DETECTION OF BRIDGE DECK DE-LAMINATIONS USING THERMAL IMAGING

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Abstract

The reinforced concrete decking used to construct the bridges of our nation's highways is continuously degrading by normal traffic and environmental exposure. This degradation is exacerbated in climatic regions where de-icing chlorides are used and in coastal regions where bridges are exposed to high airborne salt concentrations. Such deterioration requires new computerized non-destructive evaluation (NDE) test methods that aid in establishing maintenance demands. Here, the application of state-of-the-art infrared imaging sensors, supporting technologies, and sophisticated image processing techniques to perform bridge deck NDE is discussed. This is the first of two articles that explores IR technology as a contributing solution to the detection and mapping of bridge deck de-lamination.

INTRODUCTION

A study conducted in 1977 by Clemena and McKeel demonstrated that infrared imaging (IR) has advantages over conventional techniques in the detection of bridge deck de-laminations; for example, the process requires shorter inspection time resulting in fewer or shorter lane closings, thus less impact on traffic flow. This study established IR as a rapid, non-destructive detection method with the added capability to characterize individual bridge deck de-laminations.

Using the aforementioned study as motivation for the development of a new NDE technology for bridges, the author began developmental work in 1995 on a system that surpassed the (then) currently available technology (see April 1996, Roads and Bridges Magazine).

That 1995 technology has been newly configured as a commercial bridge inspection tool by building on both recent developments in IR technology and internal supporting software tools. The resultant outcome, *BridgeGuard,* is able to capture deck conditions, readily analyze and store the data, and allow future reference within its data management system. The rapid data collection eliminates lane closures and the labor intensive effort common with current NDE methods. The simplicity, cost effectiveness, and accuracy, along with the ability to analyze, manage, and store this critical data will be described in this two-part series.

IR TECHNOLOGY BACKGROUND

Remote sensing is the science of measuring an object's properties which cannot be measured by traditional contact methods. It can further be defined as the collection of electromagnetic radiation, either emitted or reflected by the targeted scene, using a suitable receiver and data processing assets. A subset of remote sensing is IR imaging.

The science of IR technology can be applied to a variety of research and analytical activities. In fact, IR has been used successfully in a wide variety of industrial, commercial, and environmental applications such as pipelines, roofs, electrical distribution systems, industrial facilities and, specific to this application, bridge decks. In fact, The American Society for Testing and Materials (ASTM) has developed a standard procedure for the bridge deck test process: ASTM Designation D4788-03 - *Standard Test Method for Detecting De-laminations in Bridge Decks Using Infrared Thermography*.

THEORETICAL DEVELOPMENT

A thermal model of a concrete bridge deck can describe the normal flow of heat within a bridge deck. As this heat movement manifests itself at the surface of the bridge deck, it becomes a candidate for the application of IR as a remote sensing modality. Using numerical techniques, a concrete slab can be modeled as a multi-layered, semi-infinite solid in which time dependent heat conduction occurs along a one-dimensional path. If a de-lamination were introduced to an otherwise homogeneous concrete slab, a disruption in thermal properties would occur at that local site. As a result, the normal flow of energy along the thermal path would be altered relative to its surroundings. This thermal disruption would eventually manifest itself at the slab surface and will be evidenced by a hot or cold spot in the IR imagery.

While the technology is weather dependant, time dependency is not limiting with the field use windows of opportunity encompassing most of a full diurnal cycle. The application widows can be segmented into two categories:

The first window begins a few hours after sun down. The daytime hours before the test should provide full irradiation by solar loading and the night hours of the test should consist of a clear night sky. The homogeneous material will quickly begin to cool in response to the cooling effect of radiation exchange with the cold night sky, drawing heat from the lower layers of the concrete based on its uninterrupted thermal properties. In contrast, the defect areas can not draw this heat from the lower layers due to the thermal path disruption. The areas above the defect will respond much faster to this cooling effect. The normal areas will exhibit whiter (warmer) characteristics and the defected areas will appear darker (cooler) in the thermal imagery. This condition will increase to a maximum point but then decrease throughout the night and into the morning hours until all surfaces drive toward thermal equilibrium.

