

DETECTION OF DELAMINATION IN BRIDGE DECKS WITH INFRARED THERMOGRAPHY

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The use of infrared thermography to define very accurately variations in surface temperatures was evaluated as a means of defining delaminated areas caused by corrosion of reinforcing steel in concrete bridge decks. Differences in the temperatures of the deck surface, shown in various shades or colors on a cathode-ray tube, were photographed to provide a permanent graphic record of the location of the warmer, distressed areas. In a comparative study of infrared thermography and conventional deck evaluation techniques, including the sounding of the surface with a hammer and chain drag and the use of a rolling delamination detector, all were found generally satisfactory in locating severe to medium delaminations. However, the infrared thermography procedure had important advantages in disclosing incipient delaminations, those in which the cracking is confined to the close vicinity of the reinforcing steel, and in providing detailed records of the separated areas.

A major problem in the repair of bridge decks is locating the areas of delamination caused by corrosion of the reinforcing steel. None of the available methods of locating delamination are completely satisfactory. The sounding method relies on subjective judgments of the hollow sound produced when the concrete is struck with a hammer or when a chain device is dragged across the deck surface. It is useful only in locating relatively severe delaminations and is subject to interference by traffic noises. A recently introduced rolling delamination detector, the Delamtec, is based on the same "sounding" principle, but it utilizes piezoelectric hydrophones to characterize vibration waves generated by steel tapping wheels striking delaminated areas.⁽¹⁾ Although it is faster than the hammer or chain drag and provides a graphic record of distressed areas, the Delamtec detects only delaminations more than 10 cm (4 in.) in width, and it allows only a relatively narrow coverage of the deck per scan.

There is a need for a more reliable method of delamination detection that is capable of locating not only severe, but also incipient, delaminations with some degree of detail and rapidity. To develop such

method, the authors evaluated the use of infrared (IR) thermography.

Rationale in Delamination Detection with Infrared Thermography

The authors conceptualized that the cracks, or physical separations, in delaminated concrete are occupied by trapped air. Considering the large difference between the volumetric heats of solid concrete and air, which are 30.0 and 0.19 Btu/(yd.³) (°F), respectively, a severely delaminated concrete area would have a volumetric heat lower than that of surrounding solid concrete and consequently would be warmer, given the same amount of solar heating. Conversely, when the solar heating disappears, the delaminated concrete would be cooler than the solid concrete. It logically follows that the more delaminated a spot is, the warmer it would be compared to adjacent sound concrete. This temperature difference could serve to define delaminated areas in concrete if one had a technique, such as infrared thermography, for rapidly mapping an accurate temperature profile of a bridge deck.

Principle of Infrared Thermography

Any object whose temperature is above absolute zero (-273°C or 0°K) emits IR radiation generated by the vibration and rotation of its atoms and molecules. The IR radiation emitted by most objects falls within a band of wavelengths from about 2 to 15 microns (μ), and is proportional to the object's absolute temperature. Thus, the temperature can be indirectly determined by measuring the intensity of the emitted IR radiation.

In IR thermography, a camera (or scanner) that incorporates a sensitive and fast-response IR detector is used to automatically scan an object and produce a thermal image of it on a cathode-ray tube. The two types of detectors most commonly used are the Indium-Antimonide (InSb) photovoltaic detector and the Mercury-Cadmium-Telluride (HgCdTe) photoconductive detector, both of which can detect a fraction of a degree temperature difference at 300°K. Indium-Antimonide has a spectral response of 2 μ to 5.6 μ , while Mercury-Cadmium-Telluride re-

sponds over a range of from 8 μ to 14 μ . These spectral ranges are different from that detectable by IR photographic film which is 0.7 μ -0.9 μ .

The thermal image, or thermogram, obtained with the scanner represents the surface temperature profile of the object under examination. In a black and white picture, which looks something like an ordinary photographic negative, the warm areas are light and cold areas are dark. In some thermal imaging systems, the picture comes out in brilliant colors, with the various tones representing different temperatures.

Study Methodology

In the study, several deck areas, mostly 180 x 360 cm (6 x 12 ft.) in size were tested for delamination with an infrared scanner. For comparison, the areas were also evaluated by sounding with a hammer and chain drag, and a delamination detector. Cores were obtained from selected spots in the test areas to verify the degree of delamination shown on the thermograms.

The scanner system used, the Thermovision Model 75J manufactured by the AGA Corporation of Secaucus, NJ, consisted of a camera unit, a display unit, a power supply, and a color monitor.

