# Structural Integrity Assessment via Coating Tolerant Forced Diffusion 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 from variations in emissivity. The technique is a derivative of Forced Diffusion Thermography (FDT) 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.

## Introduction

The thorough inspection of full bridge structures can seem like an insurmountable task. Thermal methods have been recognized above other NDI techniques for having great potential as rapid, convenient and relatively inexpensive tools; however, thermal methods must be demonstrated to tolerate emissivity variances caused by anomalies like chipped paint. This paper describes an exciting new crack detection technology, coating tolerant thermography, which is designed specifically to meet the demands of more challenging field conditions. Coating tolerant thermography is extremely sensitive to real fatigue cracks yet insensitive to paint thickness, reflective paint, paint chips and over-coated cracks.

## 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. Coating tolerant thermography projects a pattern of dynamic heat to force flow across cracks (Fig. 1b) thereby, optimizing the measurable thermal gradient (Lesniak and Boyce, 1993).

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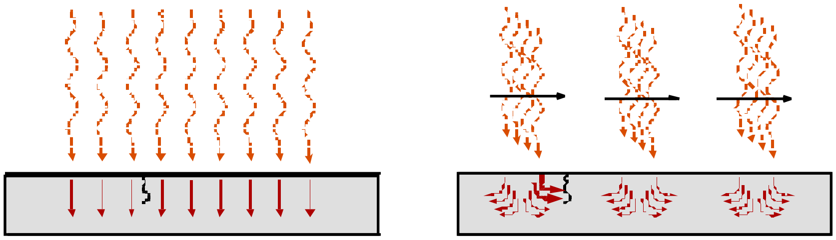
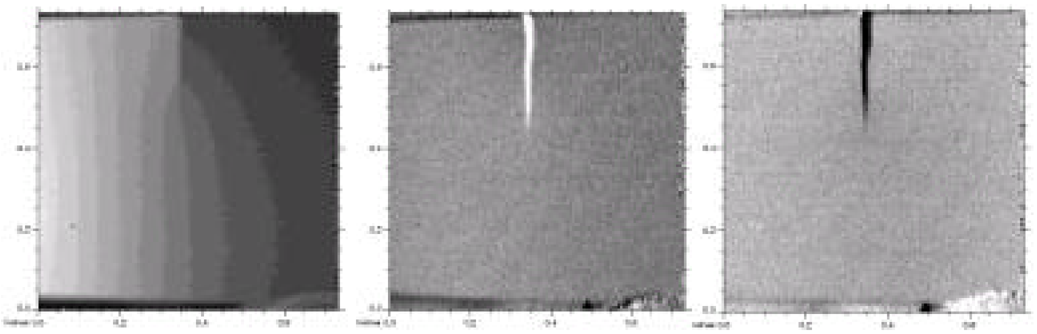


a) Uniform heating b) Forced diffusion heating

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 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 (heat left) c) Gradient (heat right)

Fig. 2 Thermal gradient across crack

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

$$I(x,y) = \varepsilon(x,y)\Delta\Phi(x,y) \tag{1}$$

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

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 image I(x,y) is

$$I_x(x,y) = \varepsilon(x,y)\Delta\Phi_x(x,y) + \varepsilon_x(x,y)\Delta\Phi(x,y) \tag{2}$$

Where $\Delta\Phi_x$ and $\varepsilon_x$ are the spatial derivatives in x.

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. When the heat is flowing from the left (Fig. 2b), the gradient is negative (as defined), because the heat builds up behind the crack on the left side. When heat is flowing from the right (Fig. 2c), the gradient changes, sign becoming positive, because now heat builds up behind the crack on the right side. Only a true structural flaw exhibits this characteristic.

Gradients caused by paint chips or other emissivity changes on the surface of the structure are not conduction direction sensitive. Because there is no flaw in the steel substrate, the region under the paint edge is uniformly heated when the material is heated from either direction. The sign of $\varepsilon_x(x,y)$ and therefore the sign of the apparent thermal gradient is independent of the direction of heat input. This is the cornerstone of coating tolerant thermography.