The second window begins in the morning a few hours after the sun has risen. The night hours before the test should consist of a clear night sky, and the morning hours should be fully irradiated with solar energy. Full solar irradiation ensures a maximum transition from cold to warm in the upper concrete layers. Again exploiting the thermal transition into the concrete, we find that the homogeneous concrete warms much slower than defected areas where the discontinuity inhibits the ability to diffuse heat from the surface. Consequently, we look for whiter areas within the deck for anomalous indications.

BRIDGEGUARD DEVELOPMENT

The author’s 1995 development effort began without a front-end study of what an IR sensor could see relative to the bridge deck, how deep could a defect could be seen, and under what environmental conditions. This lack of a front-end effort was a significant hindrance in the ability to educate potential users in the use and efficacy of the technology. Consequently, as the 1995 system redesign process began it was decided that a simulation of a bridge deck would be developed to complete the study. This simulator provides several uses including:

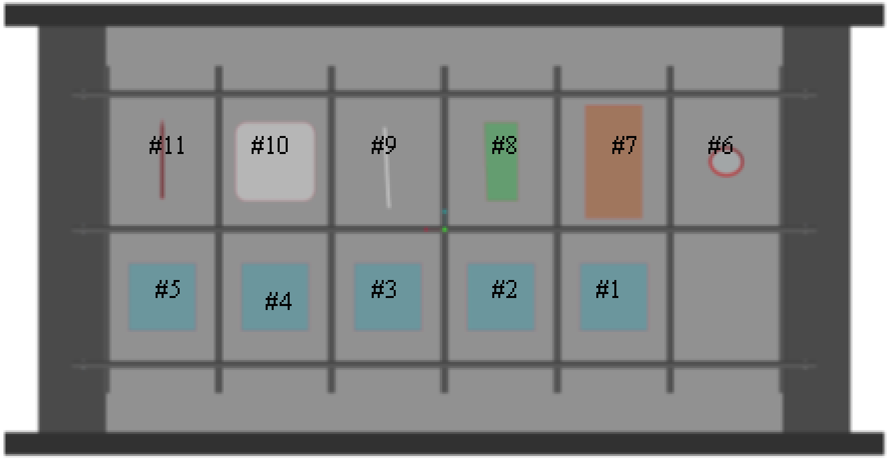
- Validating and illustrating the theory
- Developing an empirical prediction of what can be seen, when, and how deep
- A training tool for future *BridgeGuard* users

Typical concrete bridge decks in Michigan use a 9-in. structural deck and a 2-in. non-structural concrete overlay. To quantify various thermal characteristics of bridge decks, a concrete slab with an appropriate framing system was designed and poured to replicate an actual bridge deck section. The design and pour was completed in conjunction with the Civil and Environmental Engineering Department at Michigan Technological University.

To simulate an elevated bridge deck, a slab (Figure 1) was designed to mirror a typical highway bridge deck pour. The concrete consisted of an eight sack mixture rated at 5000 psi and was cast on I-beams. Additionally, five thermocouples were inserted resting at 2-in intervals within the slab to quantify the depth and extent at which the thermal conditions at the surface are felt.

Figure 1
Bridge Deck Simulator

The concrete slab was designed with intentional damage at known locations through the placement of objects replicating de-laminations within the slab. Figure 2 characterizes the location and type of damage that was intentionally embedded into the simulator.



