# Structural integrity assessment via coating tolerant thermography

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## Abstract

This paper describes a new thermal method, Coating Tolerant Forced Diffusion Thermography, specifically designed to inspect large steel bridge structures. Coating Tolerant Thermography separates the effects of structural defects and 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.

## Keywords

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

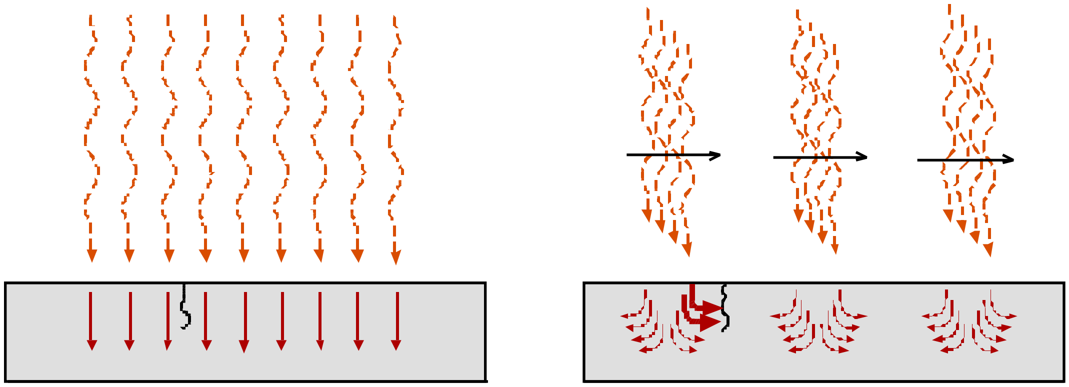
## 1.0 Introduction

The transportation infrastructure is one of this nation's most significant assets. It has taken many decades of planning and construction to create what is known around the world as a civil engineering masterpiece. 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 FHWA 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. Coating tolerant thermography is designed specifically to meet the demands of more challenging field conditions. The paper shows that coating tolerant thermography exhibits

- High probability of detection
- Low false alarms
- Easy interpretation
- Speed
- Portability

## 2.0 Technology review

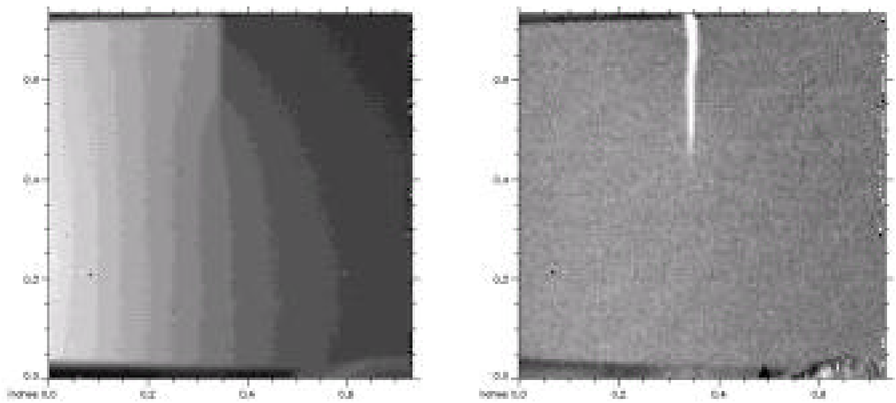
Thermal methods correlate structural integrity with thermal diffusivity. If the molecular structure is altered impairing transfer of forces, the conduction of heat energy is also impeded. Traditional thermal methods, such as thermal wave[1], project a uniform pattern of heat (Fig. 1a) that relies on the asymmetry of the structure to drive heat across cracks. Several researchers have noted the benifits of inducing in-plane heat flow to target specific flaws [2],[3]. Stress Photonics has developed a method called Forced Diffusion Thermography (FDT) that projects a pattern of dynamic heat to force flow across cracks (Fig. 1b) thereby, optimizing the measurable thermal gradient [4],[5],[6].