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. 2 by the reflection corrected image $I(x,y)$ of Eq. 1

$$\frac{I_x(x,y)}{I\ (x,y)} = \frac{\Delta\Phi_x(x,y)}{\Delta\Phi\ (x,y)} + \frac{\varepsilon_x(x,y)}{\varepsilon(x,y)} \tag{3}$$

we separate the influences of thermal distributions and emissivity gradients into two terms, one sensitive to only thermal distributions as induced by heat input and flaws, and a second that is dependent only on the emissivity variances. If two sets of images are collected and processed in this manner the difference of these images $Q(x,y)$ eliminates emissivity as a variable.

$$Q(x,y) = \frac{\Delta\Phi^1_x(x,y)}{\Delta\Phi^1(x,y)} - \frac{\Delta\Phi^2_x(x,y)}{\Delta\Phi^2(x,y)} \tag{4}$$

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.

## Experimental trials

A 12”x 2”x 1/4” steel specimen coated with a high-gloss white paint was prepared with a rusted paint chip near a fatigue crack. Figure 3 demonstrates the ability of the normalized subtraction process to accentuate cracks and eliminate false readings at paint chips.

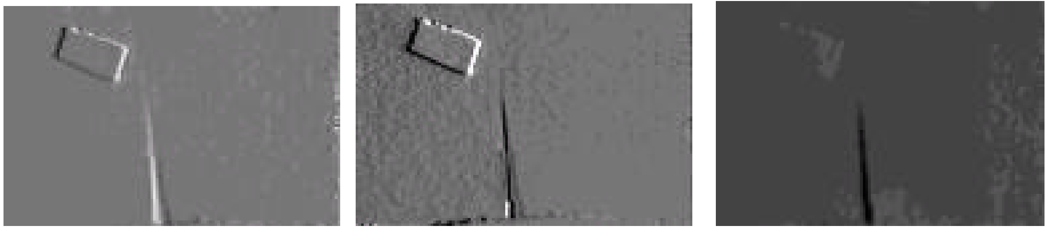

a) Heated from left b) Heated from right c) After subtraction

Fig. 3 Effects of paint anomalies

Several methods were used to calculate the desired thermal gradient images, the details of which are described in Lesniak, Bazile and Zickel, 1996.

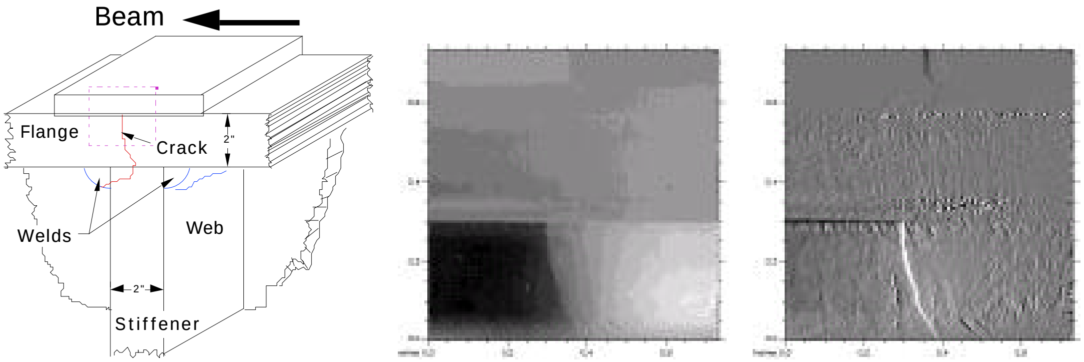
Results from Turner-Fairbanks demonstration

Stress Photonics demonstrated the coating tolerant thermography method at the FHWA Turner-Fairbanks Laboratory. At this site, a large steel girder (Fig. 4) 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. 4 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 an oscillating mirror method and an all digital method of gradient measurement were used successfully. The methods were 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. 5a). Figure 5b shows the effects of heat conduction on the crack in the girder. The structure was heated to the right, which induced a large thermal gradient at the face of the crack. Figure 5c shows the result of the full process and clearly indicates the crack, which, because it was coated with bridge paint, was invisible to the naked eye.



a) Crack in top flange b) Thermal image c) Gradient image

Fig. 5 Hidden crack in top flange of girder

## Conclusions

Coating tolerant thermography is an adaptation of Forced Diffusion Thermography 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 suppress 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.

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## References

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## Keywords

Thermography, NDE, Crack, Bridge, Coatings, Forced Diffusion Thermography