Location From Top Surface	Defect #	Defect #	Defect #
0 in. – at top surface	#9: Surface Scratch		
1 inch	#1: 6x6x1/4” Styrofoam	#10: 0.7 mil plastic sheet	#11: pencil
3 inch	#2: 6x6 x1/4” Styrofoam		
5 inch	#3: 6x6 x1/4” Styrofoam	#8: plywood	
7 inch	#4: 6x6 x1/4” Styrofoam	#7: cardboard	
7.5 inch	Rebar Structure		
9 inch	#5: 6x6 x1/4” Styrofoam	#6: pop can	

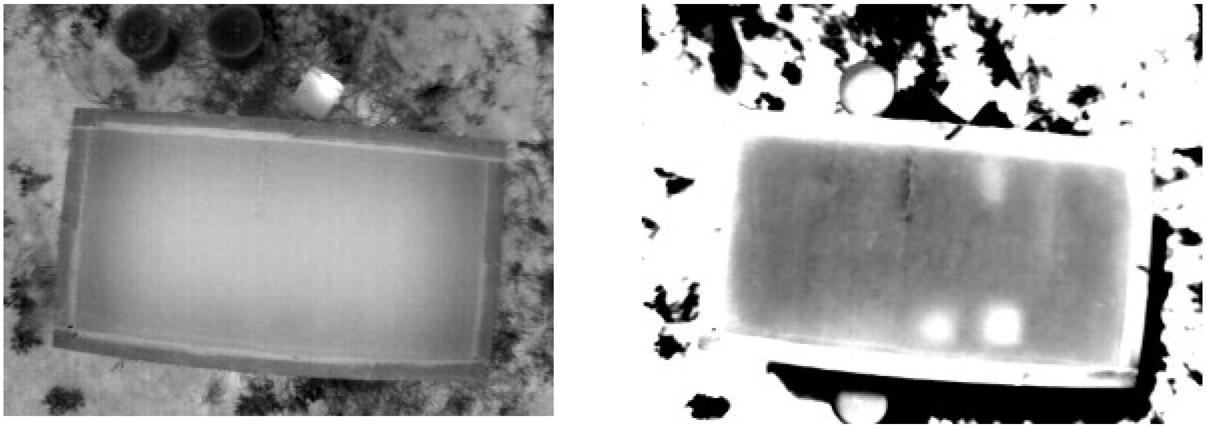
Figure 2
Bridge Deck Simulator Induced Defects

Three 6x12-in. concrete cylinders were cast according to ASTM *C31 – Standard Method for Making and Curing Concrete Test Specimens in the Field*. The cylinders were transferred to the Cement and Concrete Research Facility at Michigan Tech, an AASHTO CCRL accredited laboratory and allowed to cure for 28-days. Compression strength tests were conducted according to ASTM *C39 – Standard Test Method for Compressive Strength of Cylinder Concrete Specimens*. The average maximum compressive strength was 4140 ksi. These test results, along with documentation from the ready-mix concrete supplier, indicates that this concrete is similar to what would be cast in a typical bridge deck.

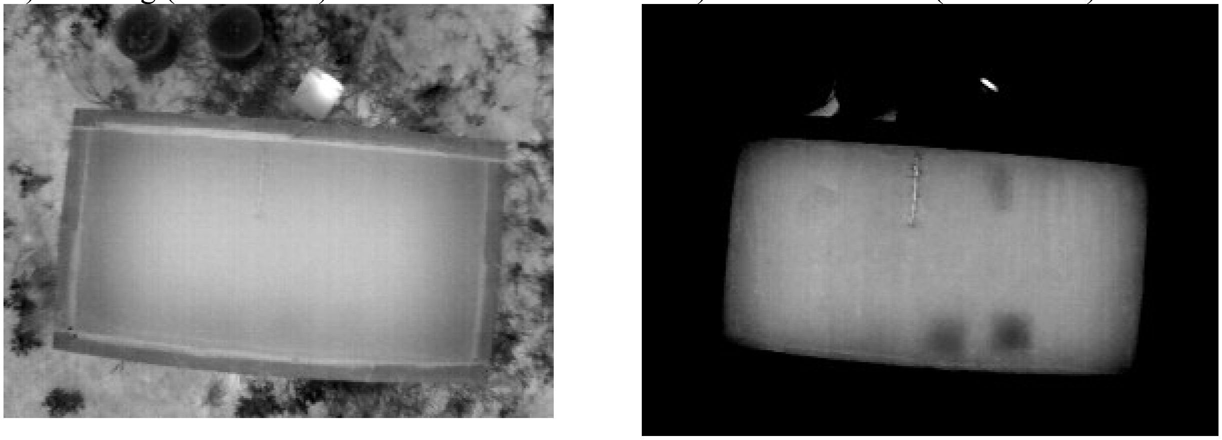
By exposing the simulator to the atmospheric and meteorological conditions that are expected on a bridge deck, the goals for the simulator can be quickly achieved both for instantaneous validation of the thermal responses expected in a concrete deck, and for the long term goal of modeling the empirical results for future study. Therefore, the bridge deck simulator was subjected to actual measured meteorological conditions for two complete diurnal cycles; the first test occurring on August 4, 2009, considered a cool summer day and the second test occurring on August 13, 2009, considered a warm summer day.

