Abridgment

Evaluation of Infrared Thermography as a Means for Detecting Delaminations in Reinforced Concrete Bridge Substructure Elements

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Analytical modeling and experimental investigation were conducted to develop a laboratory technique for the nondestructive evaluation of reinforced concrete. The methodologies were developed with the intent of eventual field implementation to ultimately determine the feasibility of using infrared thermography to inspect substructure elements of reinforced concrete bridges. An analytical model was developed using the ANSYS finite element code. A parametric study of the influence of the various, appropriate factors was conducted. Thermal analyses consistent with diurnal temperature fluctuations and various forms of applied heating were performed. Several specimen configurations were fabricated for thermographic inspection. A number of tests were performed on a variety of concrete specimens to define the implementation parameters of the technique. The necessity of using artificial heating methods for thermal input before inspection was evaluated. The present study suggests that infrared thermography cannot be applied, in a practical manner, to substructure elements. Internal thermal gradients produced by diurnal temperature fluctuation generally are not sufficient to produce variations in surface temperature patterns necessary for detecting defects. Instead, both the envelopment and artificial heating of the substructure component are required before thermographic inspection.

In recent years, the extensive use of salts and deicing chemicals has given rise to an enormous problem of premature deterioration in the nation's highways and bridges, particularly in northern and midwestern states. In the coastal regions, similar problems exist because bridges are continually subjected to saltwater spray. Salts and chemicals permeate a concrete structure, eventually reaching the reinforcement level. Once a critical level of chloride ion is present at the reinforcement level, an electrochemical process begins, causing localized corrosion to take place. As the reinforcing steel corrodes, oxides build up and exert pressure on the surrounding material. Eventually, sufficient tensile stresses are introduced to lead to localized cracking. As the damage progresses, cracks grow and interconnect, causing the eventual development of large subsurface fracture planes (delaminations). Both the continual loading of the structure (traffic) and the subjection to freeze-thaw cycles can result in large sections of concrete being completely separated from the structure. These severe damage conditions are known to exist in many concrete bridges in the United States, jeopardizing human safety and posing an enormous monetary problem.

Summarized in this paper is a report of work performed for the Strategic Highway Research Program (*1*). Described in the report are the analytical and experimental efforts undertaken to determine the feasibility of using infrared thermography for nondestructively assessing the in situ condition of substructure elements in a rapid, noncontact fashion.

PRINCIPLES OF INFRARED RADIATION THERMOGRAPHY

Infrared radiation thermography is a nondestructive testing method whereby thermal energy radiated from an object is remotely detected and converted into a video image, composed of isothermal contour lines. Typically, the visible image is displayed on a television monitor in real time, providing a detailed mapping of surface temperature. The testing method requires that a state of thermal instability be established in the test object so that differences in temperature exist throughout the volume of the test object. Temperature differences that initiate heat flow can usually be introduced by the uniform heating or cooling of a surface of the object. As heat flows through the volume of the object, subsurface regions of discontinuity conduct thermal energy differently than homogeneous regions. The localized impedance of heat flow through the thickness of the material ultimately produces variations in surface temperature that can be detected with a camera capable of sensing infrared radiation (IR). Thus, infrared thermography is useful in sensing dissimilarities in surface temperature patterns that may be attributable to subsurface thermal anomalies (defects).

All animate and inanimate material objects with temperatures above absolute zero spontaneously emit electromagnetic radiation. If the temperature of the object is below 800°K the radiation is principally in the infrared range, consisting of wavelengths longer than visible light and shorter than radio waves.

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A blackbody radiator has an emissivity of unity and is defined as a body that can absorb all incident radiation and emit the maximum amount of radiation at any temperature. Thus, blackbodies are perfect absorbers and emitters, but they only exist hypothetically. Bodies found in nature typically emit radiation at some fraction of a blackbody, and the fractional quantity is defined as the emissivity. Natural bodies possess an emissivity value lying between zero and unity. If the emissivity value of a body is dependent on the wavelength of incident radiation, the body is called a spectral or real body. However, if the emissivity value is independent of wavelength, the body is termed a gray body. Parameters that generally influence emissivity include the type of material, surface topography, surface discolorations and contaminants, and the wavelength of incident radiation.

Several factors must be considered in applying thermographic techniques. Heating or cooling of the test object to initiate one-dimensional heat flow must be done as uniformly as possible. If the test object is not heated or cooled uniformly, variations in surface temperature patterns cannot be solely attributed to the presence of subsurface discontinuities. Similarly, the surface emissivity of the test object should be kept as uniform as possible, especially if thermal input is accomplished by radiative heating.

An additional factor that demands consideration when applying thermographic techniques is the thermal conductivity of the test material. As internal temperature differences are introduced into the object, heat flows from hot to cold regions and interior thermal patterns move toward the surface. This process is governed by the respective thermal conductivity of the material. If the test material has a low thermal conductivity, differences in subsurface temperature patterns are eventually transmitted to the surface and can be detected with an infrared camera. However, in materials with a high thermal conductivity, heat readily dissipates and temperature differences equilibrate before transmission to the surface can occur. Also, the surface temperature differences that develop over defects last for a shorter time period if the material has a high thermal conductivity. Therefore, when inspecting for defects at a significant depth, it is advantageous if the thermal conductivity of the test object is relatively low.

