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INFRARED INSPECTION OF COMPOSITE-REINFORCED CONCRETE STRUCTURES

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Executive Summary

INFRARED INSPECTION OF COMPOSITE-REINFORCED CONCRETE STRUCTURES

FHWA Report No. FHWA/OH-2001/11

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The Aerospace Corporation

Ohio Department of Transportation - Job No. 14688(0)

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The Ohio Department of Transportation has been evaluating the use of composite reinforcements to enhance the safety margins in concrete deck bridges. Composite reinforcement from several vendors was bonded to the support beams of two concrete deck bridges located in rural Coshocton County, Ohio. A critical aspect of the retrofitting process is ensuring that the composite material remains bonded to the concrete beams that are subjected to prolonged exposure to the elements. The goal of this program was to select and demonstrate an appropriate nondestructive evaluation (NDE) technique for composite reinforced structures. Factors such as technique sensitivity, inspection time, data archiving, and field conditions were considered.

Thermography was chosen as the inspection technique because it has been well established within the aerospace industry for the detection of flaws and damage within composite structures. The technique utilizes anomalies in the thermal properties of the structure to identify sub-surface flaws. Thermography has advantages over more traditional NDE techniques in that it is fast, non-contacting, and capable of monitoring relatively large areas with a single image. A field-portable thermographic technique was developed during this program. The two Coshocton County bridges were inspected at 1-year intervals beginning in June of 1998 and ending in August of 2000.

The results of the program showed:

1. IR thermography can be used to reliably detect and size debonds with an area 6 in² or greater in composite retrofit systems.
2. To perform a satisfactory IR inspection, target heating and thermal soak time prior to the IR evaluation must be controlled. In addition, when evaluating the data, care must be exercised to minimize false positives due to variations in the surface emissivity
3. The IR data has the potential to detect and monitor debond growth. The sensitivity is limited by year-to-year variations in the surface condition of the retrofit material. Better confidence could be obtained by providing a more consistent field of view of the beam, better in-situ location markers, and longer dwell times during the cool-down phase of the inspection.
4. In the current set of data from 1998, 1999, and 2000, no indications were noted that were longer than 1 ft along the axis of the beam and 6 in. across the width of the beam.

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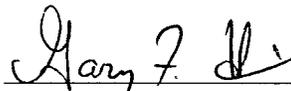
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16. Abstract The Ohio Department of Transportation has been evaluating the use of composite reinforcements to enhance the safety margins in concrete deck bridges. A critical aspect of the retrofitting process is ensuring that the composite material remains bonded to the concrete beams that are subjected to prolonged exposure to the elements. The goal of this program was to select and demonstrate an appropriate nondestructive evaluation (NDE) technique for composite reinforced structures. Thermography was chosen as the inspection technique because it has been well established within the aerospace industry for the detection of flaws and damage within composite structures. A field-portable thermographic technique was developed during this program. Two Coshocton County, Ohio bridges were inspected three times over a two-year interval. The results of the program showed that IR thermography can be used to reliably detect and size debonds with an area six square inches or greater in composite retrofit systems. The IR data has the potential to detect and monitor debond growth. In the current set of data, no indications were noted that were longer than 1 ft along the axis of the beam and 6" across the width of the beam.		13. Type of Report and Period Covered Final Report	
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1. Introduction

Fiber-reinforced composite materials are being developed as a cost-effective alternative to traditional structural materials for the retrofit and repair of concrete structures. These evolving infrastructure applications include seismic retrofitting, improving design margins, and increasing the service life of existing structures. The Ohio Department of Transportation (ODoT) has been evaluating the use of composite reinforcements to enhance the safety margins in concrete deck bridges. Composite reinforcement from several vendors was bonded to the support beams of two concrete deck bridges located in rural Coshocton County, Ohio. A critical aspect of the retrofitting process is ensuring that the composite material remains bonded to the concrete beams that are subjected to prolonged exposure to the elements. Monitoring the bond between the composite and the concrete structure presents numerous challenges when selecting an appropriate nondestructive evaluation (NDE) technique. Factors such as technique sensitivity, inspection time, data archiving, and field conditions must all be considered.

Independent studies performed at The Aerospace Corporation suggest that an infrared (IR) inspection technique is an appropriate tool for evaluating composite retrofit applications. Thermography is already an important tool within the aerospace industry for the detection of flaws and damage within composite structures. The technique utilizes anomalies in the thermal properties of the structure to identify sub-surface flaws. Thermography has advantages over more traditional NDE techniques in that it is fast, non-contacting, and capable of monitoring relatively large areas with a single image.