a) Uniform heating    b) Forced diffusion heating

Fig. 1 Thermal methods

In FDT, 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 anomaly, such as a crack (Fig. 2a), setting up an extreme thermal gradient (Fig. 2b), which clearly defines the crack.



a) Thermal image    b) Gradient image

Fig. 2 Thermal gradient across crack

### 3.0 Coating tolerant thermography

After participating in bridge inspections with the Wisconsin and Ohio Departments of Transportation and receiving input from the FHWA and the WDOT, it became apparent that successful inspection of bridge structures would require a system specifically designed to be tolerant of thick and imperfect coatings. Coating tolerant thermography is extremely sensitive to real fatigue cracks yet insensitive to

- Paint thickness
- Reflective paint
- Paint chips and variations
- Over-coated cracks

### 3.1 Coating heating

Thick bridge coatings can have both low thermal conductivity and low heat capacity. These properties can result in rapid heating of the coating which can overpower the low level thermal signatures induced by flaws. For this reason, coating tolerant thermography avoids calculating thermal gradients in irradiated areas (Fig. 3). Instead, the heat absorbed by the coating in the heated area is transferred to the steel substrate and proceeds to flow through the measurement area where the coating follows the thermal distribution of the steel substrate. This avoids over-heating the coating and also assures that the gradient is calculated only where a significant heat flow is occurring, thus improving signal to noise ratios.

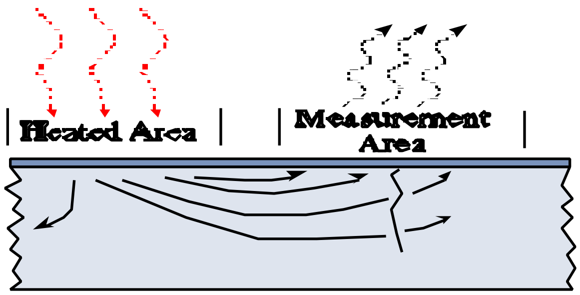



Fig. 3 Thick coating effects

### 3.2 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. This image $\varphi(x,y)$ is a combination of the potential reflected photon flux $R(x,y)$ and the potential photon emissions of the bridge $\Phi(x,y)$

$$\varphi(x,y) = R(x,y)[1 - \varepsilon(x,y)] + \Phi(x,y)\varepsilon(x,y) \tag{1}$$

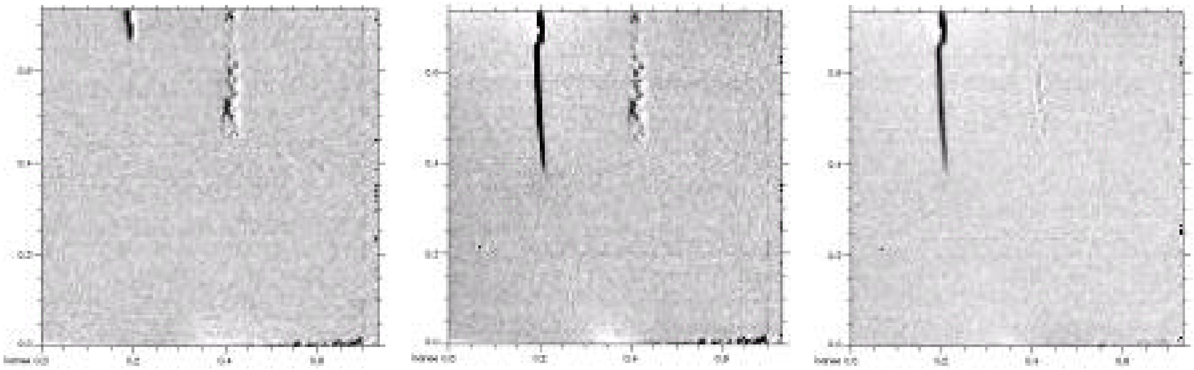
The exact mixture of these components is set by the emissivity map of the surface $\varepsilon(x,y)$ where the sum of the reflectivity and emissivity are assumed to be 1.0. After heat is added, the resulting image $\Theta(x,y)$ is a combination of the unchanged reflection $R(x,y)$, the initial thermal condition $\Phi(x,y)$, and the change in emission potential $\Delta\Phi(x,y)$ as influenced by the heat input.