The camera unit was equipped with a liquid nitrogen cooled InSb detector and an infrared lens with a 20° x 20° field of view. With the camera set at a comfortable working height of 150 cm (5.0 ft.) above a bridge deck, the deck area covered was slightly larger than 45 x 45 cm (1.5 x 1.5 ft.); and the individual profiles of the 45 cm (1.5 ft.) square areas had to be made into mosaics to obtain composite thermograms of the larger deck areas. For the mosaic to be useable, the camera must be aimed at a right angle to the deck, since any other angle gives rise to problems due to perspective, but it was not possible to point the camera straight down without spilling the liquid nitrogen. To eliminate the perspective problem, the camera was aimed parallel to the surface of the deck and a surface reflective mirror, about 10.2 x 11.4 cm (4.0 x 4.5 in.) in size, was mounted at 45° with its reflective surface directly facing the camera lens to allow focusing of the infrared camera indirectly downright at the deck. The thermogram obtained in this manner is an inverted image, but this presents no problem.

It was also found that solar radiation reflected from the deck surface interfered with the thermogram, and a filter which transmitted only wavelengths longer than 3.5 μ was needed to eliminate the reflection.

To enhance the interpretability of the thermogram, a color monitor was used so that different temperatures were represented by various colors. Specifically, a selected temperature range was divided into 10 isotherm units presented in white, yellow, orange, red, pink, violet, aquamarine, green, light blue, and dark blue, corresponding to the decreasing order of temperature level. Type 108 color Polaroid film was used to record the individual thermograms.

Discussion of Results

Optimum Time for Using Infrared Thermography

A preliminary survey of the test areas confirmed that under direct solar heating a delaminated concrete area is warmer than the surrounding solid concrete. It also revealed that for the best compromise between the maximum detectability of delaminations (i.e., the best definition of severe and even

incipient delaminations by thermography) and the stability of the temperature profile of a deck area, the period from 12:00 noon to 2:00 p.m. would be the ideal time for the use of thermography. (This period may vary in length depending on the time of year and geographic location.)

A Typical Thermogram of the Test Areas and Its Interpretation

In obtaining a thermogram of a deck area, the temperature level setting of the infrared scanner was adjusted so that a severely delaminated spot would show up as the "warmest", or white, in the color monitor. This allowed interpolation between the warmest and coldest colors so that a mediumly delaminated spot might appear one or two isotherm units below white, i.e., as yellow or orange; and an incipient delamination would appear either two or three isotherm units below white, i.e., as orange or red. The remaining cooler colors of pink, violet, etc. would represent the solid concrete. It must be emphasized that the classification of different stages of delamination is relative.

One of the typical thermograms taken in the above manner is shown in Figure 1. This mosaic thermogram, covering part of a test area, was made from individual thermograms of 45 cm (1.5 ft.) squares. In terms of pattern, the thermograms are exact duplications of the original photographs of color thermograms. However, because of the high expense of color reproductions, the warmer colors of white, yellow, orange, and red, in order of decreasing intensity; while the relatively cooler colors are left unshaded because of their relative inconsequentiality.

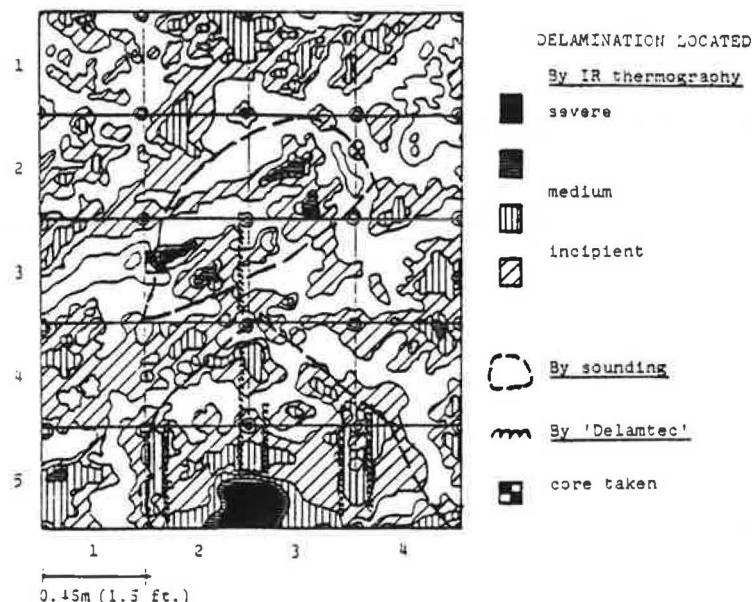
Figure 1 shows few delaminations in the medium stages; mainly the narrow band of intense shade around a spalled area that has been patched with asphaltic concrete (dark area) which overlaps squares 2-5 and 3-5, and the similarly shaded spots in squares 2-3 and 3-2. In addition, the thermogram shows semi-regular patterns, the lightly shaded areas that run approximately 50° with respect to the X-axis of the thermogram. Since this angle is similar to the skew angle of the reinforcing steel and to the direction that the two medium delaminations in squares 2-3 and 3-2 run with respect to each other, these lightly shaded areas must be incipient delaminations occurring around some of the reinforcing steel. Cores obtained from such areas confirmed this assumption.

