the paint chip is almost completely eliminated from the final data by performing the subtraction of the right and left images. The crack, because it impedes the flow of heat from both directions, is accentuated by the subtraction process.

3.0 INSTRUMENTATION

Several methods were used to calculate the desired thermal gradient images. The most straight forward is the all-digital method in which, the thermal gradient images are calculated directly from the thermal images. The data presented in this paper was collected with a differential thermography camera, which measures small oscillating temperature changes at a

specific frequency. An oscillating mirror is used to create a differential thermal signal that is proportional to the gradient (Fig. 6). The mirror's drive signal is used as the reference for the differential system. This method was employed only because of the immediate availability of the differential thermography equipment, which is optimized for differential measurements, but provides lower quality thermal images. The technique described above will work well with both the all-digital method and the differential thermography system.
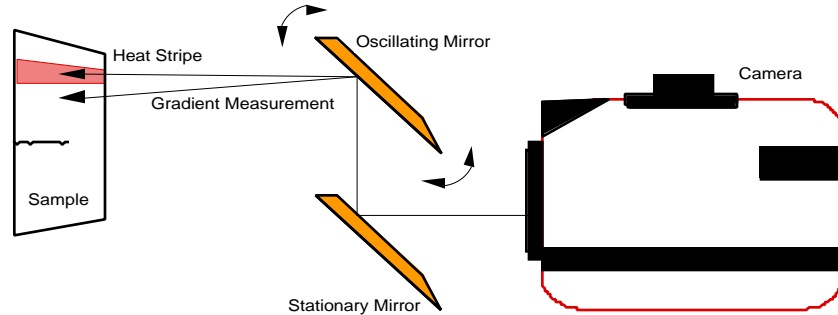

Fig. 6 Experimental oscillating mirror system

4.0 RESULTS FROM TURNER-FAIRBANKS DEMONSTRATION

Stress Photonics demonstrated the Coating Tolerant Thermography method at the FHWA Turner-Fairbanks Laboratory. At this site, a large steel girder (Fig. 7) had been fatigue tested to establish visible and invisible cracks. Steve Chase of Turner-Fairbanks picked a series of bridge details that represented typical field scenarios including cracks originating at a gusset plate, cracks in a T-weld, and an invisible crack in the flange of the girder.

Fig. 7 Steel girder at Turner-Fairbanks Lab

Only a simple stationary pattern projector was used at the demonstration. The projected hot stripe was manually moved from side to side as thermal images were collected. Both the oscillating mirror method and the all-digital method of gradient measurement were used depending on the situation. Absolutely no surface preparation was performed on any of the details on the girder.

In the most challenging example, a crack had grown in the flange above a stiffener (Fig. 8a). Figure 8b shows the effects of the crack on heat conduction in the girder. The structure was heated to the right, which induced a large thermal gradient at the face of the crack. Figure 8c shows the result of the full process and clearly indicates the crack, which after being coated with bridge paint was invisible to the naked eye.
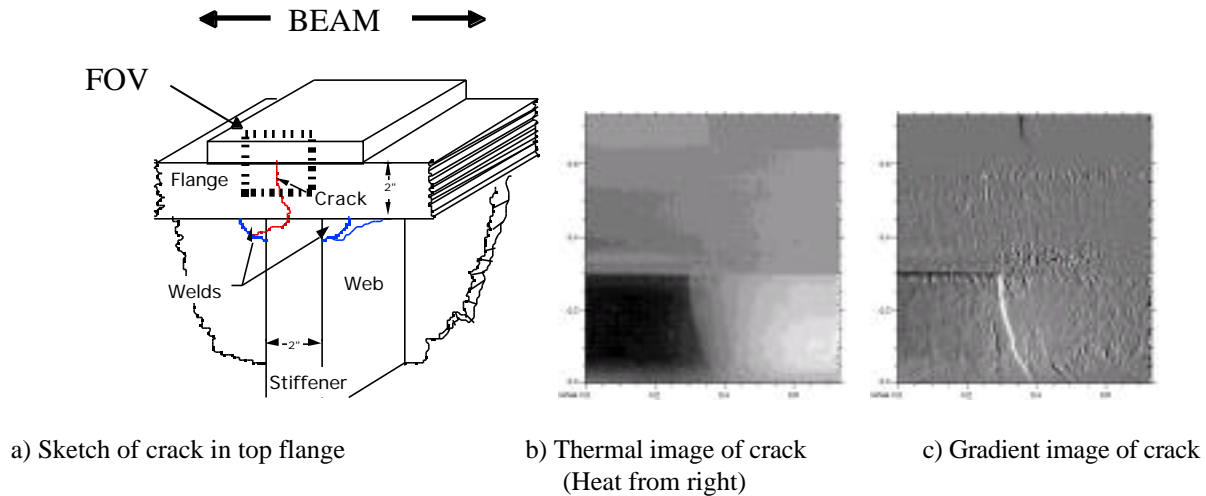
| a) Sketch of crack in top flange | b) Thermal image of crack (Heat from right) | c) Gradient image of crack |