$$\Theta(x,y) = R(x,y)[1 - \varepsilon(x,y)] + [\Phi(x,y) + \Delta\Phi(x,y)]\varepsilon(x,y) \tag{2}$$

A reflection and initial condition reduced image $I(x,y)$ can be formed by subtracting the initial image $\varphi(x,y)$ from the heated image $\Theta(x,y)$

$$I(x,y) = \Theta(x,y) - \varphi_1(x,y) = \varepsilon(x,y)\Delta\Phi(x,y) \tag{3}$$

All that remains is the photon flux resulting from the added heat or heat lost since the capture of the initial image. A specimen was fabricated to test the reflection suppression. The specimen was coated with a white super-high-gloss enamel and contains a crack as well as a highly reflective paint drip. Figure 4b shows a typical signal that can occur in the presence of reflections, and Fig. 4c shows the result with the before heating image subtraction. Notice that only the crack stands out.



a) Reflection b) After heat added c) Reflection subtracted

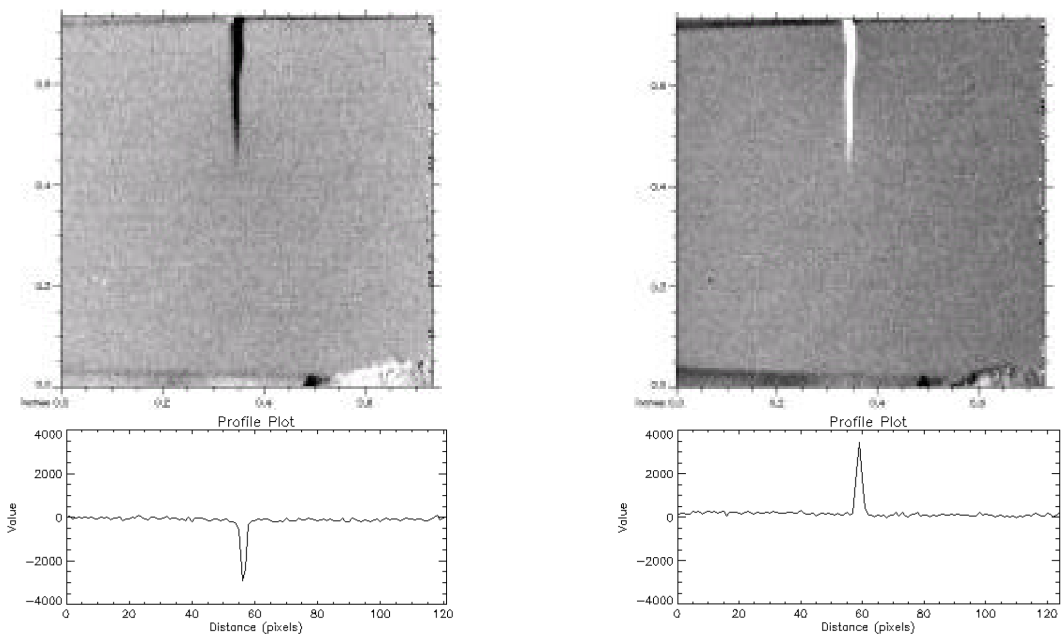
Fig. 4 Effects of reflections on gradient calculation

### 3.3 Separation of flaws and emissivity

If all structures had perfectly uniform coatings, the simple unidirectional gradient method of Fig. 2 would be sufficient to locate cracks. However, often gradients caused by emissivity variances can 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

$$I_x(x,y) = \varepsilon(x,y)\Delta\Phi_x(x,y) + \varepsilon_x(x,y)\Delta\Phi(x,y) \tag{4}$$

Emissivity gradients have similar impact 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. 5a and 5b).