As the slab was exposed to the diurnal conditions, an IR camera was mounted to record the surface every 15 minutes throughout the 24 hour cycle. Rudimentary on-site meteorological characterization was made at each interval. The IR data was used as a qualitative measure of the slab’s thermal response over the cycle and as a quantitative measurement of the equivalent black body temperatures at the surface. As more diurnal data is gathered, it is the eventual goal that an empirical model be developed to act both as a training aid and as an aid for users to determine optimum times to test bridge decks using simple input variables.

Figure 3 illustrates the described thermal cross over points measured from the morning and evening hours. As illustrated on the images, defect items 1, 2, 8, 9, are apparent in both the daytime and nighttime imagery. Items 3 and 7 are beginning to appear in the imagery from both tests but never become an obvious defect.



a) Morning (0915 hours) Thermal Cross Over b) Maximum Solar (1600 hours) Contrast



c) Evening (2145 hours) Thermal Cross Over d) Maximum Non-Solar (0300 hours) Contrast

Figure 3 (a-d)

Because defect item #10 is very thin, it is expected to act as a worse case de-lamination indicator. It is considered worse case simply because it was integral to the concrete pour therefore the thermal discontinuity (or measurable break) expected at a true de-lamination site is not as delineated. Note that, when reviewing the total data set, item #10 is detectable, even without further image processing.

To quantify the time of day that yielded the best contrast results, as determined by the measured contrasts at the defect locations, two methods were used. First, a visual evaluation of the contrast over the entire surface was conducted. The larger the visual difference, the greater the contrast score. Second, a simple statistical evaluation was carried out. Because defect item #1 provides the most obvious contrast, the mean temperature value in that region of interest was determined. The mean temperature of the background was generated in the same way. The percent mean contrast between item #1 and its background for each image was determined and the results are plotted versus time of day in Figure 4.