As part of the overall ODoT investigation into composite retrofitting of the infrastructure, Aerospace is evaluating the application of IR techniques to the field inspection of composite-reinforced concrete T-beams. Of particular interest is the development of a thermographic procedure and related equipment required for the field inspection of the composite bonding process. This study will include the evaluation of both thermal loading and thermal monitoring devices and field testing of the system over a multi-year period.

1.1 Objective of this Study

The objective of this study was to develop a portable IR inspection technique capable of detecting delaminations in composite-concrete bondlines. The technique needed to be quick to perform and robust enough to be used in field applications.

Initial work involved developing a heating system that uniformly distributes the proper amount of heat over a large surface. A portable IR detection and data recording system was constructed and calibrated. Finally, the heater and thermographic system were transported to the bridge site for the inspection. The data were recorded for analysis back at The Aerospace Corporation.

2. Infrared Thermography

Infrared (IR) thermographic inspection techniques utilize localized changes in the thermal characteristics of a structure to indicate the presence of subsurface defects. This type of inspection technique has several important advantages over other standard nondestructive evaluation (NDE) techniques such as tap testing (sounding), ultrasonics, and radiography. These advantages include fast data acquisition and evaluation, simple inspection procedures, and excellent sensitivity to voids and delaminations in composite structures. Thermography has become a standard tool within the aerospace industry for detecting delaminations and debonds within thin composite structures. The application of thermographic techniques to infrastructure inspections required the technique be extended to the evaluation of thicker composite structures located in hostile field conditions.

2.1 Background of Thermographic Inspections

A thermographic inspection is initiated by creating a temperature gradient through the structure by either heating or cooling. The surface of the test structure is then monitored during the inspection period for spatial temperature variations as it returns to thermal equilibrium. These spatial variations can be an indication of internal flaws, such as unbonds and delaminations, that tend to increase the thermal impedance of the structure. The enhanced thermal impedance due to a defect can result in localized surface temperature differentials ranging from less than 0.5°C to more than 3°C , depending on the flaw depth and the thermal characteristics of the structure. The qualitative temperature differentials that must be monitored during a typical thermographic inspection are illustrated in Figure 2.1.

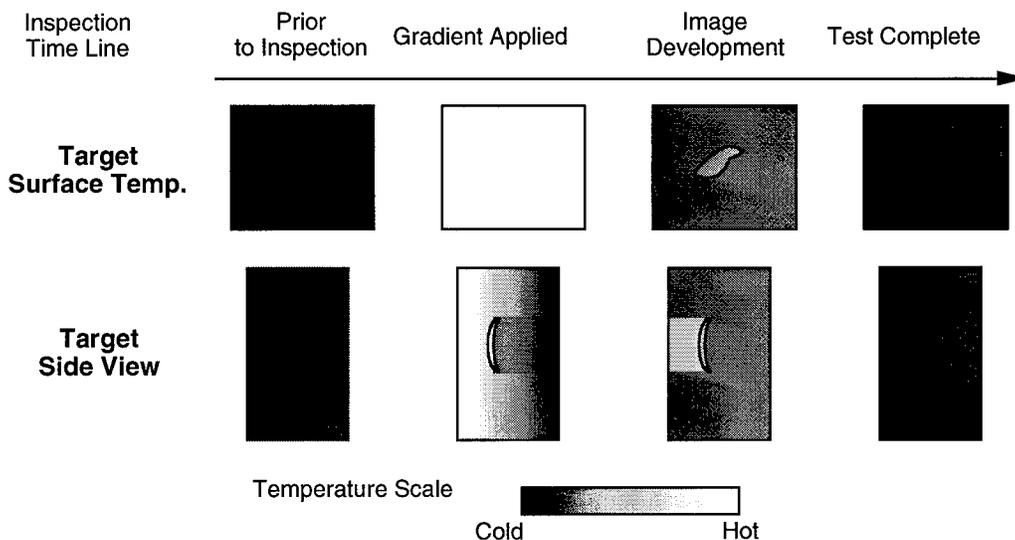


Figure 2.1. Schematic representation of the qualitative temperature differentials that are monitored during a typical IR inspection of a structure containing an internal void.

2.2 IR Imaging Cameras

There are several commercially available IR cameras that have both the temperature and spatial resolution needed to detect the small temperature changes indicative of a subsurface flaw. Other considerations for selecting an IR imager for retrofit inspections include battery operation and fast startup to facilitate field operations. The primary IR camera used for the ODoT inspections was a FLIR 570 camera manufactured by Agema. The battery-operated FLIR 570 utilizes a 320 x 240 pixel, uncooled micro-bolometer detector. It is designed to operate over a spectral range of 7–13 μm with a temperature resolution of $\sim 0.1^\circ\text{C}$. One of the advantages of the FLIR instrument is that it is radiometrically calibrated such that actual surface temperatures can be recorded provided the emittance of the target is known. The video output of the FLIR 570 camera was input into a Sony Hi-8 camcorder to archive the inspection images in real time.