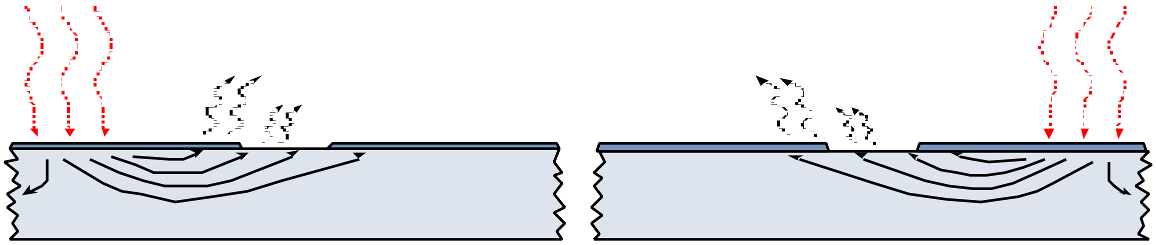



a) Heat source to left b) Heat source to right

Fig. 5 Sign change of thermal gradients

When the heat is flowing from the left, the gradient is negative (as defined) because the heat builds up behind the crack. When heat is flowing from the right, the gradient changes sign becoming positive 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.  The sign of the differential  is independent of the direction of heat flow.  As the material is heated from the left, the region under the paint edge is uniformly heated because there is no flaw in the steel substrate (Fig. 6). On the left edge of the paint chip in the example of Fig. 6a, the differential is apparently hot on the left and apparently cold on the right.  Similarly, as depicted in Fig. 6b, if the heat conducts from the right, 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. 6  Paint chips

Mathematically this can be thought of as separating the thermal distribution and emissivity variables.  If we normalize the gradient image $I_x(x,y)$ of Eq. 4 by the reflection corrected image I(x,y) of Eq. 3

$$\frac{I_x(x,y)}{I(x,y)} = \frac{\Delta\Phi_x(x,y)}{\Delta\Phi(x,y)} + \frac{\varepsilon_x(x,y)}{\varepsilon(x,y)} \tag{5}$$

we separate the influences of thermal distributions and emissivity gradients into two terms.   If two sets of images are collected and processed in this manner

$$\frac{I_x^1(x,y)}{I^1(x,y)} = \frac{\Delta\Phi_x^1(x,y)}{\Delta\Phi^1(x,y)} + \frac{\varepsilon_x(x,y)}{\varepsilon(x,y)} \tag{6a}$$

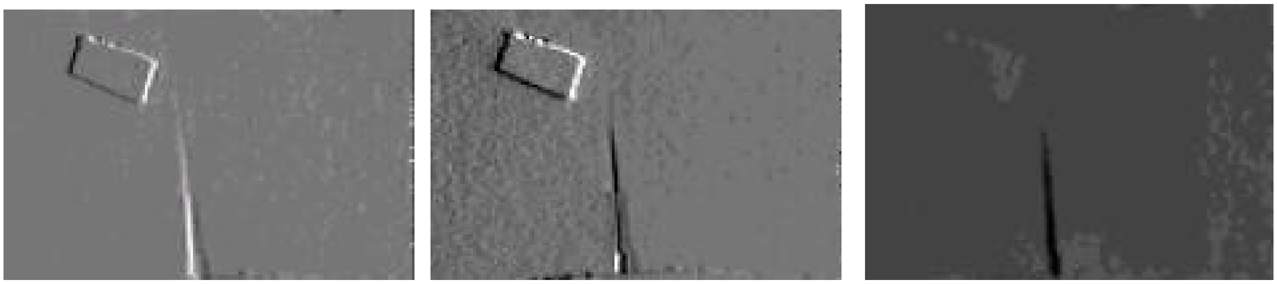
$$\frac{I_x^2(x,y)}{I^2(x,y)} = \frac{\Delta\Phi_x^2(x,y)}{\Delta\Phi^2(x,y)} + \frac{\varepsilon_x(x,y)}{\varepsilon(x,y)} \tag{6b}$$