ANALYTICAL MODELING

An analysis based on calculating surface temperature distributions for various transient thermal loadings using the ANSYS finite element computer program was performed.

The transient thermal loads are applied to the finite element model by means of a surface heat transfer coefficient and an ambient temperature given as a function of time. Surface heat fluxes are calculated using the basic equation for convective heat transfer.

In order to perform a reliable thermal analysis, the influence of the differing values for concrete conductivity, specific heat, and density needed to be quantified. The effect of the delamination thickness, cover depth, and effective conductivity on surface temperature response also needed to be investigated.

This analysis shows that the predominant characteristics governing the overall thermal response are crack depth, width, and effective conductivity. These effects govern the thermal response to a much larger extent than the differences in the thermal properties of the concrete.

EXPERIMENTAL PROGRAM

An extensive experimental program was conducted to refine techniques under controlled laboratory conditions, corroborate the analytical modeling, and develop an appropriate procedure for field implementation. Numerous specimens were fabricated of various shapes and sizes, with and without simulated delaminations.

The infrared scanning system used was the AGA Thermovision 780 model manufactured by the AGA Corporation of Secaucus, New Jersey. The system consists of a longwave scanner (8–14 microns), a black and white monitor chassis, a color monitor, and OSCAR (off-line system for computer access and recording). In addition to the Thermovision system, an Omega 650 multichannel thermocouple meter was used for internal and external temperature monitoring of specimens during heating and cooling.

Various methods of heating were employed, including an array of 10 250-W General Electric light bulbs, an industrial grade Reddy space heater, a thermal blanket, and changing ambient air temperature in an unheated laboratory storage facility. Extensive experimental examination was carried out in each of the following areas: edge effects, emissivity effects, thermal input requirements, uniformity of heating, and detectability of simulated defects.

The laboratory effort clearly established that uniform heating of the structure was necessary in order to obtain thermographic information that could be interpreted accurately regarding the presence and location of defects.

FIELD EXPERIMENT

In addition to laboratory testing, a field experiment was conducted to define field parameters. The testing site was an overpass bridge located on Interstate 81 in southwestern Virginia. The substructure elements of this particular bridge are exposed to rundown of deckwash during the winter months. The testing was done on December 1, 1989. Ambient conditions were extremely good. It was clear and sunny the entire day, and winds were minimal. Diurnal temperatures ranged from the low 20's the previous night to the mid 50's by late afternoon on the day of testing. Therefore, the structure experienced a relatively large ambient temperature swing.

Attention was focused on the substructure elements of the northbound traffic overpass. Some elements of the substructure were partially irradiated by sunlight. The substructure elements—diaphragms, pier caps, and columns—were inspected with a ball-peen hammer to identify severely delaminated areas. Several well-developed damaged regions, located in both shaded areas and direct sunlight, were selected for thermographic interrogation. The delaminated areas could easily be identified by hammering; however, they were not evident to the naked eye.

The first delaminated area of interest was located on one of the columns that was not exposed to solar radiation. The column of interest is shown in Figure 1. The delaminated region began 4 ft from the base of the column and extended approximately 6 ft vertically. Laterally, the delamination covered approximately 3 ft (one third of the column circumference). In the photograph shown, the delamination border is located 1 ft to the left and 2 ft to the right of the large vertical crack.

The severe delamination in the column could not be detected with infrared thermography. The thermal image of the column is shown in Figure 2. For this particular thermogram, the infrared camera was positioned such that the vertical border of the delamination was centered in the field of view. No variations in surface temperature were apparent in the vicinity above the delamination boundary.

Similarly, other less obvious delaminations located in shade were not detectable with infrared thermography. Only those regions where severe visible damage was present, in which sections of concrete were almost completely separated from the substructure component, were thermographically detectable.

SUMMARY AND CONCLUSIONS

An analytical and experimental program was conducted to develop a technique for the nondestructive evaluation of reinforced concrete via infrared thermography. Particular attention was given to defining field parameters for implementation of the technique to assess substructure elements of concrete bridges.

Substantial agreement was found, in every area appropriate for comparison, between analytical and experimental portions of the study.