2.3 Thermal Heating

The second aspect for successful IR testing is the generation of a uniform thermal gradient in the target by the application of a heat pulse. Common methods of heating the target include heat lamps, heated water, solar energy, and flash lamps. The selection of a particular heating technique depends on both the thermal properties of the structure (conductivity and heat capacity) and the inspection



Figure 2.2. FLIR model 570 Imager used for the ODoT Investigation.

requirements (defect sizing and depth resolution). For retrofit applications on concrete substrates, radiant heating provided the best combination of convenience, cost, and expandability. Low-power (<500-W) quartz halogen bulbs are the basic heating element for retrofit inspection systems. These bulbs have an active length of ~3 in., are readily available, inexpensive, and the output power can be sized for a particular application. The thermal evaluation of a single bulb showed the hottest region to be at the midpoint of the bulb, with significant cooling out to the ends. Uncertainties in the data evaluation can be minimized if this inherent axial temperature gradient is compensated for in the heater. Experience has shown that the heating artifacts from uncompensated heating techniques can be difficult to distinguish from actual subsurface indications.

2.4 Heater Design

An internal Aerospace investigation was undertaken to determine appropriate bulb configurations that minimize these thermal gradients and incorporate that configuration into a specific heater design. Three different bulb configurations were evaluated, a single bulb, two bulbs along a single axis, and three staggered bulbs. The normalized temperature distributions for each of these configurations is shown in Figure 2.3.

The curves in Figure 2.3 clearly show that the staggered bulb configuration provides the most uniform temperatures of the three cases. This result was incorporated into a heater sized for the 14-in. concrete beams used to support the bridge decks of interest in Coshocton County, Ohio. An image of the bulb configuration is provided in Figure 2.4.

This bulb pattern could be repeated as required to extend the active heating length to match a specific target. The ODoT testing was done using five 300-W bulbs spanning 16 in.

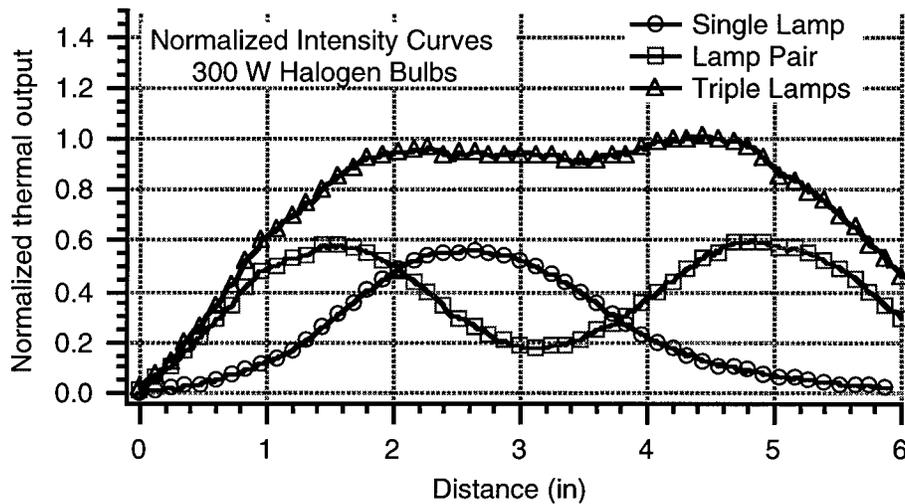


Figure 2.3. Normalized thermal output obtained from three bulb configurations (single, pair, and three staggered). The curves are centered at the midpoint of the bulb arrays.

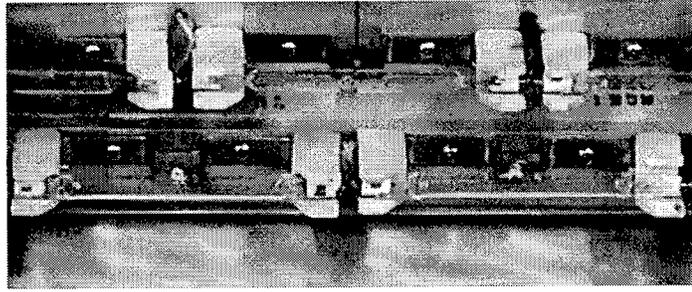


Figure 2.4. Heating element configuration used for ODoT testing.