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

$$Q(x,y) = \frac{I_x^1(x,y)}{I^1(x,y)} - \frac{I_x^2(x,y)}{I^2(x,y)} = \frac{\Delta\Phi_x^1(x,y)}{\Delta\Phi^1(x,y)} - \frac{\Delta\Phi_x^2(x,y)}{\Delta\Phi^2(x,y)} \tag{7}$$

As mentioned, 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, 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.  Figure 7 demonstrates the ability of the normalized subtraction process to accentuate cracks and eliminate false readings at paint chips.



a) Heated from left b) Heated from right c) After subtraction

Fig. 7 Effects of paint anomalies

### 3.4 Environmental influences

Experiments were conducted using a 60 cfm blower directed over the area under analysis. Only minor effects were noted. The principal effects of the sun are bulk heating and reflections. The effects of bulk heating are removed by the virtue of the image differencing that takes place in the processing. Although a hot structure may have a differential signature due to its ambient thermal distribution, these influences are removed, so that only the thermal gradients caused by the additional energy injected by the projector are actually registered. As discussed earlier, reflections are also reduced by the image differencing process. Although some moisture can be tolerated, rain directly falling on the surface to be analyzed is a complication not easily overcome by this technology. Not only will the rain alter the thermal response of the structure, but the drops can also be highly reflective and opaque to IR radiation.

## 4.0 Experimental trials

### 4.1 Instrumentation

Several methods were used to calculate the desired thermal gradient images. Most straight forward is the all digital method. In this case, the thermal gradient images are calculated directly from the thermal images. The data presented in this work was collected with a differential thermography camera, which measures small oscillating temperature changes at a specific frequency. An oscillating mirror, “the wiggler”, is used to create a differential thermal signal proportional to the gradient (Fig. 8); the mirror’s drive signal is used as the reference. 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 absolute thermal images. This system is capable of measuring thermal images as well as gradient images. The preceeding arguments are applicable to both methods of measurement gradients.

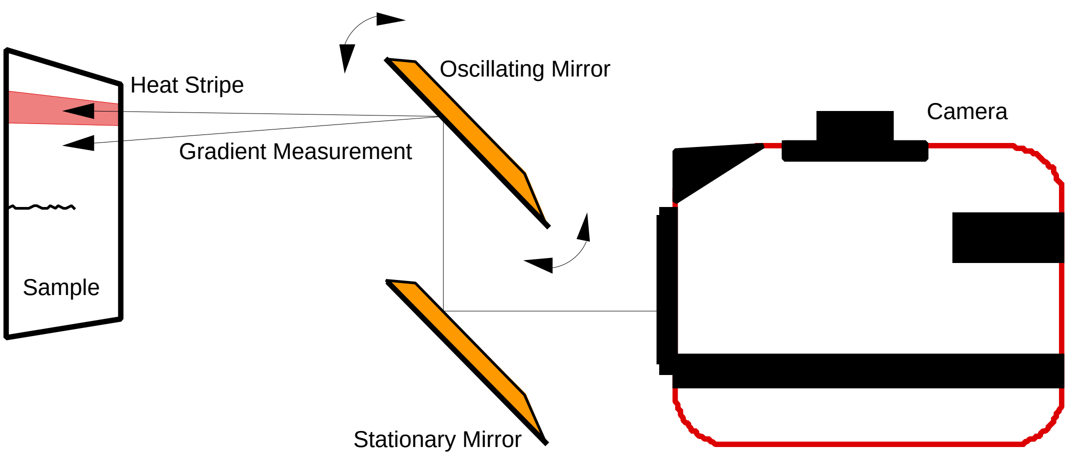



Fig. 8 Experimental oscillating mirror system, “the wiggler”

Although the data demonstrating the fundamentals of coating tolerant thermography was collected by projecting stationary radiation adjacent to cracks, a more complete system involving moving patterns 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. 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 thermal data will be placed in an image buffer for delamination or soil detection.