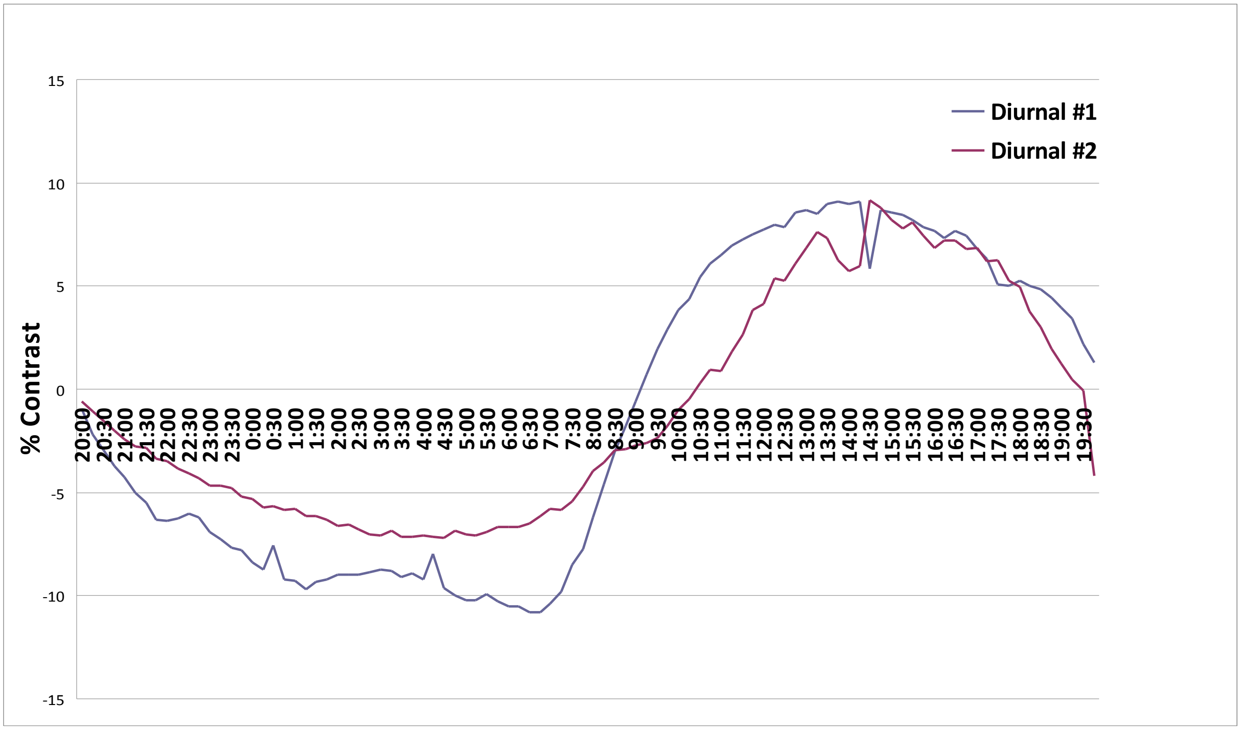


Figure 4
Percent Contrast
Defect #1 Mean versus Background Mean

Because the detection of de-laminations within a concrete slab is based on heat transfer in and out of the slab, it is important to know how the environmental exposure at the surface affects the thermal conditions deep within the slab. Figure 5 shows the thermocouple and radiometric temperatures recorded over the diurnal cycle for both tests. Note that the plot begins at the onset of the diurnal test, which is not the same time for each test. The orange plot, indicated as the slab surface temperature, is the temperature readings from the thermal imagery. As expected, this temperature vector leads the thermocouple temperatures in response to environmental exposure.