Another consideration in determining proper test heating is controlling the maximum temperature experienced by the structure. This is a function not only of the bulb wattage but also the speed at which the heater moves. Aerospace experience with inspections of similar composite systems show that a wide range of heat inputs will provide adequate heat to penetrate the structure without damaging the composite. Maintaining a constant lamp speed greater than ~1 to 2 in. per second will ensure that the peak surface temperatures do not exceed the damage threshold for most structural fiber-reinforced composites. The ODoT heater design utilized an electric drive wheel that allowed the speed to be adjusted for specific conditions and ensured that the lamps moved at a constant speed. One major drawback of the lamp heating assembly is the requirement for ac power at the test site with the associated safety concerns. For these experiments, power was supplied with a small commercial generator, extension cords, and ground fault interrupt devices.

3. IR Testing of the Composite/Concrete Interface

Initial trials were performed at Aerospace to determine the feasibility of using the thermographic inspection technique to evaluate the composite retrofit systems supplied by two manufacturers, DFI and Mitsubishi. Steve Morton, project engineer at ODoT, provided samples of these materials bonded to concrete blocks. Each sample contained several debonds created using a spacer forced under the composite during the bonding process. The spacer was removed prior to composite curing, creating a void between the composite and the cement block. The samples were inspected using IR thermography with a quartz-halogen heating source. The resulting images were recorded, and in each case the voids were easily detected. The visible and IR images from the defect samples are shown in Figure 3.1.

The proof-of-concept testing clearly showed the potential for IR thermography to accurately detect voids and unbonds between the composite and the concrete substrate.

Initial testing showed that IR thermography could be applied to the composite retrofitting projects. The challenge was to develop a comprehensive IR field procedure for reliably detecting flaws to some critical dimension. Field testing of IR thermography was performed on two concrete deck bridges located in rural Coshocton County, Ohio. The location of the bridges is shown in Figure 3.2.

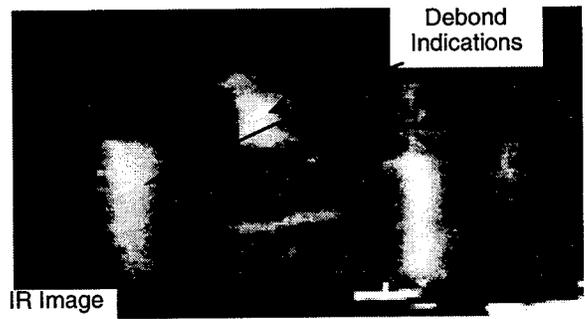
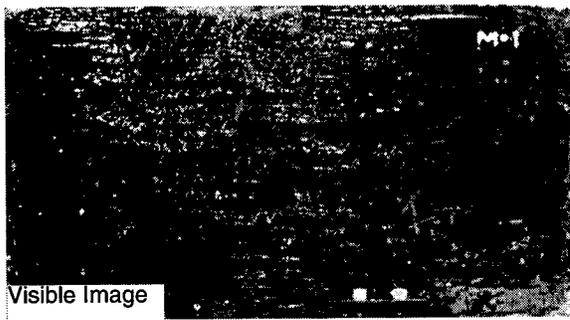
The composite materials were bonded to the underside of the concrete spans to add additional load capability to the bridge. Field testing of the IR inspection system was performed at 1-year intervals beginning in June of 1998 and ending in August of 2000. The goal of this testing was first to locate flaws in the bondline between the applied material and the concrete beams, and second to evaluate different aspects of the IR technique with the goal of improving its potential in this type of application. One of the significant challenges in performing the inspections was contending with the conditions under the bridges. During each of the three inspections there was a combination of mud, running water, and debris that had to be contended with as shown in Figures 3.3 and 3.4.

3.1 Testing of Bridge Spans (August 1998)

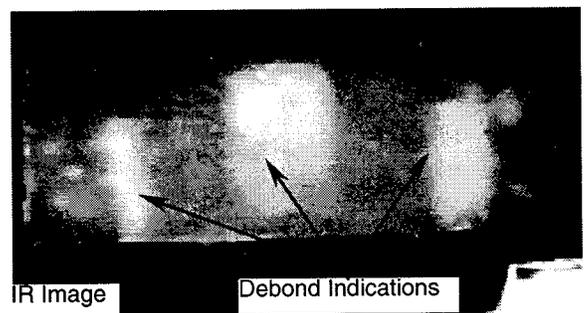
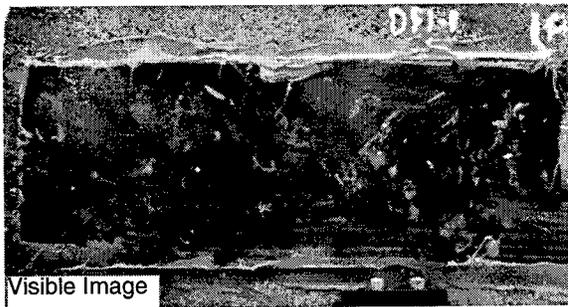
The initial inspection of the two bridges was completed in August of 1998. Numerous indications were noted at that time. A typical example is shown in Figure 3.5.