### 4.2 Results from Turner-Fairbanks demonstration

As part of the final paper, Stress Photonics demonstrated the coating tolerant thermography method at the Turner-Fairbanks Laboratory. At this site, a large steel girder (Fig. 9) 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.

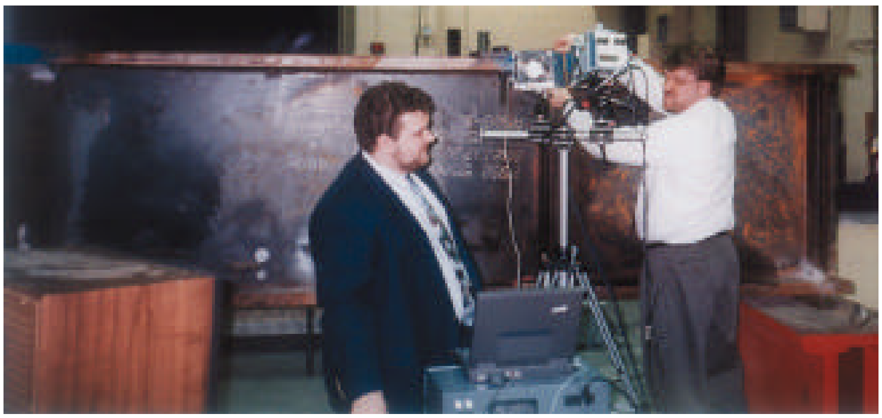
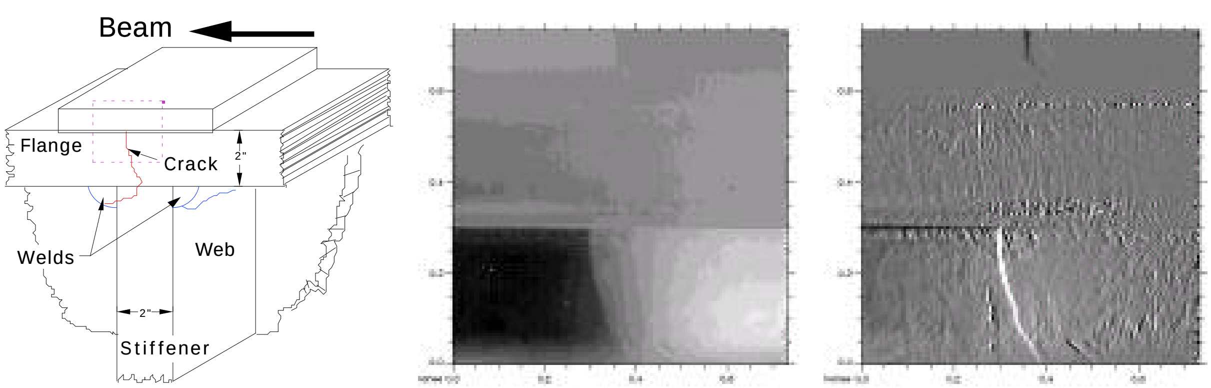


Fig. 9 Steel girder at Turner-Fairbanks Lab

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. The method was applied to the rather imperfect girder as is. Absolutely no surface preparation was performed on any of these details.

In the flange example, a crack had grown in the flange above a stiffener (Fig. 10a). Figure 10b 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 10c shows the result of the full process and clearly indicates the crack, which after being coated with bridge paint was invisble 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. 10 Hidden crack in top flange of girder

## 5.0 Conclusions

Coating tolerant thermography is an adaptation of Forced Diffusion Technology specifically designed for inspection of large, steel, heavily coated structures. To summarize coating tolerant thermography, the difference between a left heated image and a right heated image will accentuate a crack and deccentuate signals related to emissivity variance. The gradient data is normalized by the magnitude of the reflection reduced thermal image to separate emissivity effects from thermal effects. Emissivity variances are completely canceled in the final image subtraction. 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.

## 6.0 Acknowledgments

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