In order to preclude misinterpretations, infrared thermography must be supplemented with visual examinations. It has been found that spots of asphalt and tire marks appeared warmer than the concrete because they have a relatively higher infrared emissivity, and they can be mistaken for delaminations in the thermograms.

Comparison of Techniques

For comparison, the same deck areas were also evaluated with the conventional deck evaluation techniques of sounding with a hammer and a chain drag and the use of a rolling Delamtec. A chain drag device, made of five 75-cm (2.5-ft.) steel chains connected to and evenly spaced on a metal rod by ropes, was used to make a rapid initial survey of each area. Then, for more precise outlining of any delaminated spots, a hammer was used. In addition to listening for the hollow sound indicating a delamination, the surveyor placed one hand on the deck to feel for vibrations. This practice is be-

Figure 1. Typical thermogram with delamination shaded. (Delaminations located by sounding and Delamtec are superimposed.)



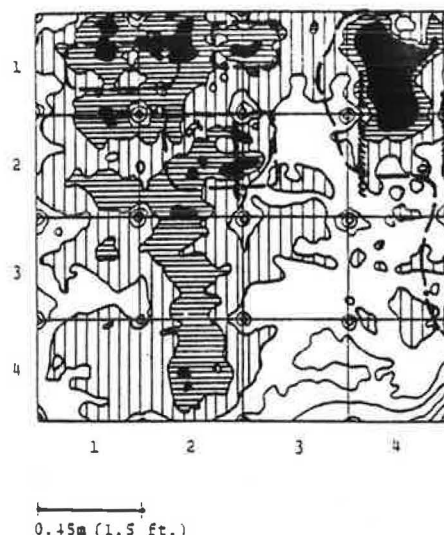
lieved to enhance the reliability of the hammer sounding. The rolling detector was rolled longitudinally over each of the test areas at 46-cm (1.5-ft.) intervals.

In terms of the number of delaminations detected in the test areas, it was found that approximately 95% of those in the medium and severe stages that were identified by thermography were also detected by sounding, while only approximately 85% were detected by the Delamtec. The delaminations missed by sounding with the chain drag and hammer were in the medium stage; such as that extending from square 2-2 down to square 2-4 of Figure 2. However, with the Delamtec, some severely delaminated areas were not detected for unknown reasons. An example is shown in Figure 2, where a few neighboring severe delaminations in squares 1-1 to 3-1 were not located by the Delamtec.

An inherent inadequacy of sounding and the delamination detector is their inability to provide detail, which made it difficult to delineate delaminations accurately. A typical example is again shown in Figure 2, wherein the severe delaminations that extended across the top of squares 1-1 and 2-1 were detected but not properly located by sounding. A similar inadequacy of the Delamtec is shown in Figure 1 where, according to thermography, two medium delaminations, each about 15 cm (3 in.) across, existed in square 2-3. The Delamtec did not detect these completely, as indicated by the presence of the detector signal on only the right side of the square, but a core taken from the left side of the square confirmed the extent of delamination indicated by thermography. A more important advantage of thermography is its ability to locate incipient delaminations. Cores from incipiently delaminated spots had cracks that had not yet completely extended across the core to separate the concrete into at least two layers, as was the case for the cores from severe and medium delaminations.

It must be pointed out, however, the occasional inconsistencies were observed in the correlation between warmth of a deck area and the severity of delaminations. In those cases the cores showed slightly more advanced delamination than the incipient delamination indicated by the thermogram. It is uncertain whether the observed inconsistency is real, or was caused by slight changes of colors in the thermo-

Figure 2. Delaminated areas located by different techniques.



grams that were occasionally observed when scattered clouds interfered with incoming solar radiation. If the inconsistency results from this cause, it can be minimized or probably eliminated by a setup incorporating videotape for rapid recording of the thermogram.

Applicability of Results

The subject research has indicated the suitability of infrared thermography in providing graphic records of delaminated areas in concrete bridge decks. The ability of the technique to disclose incipient delamination is considered particularly promising as this would provide an early warning of oncoming distress. While some degree of experience is necessary for proper interpretation of the thermograms, the problem of training operators is manageable. However, additional research is required for implementation.

With an estimated equipment cost of from \$30,000 to over \$40,000, infrared thermography, as used in this study, is not cost-effective compared to conventional survey techniques. The additional detail provided by the thermograms, while desirable, would not support the high cost differential, and it appears that the application of thermographic techniques to rapidly survey a large number of bridges must be developed for cost-effectiveness. The authors feel that this might be accomplished through the use of videotape recordings, a subject proposed for future research.

Reference

1. Moore, W. M., G. Wift, and L. J. Milberger, "An Instrument for Detecting Delamination in Concrete Bridge Decks", Report 130-4, Texas Trans. Inst., Texas A & M Univ., March 1970.

Acknowledgment

The research was financed by HPR funds administered through the Federal Highway Administration.