These indications were confirmed using a resonance “tap test” technique. Tap testing requires an inspector to strike the composite material with a hammer while listening for changes in the pitch that might indicate voids.^{1,2} The IR inspection for each year was recorded on videotape for playback in the laboratory. The evaluation process consisted of reviewing the data tapes for thermal indications of voids. Reviewing the data acquired during the first inspection identified a number of limitations in the inspection procedure to be addressed in follow-on testing. These issues included required modifications to the heating fixture, allowing for better handling of the heating elements in spite of the mud and debris in the inspection area, and changes in how the data was collected. There were two issues

Mitsubishi Gr/Ep Material



DFI Pultruded Composite Material (type 1)



DFI Pultruded Composite Material (type 2)

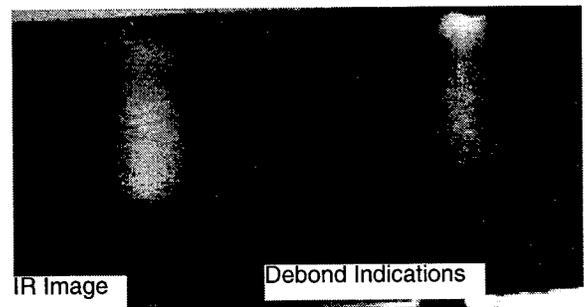
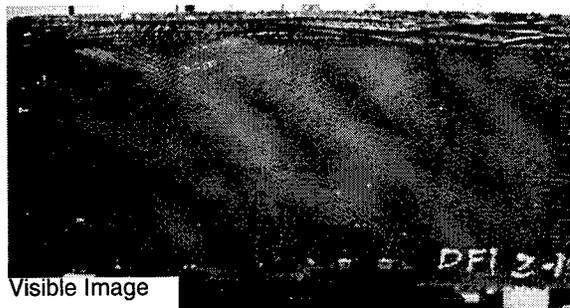


Figure 3.1. Proof-of-concept images for the IR thermographic inspection of the composite retrofitting materials selected for the ODoT study. The lighter areas in the IR images are typical of debond /delamination indications.

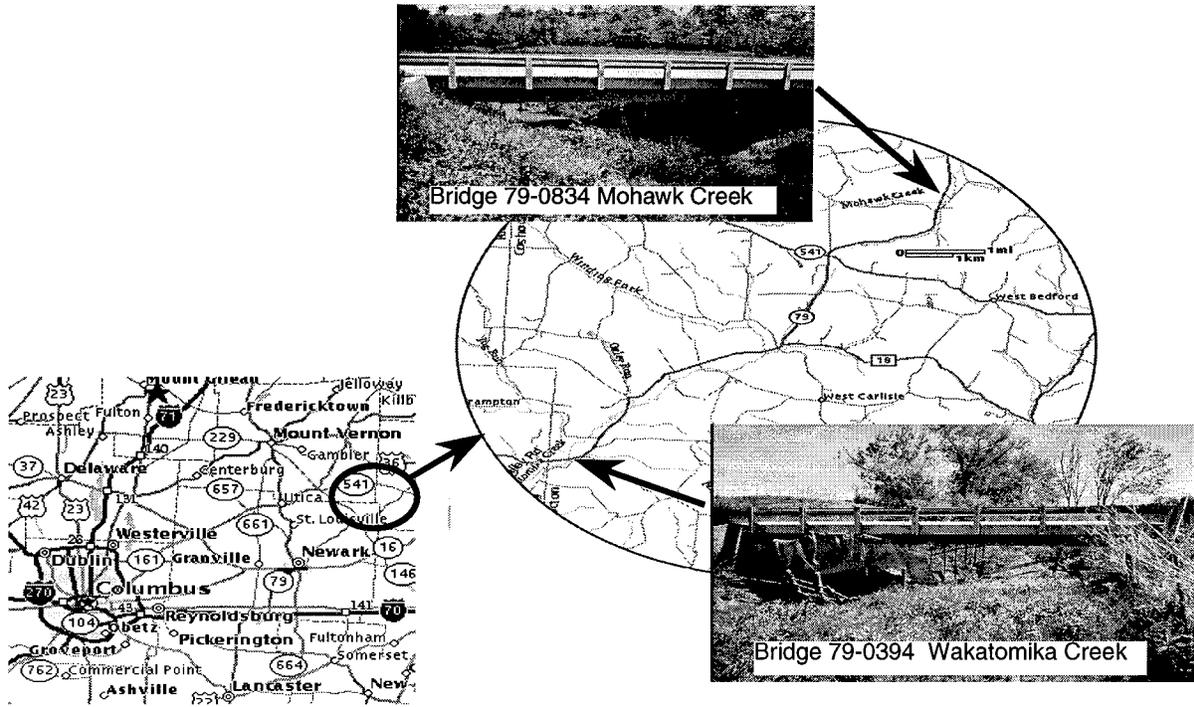


Figure 3.2. Location of the test bridges in Coshocton County, Ohio.