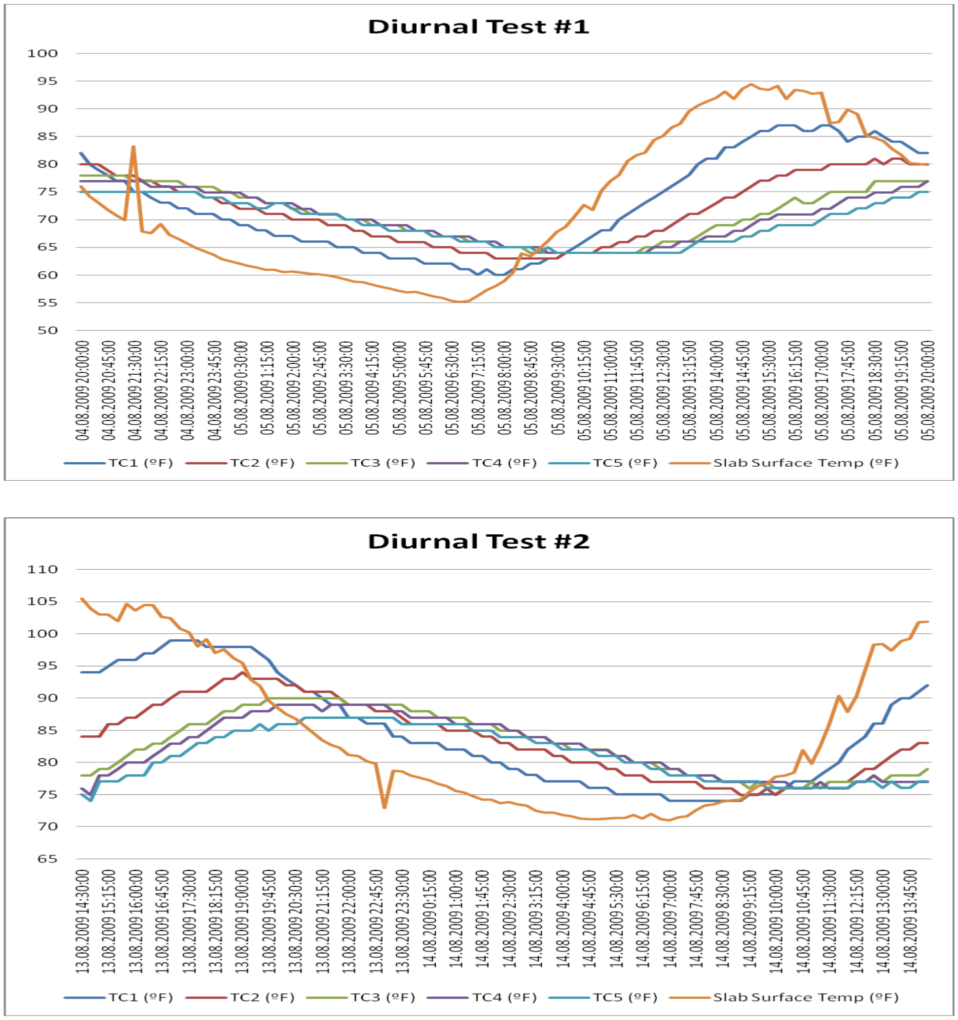


Figure 5 A and B
Thermocouple Temperature Readings

For this technology to detect thermal discontinuities within a concrete slab there must be a thermal driver to generate a temperature gradient between the slab layers. This driver is provided by the sun and by the cold, cloud free sky. The slab was raised off the ground to simulate the thermal boundary condition that exists on the underside of an actual bridge. The question remains: is there enough thermal gradient within the slab to see de-laminations near the bottom of the slab? If this is the case, a portable IR camera can be used under a bridge to detect de-laminations at the deepest depth of the decking. As evidenced by the thermocouple readings shown above, the thermal effect at the surface is well tracked at the deepest thermocouple position. Figure 6 is an IR image taken with a hand held camera during the initial development of this system in 1995. This image, with the thermocouple data as a further indicator, clearly indicates that these de-laminations can be detected under the bridge.

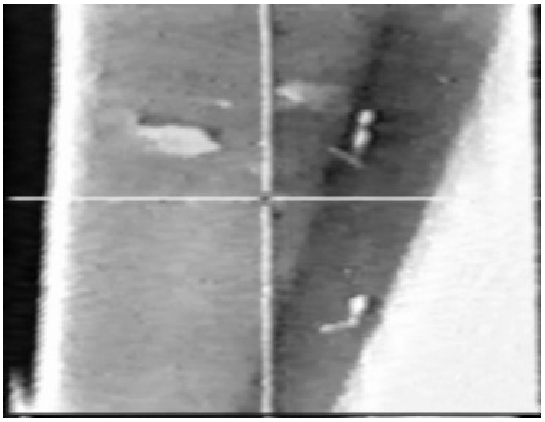


Figure 6
Thermal image taken from under a bridge with 1995 camera.

SUMMARY

It is the position of the authors that for IR to play a significant role in the detection, mapping and subsequent reporting of bridge deck de-laminations, a system had to be developed to ensure that the IR sensor implementation is the best it can be and not just another adaptation of a generic system. The background data presented in this first article provides the empirical justification for the claim that IR can play this significant role and consequently, a total product development phase is fully merited. The second article in this series will describe how this development proceeded and what capabilities resulted. For further information please visit www.bridgeguard.net.