Both laboratory and field testing has indicated that ambient temperature fluctuation does not produce the necessary internal temperature gradients to allow for the thermographic

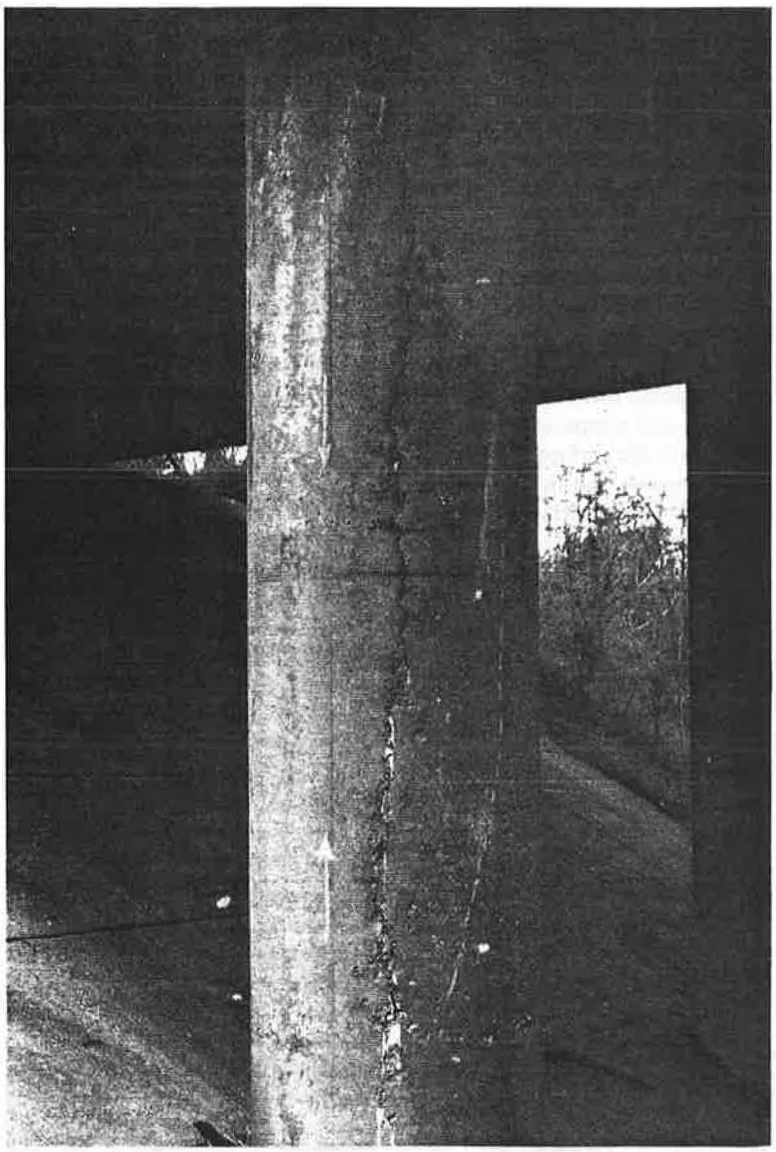

FIGURE 1 Photograph of delaminated highway bridge column.

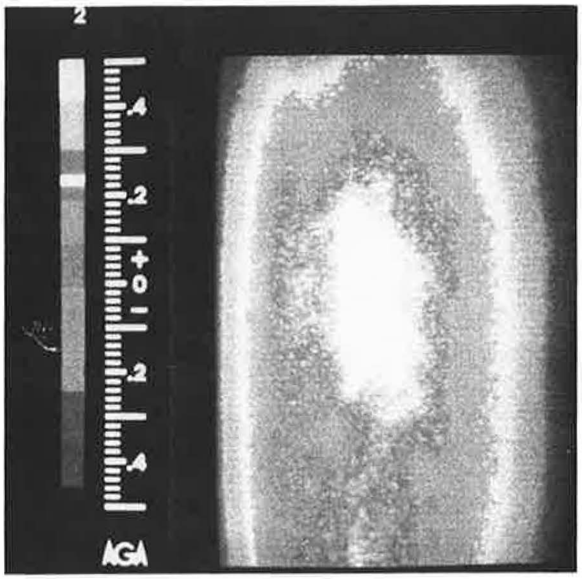

FIGURE 2 Thermogram of column shown in Figure 1, after 3 hr of infrared heating and 5 min of cooling.

detection of defects that are not visually detectable. Instead, only severely delaminated regions, where concrete sections were nearly detached from the structural reinforcement, had a significant thermal response to ambient heating and cooling and were thermographically detectable.

Regardless of the heating method employed, it was critical that input of thermal energy be accomplished uniformly. Uneven heating introduced internal temperature gradients and facilitated lateral heat flow. Because of the slow thermal response of structural concrete, variations in internal temperature introduced through nonuniform heating inevitably influence the development of true surface thermal patterns and complicate the diagnosis of thermograms and identification of damage.

Employment of the IR, or hot air, heating technique would require the use of an insulating material to create an air chamber that encloses the component of interest. Otherwise, efficiency losses would be enormous. Thus, it is the conclusion of this program that infrared thermography cannot be applied in a practical noncontact fashion when external heat sources are used. It is also concluded that diurnal temperature fluctuations are insufficient to afford a comprehensive, reliable assessment of bridge substructures by means of thermographic examination. Further, the field implementation of any thermographic technique is complicated by the wide variance in both structural design and accessibility that exists among individual field cases.

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REFERENCE

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