Figure 3.3. Debris and standing water found under the Wakatomika Creek Bridge.

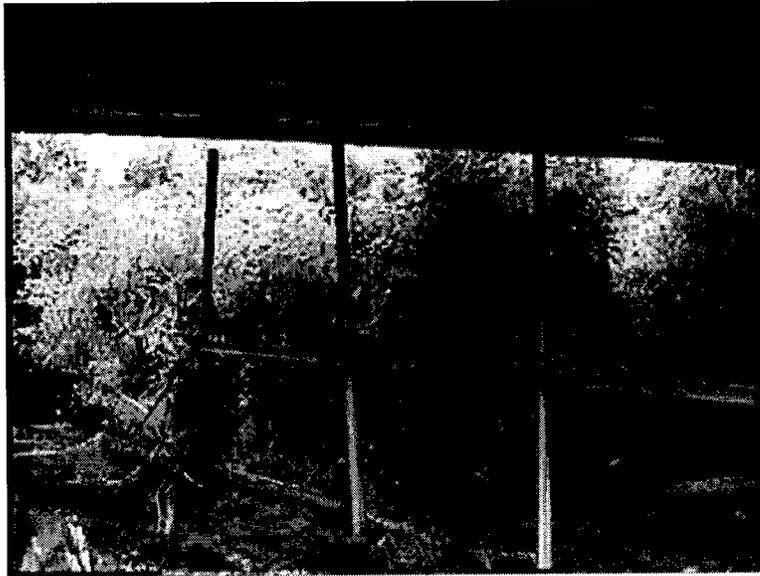


Figure 3.4. Vegetation and mud under the Mohawk Creek Bridge.

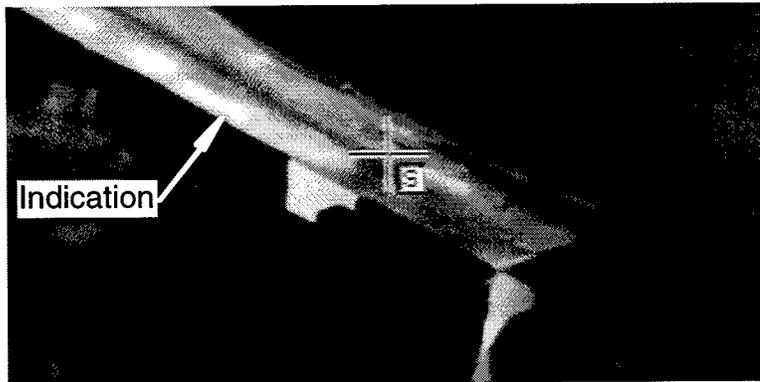


Figure 3.5. Typical IR indication in the composite retrofit material.

to be addressed in evaluating the IR data. The first was the effect that variations in the surface emissivity had on the detection confidence. These localized areas of excess matrix material inherent in the hand lay-up of the retrofit material were exacerbated by the difficulties in applying material to the underside of the beams. An extreme example of this condition was found in the DFI system. During the application of the DFI material, drips and ridges formed in the matrix material. These structures appeared as small hot spots in the IR image. Typical visible and IR images of this drip condition are shown in Figure 3.6.

In addition to the inherent material factors there were several limitations in the initial inspection procedure. After reviewing the data, it was felt that a more consistent dwell time during the thermal evaluation of the composite, better control of the image aspect ratio, and contrast control of the image would improve the inspection results. The images acquired during the initial testing performed in 1998 confirmed the potential of IR testing, but also highlighted a need for additional technique development.