Fig. 8 Hidden crack in top flange of girder

4.1 Paint delamination

The Coating Tolerant Thermography method can flag the presence of paint delaminations. A FHWA scientist asked to see if this ability could be used to quantify paint delaminations in paint test specimens. Figure 9 shows the results of a few seconds of heating. The delamination is clearly defined.
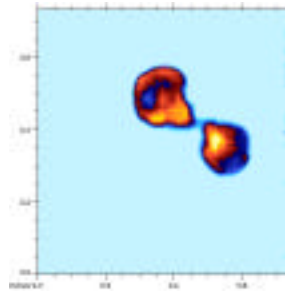

Fig. 9 Thermal image of paint delaminations

5.0 PREFERRED METHODOLOGY

Although the data demonstrating the fundamentals of Coating Tolerant Thermography were collected by projecting stationary radiation adjacent to cracks, a more complete system involving moving patterns of thermal radiation is envisioned. The final product will project slowly moving line patterns that comb the structure for cracks. The gradient data will be collected only in the region where gradients are induced (Fig. 10). The positive slope data will be normalized and added to the image buffer; the negative slope data will be normalized and subtracted from the image buffer. The resultant thermal data will be placed in an image buffer for delamination or soil detection. Some design decisions remain, for example, a choice between a continuously moving line pattern or four discrete steps must be made. In the event that four discrete locations are used the optimal order of positions must be determined. Also, the number and timing of reflection subtraction images must be examined.
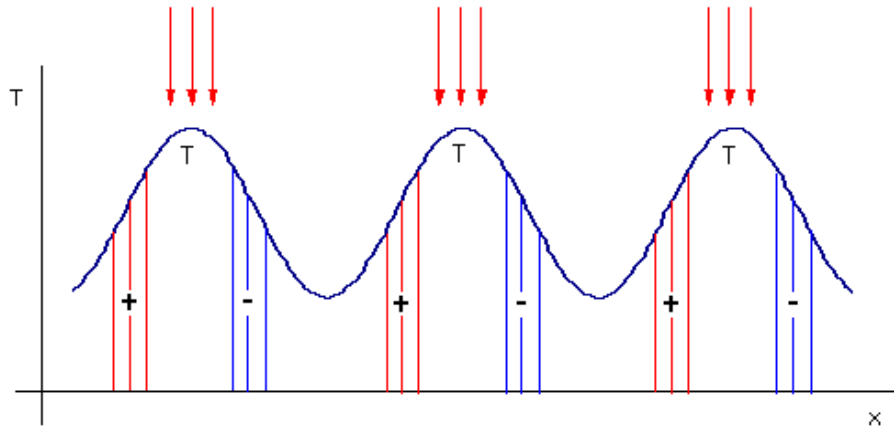
Fig. 10 Multiple stripe method

6.0 CONCLUSIONS

Coating Tolerant Thermography is an adaptation of Forced Diffusion Technology, specifically designed for inspection of large, steel, structures that are heavily and nonuniformly coated with paints and perhaps debris. To summarize Coating Tolerant Thermography, the difference between a left heated image and a right heated image will accentuate a crack and minimize signals related to emissivity variance. The gradient data is normalized by the magnitude of the reflection reduced thermal image so that emissivity effects are separated from thermal effects. Emissivity variances are completely eliminated in the final image. There is a clear path to an inexpensive hand held system that will be portable, robust, rapid and widely distributable. Most importantly, the resulting images are easy to interpret, because the existence of a crack is as clear as black on white.

ACKNOWLEDGMENTS

REFERENCES

1. Cramer, K. E. and Winfree, W. P., "Thermographic imaging of cracks in thin metal sheets," Thermosense XIV, Jan., K. Eklund, Editor, Proc. SPIE Vol. 1682, pp. 162-170,1992.

2. Osiander, R., Spicer, J. W. M. and Murphy, J. C., "Analysis methods for full-field time-resolved infrared radiometry," Thermosense XVII, April, D. D. Burleigh and J. W. M. Spicer, Editors, Proc. SPIE Vol. 2766, pp. 218-227, 1996.

3. Lesniak, J. R. and Boyce, B. R., "Forced-Diffusion Thermography," Thermosense XVII, Orlando, Sharon A. Semanovich, Editor, Proc. SPIE Vol. 2473, pp. 179-189, April 1995.

4. Lesniak, J. R. and Bazile, D. J., "Forced-Diffusion Thermography technique and projector design," Thermosense XVIII, Orlando, D. Burleigh and J. Spicer, Editors, Proc. SPIE Vol. 2766, pp. 210-217, April 1996.

5. Lesniak, J. R., Bazile, D. J. and Zickel, M. J., "Structural Integrity Assessment via Coating Tolerant Forced Diffusion Thermography," to be published in the proceedings of the 1997 ASCE Structures Congress, Portland, OR.