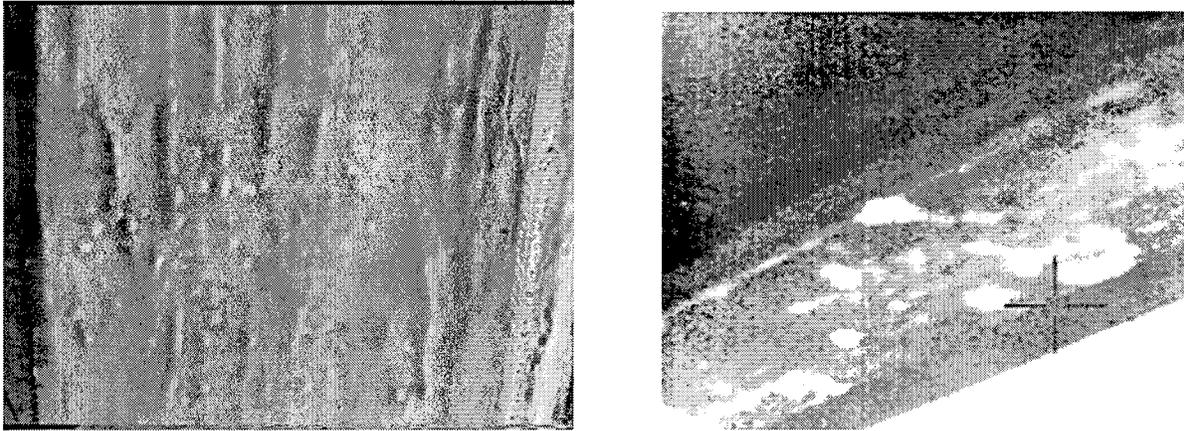


Figure 3.6. Surface condition with the DFI material. These spots of excess epoxy appear as hot spots in the IR image. Note there are several small debond indications in the IR image in addition to the surface indications.

3.2 Testing of Bridge Spans (June 1999)

The second IR inspection was completed in June of 1999. The same heat source was used in both 1998 and 1999; however, an upgraded version of the FLIR 570 camera was used for the 1999 inspection. The inspection was carried out in much the same manner, with the data being recorded to videotape. Several changes in procedure were made for the 1999 inspection. Specifically, additional care was taken to make the inspection dwell time and the field of view consistent. Again, the data was evaluated at Aerospace, and several indications were noted. A typical example of the 1999 data is shown in Figure 3.7.

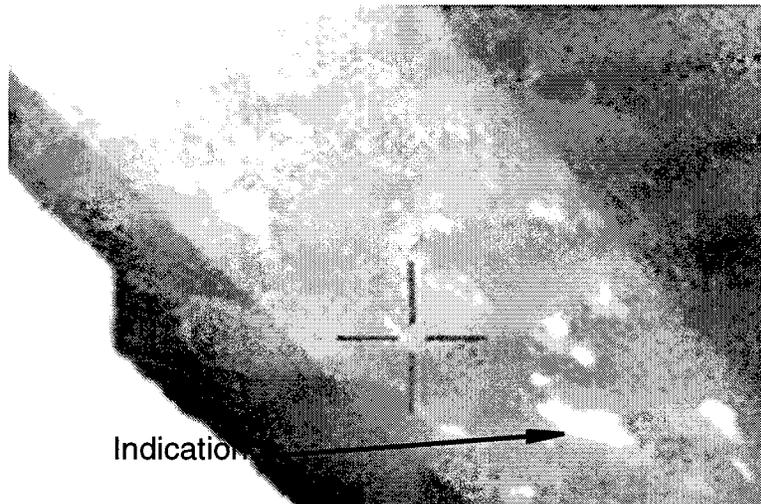


Figure 3.7. Typical IR indication found in the Mitsubishi material.

An attempt was made to evaluate potential flaw growth over the course of a year using data from both inspections. Unfortunately, because of the aforementioned changes in the data acquisition procedure, a direct comparison of the data was not feasible. Overall, the 1999 data provided a better inspection record of the composite systems, and no indications appeared significantly larger than in the initial inspection. Based on previous experience, it would be expected that changes of more than 50% in area could be reliably detected.

3.3 Testing of Bridge Spans (August 2000)

In September of 2000, a final inspection of the reinforced bridge beams was performed. A primary goal of this inspection was to address a deficiency in the previous year's data: specifically, that a method for accurately referencing indications on the tape to the actual beam had to be developed. The initial approach was to use aluminized tape markers constructed in the laboratory as markers. This is a passive marker that utilizes the large difference in the emittance between the aluminum and the composite to highlight a location on the beam. While this worked well in the laboratory, in the field it suffered from a number of difficulties. Not only was it hard to reach the beam to apply the tape, but the surface condition of the composite (dirt, scale) inhibited the adhesion of the tape. Additional work should be undertaken to further address this issue. The actual inspection data was comparable to the previous inspections. Examples of the indications found in the DFI and Mitsubishi material are shown in Figures 3.8 and 3.9.

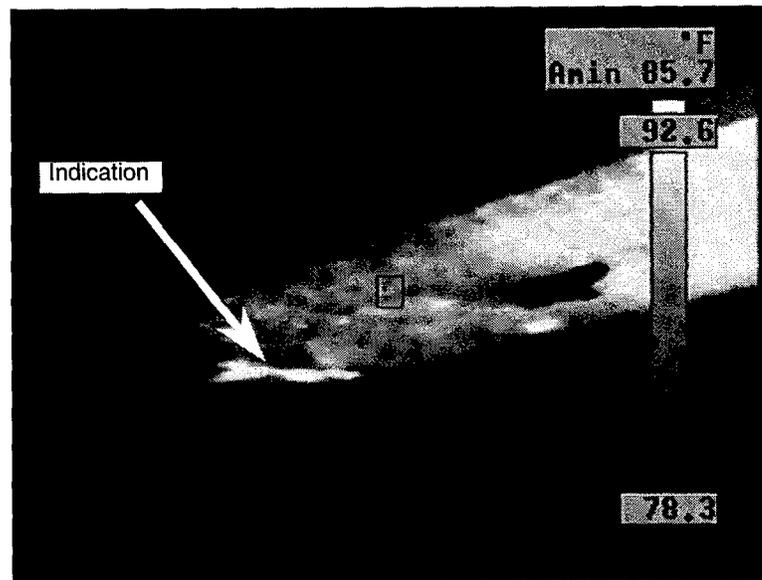


Figure 3.8. IR image of the Mitsubishi retrofit material showing a well-defined indication.

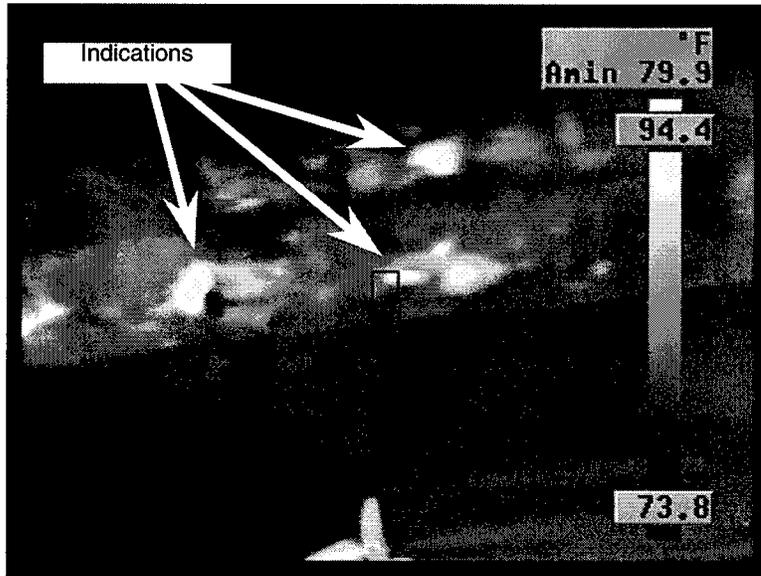


Figure 3.9. IR image of DFI material showing 3 well-defined indications.

4. Conclusions

The development program for the field inspection of bridge beams retrofit with composite materials using Infrared inspection techniques suggests the following conclusions.

- (1) IR thermography can be used to inspect the composite retrofit systems being evaluated by ODoT. In evaluating the data, care must be exercised to minimize false positives due to variations in the surface emissivity. Some of the uncertainty can be avoided by using the calibration samples built for this program that provide a distinct 6-in² debond for comparing to the actual data.
- (2) To perform a satisfactory IR inspection, several test parameters must be controlled. These include, target heating, thermal soak time prior to the IR evaluation, and the camera's field of view. These parameters will ultimately depend on the inspection requirements. They will become more critical when trying to measure flaw growth than simply identifying flawed areas.
- (3) The IR data has the potential to detect and monitor debond growth. The current dataset would require that the surface area of the flaw change by at least 50% to confidently identify growth. This low sensitivity is due to the noise in the IR images caused by variations in the surface condition of the retrofit material. While the variations are inherent in the composite system, better confidence could be obtained by additional work to provide a more consistent field of view of the beam, better in-situ location markers, and longer dwell times during the cool-down phase of the inspection.
- (4) In the current set of data from 1998,1999, and 2000, no indications were noted that were longer than 1 ft along the axis of the beam and 6 in. across the width of the beam.

5. References

1. P. Cawley and R.D. Adams, "Sensitivity of the Coin-Tap Method of Nondestructive Testing," *Materials Evaluation* **47**, May 1989, pp 558–563.
2. D. Hagemaiier and R. Fassbender, "Nondestructive Testing of Adhesively Bonded Structures," *SAMPE Quarterly* **9**, July 1978, pp 36–58.
3. V. P. Vavilov and X. Maldague, "Optimization of Heating Protocol in Thermal NDT, Short and Long Heating Pulses: A Discussion," *Res Nondestr Eval* **6**: 1–17 (1994).

